A TRICKLE RUNS THROUGH IT: AN ENVIRONMENTAL HISTORY OF THE SANTA FE RIVER, NEW MEXICO.

by

Tara Marie Plewa

Bachelor of Arts
Millersville University, 1998

Master of Science
University of South Carolina, 2003

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Accepted by:

William L. Graf, Major Professor

Edward R. Carr, Committee Member

John A. Kupfer, Committee Member

F. James Cumberland, Jr., Committee Member

James Buggy, Interim Dean of the Graduate School

DEDICATION

This dissertation is dedicated to the past and present members of acequia associations in Santa Fe, New Mexico. Your dedication to the land and to each other is a testament to the power of community.

… and to my Dad, who unknowingly reminded me at the moment when I needed to hear it most, that I can do anything.

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ABSTRACT

Over the past four-hundred years in northern New Mexico, the Santa Fe River's evolution from clear mountain stream to dewatered urban ditch is closely tied to basin physiography and landscape processes, governmental and demographic changes, and the conflicting ideologies dividing its finite waters. This research underscores the connection between the natural system and the effects of humans in molding its past and present condition. The Santa Fe River was once the community's lifeblood, providing a means of sustenance and a sense of place. People gave the river animate qualities, treated it as a living part of the community, and shared its water equitably and beneficially. Now the often ignored, dry channel sits several feet below street-level. Past traditions of water allocation and governance via acequia (irrigation ditch) communities are starkly different from the present piping infrastructure, where river water is stored behind dams and delivery occurs at a price. Research objectives include: (1) describing the past and present conditions of the Santa Fe River from a physical perspective, including the effects of human actions on hydrology (flow) and geomorphology (form); and (2) documenting river function throughout the last four centuries of its history, while emphasizing the role of water in the region's initial survival, subsequent growth, current prosperity, and future challenges. This research meets these objectives by applying geographic methods inherent to GIScience, hydrology, and fluvial geomorphology. The digital reconstruction of historical acequia networks, the estimation of irrigation land totals from the rectification of historical maps, and the correlation of streamflow (reconstructed from tree-ring data) to yearly irrigation potential are new methods that connect river water availability and historical events. This research also presents new hypotheses for cienega complex (wetland features) formation in downtown Santa Fe. Findings indicate the influence of acequia agriculture on river hydrology and fluvial geomorphology is underemphasized. This environmental history of the Santa Fe River presents significant findings within a framework of flow, form, and function to elucidate the dominant role of humans in transforming land and water resources at the foot of the Sangre de Cristo Mountains.

PREFACE

It was almost four in the afternoon when I first rolled into Santa Fe. I had spent the previous night outside of Amarillo, Texas, and after having driven for hours over dusty back roads and occasional cattle guards, the mountains that I had watched grow slowly taller over the hours were before me. Even though the calendar read mid-June of 2004, I could see pockets of snow upon their rounded tops and began to anticipate the cool air that would replace the hot, gritty winds that blew through the open windows of my pickup truck. Upon entering the city limits from the south, like any typical tourist I shamelessly followed signs leading me to the visitor's center. Inside, I began to randomly gather glossy colored pamphlets advertising the many sights of this *City Different* just as I had in numerous towns, at national parks, and at natural wonders in the weeks before. This journey was more than a typical youth's rite of passage: a "road trip" beyond picking up hitchhikers, eating foul convenience store food, and taking photographs with buddies while hugging classic symbols of Americana. This trip was about redefining the vision of my future… identifying potential dissertation topics was just a byproduct.

The next morning, after prioritizing my pamphlets and armed with my manual 35mm camera, I set out exploring. By late afternoon, I happened upon the Oldest House: a structure claiming to be the longest standing home in the United States. After paying a single dollar, wandering within the small dark rooms and being handed yet another pamphlet, I moved on. Quite skeptical of the "oldest" claims, I began to read the purple printed paper and took immediate pause. It read, “the river provided ample water for the irrigation of their cornfields.” With this vision in my mind, I immediately set out to find this ample river. Over an hour later, and after inadvertently walking over it a half-dozen times, I noticed that several feet below street level, within a wet-bottomed ditch littered with trash, was a teenager holding a dead fish. I watched as he placed his thumb under its chin and with a swift motion, drew out the guts and flicked them onto the cobbles at his feet. I was immediately intrigued and somewhat confused. Given the state of my surroundings, I knew that he could not have caught the fish in the ditch, but upon approaching him, I asked anyway,

“Is this the river?” thinking perhaps I was just in the wrong place, and that he could simply point me toward the *ample* river where he had caught it.

“Yeah,” he said, while giving me a look indicative of irritation with my ignorance and touristy appearance.

“Does it always look like this?” I asked, still thoroughly confused.

“Yeah,” he said while continuing to flick fish guts onto the ground. “Ever since the dams.”

Beginning to get excited, I pressed: “Well, when were the dams put in?”

“I don’t know… a long time ago. But I bet you could find some old-timers to tell you about when it ran,” he countered.

It was at this moment that I knew I had found my vision. It has taken four years since that encounter to articulate why now only *a trickle runs through it*, but the complex answer to those simple questions lies herein. With the hope that someday *ample* will once again be used to describe it, mis amigos, empecemos...

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INTRODUCTION

¡Feliz cumpleaños Santa Fe, New Mexico! The year of your Cuarto Centenario, 2010, marks a milestone that no other capital city in the United States has yet to reach: you are indeed *City Different*. With this modern slogan, the City of Santa Fe emphasizes its unique standing as this country's longest occupied governmental, military, and ecclesiastical center, and draws attention to place: fostering curiosity about what special intrinsic qualities make it so. The amalgamation of affluence, culture, language, religion, architecture, and art that this beautiful, modern city carefully crafts, and portrays to the outside world contrasts starkly with the reality of its past. Instead, history describes centuries of struggle in the high, arid climate where the small, dilapidated community of poor agrarians, military, and clergymen sustained itself via the unglamorous toils of irrigated agriculture and grazing. For four-hundred years, the delicate balance between settlement success and failure at the foothills of the Sangre de Cristo Mountains in northern New Mexico has been related to the availability of water and its management. Although the character of Santa Fe has changed, the basic arguments over water have not.

This research investigates the Santa Fe River through the last four centuries, pairs evidence of physical landscape change with human actions, and explains the evolution of water resources within the basin through space and time. Scholars familiar with the history of the arid Southwest recognize the presence of the Santa Fe River as one of the reasons for Governor Peralta's initial site selection around 1608, and acknowledge its role in sustaining the people via traditional irrigation practices. The evolution of the river from a clear mountain stream to an entrenched, urban ditch is tied closely to the basin's physical setting and landscape processes, traditional land use practices, law and governmental changes, and the politics dividing its finite waters. This spatial and temporal examination of the physical environment's response to human action brings additional context and unforeseen clarity to many of the historic events found in the research of Santa Fe scholars. This research finds that significant evidence exists for past saturation beneath Santa Fe. Field observations and landscape change detection, streamflow reconstruction and hydrologic regime analysis, channel surveys, archival research, personal interviews, and Geographic Information System (GIS) modeling of physical features and acequia (irrigation ditch) network combine to illustrate the effects of humans on the physical environment. This research contributes novel methods and applies new findings to the history of Santa Fe. These methods, including the conversion of tree-ring chronologies to river carrying capacity for irrigated agriculture, and the spatial reconstruction of a historical acequia network, emphasize the importance of acequia agriculture in river system evolution over the last four-hundred years, and can translate to other areas with similar datasets and histories.

Sustainable river restoration and management decisions are made best when scientists understand system variables and limitations. Geographic study helps unravel the complex and intricate connections between system variables, and thereby explains the interconnectivity between nature and humans (NRC 1997). Such studies are beneficial because they directly link human actions to environmental outcomes, and highlight the relevance of the geographic discipline in both science and policy. In modern Santa Fe, the throes of population expansion, competing interests, water scarcity, and its sustainable management all challenge scientists and policymakers involved in river restoration. River flow helps support a multitude of needs within the growing, multifarious population of 72,000: a highly variable ethnographic landscape of farmers, artisans, professionals, laborers, and civil servants (U.S. Census Bureau 2005). Continued population growth (and tourism) and concurrent increases in water usage limit the natural interactions between the river's hydrologic regime and the land through which it flows. Economic priorities for water distribution override the community mentality that used to be so prevalent here. The Santa Fe River provided a means of sustenance and a sense of place (Acequia Madre de Santa Fe 1995). People gave the river animate qualities, treated it as a living part of the community, and shared its water equitably and beneficially. Now the dry channel sits several feet below street level and is often discounted and ignored by the thousands of tourists that cross its bridges each year. Past traditions of water allocation and governance via acequia communities are starkly different from the present piping infrastructure, where water delivery occurs at a price. A challenge in cooperation and compromise presents itself for the multiple stakeholders whose objectives strive to divide the water differently. Research findings combine the results of quantitative geographic methods, descriptive materials, and archival documents to highlight the evolution of the river from initial settlement through the present. If applied, the findings of this dissertation may lead to a better balance between the two predominant, yet conflicting, river management strategies: a ditch for stormflow conveyance, and the romantic vision of a living river. *A Trickle Runs Through It: An Environmental History of the Santa Fe River, New Mexico* highlights the connections between the physical system and the human actions molding its past and present condition.

1.1 GENERAL RESEARCH OBJECTIVES

The first research objective is to describe the past and present condition of the Santa Fe River and its watershed from a physical perspective, including the effects of human actions on hydrology (flow) and fluvial geomorphology (form). A watershed's geography, or setting, explains the spatial and temporal interconnectivity of its physical elements. Factors of climate, elevation, and geology relate directly to the variations in ground and surface water availability, river geomorphology, and landcover. This research links in-situ physical conditions and human actions to river responses through the explanation of process-form relationships. The result is a highly modified system. Human-induced changes, such as irrigation ditches (acequias), dams, water distribution (piping) infrastructure, in-channel aggregate mines, wastewater treatment plant discharges, groundwater well withdrawals, erosion controlling check-dams, and constricting channel walls all contribute to an unstable, artificial river that is disconnected from its floodplain and that fails to flow for a majority of the year. A GIS database, supplemented with aerial photography, satellite imagery, precipitation and river discharge data, supports the research outcome.

The second objective is to document Santa Fe River function throughout the last four centuries of its history, while emphasizing the role of water in the region's initial survival, subsequent growth, current prosperity, and future challenges. Geographically, the City of Santa Fe was sited near available water, as were several pre-Columbian pueblos within the watershed (evidence of which is found in downtown Santa Fe, the

Village of Agua Fria, and La Bajada) (Spiegel and Baldwin 1963). The community grew slowly from agropastoral beginnings, supported by river and spring water via irrigation. Water was, and still is, diverted from the river and delivered to crops through a network of unlined gravity-driven ditches called acequias. Acequia managers, or mayordomos, control water distribution through the ditches by opening and closing a series of gates. The water distribution, ditch operation, and maintenance rules brought to Santa Fe by its founders are based on Moorish influences in Old-World Spain (Meyer 1984). Through centuries of oral traditions, acequia communities establish close connections with the land and with each other, continuously seek balance between water availability and distribution, and believe in water's equitable and beneficial use (Rivera 1998). Acequia communities and their oral traditions contrast with the ideas about land and water brought to Santa Fe by Anglo Americans. The clash of ideals makes for a unique and dynamic history that plays out on the land. The history of the river includes water company foundations and infrastructure construction, prior appropriation disputes and adjudication requests, land use and channel changes, and conflicting water management strategies.

Changes in political control strongly influence the history of Santa Fe and the manipulation of water resources within the basin. Ruled by Spain (1590s to 1821), Mexico (1821 to 1846), and the United States, first as a territory (1846 to 1912) then as a state (1912 to present), northern New Mexico's water management connects strongly to its contemporary governing body. The complex nature of Santa Fe's water resources currently are further complicated by the numerous entities involved in its management. The river itself is owned/managed in part by the USDA Forest Service (USFS), the City of Santa Fe, Santa Fe County, the U.S. Bureau of Land Management (BLM), the New

Mexico Trust for Public Lands (State Land Office) and The Nature Conservancy (both non-profit groups), and private entities and persons. With so many stakeholders, cooperation and compromise are required for collaborative management to occur. This research provides direct evidence to show that managing the river in small reaches based on land ownership creates several pieces of a puzzle that do not fit together. In order for the river to function as a system, it must be managed as such.

1.2 DISSERTATION RESEARCH QUESTIONS

1. Over the past four centuries, how have the effects of humans transformed the hydrology and fluvial geomorphology of the Santa Fe River?

2. Over the past four centuries, how have humans influenced the evolution of land and water resources in the Santa Fe River Basin?

1.3 PRESENT RESEARCH NEEDS, INTENDED AUDIENCE, AND EXPECTED SIGNIFICANCE

As part of the Clean Water Action Plan initiated by President Clinton in 1998, New Mexico identified the Santa Fe River watershed as urgently needing restoration (Grant 2002). In 2007, American Rivers named the Santa Fe River the most endangered river in the U.S. (American Rivers 2007). The city relies on the river to fulfill about 40 percent of its needs, which have increased in concert with urban expansion and tourism (Grant 2002). Growing water use produces several environmental consequences: aquifer drawdown, no groundwater-surface water interaction, complete dewatering of the river, riparian ecosystem desiccation, loss of biodiversity, stream-bank destabilization and failure, and channel incision (*ibid.*).

Since statehood, studies have attempted to quantify river and groundwater availability (State Engineer's Office 1919; Murray 1946; Spiegel and Baldwin 1963; Santa Fe City Planning Department 1971; Consulting Professionals, Inc. 1975; State

Engineer's Office 1976; Woodward-Clyde Consultants 1980; Lee Wilson & Associates, Inc. 1984; Glorieta Geosciences, Inc. 1985; Harza Engineering *et al.* 1988; Fleming 1989; Thomas 2000; Camp Dresser & McKee Inc. 2001; City of Santa Fe 2001; City of Santa Fe 2008).[1] However, most of these studies failed to address the relationship between landscape conditions and the effects of human action on the river (from both a hydrologic and geomorphic perspective). As a result, elements of river restoration initiatives have been less than successful because they miscalculated system responses and downplayed the importance of understanding the current, highly modified landscape dynamics. Now, as river restoration initiatives are becoming larger, more heavily funded, and more important to watershed residents, the need for a comprehensive study of basin hydrology, process-form relationships, and the effects of human-induced landcover change on the river system is becoming more critical for sustainable restoration success. This research fills the current void in the literature by deconstructing the hydrologic and geomorphic conditions of the river, and informing basin managers and river restorers of system limitations prior to design and construction. The National Research Council (1997: 34) recognized that "efforts to understand the feedbacks among environmental processes, including human activities, also are central to the geographic study of environmental dynamics." Without the application of the research findings contained herein, continued restoration efforts are bound to contain design flaws.

This dissertation is authored to benefit three specific audiences: (1) Santa Fe River and watershed stakeholders and their restoration initiatives; (2) basin managers, scientists, and academics working in arid, urbanizing watersheds; and (3) anthropologists and historians of the Hispanic Southwest. This work is likely to also be informative to an educated general readership interested in the history of Santa Fe or of water in the American West; however, the framework of this document is constructed to benefit a scientifically oriented community. A historical narrative presents significant findings resulting from hydrologic, geomorphic, and GIScience techniques. Endnotes contain details of each technique, so that water resource scientists interested in replication can do so in other environments with similar datasets and histories. Watershed managers, both in Santa Fe and beyond, will benefit from the findings of this work through its framing and presentation of complex system dynamics, process-form relationships, and physical landscape evolution. Prior to the completion of this dissertation, water resource investigations in Santa Fe continued to compartmentalize the system by political jurisdiction or reach geography, and continued to devalue the importance of understanding landscape evolution when formulating restoration strategies and initiatives. As a result, restoration initiatives, based on incomplete information, have fallen short of their objectives due to design flaws. Anthropologists and historians of the Hispanic Southwest will glean new insight into Santa Fe's historic events through their pairings with scientific methods and outcomes (specifically the annual streamflow reconstruction from tree-rings, the digital reassembly of the historical acequia network, and the deconstruction of the cienega[2] complex's formation).

The outcome of this research is a synthesis of geographic techniques. In 1997, the National Research Council described how geography attempts to "understand how different processes and phenomena interact in regions and localities, including an understanding of how these interactions give places their distinctive character" (NRC 1997: 30). In Santa Fe, the interactions between the land, water, and people have shaped the basin's character over time. This project is significant because it highlights the importance of geography in combining scientific data; geographic information technologies; and social, political, and historical themes to construct an understanding of current conditions. This study also provides the foundation for river management from a watershed perspective, and fills local research needs by integrating past studies and histories with current condition analyses. Research conclusions offer recommendations for future system management. As a showcase for data integration, this research provides a useful example of how to frame a resource management strategy wherever water is scarce. To reunite the system into a dynamic and functioning river, it cannot be examined in separate pieces: all must be integrated together via geographic inquiry.

1.4 RESEARCH OUTCOME

Beyond these introductory pages, Chapters 2, 3, and 4 introduce the setting, detail relevant literature, and describe research methods, respectively. Chapters 5, 6, 7, and 8 present research findings and meet the stated objectives through the organization of materials based on reach geography and subject. Chapter 5, Santa Fe River Flow, includes discussions of streamflow geography through space and time, the reconstruction of annual river discharge and irrigable carrying capacity from tree-ring chronologies, the influence of irrigated agriculture on streamflow, and the effects of dams on the hydrologic regime. Within Chapter 6, Santa Fe River Form, are reach-level geomorphic descriptions of past and present planform and cross-sectional geometries, as well as the effects of resource extraction, dams, and other human-induced landscape changes on fluvial geomorphology. Chapter 7, Santa Fe River Function, details the functions of the river in its upper, urban, and lower reaches, and presents new methods and findings on

Santa Fe acequias from a physical and institutional perspective. This chapter includes a section published by the School for Advanced Research, compiled to celebrate Santa Fe's 400th anniversary. Chapter 7 also presents hypotheses on the formation and historic importance of the cienega (swamp) complex in downtown Santa Fe. Chapter 8, The Living River, synthesizes the birth of environmental awareness and river restoration initiatives within the watershed from 1985 through the present. The steps taken to bring life back to the river include watershed studies, "channel restoration," changes in landscape management and dam operations, and efforts to bring water resources management to the forefront of public and private endeavors. Chapter 8 offers recommendations for river management and projections for the watershed. Conclusions lend understanding to the complex evolution of water resources over the last four-hundred years, and offer useful connections between basin residents and their effect on the physical system. "Providing a historical context for evaluating present conditions may be one of the most important uses of historical knowledge as we face increasing concerns about human-caused environmental changes in the 20th century" (Swetnam, Allen, and Betancourt 1999: 1201). In Santa Fe, such knowledge is required for effective existing and future water resource management, given the growing population, limited water sources, and the unknowns of global climate change.

PROJECT SETTING

35° 37’ 3.28” N 106° 4’ 13.11” W

2.0 CHAPTER OVERVIEW

Deconstructing Santa Fe River flow, form, and function within the context of human-induced change requires a foundation of information about basin-level conditions and landscape processes. In this study, geographic inquiry unravels the connections between site and situation: a coalescence of independent factors that drive basin processes. The river’s location in northern New Mexico connotes a distinguishing fabric of physical landscape conditions and social history. This fabric sets the stage for explaining past and present river hydrology, fluvial geomorphology, and the landscape expression of environmental-societal interactions within the watershed. Physical changes in the river and the distribution of landscape conditions correlate closely with this fabric, and adjust in the downstream direction from the river’s headwaters to its mouth.

This dissertation defines and organizes this research by dividing the Santa Fe River and its watershed into three distinct reaches. Though historically the river reflected a continuum of process-form relationships, this study defines these three divisions based on modern landscape conditions. The scale of the study area is the sub-basin unit, which limits the breadth and depth of the work to a manageable level of landscape description. This chapter describes the project setting (2.1), basin weather and climate (2.2), geology and groundwater dynamics (2.3), hydrology and water quality (2.4), landcover and vegetation (2.5), and land use and land ownership (2.6).

2.1 PROJECT SETTING: THE CITY OF SANTA FE AND ITS WATERSHED

Currently, the City of Santa Fe covers 14 percent of the watershed. In 2001, approximately 87,700 people lived in the city and surrounding area (Bureau of Business and Economic Research 2005). As the state capital of New Mexico, Santa Fe has continued to be a major governmental center in the region since settlement. New Mexico state agencies, legislature and judicial courts, the City of Santa Fe and Santa Fe County offices, as well as the offices of several federal agencies, are within close proximity. Most employment is concentrated in the sectors of government and tourism, which together generate the majority of city revenue. The city receives between one and two million visitors each year: thirty percent are meeting attendees who stay 3 to 4 days, while 70 percent are tourists whose lengths of stay varies between 4 and 5 days (Santa Fe Convention and Visitors Bureau 2008).

Because tourism is such a major economic contributor, the city carefully controls the modern landscape to create an experience for tourists through historicity and enforcement of the architectural Santa Fe style. In the year of statehood (1912), the Santa Fe Plan set the stage for the city's remaking as an exotic tourist destination. Through the manipulation of cultural and historical symbolism, the city sought to reverse its failing economy by attracting visitors seeking history, art, and culture (Wilson 1997). Although the city's appearance had been modernizing after the railroad's arrival in 1880, the Plan pulled from several selected architectural elements to define the Santa Fe style (known as Spanish Pueblo revival), and reversed the hodgepodge of structures and features that were reflective of its changing demographics. Named "City Different" by the Visitors Bureau, modern tourists visit Santa Fe to shop downtown amid the large, (yet unhistorical) adobe buildings. The low, pueblo-styled buildings are painted earth tones to simulate a blending with nature, and to project a romanticized image of a harmonious and minimalistic past. "Santa Fe has created an unusually successful illusion… they deny their modern origins, while claiming historical authenticity" (Wilson 1997: 4). Long-standing residents, critical of the false scene portrayed by the city, often refer to the downtown environment as "adobe Disneyland."

Within the Santa Fe River drainage basin, the river's makeup changes as it flows through varying topography, geology and climate; thus, the river's headwaters bear little resemblance to its mouth. Within this small sub-basin of the Rio Grande, the Santa Fe River is approximately 74 kilometers (km) in length (46 miles (mi)), and drains an area of 665 square kilometers (km^2) (257 square miles (mi^2)). The headwaters begin in Santa Fe Lake, an alpine pond in a glacial cirque, located high in the Sangre de Cristo Mountains. Here, in the highest part of the watershed (3,782 meters (m) (12,408 feet (ft)) above mean sea level (msl)), steep slopes average 36 percent, and in some locations, approach 40 percent. The central part of the watershed has an average elevation of 2,073 m (6,801 ft) above msl. Slopes become more gradual beyond the mountain front, and average 9 percent. Gently rolling hills and dry drainages characterize this central third of the watershed. As the river flows southwest toward its confluence with the Rio Grande (at an elevation of 1,591 m (5,220 ft) above msl), it passes through the watershed's lower third: upon entering the Caja del Rio (the *box of the river* formed by a Quaternary basaltic extrusion), the river slope decreases to approximately 5 percent.

2.2 BASIN WEATHER AND CLIMATE

In this region of the arid Southwest, for every 1,000-foot change in elevation, the mean annual temperature will vary by 3° Fahrenheit (Pratt and Snow 1988). Near downtown Santa Fe, warm summers range from 55˚ to 86˚ Fahrenheit, while cool winters range from 14˚ to 40˚ Fahrenheit (Western Regional Climate Center 2009). There is also a strong correlation between increasing elevation and increasing precipitation through the basin. On average, the highest portion of the watershed receives 89 centimeters (cm) (35 inches (in)) of precipitation each year, and is the only area receiving an annual net gain (Grant 2002). The central part of the watershed receives about 30 cm (12 in) of precipitation annually, while in the watershed's lower third, precipitation totals only 20.3 cm (8 in) a year. The lack of atmospheric moisture in the lower two thirds of the watershed emphasizes the importance of groundwater in sustaining river baseflow.

Watershed site and situation strongly control synoptic and climatic variability. The study basin lies within the Sangre de Cristo range on the eastern side of the Rio Grande trough, and is oriented in a southwesterly direction. These specifics place the basin within a dynamic region influenced by global atmospheric circulation patterns, sea surface temperatures, and local topography. These influences combine to dominate seasonal synoptic patterns in precipitation and multidecadal periodicities in climate trends. There is much attention to these topics in the current climate literature of the southwestern U.S. (Hidalgo and Dracup 2003; Ni *et al.* 2002; Meko and Woodhouse 2005; Guan, Vivoni, and Wilson 2005). A more advanced treatment of these topics is beyond the scope of this research; however, the annual, decadal, and century timescale linkages between these trends and the river's hydrologic regime warrants a basic review. The Santa Fe River basin's distinct synoptic and climatic influences include winter moisture from mid-latitude cyclones, summer convective activity from the North

American Monsoon, the El Niño Southern Oscillation (ENSO), and the Pacific Decadal Oscillation (PDO) teleconnections.

The majority of precipitation to the Santa Fe basin each year originates with winter frontal activity, and North American Monsoon summer convective activity. When temperatures are below freezing, snowfall from frontal activity is caused by moist air being pushed onshore by westerly winds originating from the clockwise rotation of the subtropical Pacific high. After traveling eastward from the Pacific Ocean and upon encountering the western facing aspect of the Sangre de Cristo Mountains, the moist air is forced to rise orographically, subsequently cools, and produces snow (Rose, Dean, and Robinson 1981). Maximum snowfall events occur in January and February. Snow accumulations in the alpine tundra are usually deep (tens of feet) and long lasting (approximately 6 months) (Grant 2002). The annual snow volume delivered to the upper watershed depends upon the combination of winter moisture availability and temperature, and is reflected in the periodicity of long-term climatic events. Melting snow generates the majority of river discharge and creates perennial, gaining-stream conditions in the upper reach. The hydrologic regime reflects seasonal patterns of snowmelt in the timing, duration, frequency, and magnitude of flows. Snowmelt is characteristically of high quality and contains low amounts of suspended sediment (Uday 2004).

During summer months, a singularity dominates precipitation across the arid Southwest. Referred to in the literature as the North American Monsoon (Adams and Comrie 1997), the pronounced increase in rainfall typically begins in July when midtropospheric flow changes from a westerly to easterly direction, and lasts until mid-September (Douglas *et al.* 1993). In Santa Fe, July receives more precipitation on average than any other month (Western Regional Climate Center 2009). "The combination of seasonally warm land surfaces in lowlands and elevated areas together with atmospheric moisture supplied by nearby maritime sources is conducive to the formation of a monsoonlike system" (Adams and Comrie 1997: 2199). Violent, typically localized thunderstorms deliver most precipitation in large volumes over short durations. Although there lacks a consensus on the origins of moisture feeding these convective systems, scientists do agree that "New Mexico appears to be the state most influenced by the monsoon in the United States" (Douglas *et al.* 1993: 1669). This pattern appears affected on a synoptic and mesoscale, but "is not strongly linked to El Niño or other common sources of interannual circulation variability" (Adams and Comrie 1997: 2197).

Besides these seasonal synoptic patterns, there exist long-term, decadal and multidecadal oceanic-atmospheric influences that affect precipitation in northern New Mexico. The departure from long-term mean ocean temperatures in Pacific waters that spread westward along the Equator result in El Niño/La Niña events (Redmond 1998). These coupled oceanic-atmospheric phenomena periodically fluctuate every 3 to 7 years. During El Niño, warmer ocean waters generate excessive atmospheric moisture, and due to global circulation patterns, create wetter than normal winters in the southwestern U.S. Winter temperatures during El Niño tend to be cooler than normal in this area, and coupled with above average moisture, typically yield a deeper snowpack (Redmond 1998). La Niña events are the inverse of El Niño, generating warmer and drier than average winters to northern New Mexico. El Niño and La Niña are not complete opposites: within the higher elevations of the Sangre de Cristos, the expression of La Niña tends to be less reliable than its counterpart (National Oceanic and Atmospheric

Administration (NOAA) 2009). This climate signal is counter to generalities mentioned in the literature by Redmond (1998), who stated, “there are no exceptions” during the past 65 years to the dry winters of La Niña’s in the Southwest. Yet NOAA (2009), while reporting on collected data within New Mexico’s climate division 2 (the location of the Santa Fe basin), found “there are years during which a La Niña was in progress but the winter season had above normal precipitation.” These conflicting findings illustrate the variability within the academic literature depending on the study area.

Climatologists often describe El Niño and La Niña in combination with the Southern Oscillation, a global atmospheric pressure signal that reflects opposing barometric pressures at Darwin, Australia and Tahiti. Although the Southern Oscillation pertains to both pressure oscillations, “[b]ecause more attention has been devoted to El Niño,… the research community began to refer to the combination as ENSO (El Niño/Southern Oscillation)” (Redmond 1998: 2). To follow trends in the literature, this research will refer to El Niño events as warm ENSO, and La Niña events as cold ENSO. In Santa Fe, there is a strong relationship between ENSO timing and strength, and annual streamflow discharges reconstructed from tree-ring data (Chapter 5, Section 5.2.1). In the southwestern U.S., the PDO also influences the relationship between ENSO and winter precipitation (Gutzler *et al*. 2002). The PDO has similar climatic characteristics as ENSO but different temporal behavior; oscillations in sea level pressures and sea surface temperatures yield a cycle of PDO events on a 20 to 30 year recurrence interval (Mantua 2009). When examined independently, Guan, Vivoni, and Wilson (2005) found PDO to be a more dominant influence on winter and spring precipitation in northern New Mexico than ENSO, although higher elevations modulate the effects. Given its setting, this research recommends a more thorough investigation of PDO effects on streamflow in the Santa Fe basin to determine the degree of elevation modulation.

2.3 GEOLOGY AND GROUNDWATER DYNAMICS

The severe drought of 1946 accentuated the need for more detailed information on geologic conditions in Santa Fe. Potential groundwater availability beneath the city was unknown, and water managers desperately sought more comprehensive data than was contained in the available regional geologic descriptions. As a result, the first comprehensive mapping project began in the early 1950s. This work, compiled by Zane Spiegel and Brewster Baldwin in 1963, includes four 1:24,000 quadrangles that cover the central third of the watershed. Their mapping project was the first to detail stratigraphy, unit nomenclature, and structural conditions for the area. Their work has become an invaluable resource for scientists and water managers to understand the complex interactions between surface and groundwater. This dissertation research completes the rectification and digitization of these four geologic quadrangles in a GIS.[3] The result, a seamless geologic layer covering a majority of the watershed, is helpful in discerning the spatial relationships between landscape factors, and presenting hypotheses on river flow, form, and function (Figure 2.A).

The Santa Fe watershed is on the eastern side of the Rio Grande trough (a structural depression about 64 km (40 mi) wide). The Sangre de Cristo Mountains on the east and the Sierra Nacimiento on the west flank the trough. These two north-south running ranges are part of the lower Rocky Mountains. Geologists classify the trough as part of the Basin and Range physiographic province (Spiegel and Baldwin 1963). The

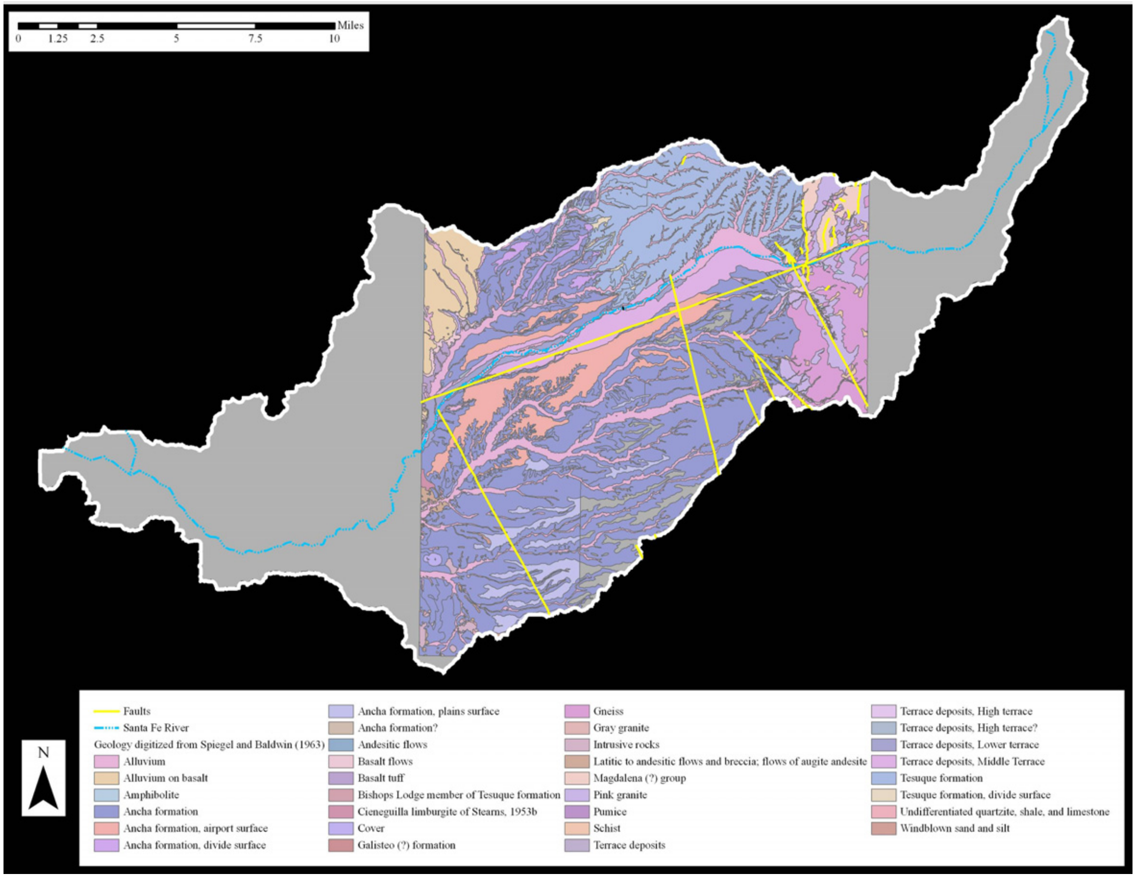


Figure 2.A. Digitized geology layers from Spiegel and Baldwin (1963)
Source: map and layers by author (2009)

Santa Fe watershed runs from east to west, and consists of three major physiographic regions: high mountains in the east, a basaltic mesa that forms the north and west drainage divides, and a piedmont of westward-sloping sedimentary units covering the majority of the watershed's central area. The high mountains of the Sangre de Cristo range are comprised of foliated metamorphic Precambrian and Pennsylvanian-aged rocks. Compared to the weathered, rounded peaks of the highest reaches, the mountain foothills (between 2,134 m (7,000 ft) and 2,743 m (9,000 ft) above msl) are highly faulted and appear rugged and youthful. The Caja del Rio, a basaltic-capped Quaternary intrusion, forms the northern and western watershed boundaries. Geologists believe the river had a westerly trend for the majority of its length before intrusives originating from the Valles

Caldera blocked its path and redirected it southward before it successfully dissected the igneous rocks and rejoined the Rio Grande.

At the base of the Sangre de Cristo Mountain foothills (approximately 2,134 m (7,000 ft) above msl), slopes become more gradual as the river flows through a piedmont of Tertiary and Quaternary sediments of the Santa Fe Group (Grant 2002). These units grade from east to west. Geologists describe these units as the Rio Grande trough's basin fill, which include both terrace deposits and channel alluvium (Spiegel and Baldwin 1963). The major formation of the Santa Fe Group is the Tesuque formation; a pinkish-tan silty sandstone that is several thousand feet thick, and that dips to the west by about ten degrees. The Tesuque formation is an alluvial deposit that was laid down rapidly during the block faulting of the Miocene. The composition of the sandstone is primarily the Precambrian rock of the eastern sierra. Though it has only moderate porosity, the Tesuque is the main aquifer unit of the watershed: groundwater originating from the Pleistocene epoch is at a depth of 610 m (2000 ft) in this unit and does not receive recharge from current precipitation (Johnson 2004). The Ancha formation of unconsolidated, poorly sorted gravels, sands, and silts, sits atop an erosion surface of the Tesuque with angular unconformity (Figure 2.B). The Ancha grades from very thin in the east at the mountain base to a thickness of 91 m (300 ft) in the west near the Quaternary lava flows. Although mostly comprised of Precambrian rock from the mountains, there are basaltic tuffs interbedded with the gravels near the lavas in the west (Figure 2.C). The Ancha formation has a variety of origins, including poorly sorted alluvial deposits and some sorted gravel deposits indicative of fluvial workings. These deposits range in age from the Pliocene to Pleistocene. The well rounded, larger

Figure 2.B. Ancha (top) and Tesuque (bottom) units separated by unconformity
Source: photo by author (2005)

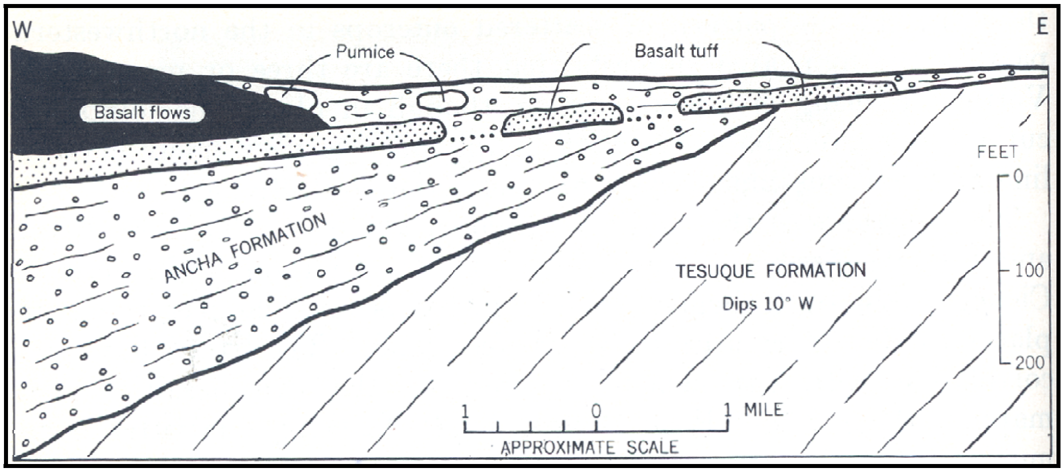


Figure 2.C. Post-Tesuque unit relationships
Source: Spiegel and Baldwin (1963: 54)

materials of the Ancha indicate a long-term migration. The Ancha has high porosity and permeability; surface water easily moves through the unit until it reaches the unconformity where it perches atop the Tesuque, travels under gravity toward the river via subsurface flow, and contributes to baseflow.

2.4 HYDROLOGY AND WATER QUALITY

The Santa Fe River watershed is designated as Hydrologic Unit Area (HUC) #1302020103; the central part of a three-basin area #13020201 (Rio Grande-Santa Fe) that includes the Rio Grande, Santa Fe, and Galisteo basins. The watershed has an elongated dendritic pattern that trends northeast to southwest. The upper watershed, being narrow and steep, has a small catchment size in relation to its length, and limits the amount of water delivered to the river. The upper watershed's shape, slope, aspect, and elongated network configuration illustrates the importance of geology in determining many of the landscape factors within the Santa Fe stream network. In the upper watershed, annual average streamflow rates have ranged from a maximum of 0.742 cubic meters per second (cms) (26.2 cubic feet per second (cfs)) in 1919 to a minimum of 0.051 cms (1.8 cfs) in 2002 (U.S. Geological Survey 2009). Within the stream network, Cienega Creek is the only perennial tributary to the river. On average, it contributes between 0.014 cms (0.5 cfs) to 0.085 cms (3.0 cfs) to the river, while the ephemeral Arroyo Mascaras and Arroyo Hondo contribute flows during large storm events (Potter 1985).

This research divides the river into three reaches based on hydrologic conditions (Figure 2.D). The upper reach begins at the river's headwaters in Lake Peak, and continues downstream to and includes the existing dams and their reservoirs. This reach terminates in the Upper Canyon Preserve, the previous site of Two-Mile Dam, and totals 18.5 river km (11.5 river mi) (purple). The urban reach begins below the Two-Mile Dam site, flows through downtown Santa Fe, through the Village of Agua Fria, and terminates at the city's wastewater treatment plant (WWTP) (totaling 22.7 river km (14.1 river mi) (green)). The lower reach begins at the city's WWTP and continues downstream until its bifurcated confluence with the Rio Grande and Cochiti reservoir diversion (a total stream distance of 33.5 km (20.8 mi) (blue)). River continuity is important for the maintenance of system functionality; however, basin management in Santa Fe since the first dam installation in 1880 has left river flow, form, and function distinctly divided.

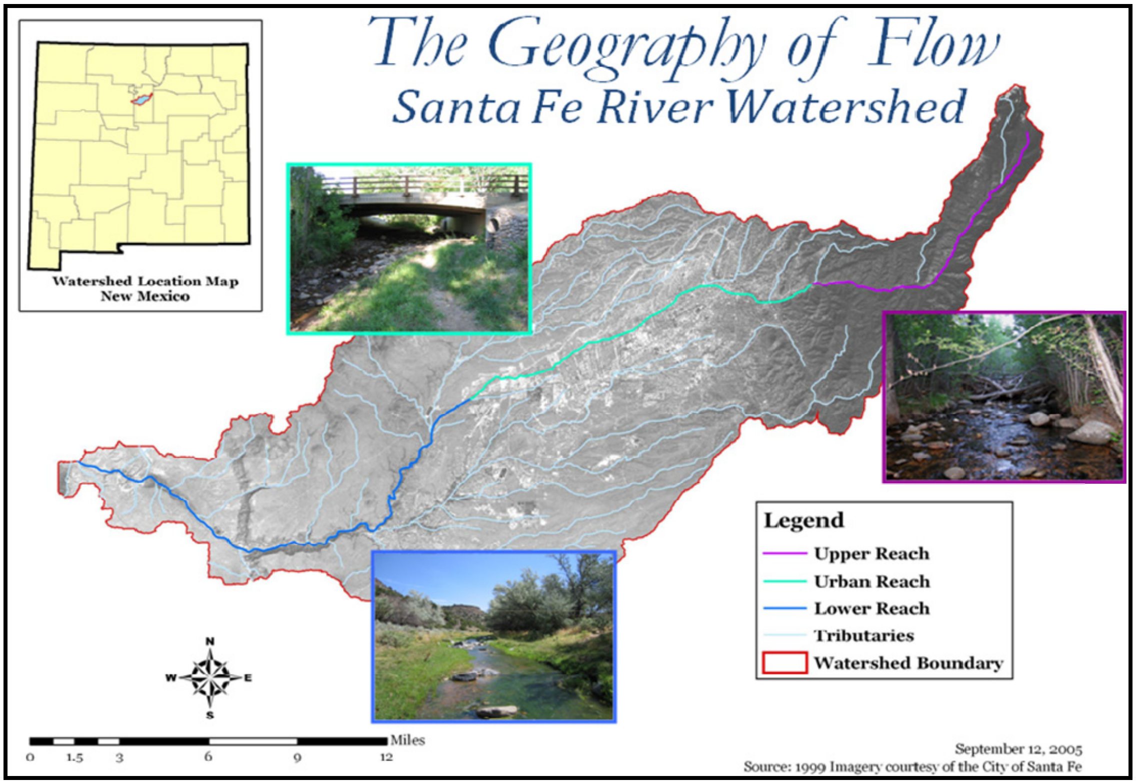


Figure 2.D. Santa Fe River and watershed geography
Source: map by author (2005); imagery, City of Santa Fe (2005b)

The Santa Fe River is currently on New Mexico's Clean Water Act Section 303d list of impaired waters: Section 303d calls for the identification and restoration of polluted waters through the Total Maximum Daily Load (TMDL) program (33 U.S.C. §

1313 (d) (2006)). Water quality standards for pH, chlorine, dissolved oxygen, and stream-bottom deposits (sediment) are set because of poor surface water quality below the city's WWTP. The goal of the program is to attain a level of water quality capable of supporting the designated river functions of marginal cold-water fishery, warm water fishery, and livestock watering (Grant 2002). Countering this goal is the stormwater runoff generated by impervious surfaces that routes to the river during storm events, scours the channel, and impairs river flow and form. Petroleum products, trash, sediment, and debris heavily contaminate this runoff water (Figure 2.E).

Figure 2.E. Poor water quality in the river after rainfall events
Photo facing upstream
Source: photo by author (2006)

2.5 LANDCOVER AND VEGETATION

There is a direct correlation between upper watershed vegetation type and elevation. As a result, several ecological zones transition from alpine tundra on the mountain peaks, to short grass prairie at the river's confluence with the Rio Grande. At the tree line, the alpine tundra transitions to predominantly spruce-fir forest, which grades to mixed conifer, then Ponderosa pine with decreasing elevation (Figure 2.F; Grant 2002). It is likely that early in settlement, the use of the many different ecological zones supplemented irrigated agriculture by providing nuts, seeds, and grasses to the local population (Rose, Dean, and Robinson 1981). A piñion-juniper woodland/grassland-juniper ecotone currently covers about 80 percent of the watershed. Past conditions may have included spatially larger short grass prairie patches; however, extensive grazing reduced grass cover and rendered the landscape unable to support fire (a natural tree-thinning agent) (Grant 2002). Without the stabilizing effects of grassland root systems, much of the watershed is susceptible to erosion. There is no riparian ecosystem within many of the drainages. Where riparian vegetation survives, it is dominated by exotic species.

2.6 LAND USE AND OWNERSHIP

Approximately 97 percent of the watershed lies within the County of Santa Fe. Of the basin's 164,350 total acres (665 km^2), about 7,000 acres (28 km^2) within the upper watershed lies in the Pecos Wilderness, and its use is highly restricted. The USFS owns an additional 10,000 acres (40 km^2) of the upper watershed as part of the Santa Fe National Forest, and manages it for the protection of the downstream water supply. The City of Santa Fe owns 22,991 acres (93 km^2) (Grant 2002). Close to the city's official eastern boundary are small pockets of city and private ownership. Much of the central watershed is open land, mixed density urban development, and large areas of impervious surfaces; all of which exacerbate the magnitude of erosive storm flows. Lastly, agricultural pursuits in La Cienega and La Bajada claim 100 acres (0.4 km^2) of irrigated lands while Cochiti Pueblo uses its 20,181 acres (82 km^2) at the river's mouth primarily for grazing. Grazing allotments are also on BLM lands within the Caja del Rio.

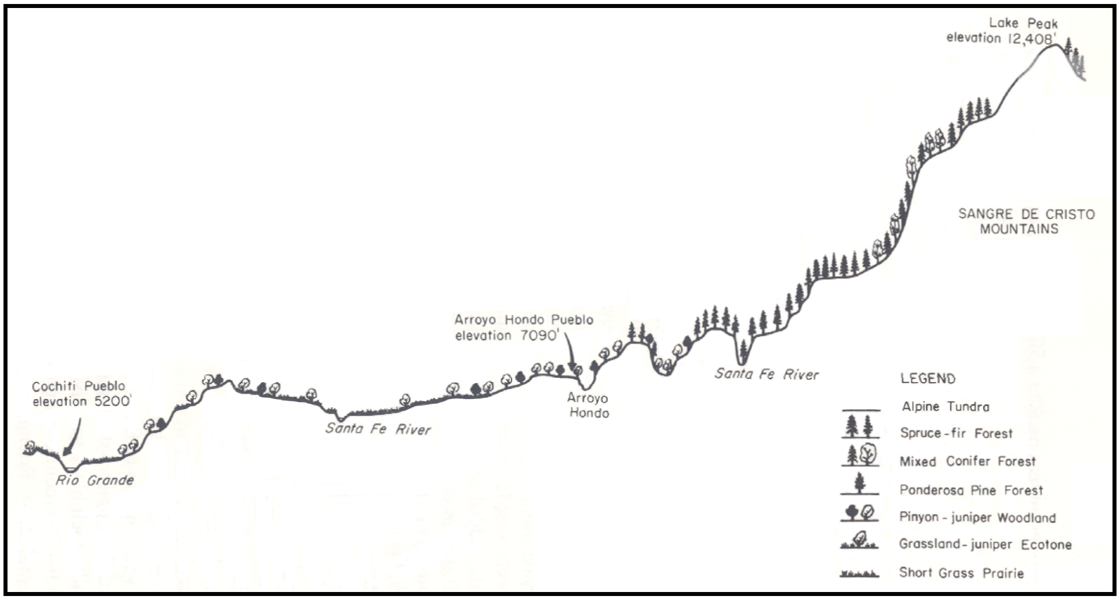


Figure 2.F. Santa Fe watershed vegetation zones, transect of headwaters to mouth
Source: Rose, Dean, and Robinson (1981)

LITERATURE REVIEW

3.0 CHAPTER OVERVIEW

As the longest occupied governmental, military, and ecclesiastical center in the U.S., Santa Fe, New Mexico has unique historical significance. An existing body of literature documents the evolution of the City of Santa Fe from initial site selection and subsequent settlement (Twitchell 1925; Noble 2008), through political and cultural adjustments to changes in government (Horgan 1956; Meyer 1984; Noble 1989; Wilson 1997), to the roles of technology and infrastructure in city modernization (Meem 1972; Lewis 1996; Tobias and Woodhouse 2001). This dissertation seeks to expand upon this existing literature by introducing the role of the Santa Fe River into each of these themes. This research extends these historical works to enlighten anthropologists, historians, and water resource managers of new findings regarding basin hydrology, fluvial geomorphology, and the effects of humans on the Santa Fe watershed.

To extend beyond these themes and to inform this dissertation research, the environmental history of the Santa Fe River draws from three main motifs to frame its discussion on flow, form, and function. The first motif includes a review of relevant works concerning the hydrologic regime and dam-induced change (Section 3.1). This section of the literature review compliments the discussion of Santa Fe River flow by focusing on research that quantifies the downstream effects of dams via the Indicators of Hydrologic Alteration (IHA) method (Richter *et al.* 1996; Richter 1999; Magilligan and Nislow 2001; Galat and Lipkin 2000; Maingi and Marsh 2002; Magilligan and Nislow

2005; Graf 2006). Although these IHA treatments center mostly on rivers in humid regions, the usefulness of this method is not space-specific, as illustrated by Magilligan and Nislow (2001) and Graf (2006). IHA application in the arid, Southwestern basin of Santa Fe extends this literature.

Richter *et al.* (1996) parameterized the hydrologic regime by magnitude, timing, frequency, duration and rate of change of flow. Through various studies, the academic community has shown that these hydrologic regime parameters are essential to ecosystem structure and function (Poff *et al.* 1997; Glenn *et al.* 2008; Bhattacharjee *et al.* 2008; Mahoney and Rood 1998; Everitt 1995; Stromberg and Patten 1995; Scott *et al.*1996; Hinojosa-Huerta 2006). Flow regime alteration by dams drives ecosystem adjustments. This review discusses these adjustments within the context of parameter alteration; many of which are similar to downstream responses observed on the Santa Fe River after a series of dam installations. Research within the academic literature provides many examples of each altered parameter and subsequent system response within western basin ecosystems (Rood, Braatne, and Goater 2009; Stromberg 2001; Pollock *et al.* 1998; Howe and Knopf 1991; Katz, Friedman, and Beatty 2005; Rood and Mahoney 1990; Beauchamp and Stromberg 2008; Uowolo, Binkley and Adair 2005).

The discussion of Santa Fe River form draws from a second literature motif to illustrate the effects of dams on fluvial geomorphology (Section 3.2). These works characterize fluvial forms and processes, and contextualize channel adjustment after dam installations and other human modifications. A literature review of fluvial geomorphology would be incomplete without mention of the importance of dominant discharge (Williams and Wolman 1984; Knighton 1998; Graf 2000), and the characteristics of channel change (Petts 1979; Petts 1980; Knighton 1998). As dams capture and store sediment, downstream channel form responds to the altered sediment load. To frame the progression of downstream effects, scientists often estimate reservoir trap efficiency (TE) via empirical (Brown 1943; Churchill 1948; Brune 1953; Moore *et al.*1960; Borland 1971; Bube and Trimble 1986) and theoretical models (Camp 1945; Chen 1975; Ward *et al.* 1977; Wilson *et al.* 1984; Wilson and Barfield 1984; Flanagan and Nearing 1995; Lindley *et al.* 1998).

Works that present findings on the effects of dams on cross-sectional form (Petts 1979; Petts 1984; Williams and Wolman 1984; Sanchez and Baird 1997; Knighton 1998; Everitt 1995), channel sinuosity (Williams and Wolman 1984, Church 1995; Knighton 1998; Graf 2000; Graf 2002), channel pattern (Church 1995; Xu 1996; Knighton 1998; Friedman *et al.* 1998; Van Steeter and Pitlick 1998; Merritt and Cooper 2000; Graf 2000; Shields *et al.* 2000), channel gradient (Petts 1980; Williams and Wolman 1984), and the water table (Harrison and Clayton 1970; Harris, Fox, and Risser 1987; Kondolf *et al.*1987; Horton and Clark 2001; Stromberg 2001) inform this research. From channel adjustment comes ecological responses. Characteristics of ecosystem responses relate directly to structure size (Graf 1999; Kondolf 1997) and length of damming (Church 1995; Rood and Heinze-Milne 1989). Landform adjustments due to dams are found to reduce biodiversity and native species (Harris, Fox, and Risser 1987; Kondolf *et al.* 1987; Stromberg 2001; Williams 1997; Rood, Braatne, and Goater 2009; Bednarek 2001; Shafroth *et al.* 2002a; Molles, Jr. *et al.* 1998), to fragment the riparian corridor (Bednarek 2001; Nilsson, Jansson, and Zinko 1997), and to alter the spatial distribution of riparian vegetation and channel pattern (Anderson, Nilsson, and Johansson 2000; Merritt and

Cooper 2000; Scott *et al.* 1996; Church 1995; Friedman *et al*. 1998; Bendix and Hupp 2000; Smith 1976; Ostercamp and Costa 1987).

A third motif, site and situational context, informs the discussion of Santa Fe River function via two topics: (1) the history of water in the American West, and (2) the evolution of western water law through case studies (Section 3.3). Literature documenting the history of water in the American West uses many approaches, yet all works within this topic return to a central theme: water control (including the rivers that conduct it), within the dryland environments west of the one-hundredth meridian. Unlike other topics where scholarly findings are presented in academic journals, the history of water in the American West is detailed in a rich and diverse series of books. The sheer number of works precludes a discussion of all treatments of this topic. Therefore, not an exhaustive, but a representative sample of several emphases is the goal of this review, as these book-length treatments are extensive and it is beyond the scope of this work to describe each in detail. Each treatment commands a complex blend of physical, governmental, and social factors that range in spatial and temporal scale; influencing different emphases and styles by each author. Within the context of water history in the American West, the emphases in focus within this literature review include works which discuss a single river basin (Horgan 1954; Scurlock 1998), focus on a state or region (Clark 1987; Meyer 1984; deBuys 1985), or concentrate on governmental agencies, individual characters, specific historic events, and management decisions (Reisner 1986; Pisani 1996; Pisani 2002). Telling the environmental history of the Santa Fe River includes incorporating elements of each of these emphases to explain the river's evolution.

Case law documents the history of water law in the West, and the evolution of New Mexican water law around the community acequia. This research reviews the roots of western water law via Moorish influences, the first guidelines of water allocation on the Iberian Peninsula, and the influence of Old World Spanish royal decrees on settlement in New Spain. With Mexican independence, changes in laws placed within the context of history contrast with the territorial laws of New Mexico after U.S. occupation. Many changes follow statehood. The foundations of prior appropriation and river system adjudication, established through federal case law, reflect on the original Moorish influences. Given the basin's setting, cases within Santa Fe District court and tribal law are also relevant to the foundation of this research.

3.1 THE HYDROLOGIC REGIME AND DAM-INDUCED CHANGE

In almost all rivers, flow is variable (Poff *et al.* 1997). Hydrologic regime variability is regional: influenced by geology, topography, and climate. This variability determines directly the geomorphic and ecologic structure within channels and floodplains by organizing the spatial and temporal distribution of water and sediment (Scott *et al.*1996). Richter *et al.* (1996) classified attributes of the hydrologic regime into five parameter categories: magnitude of the event, timing of occurrence, frequency of occurrence, duration of the event, and rate of change in the event. To quantify changes in these parameters, Richter *et al.* (1996) developed the IHA method. Since its creation, many studies have used IHA to characterize the downstream regime after dam installation (Magilligan and Nislow 2001; Galat and Lipkin 2000; Maingi and Marsh 2002; Magilligan and Nislow 2005; Graf 2006). IHA connects post-dam flows to channel morphology adjustment and/or riparian ecosystem alteration. These responses are specific to dam operation and basin physiography.

Maingi and Marsh (2002) placed the effects of dam construction into two categories: those that are inherent to the dam as an engineered structure, and those that are due to the specific mode of dam operation. One of the most important outcomes from the results of IHA is gaining understanding of the *degree* of change from the pre-dam regime. If dam operating rules were made to more closely resemble the pre-dam hydrologic regime, the riverine ecosystem would likely benefit dramatically (Poff *et al.* 1997). For arid rivers, periodic flooding with specific magnitude, timing, and rate of change would improve local ecosystem health by providing needed water and sediment to a riparian ecosystem dependent on its occurrence (Galat and Lipkin 2000).

IHA inputs require a pre-dam record of streamflow data of adequate length (at least 25 years) for effective analysis. Due to the spatial and temporal variability in stream gages, these data are not always available. Magilligan and Nislow (2001) showed that streamflow data from free-flowing rivers with similar drainage areas, geologic, climatic, and land-use characteristics can be used to synthesize data for sites without pre-dam records. To extend its usefulness, these authors illustrated the use of IHA in combination with other statistical metrics. Magilligan and Nislow (2001) examined hydrologic regime changes using both IHA and a log-Pearson Type III flood frequency analysis to describe statistically significant changes in the Upper Connecticut River watershed. Unlike previous studies applying these methods, all IHA indices and time, in years, were regressed to highlight any land-use or climatic effects in the original data. The analysis of these data revealed an impact on the characteristics of extreme conditions, including the magnitude and number of high and low flows. These results were found dependent upon the degree of reforestation after agriculture, dam type, management of the flow, and/or basin size.

Applications of IHA can extend beyond the focus on a specific dam. The broader application of IHA on a regional scale can quantify hydrosystem alteration basin-wide. Galat and Lipkin (2000) utilized IHA to assess the flow regime of the Missouri River. They used a geographic perspective on hydrologic regime alteration by investigating the effects of dams on a large area of the watershed, and included the examination of ten USGS stream-gaging stations. Magilligan and Nislow (2001) described pre- and post-dam conditions in several watersheds of various sizes, with a wide range of reservoir sizes and dam types.

Magilligan and Nislow (2005) extended the application of IHA beyond the basin to compare varying hydrologic and climatic regions of the U.S. IHA and flood frequency analysis results indicated that, in humid environments, the effects of medium-sized dams on the hydrologic regime can be as substantial as large dams located in more arid climates (Magilligan and Nislow 2001). Graf (2006) discussed the hydrologic effects of dams on a continental scale, and applied IHA, in combination with other techniques, at 36 locations within the conterminous U.S. This application effectively characterized basin responses to dams by region and allowed for valuable comparisons between them. Elucidating hydrologic regime thresholds at multiple scales gives the scientific and planning communities a more in-depth understanding of dam effects on river flow regimes. By classifying flow variability into quantifiable parameters, IHA makes the prediction of potential landform adjustment, the amount of disturbance, and the environmental stress incurred by the riparian ecosystem possible on multiple spatial and temporal scales (Richter 1999).

Hydrologic regime parameters strongly influence native riparian ecosystems (Shafroth *et al*. 2002a; Poff *et al.* 1997; Glenn *et al.* 2008; Stromberg 2001). Numerous examples in the academic literature illustrate the importance of regime attributes in ecosystem structure and function (Poff *et al.* 1997; Glenn *et al.* 2008; Bhattacharjee *et al.* 2008; Mahoney and Rood 1998; Everitt 1995; Stromberg and Patten 1995; Scott *et al.* 1996; Hinojosa-Huerta 2006). Although not an exhaustive treatment, these examples highlight representative findings in southwestern rivers where, in general, ecosystem diversity is dependent on high levels of disturbance for maximization. Low baseflows and highly variable hydrographs typically characterize the hydrologic regime, and as a result, native vegetation in these areas has adapted to the disturbance (Poff *et al.* 1997). In watersheds with seasonal precipitation, the predictable timing of patterns, like snowmelt, dominate river regimes (*ibid.*). Because of these dynamic flow patterns, dryland riparian species have come to rely on harsh conditions like floods for regeneration. High flows flush salts from soil, scour fresh growth surfaces for native vegetation, and germinate seeds (Glenn *et al.* 2008). In arid rivers, *Populus fremontii* (cottonwood) establishment ties to the rate of water recession (i.e. rate of change) (Bhattacharjee *et al.* 2008) and flood timing (Mahoney and Rood 1998), although high growing season flows (i.e. magnitude) are equally important (Everitt 1995). Once cottonwoods are established, the annual frequency and timing of floods, and the maintenance of low flow requirements determine survival (Stromberg and Patten 1995). Hinojosa-Huerta (2006) found the presence of instream flows (although low in magnitude) to be a requirement for wildlife habitat, even more so than the presence of native vegetation. Sediment particle size, a factor determined by regime magnitude, is perhaps important, too (Scott *et al*. 1996).

Humans alter the hydrologic regimes of rivers through the installation and operation of dams (Williams and Wolman 1984; Graf 1999). Dams modify hydrologic regime parameters based on structure size, dam type, and operating rules. An extensive body of literature details the effects of specific dams on downstream hydrology (Graf 2006). Although a complete review is beyond the scope of this chapter, these publications indicate that, in general, dams increase low flows, reduce peak flows, and modify the timing of these events (*ibid*.).

As shown, riparian environments depend on specific hydrologic regime attributes for biological life-cycle cues and survival. Numerous studies conclude that ecosystem adjustment occurs downstream from dams because of altered flow regimes. A complete review within this dissertation is not possible; however, Poff *et al.* (1997) provides an excellent review of studies connecting hydrologic regime change to altered ecosystems. In this paper, a selection of research highlights ecosystem responses typical of the study area (Rood, Braatne, and Goater 2009; Harris, Fox and Risser 1987; Shafroth *et al*. 2002b; Stromberg 2001; Pollock *et al.* 1998; Howe and Knopf 1991; Katz, Friedman, and Beatty 2005; Rood and Mahoney 1990; Beauchamp and Stromberg 2008; Uowolo, Binkley and Adair 2005; Williams 1997).

Spring flooding provides space for new growth by destroying dead plant structures from the previous year and creating seedbeds for pioneer species. When dams reduce the magnitude and frequency of this natural flood scour and flows fail to remove the dead plant structures, the composition, species diversity, density, and spatial extents of the riparian ecosystem change (Kondolf *et al.* 1987). Without large magnitude flood events, "vegetation that becomes established in the channel during years of low flow becomes increasingly resistant to removal by subsequent flows as a function of time" (Merritt and Cooper 2000: 560). These post-dam conditions cause for the displacement of native faunal species as well, who rely on specific vegetation for food, reproductive environments, and migratory corridors. Williams (1997) discussed the ecological integrity of aquatic systems, where reductions in riverside plant life may significantly affect the health of aquatic communities.

The magnitude and character of fluvial-geomorphic change mediates riparian forest adjustment (Katz, Friedman, and Beatty 2005). Dams reduce downstream flow magnitudes, which contributes to forest decline by inducing drought stress to seedlings (Rood and Mahoney 1990). Beauchamp and Stromberg (2008) found that altered regimes reduce sediment transport within the riparian corridor: a factor important for herbaceous community maintenance. Regulated rivers also no longer benefit from the redistribution of organic material either laterally downstream or horizontally up the riverbanks (Anderson, Nilsson, and Johansson 2000). When the spatial and temporal diversity of flood disturbance declines, so too does species diversity (Pollock *et al.* 1998). Howe and Knopf (1991) predicted that exotic shrubs would come to dominate the Rio Grande riparian ecosystem in the next 50 to 100 years due to flood suppression. This prediction is unfortunate given "the riparian forest along the middle Rio Grande in central New Mexico is the most extensive cottonwood-willow forest left in the south-western United States" (Molles, Jr. *et al.* 1998: 750). Within the Yampa and Green river systems, Uowolo, Binkley, and Adair (2005) measured reduced species richness and native species decline downstream from dams and found an additive effect. Because regional inputs to the system and long-distance dispersal are no longer possible, species richness is dependent on in-situ sources for seed contribution (Anderson, Nilsson, and Johansson 2000). As time passes and new species' seed are not introduced from upstream, the dominance of only a few species emerges and a drop in biodiversity affects the entire ecosystem. "The dispersal power of water contributes to the fact that riparian corridors are usually rich in plant species, maintain a series of successional stages, and are target areas for the invasion and the spread of weeds and exotic species" (Anderson, Nilsson, and Johansson 2000: 83). Williams (1997) showed that the number of species in riparian communities along regulated rivers is significantly less than in communities flanking unregulated rivers.

Rood, Braatne, and Goater (2009) emphasized the effects of dams on obligate species due to their sensitivity to river regulation. They found that within the Snake River basin, obligates are more likely to exhibit stress downstream from dams than facultative species. Commonly, adjustments after dam installation included a shift in composition and a reduced frequency of obligates, which were absent on 70 percent of downstream transects (Harris, Fox, and Risser 1987; Shafroth *et al*. 2002b). Similarly, Stromberg (2001) illustrated how the combination of physical and vegetative change resulting from flow regime alteration caused species endangerment. Through these selected examples, the academic literature illustrates the multifarious effects of modified hydrologic regimes on ecosystems.

3.2 FLUVIAL GEOMORPHOLOGY AND DAM-INDUCED CHANGE

Within a watershed, landscape and channel processes induce specific river forms. Independent factors of climate, geology, vegetation, and valley gradient dictate these processes at basin and reach scales. Climate controls the amount of water available to the stream system as discharge and is a primary determinant of river form via bankfull flows. Geology dictates the amount of available sediment and may control channel pattern via resistant material or geologic structures, like faults. Geology also may limit the bed and bank configuration because of material composition and particle size. Vegetation stabilizes channel boundaries through the cohesion of roots. It also acts as a disturbance factor to channel geometry and captures sediment as it grows within the channel (Knighton 1998). Valley gradient and the relative base level influences whether the river will be aggrading or degrading throughout the reach.

The most important of these independent factors is discharge. Stream discharge accounts for more variability in fluvial systems than any other factor (Graf 2000). The hydrologic regime determines sediment transport capacity, channel gradient, and channel roughness: factors dependent upon discharge magnitude (Knighton 1998). River channels are dynamic forms, continually adjusting their cross-section, bed configuration, sinuosity, and planform in response to hydrologic regime change. Scientists understand dominant discharge, or bankfull flow, to be the most influential factor determining channel morphology. Dominant discharge occurs approximately every one to two years in unregulated rivers and determines channel parameters, such as meander wavelength and cross-sectional geometry (Knighton 1998).

Dams alter process-form relationships. Their installation modifies the frequency of dominant discharge, limits flow magnitude, and consequently compromises the maintenance of specific channel morphologies. Because each dam affects discharge uniquely, the downstream effects are space-specific. Ultimately, local geologic conditions, the size and operating rules of the impoundment structure, and the number of years since dam closure determine adjustments (Williams and Wolman 1984). Graf (2006) found that three themes categorize the scientific literature describing downstream channel adjustments due to dams: the effects of sediment storage, the effects on specific river forms, and the effects on planform geometry. A complete review of the extensive literature concerning post-dam geomorphic adjustment is beyond the scope of this chapter; however, literature documenting fluvial processes and forms, and their subsequent responses to dams characteristic of the study basin are chosen to inform this research.

Reservoirs capture inflowing sediment by reducing flow velocity and carrying capacity. Scientists use either empirical or theoretical trap efficiency (TE) models to estimate the volume of sediment captured by reservoirs. This literature review examines empirical models: the most appropriate application choice for this research. Scientists using empirical models have experimented with various relationships and inputs to quantify the percentage of sediment stored by reservoirs. Brown (1943) related TE to the ratio of reservoir storage capacity and catchment area, while Brune (1953) saw the need to modify this relationship to include annual inflow. Moore *et al.* (1960) expanded on Brown (1943) by replacing a value determined by reservoir characteristics with an empirical constant. Churchill (1948) developed a TE model based on measurements of suspended sediment, and related the retention period to mean inflow velocity. He found that the relationship between retention period and the value of 100-TE (percent) yields a logarithmic, predictive curve (Verstraeten and Poesen 2000). Borland (1971) expanded on Churchill's curve by including data from semi-dry reservoirs and found a correspondence that yields a better prediction for dry environments than Brune (1953). Bube and Trimble (1986) further refined the Churchill (1948) relationship by using a smoothing spline to combine the original data from Churchill (1948) and the additions of Borland (1971). Verstraeten and Poesen (2000) found, however, that although this spline method may yield an improved TE prediction, the application of models by Brune (1953) and Moore *et al.* (1960) occurs more frequently within watershed studies due to the difficulty in obtaining sediment input data. Overall, the models indicate that the effectiveness of this capture process, and the concurrent downstream form response, is a product of several factors including dam type, reservoir size, sediment texture characteristics, and the hydrologic regime (Graf 2002). Understanding the TE of reservoirs may inform basin managers of the expected downstream geomorphic adjustment after closure and/or the rate of reservoir sedimentation.

Response to dam installation often includes rapid downcutting of the channel bed directly below the impoundment. This incision is in part due to the decreased sediment in the reservoir's release water and the river's attempt to reestablish its load (Petts 1984). Church (1995) identified the initial effect of dam installation on the Peace River in British Columbia as degradation, due to a lack of entrained sediment arriving from upstream reaches. Sanchez and Baird (1997) documented degradation below Cochiti Dam for over 200 km (125 mi) beyond the structure. Bed incision may continue downstream until a bed material is reached that is too large to be moved by the available stream power (Knighton 1998). This condition, described as bed armoring, discontinues the incision process because the limited flow velocity released from the dam no longer is able to dislodge bed particles for transport. Once armoring occurs, rivers often begin to widen to meet their sediment demands. The reach of the Peace River continually widened over a twenty-year period to meet sediment supply needs, as the channel bed was not broken (Church 1995). These types of channel adjustments will continue downstream from the impoundment until injections of sediment from tributaries and water transported throughout the catchment area negate the dam-induced imbalance (Petts 1980). As opposed to incision, Williams and Wolman (1984) described a channel-widening response and bank erosion of several meandering streams due to a decreased sediment load. High peak flows and highly variable flows often have led to wider channels, especially in arid environments where bank materials lack cohesiveness (Knighton 1998). The characteristics of the alluvial sediments strongly influence the nature of channel adjustment after impoundment (Church 1995).

Dam installation inserts a relative baselevel in the midst of a longitudinal continuum. To adjust to the disruption in the longitudinal profile, channel changes occur both upstream and downstream from the impoundment. Channel pattern will adjust upstream from the dam to compensate for the new base level, and aggradation may result. While downstream, channel degradation will lead to a flatter longitudinal profile as time progresses (Williams and Wolman 1984). The effects of dams on channel gradient are site specific, depending on local geology, tributary sediment supplies, and the variability of flow.

After dam installation, many rivers undergo geomorphic changes in cross-sectional form, specifically width and/or depth. The width-to-depth ratio is a measure of cross-sectional shape that characteristically increases with bank erodibility and stream power (Brandt 2000). Adjustment in channel shape typically occurs due to the altered discharge and sediment load conditions (Brandt 2000). The hydrologic regime influences channel cross-sectional area (Knighton 1998), and as dam installation reduces stream power, so does the water's ability to erode stream banks. Reservoirs large enough to repress the largest floods have the greatest channel narrowing (Williams and Wolman 1984). Ultimately, bed and bank material, along with sediment transport capacity, will be the determining factors in the erosion process and channel cross-section adjustment (Brandt 2000). A reduction in sediment transport capacity may result in bed aggradation. Aggradation is a slow process that requires the introduction and redistribution of additional sediment within the system (Petts 1979). In an aggraded channel, flooding may occur due to the channel's reduced ability to hold the water it could previously transport (Petts 1984). For example, the process of in-channel aggradation occurred downstream of Elephant Butte Dam on the Rio Grande due to sediment contributions via tributaries, and as a result, overbank flows began aggrading the floodplain as well (Everitt 1995).

Estimating channel pattern is possible based on river regime conditions (Church 1995; Rosgen 1994). Knighton (1998) argued that planimetric channel pattern is dependent on sedimentary factors as well as hydraulic ones. "Pattern is a useful integrating parameter because it is an expression of hydraulic behavior responsive to climatic or human influences" (Graf 2000: 9). In general, fluvial geomorphologists describe a channel's pattern, or planform, as single-thread straight, single-thread meandering, braided, or compound. Local conditions, such as flow velocity and discharge volume, sediment size, sediment load, stream power (slope), and the presence of vegetation, can determine each channel pattern, while hydraulic geometry equations can estimate channel geometry. For example, an abundant bed load, erodible banks, highly variable discharge, and steep valley slopes are all characteristics of a braided-river environment (Knighton 1998).

Changes to a river's pattern following dam construction will vary in concert with changes to several characteristics, including: flood rise and fall rates; shear stress at the bed (determined by discharge); the width-to-depth ratio at bankfull stage; local substrate texture; valley gradient; and the site's geophysical history (Merritt and Cooper 2000). Williams and Wolman (1984) found channel change to be inversely related to sediment size. Maingi and Marsh (2002) noted that with the reduction in peak flows occurring after dam installation, channel migration rate slowed significantly, and the number of vegetation establishment sites dropped concurrently. "Because of the reduction in sediment transport, the channel pattern near the point of regulation may ultimately be changed from braided to split or single thread" (Church 1995: 3). Numerous studies document adjustments in channel pattern after the installation of dams (Williams and Wolman 1984; Shields *et al.* 2000; Xu 1996; Friedman *et al.* 1998), most of which illustrate channel simplification (Brookes 1992). For example, the Colorado River's response to dam installation was a reduction in complexity, with concurrent decreases in the main channel width and landform features (Van Steeter and Pitlick 1998). Richard (2001) found that the Rio Grande downstream from Cochiti Dam shifted from a multi-thread to single-thread pattern because of hydrologic regime adjustment. Merritt and Cooper (2000) documented stages of channel adjustment over a 37-year period on the

Green River below Flaming Gorge Dam, which included pattern adjustment from a deep, meandering channel to a shallow, braided channel.

Changes to process-form relationships in fluvial systems results in concurrent ecosystem responses. Hydrophytic vegetation adapted to river edges in arid environments typically has shallow root systems that span large horizontal distances. These modified roots allow the species to remain stable during flood events, and to absorb water during frequent inundation. After dam construction, water tables downstream decline because of reduced inflow from floods and the reduced spatial extent of the river channel itself. Many shallow root systems do not reach deep enough to compensate. Studies in the Sierra Nevada region have shown how the lack of moisture available to plant roots has resulted in riparian floral foliage thinning (Harris, Fox, and Risser 1987). When southwestern river corridors narrow from flood suppression, native trees are likely to decline, while more drought-tolerant, flood-intolerant species, such as saltcedar (*Tamarix ramosissima*) and Russian-olive (*Elaeagnus angustifolia*), take over (Crawford *et al.* 1996). A narrow corridor within levees now confines marshes, wet meadows, and the riparian bosque once characteristic of the wide Rio Grande floodplain (Molles, Jr. *et al.* 1998). Understanding the interaction between the water table and river flow enables a more accurate prediction of riparian ecosystem response to regime regulation (Kondolf *et al.* 1987; Figure 3.A).

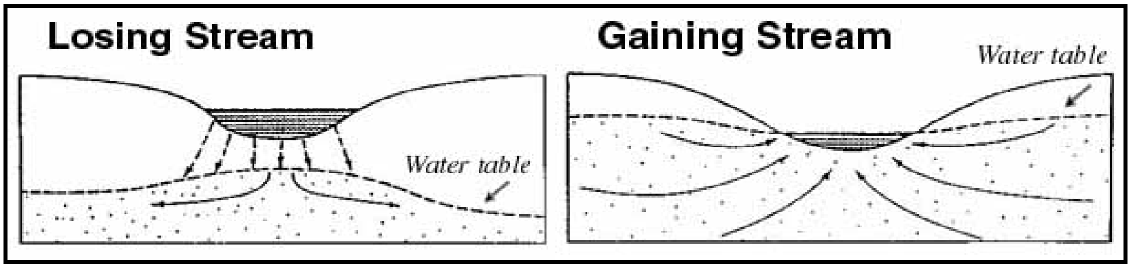


Figure 3.A. Losing and gaining stream dynamics
Source: EPA (2005)

The scientific community accepts that perennial rivers gain water from the water table and ephemeral rivers contribute water to the water table (Harrison and Clayton 1970; Figure 3.A). Ephemeral reaches are more sensitive to regulation than are gaining streams (Stromberg 2001). Stream behavior may vary seasonally, as many are gaining streams during high water table seasons such as winter and spring, while becoming losing reaches during drier months. Water needs are higher during the growing season, which corresponds to high water table events (Friedman *et al.* 1998). Horton and Clark (2001) found that rapid water table changes lead to water stress on new seedlings and ultimate mortality. Regulation affects vegetation and causes the stream to be a losing stream throughout the year. Horton and Clark (2001) also argued that abrupt declines in the water table downstream of regulated rivers have lead to declines in riparian habitat.

The overall effects of dams on riparian ecosystems depend on the size of the impoundment (Graf 1999). Small, run-of-river structures are less likely to have as many impacts on the river system and dependent ecosystems as are large multi-million acre-foot structures (one acre-foot is equal to the volume of water it takes to cover one square acre of land with one foot of water). Smaller dams and diversion structures are more likely to allow moderate or large-sized flood events to travel over and/or around the impoundment; thus, some distribution of sediment, nutrients, and organic debris takes place (Kondolf 1997). In this situation, vegetation occasionally is supplied the elements needed for riparian system maintenance. However, hydrophytic flora depends on frequent floods. If floods are limited in magnitude and frequency, it is possible that the riparian flora will decline in health regardless of the downstream movement of sediment and organics. In contrast, very large impoundments are the most likely to disrupt ecosystems. Large dams trap even the largest flood events, along with their sediment, nutrients, and organic debris. Thus, all dams inevitably alter downstream landforms and riparian environments in some way.

Because forests take several decades or even centuries to develop to maturity, adjustment to upstream dams also will involve such a time-scale (Church 1995). The degree of riparian forest decline often correlates directly to the length of damming (Rood and Heinze-Milne 1989), the severity of regime regulation, and the type of impoundment structure (Church 1995). "Time-scales for adjustment will obviously be influenced by whether the incidence of channel-forming flows is increased or decreased" (Church 1995: 4). If the regime transition is to lower flows after regulation, the riparian vegetation response may take longer to observe. For example, the riparian forest now under investigation on the middle Rio Grande was established primarily during the last large flood event in 1941-1942 (Molles, Jr. *et al.* 1998). Therefore, it may take a half-century to understand fully the effects of major flood suppression on riparian forests by large dams.

A series of vegetative gradients are present on a natural river, where annual species are located in, or close to the channel. River margin vegetation is zoned horizontally with bank position, with herbaceous plants located closest to the water surface, aggrading to forest communities at the bank top (Anderson, Nilsson, and Johansson 2000). Each floral species has different tolerances for drought, flooding, and disturbance. These differences invariably lead to their spatial position on the floodplain (Merritt and Cooper 2000). Bendix and Hupp (2000) reported a spatial correlation between certain species and their locations on particular fluvial landforms. Friedman *et* *al.* (1998) found that riparian vegetation correlates spatially to landform type. As the prediction of landform adjustments is possible by understanding the hydrologic regime (Rosgen 1994), it also is possible to predict concurrent responses of vegetation to dam installation. A specific plant species may persist on a landform for historical reasons, hydrological reasons, or because its moisture and/or nutrient requirements are fulfilled (Bendix and Hupp 2000).

As channel pattern changes in response to the construction of dams, so does species composition and the spatial distribution of riparian communities. In many cases, a channel pattern that previously was meandering will braid, as was the case on the Green River, after the installation of the Flaming Gorge Dam (Merritt and Cooper 2000). Lateral accretion and bar emergence encourage vegetation establishment where a once-active channel existed: vegetation colonization occurs after the river abandons its former bed. Vegetation acts to secure the new channel pattern because it "promotes deposition of fine sediments (Ostercamp and Costa 1987) and increases resistance to erosion (Smith 1976), thus stabilizing the channel at a narrower width;" a pattern more characteristic of braided, arid rivers than meandering systems in humid regions (Scott *et al.* 1996: 329). The old floodplain metamorphoses into a terrace, and former channel bar landforms become areas of new vegetation growth (Church 1995). Merritt and Cooper (2000) found evidence for these adjustments where discharge reductions have lessened the occurrence of scouring flows and have encouraged vegetation growth in the previously active channel, which otherwise would have been naturally removed. An invasion of various annuals and woody species occurs on the once-active in-channel sediments (Scott *et al.* 1996). As plants trap sediment, adjustments cause reductions in total channel length, as is indicated by the ‘braid index’ or “the ratio of total channel length to the main channel length” (Church 1995: 9). Plant roots encourage sediment stabilization on channel fringes, channel bars and islands. This stabilization adds to the progression of channel pattern from natural to more artificial, post-dam conditions. “The progradation of riparian vegetation down the banks of the regulated channel may be an important element of long-term width and pattern adjustment, which ultimately leads to a substantially narrower channel because a smaller conveyance area is required” (Church 1995: 3).

Spatially, riparian habitat exists as a longitudinal corridor along the river margin. Dams affect the spatial distribution of plant species by “fragmenting the continuity of rivers” (Bednarek 2001: 803), and altering a once seamless vegetative community to an alternating series of lentic and lotic vegetative environments. As habitat is fragmented, species are isolated in patches and community development is negatively impacted. This fragmentation causes migration difficulty for terrestrial fauna. Species diversity, and the seasonality of natural flow is directly affected by the alteration of a natural river to a series of stair-step lake-like water bodies resulting from dam installation (Nilsson, Jansson, and Zinko 1997). Because riparian forests change in composition with distance downstream, the effect of river fragmentation may vary along the length of the system.

3.3 SITE AND SITUATIONAL CONTEXT

3.3.1 History of Water in the American West

Due to its pivotal role in settlement, survival, and development, the history of water in the American West has received much attention in the literature. As a scholarly topic, water history west of the one-hundredth meridian is broad and richly studied. This selection of book-length treatments serves as a representative sample of works within this literature base that are highly regarded, and are found most relevant to informing the site and situational context of this research. This section begins with some commonalities authors found among all western basins, then moves on to discuss specific literary works that: highlight a single river basin; focus on a state or region; concentrate on governmental agencies, individual characters, specific historic events, and/or management decisions.

Water influences the turnings of political, cultural, and economic factors, and without it, settlement patterns in the arid West would have been very different (Worster 1985). Early in colonial history, water provided a means for Spanish exploration and expansion. Although the Rio Grande (*Rio del Norte*) was not navigable, water "determined the original paths of exploration and the foundation and settlement of new towns" due to the region's severe aridity and the lack of other sources for sustenance during travel (Meyer 1984: 26). Water was a means for exploration in other western basins as well: Lewis and Clark followed the Missouri River to the mouth of the Columbia; Zebulon Pike, Jr. sought the headwaters of the Red and Arkansas; John Wesley Powell miraculously navigated the treacherous Colorado. Water reliability was also the basis for villa siting in New Spain due to royal decree mandates (Section 3.3.2). Beyond the Rio Grande basin, an examination of any western U.S. map reveals an extension of this pattern, as countless placenames tie to water: Cieneguita, Arroyo Seco, Los Alamos, Laguna, Arroyo de Agua, Jardines del Rio, Agua Grande, and Mesa Verde are only a few. Centuries later in large western basins, the presence of water was no longer a limiting factor to progress, as water was stored behind large dams and directed through conduits for long-distance transport. Interstate compacts mandated states that shared drainage basins to also share the waters. Water delivery facilitated the growth of cities and the explosion of corporate agriculture in otherwise geographically unfitting areas. Now, users divide all available water on each stream system based on complex rights (Section 3.3.2).

Several authors treat the history of water in the American West from the perspective of a single basin (Horgan 1954; Scurlock 1998). Their approaches differ in that some are chronological, while others divide chapters into dominant themes; however, the underlying theme of water control dominates these works. Horgan's (1954) treatment of the Rio Grande informs this dissertation research by chronologically tracing the history of the basin through two major books: Indians and Spain; Mexico and the U.S. Horgan (1954) used the Rio Grande as a unifying point for the intricate connections between the dominant historical groups. He found that using the basin-perspective for history telling in the West reduced the importance of today's superimposed political boundaries. By regionalizing the Rio Grande basin around a common history, Horgan (1954) effectively elucidated the conflict between century-old traditions and the water management views of the incoming U.S. government. Horgan (1954) enlightens this research through the contextualization of this conflict within a regional history. Horgan (1954) found that having roots in a common history explained clearly why the communities of northern New Mexico were so fiercely opposed to the new U.S. governmental impositions of water control infrastructure like dams, utilities, corporations and commodities.

Scurlock (1998) took a different approach to describing the middle Rio Grande's history by dividing the work into dominant themes: modern and historical climate; human settlement patterns, populations and resource use; historical basin descriptions and reconstruction; science, management and conservation. His treatment of a portion of the watershed also focused closely on the changing physical environment and the implications of human action; a similarity to this dissertation research. Scurlock (1998) found that the Hispanos of the region were not immune to creating adverse impacts on the basin, although irrigated agriculture was, in general, a successful adaptation to the local ecosystem. His research accentuated how the traditions of irrigated agriculture and grazing were not perfectly harmonious pursuits; through time, the intensification of these activities by a growing population, along with methodological changes (like the suppression of range fires by Anglo ranchers), caused extensive ecosystem damage. Scurlock (1998) informs this dissertation by providing examples of physical system-human interactions within this region, some of which mirror the findings of this dissertation.

Many works within the topic of Western water history focus on a state (Clark 1987) or region (Meyer 1984; deBuys 1985). These treatments are beneficial because they do not isolate the basin from its exterior influences. Researchers often rank Clark (1987) as one of the foremost comprehensive works on Western water history. With a focus on New Mexico, Clark (1987: 695) found that from the colonial period to the present, the constant readjustment of water policy "to specific local conditions has been the most important single factor" in its development, and that these policies were most often a response to local problems, not the product of conscious planning. These findings by Clark closely parallel several conclusions of this dissertation regarding Santa Fe River and basin management (especially in the upper watershed). The author found U.S. territorial legislative and judicial interpretations of traditional community rules added refinement without altering substance. As the author followed the treatment of water resource allocation via case law at local, regional, and national scales, he found that the changing emphasis of water use from subsistence-agriculture to multiple applications not only modified local attitudes about U.S. citizenship, but profoundly altered federal-state relations. Clark (1987) looked beyond state borders to elucidate the turnings of New Mexico's water history by incorporating external influences into the chronology. However, Clark's most fundamental finding regarding water in New Mexico has been that regardless of economic or governmental situation, the appropriate administration of water resources was pivotal in preserving stability.

Meyer's (1984: 8) regional treatment of the Hispanic Southwest extended the theme of water control beyond the physical to a means of exerting power. In his social and legal history, the author credited settlement of the Spanish in locations near native peoples, not simply because of their clustering around water sources, but because native populations "offered bodies to be worked and souls to be saved." The author's focus on colonial times showed that, like Clark (1987), the theme of water control dominated its administration. Meyer's contributions, however, lie in his discernment of the methods by which administration disputes were resolved. The author found that Spanish officials often seemed devoted to following established laws, until it threatened to work against their interests. Surprisingly, however, "enough examples of Indians, mestizos, and poor Spaniards coming out of the courts with more water than when they entered" illustrated that the laws designed to protect the disadvantaged, did so (166). These accounts differ strongly from the happenings after administration came under the jurisdiction of Anglo Americans (Clark 1987). In the Santa Fe watershed, there are several examples from the historical record to illustrate both cases. Baxter (1997) marked the case of drought in 1722 where water administration of Santa Fe River water prohibited the favoritism toward relatives or *compadres*, while in the early twentieth century, the courts continuously rejected the acequia associations' claims for water (Section 3.3.2). Similar to the findings of this dissertation, Meyer (1984) also found that the arrival of more advanced technology increased the severity of environmental effects and water controversies.

Although not a work exclusively about water, deBuys (1985) illustrated a dual-sided treatment of land and water resource manipulation in northern New Mexico. Within this regional focus, the author challenged the oftentimes-utopian view of past Hispano community harmony with nature. Like Scurlock (1998), deBuys found ample evidence of natural resource exploitation and subsequent environmental degradation, including species extinctions, unsustainable grazing practices, forest clearings, and water misappropriation. Yet deBuys's findings extend beyond those of Scurlock to accentuate how while adapting to the harsh, montane environment of the Sangre de Cristos, the inhabitants both purposefully and inadvertently changed the dynamics of the physical landscape. In attempts to readapt, they then changed it further: a cycle that most often led to intensified environmental degradation. These findings by deBuys (1985) are directly applicable to the environmental history of the Santa Fe River, most specifically in the modern management of the river's fluvial geomorphology. deBuys (1985) informs this research by tying natural resource competition and human action within the Santa Fe watershed to the evolution of the physical system.

Several important works chronicle the history of water in the American West by concentrating on governmental agencies, individual characters, management decisions, and/or historic events (Reisner 1986; Pisani 1996; Pisani 2002). Reisner (1986) provided a chronicle of dam installations, water diversions, and irrigation projects that emphasized the entrenched federal role in decision-making, promulgated by the Reclamation Act of 1902. Like other historians (Worster 1985; Worster 2001a; Hundley 1975), the author found this Act, the massive dam constructions, and the agricultural landscape development that followed, to be symbols of national natural resource control and exploitation. Reisner connected the results of this Act to the systematic damming of virtually all major rivers in the West. Of greatest import to this dissertation is that Reisner (1986) found the conflict between the U.S. Army Corps of Engineers (ACOE) and the Bureau of Reclamation over western river constructions and irrigation projects to be a dominant motif of control that permeates the region. The Rio Grande was not immune to this conflict: this skirmish entangled its first major dam, Elephant Butte. The author elucidated how the battle between these two agencies for domination over project administration prioritized the decision-making process over economics, politics, and the environment. The author found that were it not for this fierce federal rivalry, the landscape of the West would be quite different. Reisner also documented how a century ago, within a much smaller federal government, power at the level of the individual was achievable, and included opportunity to generate profound change in policy, project implementation, and water control.

In contrast, Pisani (2002) described a mosaic of Western water control divided by local allegiances. He found that decisions made at the small scale translated to the state and federal levels, and that the Reclamation Act (and the irrigation and supporting infrastructure) was more a continuation of the nineteenth century frontier settlement policies of bettering autonomous farmers than strategic economic development. Pisani's (1996) contribution to this literature is also different from Resiner (1986) because it does not excuse or condemn past actions, but gives fair treatment to the different temporal setting of the decision makers. A clear divergence from other literature in this suite, Pisani (1996) acknowledged that the turnings of history concerning water and natural resource management were motivated by different value systems and concerns, and purposefully refrained from judgment.

Numerous other examples in the literature chronicle water in the American West, and regrettably, could not be included in this review because of the topic's sheer breadth and depth. Table 3.1 provides additional selections for reference to the emphases of this review. These works extend the topic of water control to different basins, regions, governmental agencies, decision makers, and specific events that formed the western water landscape.

Table 3.1. Additional Readings on the History of Water in the American West

Author (s)	Emphasis	General Topic
Gumprecht 1999	Single basin	Environmental history of the Los Angeles River
Carothers and Brown (1991)	Single basin	Environmental history of the Colorado River through Grand Canyon
Fradkin (1996)	Single basin	History of the Colorado River
Harden (1996)	Single basin	Environmental history of the Columbia River
Aton and McPherson (2000)	Single basin	Environmental history of the Lower San Juan River
Williams (1951)	State or region	Water development in five western basins
Worster (1992)	State or region	Roots of western identity through case studies
Baxter (1997)	State or region	New Mexico water administration 1700-1912
Miller ed. (2001)	State or region	Multiple author subject treatments
Berman and Viscusi (1973)	Governmental agencies, decision makers, and/or specific events	History of large western dams
Hundley (1975)	Governmental agencies, decision makers, and/or specific events	The Colorado River Compact and politics of water division
Worster (1985)	Governmental agencies, decision makers, and/or specific events	Harmonious irrigation societies versus large-scale irrigation districts and associated exploitation
Martin (1989)	Governmental agencies, decision makers, and/or specific events	History of Glen Canyon Dam

August, Jr (1999)	Governmental agencies, decision makers, and/or specific events	Congressman Carl Hayden, the lower Colorado, and the CAP (Central Arizona Project)
Worster (2001b)	Governmental agencies, decision makers, and/or specific events	Narrative of the life of John Wesley Powell
August, Jr. (2007)	Governmental agencies, decision makers, and/or specific events	Water attorney Mark Wilmer and *Arizona v. California*, 373 U.S. 546 (1963)

3.3.2 Water Law in the Southwestern United States

Scarcity makes rules and laws fundamental to the management of water in the southwestern U.S. Southwestern irrigation practices of today follow foundational rules established long ago, rooted in the tenets of Islam (Meyer 1984). These tenets developed slowly to become the codified laws and written rules of water rights and distribution. Under the crown of Spain for over two-hundred years, southwestern water laws experienced few changes. Acequia communities served as local forms of government as well as water democracies. Mexican rule did little to disrupt the long-established traditions of water management and distribution. Under the United States, the doctrine of prior appropriation codified water laws and rights. Today's laws are an amalgamation of Spanish, Mexican, and U.S. influences, and are a testament to the influence of tradition in the molding of modern times.

Irrigation practices on the semi-arid Iberian Peninsula had technological and legal roots in Roman and Moorish influences (Clark 1987). The Moors were more influential in water law development than were the Romans. Water law foundations originated in Islam and "the law of thirst, which granted to all living things completely free access to all waters to satisfy this need, derived directly from the teachings of the Prophet" (Clark 1987: 9). Irrigation in practice dictated the practicality for established rules. Though variations occurred, "all recognized beneficial use as the basis for granting the right initially and assuring its continuation" (*ibid*.). These ideas, established over 1,000 years ago, are the foundations of contemporary water laws in the western U.S. today. Applying water for beneficial use and limiting waste, establishing rights to water through initial and continued use, and the appropriation of water are rooted in this tenet of Islam.

King Alphonso X first codified water law on the Iberian Peninsula in the mid-thirteenth century (Meyer 1984). Alphonso the Wise drew heavily on Roman code and Moorish customs to establish basic water principles in *Las Siete Partidas.* Although guidelines for water allocation to individuals were lacking, the laws reinforced the Moorish tenets of rivers as "property of all men in common" and the consciousness of efficient utilization (Clark 1987).

The application of Spanish water law in the kingdom of New Spain was not a direct translation. Laws in the colonies began with royal ordinances and decrees. King Philip II, in 1573, established such orders for the development of new settlements, including the distribution of cropland and water to its residents (Twichell 1925). The Laws of the Indies or *Recopilacion de Leyes de los Reynos de las Indias*, established specific requirements for villa site selection:

> having water close by which may be conducted to the *pueblo* and the tillable lands, disposing the same, if possible, for its better use and for the materials necessary for buildings, farm lands, agricultural and grazing, thereby obviating much labor and expense arising on account of distances. Sites must not be selected in very high elevations, on account of the winds and the difficulty of service and transportation; nor in low places as they are likely to produce sickness; establishing always in moderately high locations, which enjoy freely the breezes from the north at midday; and if there happen to be mountains or hills, they should be on the east and west; and if impossible to avoid high locations, the founding should be where they will not be subjected to fogs, having care always for health and casualties which may occur; and in the event of building along the banks of a river, the settlement should be laid out that the setting sun falls first upon the *pueblo* and then upon the water (Twichell 1925: 35).

In these orders, the needs of the villa were allocated before individual needs, fostering a community mentality (Meyer 1984). This foundational document dictates the sharing of water equally among users, assuring downstream users of adequate supply.

The Laws of the Indies were comprised of "nine books, two hundred eighteen titles, and 6,177 laws" (Clark 1987: 11). Given their length, complexity, and lack of direct application, a need arose for a more concrete, straightforward document to describe water provisions in New Spain. The Plan de Pitic of 1789 was a simplified founding ordinance for the settlement of Pitic, or Hermosillo, Sonora (Meyer 1984). This document is a source of controversy due to some date discrepancies; however, several articles are important in the development of western water law. Many areas of New Spain put articles in the Plan into practice. In the Plan, Article 6 directs that water be shared equally between Indians and non-Indians. Article 19 describes community irrigation as the foundation for villa development. The article also dictates that each arable plot is to have water access via acequias. This water is to be divided carefully by a ditch commissioner (*mayordomo*) to ensure that each landowner receives a fair share, does not abuse his neighbor's water, or does not use more than is absolutely necessary (Meyer 1984). Ultimately, the Plan represented "a codification of water practice prior to and at the time of its promulgation" (37).

During villa establishment in New Spain in the early 1600s, irrigation ditches (acequias) were the first constructions, before public buildings, churches, and houses (Meyer 1984). The Spanish tradition of irrigation farming translated well to the semi-arid Southwest; therefore, most residents relied on subsistence farming and grazing. Due to the aridity of the environment, careful allocation and distribution of water was necessary for survival. Long-established Spanish methodologies were compatible with the physical landscape and even familiar to some native Indians, who also practiced community-based irrigation and used ditches as a water distribution mechanism (Clark 1987). These first communities in Spanish territory were extremely isolated: laws passed by Spain traveled through Mexico City in the south, and took several years to reach the northern settlements. New laws were mostly ignored, as "local custom was more often the basis for decision than were formal rules of Spanish law" (Rivera 1998: 38). Farmers governed themselves in the first water democracies, or acequia organizations.

> Since each system was different, the crafting of rules to work out effective arrangements for the community as a whole became very much a local process that obviated the need for a uniform set of written laws issued by a higher level of authority. Rather than a codified set of laws, the irrigators needed a small number of rules that were clear, fair, and understood by all the users (Rivera 1998: 40).

Because of their straightforward nature, the rules passed between generations orally. It is important to note that understanding the effects of humans on the landscape does not necessitate literacy of the written word, or the explicit documentation of human actions. Stock (1983) illustrates the incorporation of illiterate individuals and societies into textual interpretations of landscape. The oral, unwritten traditions of acequia communities do not detract from their overall influence on the physical environment. It is important to emphasize, especially in the context of Santa Fe, that descriptions of the landscape do not require written words, as a majority of the population was illiterate throughout the Spanish and Mexican periods. The oral traditions that govern acequias manifest themselves in their physical condition. Water in ditches that runs without obstruction tells of organized cleanings (Rivera 1998). Water effectively delivered to fields signals a functioning delivery system directly attributed to long-established traditions of water allocation, ditch construction and maintenance. Successful crop yields among community members signify equitable water resource divisions. These traditions (unwritten until most recently) act as a text from which the history of Santa Fe materializes.

Acequia organizations perform social and political functions as well, providing local government below the county level (Rivera 1998). Each ditch has its own community, and overseeing each acequia is a mayordomo. Elected to a one-year term by his peers, this water superintendent oversees ditch maintenance and water distribution, and handles water grievances, such as water theft and cattle damage, between irrigators. Irrigators who failed to follow established rules and found guilty by the community commonly were given ditch maintenance work (or *tareas*) to settle the issue. This close connection to nature and to each other fostered acequia community customs: members of acequia organizations attach feelings of pride, identity, and community to the group and to the land (Rodriguez 2006). Through modern times, acequias provide a sense of place for community members; where many describe where they are from not by their villa or town name, by the name of the ditch they use (Bové 2006: personal communication). For centuries, harsh natural conditions in the arid environment of northern New Mexico made for a challenging agricultural existence. The phrase "*ocho meses de invierno y quatro de infierno*" (eight months of winter and four of hell) was a common utterance (Hammond and Rey 2, 1953: 656). The community effort of ditch cleaning and maintenance reinforced the common strife for survival and bound the people together (Rivera 1998).

Traditions of Old World Spain modified the physical environment of northern New Mexico (Clark 1987). "Due to the Spanish custom of subdividing the estate among all the children in a family, individually owned tracts increased in number but decreased in size. This resulted in elongated acreages with narrow frontages on the ditch, a striking feature of land tenure still evident in certain areas in New Mexico" (16). In the Santa Fe watershed, long lots flank the river near the Village of Agua Fria. Although no longer under irrigation, the land use pattern is clearly visible in aerial photography. Through the present, community interactions in these spatially unique landscapes happen not in a cul-du-sac or city block, but longitudinally. Farmers connected linearly by ditches are more likely to interact with others on their ditch then perhaps someone on *"la otra banda"* (the other side or across the road). These communities became quasi-families: plots passed from generation to generation fostered interactions between the same families, and as oral traditions taught the young, all participated to survive.

Mexican Independence in 1821 did not alter prevailing water laws or traditions. With the drafting of the Mexican Constitution in 1824, the opportunity for change presented itself, but none occurred. The Most Excellent Provincial Deputation, a small legislative council that simply reinforced existing practices, issued a series of laws early in Mexican rule. Monetary fines for water and ditch violations replaced the traditional *tarea*, or prescription of labor (Clark 1987). This amendment is indicative of changing times, in which a physical currency became available due to wider circulation.

In 1846, U.S. General Stephen Kearny began an occupation of New Mexico in Santa Fe. Kearny ordered lawyer members of his Missouri volunteers to begin drafting a code of laws for the new territory (Clark 1987). Called the Kearny Code, this bill of rights stated that water laws were to remain unchanged, and that established irrigation ditches were not to be disturbed (Rivera 1998). New Mexico became a territory of the United States in 1850. In 1851 and 1852, the New Mexico Territorial Laws, or *Leyes Generales del Territorio de Nuevo Mexico*, for the first time crystallized oral traditions into codified laws (Prince 1882). These laws were "significant because they reduced to writing and in perpetuity the acequia practices that had evolved in the former Spanish-

Mexican province for two and a half centuries, from 1598 to 1851" (Rivera 1998: 50). These laws reflected the important aspects of New Mexican life: "the primary dedication of water to agricultural purposes and the clustering of water usage around the institution of the community acequia" (Clark 1987: 25). Without significant alteration, the New Mexico territorial assembly transformed existing water practices into statutory form (*ibid*.). After the secession of Mexico, the fifty years to follow was a period of transition during which Spanish customs and laws gradually assimilated into those of the U.S. Only small changes occurred at first to accommodate new problems or elucidate obscurities.

Significant acequia legislation became New Mexico territorial law on February 28, 1895. The act defined "community ditch," "acequia," and their legal status. Acequia communities became corporate entities and were given standing initially "to protest water-transfer applications and to present testimony and other evidence of negative public-welfare impacts" (Rivera 1998: 162). These organizations now could sue, be sued, and collect fees. In addition, they were required to publicize rules and regulations. Communities also were required to elect ditch commissioners and could deny water to those users who were in default. This denial power was a drastic deviation from tradition, as users never refused water before. The prevailing belief had been that water was a God-given right. In June 1881, *The Santa Fe New Mexican* printed the following statement supporting this ideology:

> We, the majority of the people of Santa Fe, declare and maintain that whereas we have been entitled to the water in the Santa Fe River since the conquest of this country, have used it for the purpose of irrigating our fields and quenching the thirst of our families, that the water has been given to us by the sublime will of God…

A water right is a right to divert water from a stream or water body for beneficial use. The user establishes this right through continued use and need. A user who is the first to establish and continually use the water from a particular stream receives senior water rights. This user has priority to the water over others who establish their right later in time. The phrase 'first in time, first in right' best explains this doctrine, known as prior appropriation. The prior appropriation doctrine also allows for the delivery of water to lands not directly adjacent to the watercourse via irrigation mechanisms such as acequias. As part of the effort to achieve statehood, New Mexico drafted a proposed constitution of 1889 and committed to the prior appropriation doctrine (Clark 1987). This commitment was challenged in 1891 in the *Trambley* v. *Luterman* case (6 N.M. 15, 27 P. 312 (N.M. Terr. 1891)). This case positioned the appropriation doctrine against the riparian rights doctrine. In the eastern U.S. where water is plentiful, riparian water rights are most common. Under the riparian doctrine, water is diverted and applied to land directly adjacent to the stream, and there is no stipulation of prior use to establish a water right.

> The court found that adverse, continuous, and uninterrupted use over many years, with the knowledge and acquiescence of the ditch owners, had established Trambley's right against subsequent users. In rejecting Luterman's contention that a riparian owner had the right to reasonable use of water as one going with ownership of the land, the court answered that 'common law, as to rights of riparian owners, is not in force in this territory (Clark 1987: 43).

This case solidified the appropriation doctrine as New Mexican law (*ibid.*). In practice, this law has settled many water disputes between landowners. However, acequia communities commonly ignore this law due to its impracticality in water delivery. Given that water flows under gravity, when it first is released into the ditch for distribution, it is delivered most easily and effectively to the field it encounters first. Distribution continues under gravity: each field sequentially farther down the ditch receives its due amount of water after its adjacent neighbor, until each has received its allocation. If acequia communities followed this law, and landowners who purchased their rights earlier in time received water first, the simple gravity system would become defunct, and those landowners higher on the ditch would not benefit from the greatest amount of hydrostatic head.

River adjudication is a legal process settling all water rights claims on an entire stream system. The state legislature established the New Mexico Office of the State Engineer (hereafter State Engineer) in 1907, mandated a survey of existing waters within the state, and the adjudication of all water rights (Acequia Madre de Santa Fe 1995). Citizens of Santa Fe (many of them acequia farmers) petitioned the State Engineer in 1914 for adjudication of the Santa Fe River, in the hopes that this process would confirm their water rights (many beginning "time immemorial and prior to 1680"). Adjudication would (theoretically) force the owners of upstream dams (the Public Service Company of New Mexico, or PNM) to release impounded water downstream into the river and acequias (Acequia Madre de Santa Fe 1995). The adjudication process occurred haphazardly for several decades. It is not yet complete in Santa Fe. An order, issued by the Santa Fe District Court in 1975, directed the State Engineer's Office to survey all claims to river waters. "In March, 1990 the Acequia Cerro Gordo and the Acequia Madre went to court and asked for interim relief because the adjudication had gone on for 15 years and there was no end in sight" (Acequia Madre de Santa Fe 1995: 3).

On June 22, 1990, the First Judicial District Court of New Mexico found in favor of the acequias. *Henry Anaya, et al. v. Public Service Company, et al.,* No. SF 71.43, 347 (C) the court ordered the water company (Public Service Company of New Mexico, or

PNM) to release water into the Santa Fe River for acequia distribution. The court interpreted an 1880 deed from the Santa Fe County Board of Commissioners as granting the water company the authority to collect, store, and deliver water. However, PNM does not own the water rights themselves. The water company and its predecessors had overstepped their rights by categorically denying water to downstream users for over a century. Today, the City of Santa Fe owns and operates the water system, and has the right (as declared by the State Engineer) to 5,040 acre-feet of river water annually that they may store and distribute to utility customers. The Acequia Madre Association receives a required allocation of 66.8 acre-feet and the Cerro Gordo Association receives 8 acre-feet, annually (Acequia Madre de Santa Fe 1995). Any remaining water is released to the river (some of which goes to fulfilling requirements of the Rio Grande Compact[4]). To meet Compact requirements, the State Engineer designates an annual volume of water for delivery to the Rio Grande via the Santa Fe River. The city must be cautious not to overallocate its existing resources in their reservoirs so to uphold Compact requirements; however, this requirement can be, and is mostly dealt with through an accounting process. Because the city also owns the WWTP on the lower reach, the physical *release* of water can occur through plant discharges.

Today, in the State of New Mexico, water belongs to the public, and it is held in trust by the state (Clark 1987). New Mexico recognizes Indian and Pueblo rights to water, as these settlements used water prior to the arrival of Europeans. Tribal law, discussed briefly below, is complex and unique. Two organizations manage New Mexico's water resources: the State Engineer and the Interstate Stream Commission. The State Engineer is responsible for the administration of water rights and investigations of a technical nature. The Interstate Stream Commission handles stream management and protection (Holland and Hart 2005). Federal laws and regulations, promulgated through the Clean Water Act, also affect New Mexico waters. This act, amended in 1972, establishes goals for water quality and calls for the elimination of pollution discharges from point sources into navigable waterways (33 U.S.C § 1251 (2006)). Later amendments to this act have sought to improve the physical, chemical, and biological integrity of U.S. waters by protecting wetlands; identifying impaired waters; limiting nonpoint source pollutants; and tracking, through permits, direct pollution discharges to waterways (33 U.S.C § 1251 (2006)).

The 20,181 acres (82 km^2 or 32 mi^2) of tribal lands that exist at the mouth of the Santa Fe watershed necessitates a brief review of tribal water law. Cochiti Pueblo owns, and primarily uses these lands for grazing. The interaction between American Indians and the residents of Santa Fe has been ongoing since initial settlement. Prior to the arrival of the Spanish, some Pueblos constructed and maintained irrigation systems to sustain their agrarian, sedentary lifestyle. Francisco Vasquez de Coronado noted fields of corn, beans, and melons, and, to a lesser extent, cotton during his explorations in 1540-1542 (Clark 1987). Water was not property to be bought, sold, or traded (Meyer 1984). To the Indians, water was a facet of nature and respected as a vital element of life. Coronado noted, “so far as I can find out, the water is what these Indians worship, because they say that it makes the corn grow and sustains their life, and that the only reason they know is because their ancestors did so” (Clark 1987: 1).

Irrigated agriculture is a labor-intensive community effort. Large labor forces were necessary to maintain ditches and crops. Anthropologists suggest the development of a hierarchical system of central control within Indian communities to deal with water distribution and management. "There had to be certain rules and regulations to assure the maintenance, operation, and orderly use of water facilities, but it is doubtful that it was uniform among all the Indian farming communities" (Clark 1987: 7). Throughout the Spanish conquest in New Spain, Indians were the focus of religious conversion efforts. Friars were compelled to save Indian souls from eternal damnation by converting the native population to Catholicism, while ironically respecting their land and water rights. The Laws of the Indies "followed a policy of respecting native institutions and customs insofar as these were not incompatible with those of the laws and faith of Spain and the Church" (8). These laws, along with the efforts of the friars, were effective in protecting native agricultural communities through the Mexican period.

Large tracts of land began to change hands with the onset of U.S. control, as tribes signed treaties with the incoming government. Tribal rights to water have been established and upheld through various court cases: *Winters v. United States* (207 U.S. 564 (1908)), *Wyoming v. United States* (*Big Horn 1)* (753 P.2d 76 (Wyo. 1988)), and *Alexander v. United States* (*Big Horn 2*) (803 P.2d 61 (Wyo. 1990)). In *Winters v. United States*, the U.S. Supreme court upheld earlier rulings that established tribal rights to water on reservation land. Actions by upstream users that deny water to reservation land and impede irrigation, such as dam installation, were outlawed. *Winters v. United States* also established reserved rights to water for reservation land. Reserved rights to water include sufficient rights to provide for the tribe's survival as agrarian and pastoral people. This case is important for tribes because it enforces the delivery of water to reservation land, and establishes a right to enough water to support reservation needs.

The case formally titled *General Adjudication of all Rights to Use Water in the Big Horn River System and all other sources, State of Wyoming*, (*Big Horn 1* and *Big Horn 2*) cases solidified tribal rights to water (48 P.3d 1040 (Wyo. 2002)). Decisions in *Big Horn 1* (1988) support: (1) the Wind River tribes' rights to water precede all other users, and (2) since the reservation's main purpose is to support agriculture, the practicably irrigable acreage, or amount of land capable of supporting agriculture, was to determine the amount of water in the reserved right. In *Big Horn 2*, the court found that tribal water rights destined for agriculture could not be converted to instream flows without following Wyoming state procedures. In Wyoming, only the state holds rights to instream flow. These cases clearly establish a prior right to water for tribes above all other users, a quantity of water to irrigate all land that is appropriate for agriculture, and that tribal water use must follow state law.

METHODS OF INVESTIGATION

4.0 CHAPTER OVERVIEW

Many decades ago, environmentalists Aldo Leopold and Walter Prescott Webb encouraged the application of "an ecological interpretation of history" (Scurlock 1998: 5). Since the environmental movement of the 1960s and the creation of the American Society of Environmental History in 1976, academia has recognized environmental history as an academic discipline, and has contributed to expanding Leopold's view (Worster 1993). Now, the scientific community views environmental history as an approach that "increase[s] our understanding of the dynamic nature of landscapes and provide[s] a frame of reference for assessing modern patterns and processes" (Swetnam, Allen, and Betancourt 1999: 1189). Related fields like climatology, anthropology, agricultural history, landscape ecology, and fire history embrace environmental history as a way to include human influences on physical processes (Scurlock 1998). Just like the goals of this research, other environmental histories have "provided pertinent data for biological scientists and resource managers to use in developing a more comprehensive approach to bioremediation, reconstruction of ecosystems, and determination of sustainability" (5).

When establishing a framework for the geographic study of a physical system, like the Santa Fe River, it is clear why much of the approach is quantitative. Interrelationships within a fluvial system are inherently part of the physical world, and statistical metrics quantitatively measure spatial and temporal variations in factors like climate, geology, soils, and vegetation. Due to the pervasive nature of humankind, it is becoming ever more difficult to conduct physical systems studies in locations not influenced by its actions. As a discipline, geography emphasizes the importance of including environmental-societal dynamics when deconstructing physical systems and connects the degree of physical landscape change to the importance of the human element (NRC 1997). Therefore, the contemporary construction of the basin's physical history must also include an examination of the explicit and unintentional effects of human action. The Santa Fe River environmental history draws upon the geographic discipline to generate an outcome that makes use of physical geography methods (i.e. hydrology and fluvial geomorphology), qualitative research methods, and GIScience techniques. The methods organized within this chapter act as a guide to the content and findings in the remainder of the document.

4.1 SANTA FE RIVER FLOW

Revealing the geography and character of flow in the Santa Fe River through time includes the use of both quantitative techniques and historical descriptions. Methods of hydrologic analysis include: (1) unraveling the geography of river flow from settlement through the present, including the examination of flow records from stream gages, (2) reconstructing streamflow via linear regression using tree-ring data, (3) evaluating the influence of irrigated agriculture on river flow, (4) assessing the influence of precipitation on river flow, and (5) quantifying the effects of dam installation on the river by applying IHA to existing stream-gaging data. Historical materials supplement descriptions of flow through time by tying physical changes to human actions. "Converging lines of historical evidence from many locations are most convincing, particularly when coupled with sound knowledge of mechanisms established by modern observations and experiments" (Swetnam, Allen, and Betancourt 1999: 1201).

4.1.1 The Geography of Santa Fe River Flow through Space and Time

Today, the river is a disconnected system. Perennial flow occurs in the upper watershed above a series of dams. These dams store a majority of river water (up to 5,040 acre-feet) and divert this water into pipes for distribution to city customers. Below the dams, sediment-free water flows into the urban reach only after the upstream reservoirs have reached their water rights limits, after acequia and Rio Grande Compact[4] obligations are met, or during spring snowmelt surpluses. The urban reach channel also receives unsaturated overland flows of poor quality from impervious surfaces after localized precipitation events. The channel is ephemeral through the Village of Agua Fria until it reaches the city's WWTP. Here, the plant discharges effluent into the channel, and the river is again perennial due to the constant supply of treated wastewater. This water flows downstream for about two miles until it percolates to groundwater. A small distance later near La Cienega, water reaches the surface via springs, due to a change in geologic units and crosscutting faults. From this point onward, the river flows year-round through La Bajada, until it reaches its bifurcated connection with the Rio Grande and Cochiti Reservoir.

A goal of this research is to clarify past river flow geography because the disconnected system of today differs from historical accounts. Conflicting reports detail where and when certain reaches of the river flowed perennially in the past. As a result, the timing and geography of river flow is a highly contentions topic among historians. Long-time residents recount a flowing river through the urban reach and Agua Fria throughout the year: springs, ponds, and wetlands now exist only in their memories (Grant 2002). A chronology of flow is assembled via existing flow records; historical maps; geologic studies and maps; historical and contemporary aerial photography; and written descriptions by residents, clergy, and visitors (diaries and newspaper accounts). "Blending different methods and data types can extend information about environmental change across a broad range of temporal and spatial scales" (Swetman, Allen, and Betancourt 1999: 1191). This research pieces the evidence together to reveal the past and present geography of river flow.

Measuring the stage or discharge at a particular location on a stream, at a given time determines a stream's flow rate.[5] Several analyses in this research apply the records from two USGS stream gages on the river (Table 4.1). Although contemporary in nature, these records establish baseline conditions for river flow. The investigation of existing conditions is necessary for future river management. Statistical tests applied to these datasets allow river managers to develop river restoration strategies accordingly.

Table 4.1. USGS Stream Gauging Stations used in Analyses

Station Name	**Station Number**	**Installation Year**	**River Mile**	**Watershed Area (mi^2)**
McClure Reservoir near Santa Fe (SRM) (USGS 2009a)	USGS 08315480	1998	8.0	12.9241
Santa Fe River near Santa Fe (SRS) (USGS 2009b)	USGS 08316000	1913	9.2	18.2546

In previous research (Grant 2002; Uday 2004), plots of annual streamflow from the SRS gaging record were fit with a trendline, and indicated that upper reach streamflow decreased by 20 to 33 percent since 1913. Hypotheses for this reduction include: (1) climate change, (2) snow ablation from the canopy instead of melting to supply the river (USFS 1998), and/or (3) dense tree resurgence and their increased water use after watershed closure in 1932 (Uday 2004). Leopold (1951) examined precipitation in Santa Fe from 1853 to 1949. He found that, in contrast to the late 1800s, fewer, lighter rains occurred in the early 1900s. This change potentially encouraged rapid regeneration of vegetation in the upper watershed (Grant 2002), and the concurrent reduction in streamflow.

However, the research citing this reduction (Grant 2002; Uday 2004) does not clarify whether the effects of dams (constructed upstream of the SRS gage in 1925) were removed from these data before analysis. Therefore, additional examination is necessary: (1) to determine if there is indeed a reduction in annual streamflow volume irrespective of dams, and (2) to test the other hypotheses. To identify a statistically significant streamflow reduction independent of dams, a Kolmogorov-Smirnov test (K-S test) compares the populations of unimpounded daily mean streamflow at the SRS gage prior to dam installation (1913-1925) and unimpounded flow above McClure reservoir at the SRM gage (1998-2008). These daily data, normalized by contributing watershed area, reveal whether total flow volume prior to watershed closure is statistically different from the present through the comparison of their frequency distributions. Because of the temporal nature of streamflow data and their correlation with climatic influences over multiple year timescales, seasonal similarities in flows commonly exist between years instead of within years. Therefore, to identify any temporal autocorrelation within these datasets, a correlogram plots sample autocorrelations against time lags. Secondly, IHA two-period analysis identifies changes in hydrologic parameters between these two normalized periods of flow. Comparing IHA indices at two stations on the same stream, separated by eighty years, elucidates changes in the character of flow between pre- and post- watershed closure. As a result, watershed managers may come closer to understanding the details of climate and landcover changes influencing the hydrologic regime, independent of dams. Results of these examinations identify and discuss limitations of the datasets, the specifics of the statistical tests, and the influence of long-term climate trends (Section 5.1.1, Chapter 5).

4.1.2 Santa Fe River Flow Reconstruction

In recent studies, scholars used tree-ring chronologies as a proxy for streamflow (Brito-Castillo *et al.* 2003; Lara *et al.* 2005; Watson and Luckman 2005; Case and MacDonald 2003; Meko *et al.* 2001; Meko and Stockton 1984; Meko and Graybill 1995; Meko and Woodhouse 2005). Western North American trees were first used by Douglas (1914) and then Schulman (1956) to demonstrate the positive relationship between the width of annual growth rings and the volume of winter rainfall preceding each growing season (Rose, Dean, and Robinson 1981). In the arid Southwest, conifer growth is determined primarily by this relationship, and secondarily by growing season rainfall. From a biological standpoint, in this geographic region tree-ring growth rate is determined first by the amount of stored food in cells, and second by the availability of soil moisture. Thus, if photosynthetic conditions create a food surplus during the previous year, then the tree will exhibit a wide growth ring in spring regardless of the moisture conditions.

A tree-ring chronology for the Arroyo Hondo Pueblo (an archaeological site approximately 6.4 km (4 mi) from the downtown Plaza) is the closest assembled data set and provides a proxy for precipitation from within the watershed from 985 A.D. to 1970 A.D. The Arroyo Hondo is an ephemeral tributary to the Santa Fe River. Annual tree-ring data values between 1913 and 1925 are regressed linearly with recorded streamflow values from the river's unimpounded gaging record. The significant relationship established between these variables reconstructs long-term streamflow records.[6] In northern New Mexico, warm ENSO and cold ENSO events correlate to extremes in precipitation. This analysis includes a discussion of the effects of ENSO events and climate variability on the reconstructed streamflow.

4.1.3 Evaluating the Influence of Irrigated Agriculture on Santa Fe River Flow

Irrigated agriculture highly influences river flow. Spiegel and Baldwin (1963) highlighted the importance of agriculture on the Santa Fe River:

> early agricultural practices constituted an excellent form of artificial recharge of a part of the diverted water to the underlying aquifers because of ditch leakage and extensive water spreading. Despite the consumptive use by the irrigated fields, probably a larger proportion (possibly 30-50 percent) of the streamflow reached the zone of saturation after irrigation began than did under natural conditions (in Grant 2002: 10).

Phil Bové, commissioner of the Acequia Madre Ditch Association, echoed Spiegel and Baldwin (1963) when he confirmed that 66 to 80 percent of the ditch's flow is lost to evapotranspiration either from trees lining the ditches or to groundwater via the ditch itself (Bové 2005: personal communication). Rivera (1998: 32) contextualized the multiple hydrologic benefits of acequias:

> [t]he earthen acequia watercourse itself helps to recharge the local aquifer through the natural process of seepage. Aided by gravity flow, water that continues to flow in the ditch, in turn, serves to extend the stream to a new, wider landscape, resulting in a benign irrigation technology which helps control soil erosion. Water that percolates down to the aquifer aids in the cleansing of groundwater. Seepage throughout the ditch system nourishes the cottonwood bosques as well as native shrubs such as plum, *capulín*, and willows, which in turn, provide shelter for wildlife. Any unused waters are returned to the stream as *sobrantes*, or surplus waters, destined to support other values or users downstream.

As land in irrigated agriculture converted to urban landcover, the amount of water delivered to shallow groundwater, and ultimately to the river, declined significantly. Thirty-eight ditches supported approximately 1,200 irrigated acres in 1914, while only four ditches support about 100 acres today (State Engineer's Office 1976; Grant 2002).

This dissertation documents the past and present geographic distribution of acequias and irrigated cropland via three GIScience techniques. First, Snow (1988) recorded the locations of past and present acequias on the plat maps of the 1919 Hydrographic Survey via field reconnaissance and archaeological investigation. These maps are remarkably accurate when rectified to recent aerial photography. The acequias are digitized from these maps.[7] Second, GIS-based hydrologic modeling reconstructs sections of acequias no longer visible during field reconnaissance. LiDAR data model a highly accurate raster surface of flow accumulation: when reclassified to show cells with contributing areas of less than 20 cell units, the result is a grid of microtopographic flow lines that indicate the most likely acequia placement.[8] These flow lines connect some of the missing sections of the digitized acequia network. Third, rectified historical aerial imagery from 1936 and 1951 clearly shows acequias as dark, linear features indicative of saturated conditions. Unsupervised classification identifies cells with a specific spectral signature indicative of saturation.[9] Ultimately, identifying much of the original acequia network long covered by suburban sprawl is possible through the combination of these three techniques.

This research relates spatial changes in irrigated farmland to the distribution of historical and present day acequias. Maps documenting the location of irrigated fields in 1768 and 1846 are rectified,[20] and the fields digitized in a GIS to show spatial and temporal changes in irrigated acreage. Unsupervised classification of aerial photography from 1936 and 1951 also identifies lands in irrigation due to their spectral signature.[9] "Repeat aerial photography and other remote sensing data (e.g., satellite imagery) can be very useful for assessing landscape changes in recent decades, particularly when used in concert with geographic information systems" (Swetnam, Allen, and Betancourt 1999: 1196).

Given the known water application rate for Santa Fe fields, the reconstructed streamflow values from tree-rings reveal supportable quantities of arable land on an annual basis. These spatial limits pair with known historic events to show the carrying capacity of the river through wet and dry years in the last four centuries. While reflecting on the findings of Spiegel and Baldwin (1963), Bové (2005), and Rivera (1998), a discussion of the irrigated acreage decline and acequia loss in conjunction with changes in river flow highlights the underemphasized role that acequias and irrigated agriculture played in maintaining baseflow in the river through the urban reach.

4.1.4 Regional Climate Change and Effects on Flow

An accurate account of the hydrologic effects of dams requires knowledge of the potentially confusing effects of climate change (Williams and Wolman 1984). On a century-long time scale, climatic adjustments may explain decreases or increases in discharges regardless of the influence of dams. McCabe and Wolock (2002) found changes in annual streamflow occur because of climate change through the intermediaries of precipitation and runoff. Significant changes in annual minimum and median daily streamflow appears to have occurred in the conterminous U.S. between 1941 and 1999, in the form of a step change instead of a gradual change (McCabe and Wolock 2002). Their study included precipitation data from northern New Mexico, which showed that there has not been a significant increase or decrease in streamflow in this locale.

In order to define human-induced changes to the hydrologic regime of the Santa Fe River, it first is necessary to define any long-term climatic changes that are separate from, and unrelated to the effects of dams. Using assembled precipitation records (monthly and annual totals) from 1849 to 2008, regression techniques identify changes in precipitation through time. The precipitation records begin prior to the hydrologic record of the Santa Fe River, and provide a context for stream flow data.

Regression techniques applied to precipitation data can identify regional climate change. To detect changes, a precipitation anomaly value generated and regressed against time reveals any increase or decrease in precipitation.[10] The regression equation and R^2 value for each month's trend line will show any significant changes in precipitation volumes since 1849. If differences exist between months, there is no time trend. Any changes in stream flow volume over time, recorded by the USGS stream-gaging stations, are then unlikely a result of regional climate changes.

4.1.5 Dam Installations on the Santa Fe River and their Effects on Flow

A discussion of sequential dam installations on the river highlights the geography, nature, and magnitude of flow disruption, while a chronology connects dam and water system operations to flow records. Santa Fe dams, both past and present, function as public water supply reservoirs, flood control structures, and water sources for fire suppression in the upper watershed. They also act as hindrances to the natural river flow. Originally created as a management tool for The Nature Conservancy, the subsequent series of successful IHA applications extends its usefulness to general research applications. On the Santa Fe River, IHA identifies statistically significant differences in regime flow parameters (listed in Appendix A), between pre- (1913-1925) and post-

(1926-2008) dam installation. This analysis applies non-parametric tests because the number of years for the pre- impact period was too small to use parametric tests (the software specifies at least 25 years are necessary).

4.2 SANTA FE RIVER FORM

Longitudinal adjustment in river geomorphology correlates directly with local variations in climate, vegetation, geology, and past and present land management practices. Methods of geomorphic analysis include: (1) generating a longitudinal profile using GIS techniques; (2) describing river form in each reach before humans, channel changes after Spanish settlement to 1880, and post-dam geomorphic adjustments; (3) quantifying the effects of dams (including reservoir trap efficiencies), and evaluating upper watershed resource extraction and closure on river cross-sectional geometry; and (4) quantifying planimetric adjustment through time.

4.2.1 Generating a Santa Fe River longitudinal profile using GIS techniques

This research uses a GIS to derive the river's longitudinal profile.[11] Important locations within the profile are demarcated by calculating their distance from the outlet. The profile explains a great deal about the fluvial form adjustments that take place along the river course because of spatially varying landscape processes. Some human-induced changes to channel form, such as sand and gravel mining, are so extensive they are visible on the profile at the watershed scale.

4.2.2 Description of geomorphic change 1600 to the present

This research generally describes river form prior to the arrival of Spanish by applying knowledge of geology and sediment conditions, topography (from the longitudinal profile), and flow (from streamflow reconstruction and pre-dam gage data). Understanding process-form relationships allows for an extrapolation of channel morphology and planform from the river's headwaters to its confluence with the Rio Grande. "The resulting physical appearance and character of the river is a product of adjustment of its boundaries to the current streamflow and sediment regime" (Rosgen 1994: 169). Prior to human habitation, these boundaries cause form adjustment at the mountain front, and at the entrance to La Bajada canyon, where channel pattern adjusts from meandering to compound, and from braided to meandering, respectively.

Currently, human-induced form adjustment dominates geomorphic processes in Santa Fe. Channel conditions in the modern urban reach, categorized by this research via measurements of cross-sectional geometry and channel planform, illustrate the vast deviation from its pre-human condition. By 1610, earthen berms constructed in the channel diverted water into acequias. These and other channel modifications, such as levees (*estacadas*) and elevated bridges, were small compared to the dams and engineering works that began to appear on the river in the late 1800s. Historical photography shows channel incision beginning in the downtown reach around 1910, potentially because of upstream sediment impoundment or episodic arroyo development characteristic of Southwestern streams during this time. Between 1880 and 1940, the western U.S. experienced a period of episodic arroyo development (Webb and Leake 2006). The possibility that the river and its tributaries experienced these channel responses irrespective of human influence is vetted against historical evidence of channel adjustment, downstream responses to dam installation, documented landcover and land use changes, and other human-induced changes (such as aquifer drawdown) understood to have similar effects on channel geomorphology.

Engineers of the 1950s and 1960s, concerned with protecting city infrastructure, allowed the urban reach to incise further, creating larger channel capacities to hold floodwaters (while allowing for city development up to the river's edge) (Coss 2005). Research indicates that, in addition to these actions and the upstream dams, many factors including the drop in shallow groundwater from well pumping, landcover conversion from agriculture to impervious surfaces, loss of riparian vegetation, concentrated flood flows from upstream, and headward erosion from downstream sand and gravel mines, contributed to the degradation of this area.

Within a century of the first dam's installation, the results of human modifications and form adjustment are a highly unnatural urban channel, which functions primarily as a drainage ditch for conducting stormflow out of the city. This research illustrates how channel degradation escalated quickly after dam installation. Cross-sections in the urban area quantify the degree of channel modification within the highly constructed environment. There is no active floodplain. Many pipes from storm drains and building rooftops conduct water directly into the channel. Various documents, including newspaper articles describing bridge installations and destructive floods, river master planning materials, engineering drawings, maps, ACOE recommendations, historical and contemporary photographs, and GIS data and LiDAR, all contribute to describe the river's urban reach both past and present.

Beyond downtown, the urban reach through the Village of Agua Fria poses a massive challenge to engineers and river planners. The channel has incised to depths of up to 20 m (60 ft) despite the installation of grade controls. Landowners use the skeletons of vehicles and collapsed structures to stabilize the banks and fill arroyos. This research highlights the dramatic and currently underemphasized effects of downstream aggregate mines, which removed massive quantities of material from the channel, and resulted in widening and deepening. A 3-D triangulated irregular network (TIN) generated from LiDAR and field measurements quantify the volume of material excavated from the channel.[12] The photographs and TIN help describe areas where channel surveys were beyond the limits of basic field equipment.

There is a stark adjustment in river geomorphology in the lower reach due to the city's WWTP. A constant supply of nutrient-rich effluent supports ample vegetation: root systems hold channel banks in-place. Finer channel materials (sand and gravel) that are almost absent from the upstream bed comprise the majority of instream particles below the WWTP. This sub-reach, although beautiful, is the antithesis of the dry channel upstream.

As the river flows through La Cieneguilla and La Bajada, the fluvial geomorphology reflects the influence of changing local geology. The river has dissected the plateau's quaternary basalt extrusions, and now is confined between steep canyon walls. Cross-sections evaluate geomorphic condition and the effects of grazing on bank stability. Repeat aerial photography describes the changes in channel planform after the bifurcation and water diversion to Cochiti reservoir in 1975. There is a precedent for this technique, as several studies in the southwestern U.S. include the use of photography in repeat locations to assess river change (Turner and Karpiscak 1980; Webb 1996; Turner *et al*. 2003; Webb *et al*. 2004).

4.2.3 Quantifying the effects of dams, upper watershed resource extraction and closure on channel form

In the upper watershed, the river resembles an archetypical mountain stream, with large channel materials and woody debris. Mid-reach of the upper watershed, the river is very healthy (interacting with its floodplain and riparian ecosystem), and “could serve as a model for what mid to high elevation streams in northern New Mexico should look like” (USFS 1998: 13). Generous streamside shade keeps water temperatures low and riparian communities healthy. Beaver (*Castor canadensis*) are present and create small ponds, while introduced Rainbow (*Oncorhynchus mykiss*) and “cutbow” (*Oncorhynchus clarkii* x *mykiss*) trout (hybrids of rainbows and native cutthroats) exist in healthy populations (USFS 1998). The USFS makes channel cross-section and riparian characterization data available in several studies because the upper watershed is closed to public entry. Eighteen cross-sections document the state of the channel, describe, and assess changing geomorphic conditions through the upper watershed; from a very steep, geologically controlled area, through a functioning riparian community, to the section influenced by reservoir installation, water system infrastructure, and exotic species.

The condition of the upper watershed has not always appeared so pristine. After more than three-hundred years of resource extraction from the community-used lands of the nearby sierra, the hillsides were devoid of most vegetation. Grazing and logging left hillslopes highly susceptible to saturated overland flow during rainstorms, and the delivery of sediment to streams threatened reservoir water quality and storage capacity. This sediment delivery and migration is reminiscent of east coast processes, described by Meade and Trimble (1974), because of poor land management and dam construction. The effects of sediment delivery and migration within the stream, as well as the mitigation efforts by Santa Feans (i.e. watershed closure), set the stage for future management strategies within the watershed (i.e. stand thinning). Using the reservoir trap efficiency equation from Moore *et al.* (1960), the percentage of sediment load trapped by the sequentially installed reservoirs are quantified through time, and the subsequent effects are discussed in reference to upstream and downstream channel form. This method is appropriate for estimating Santa Fe reservoir TE because the required model inputs are easily estimated using a GIS, and do not require data on sediment concentrations or annual inflows (which are not readily available or of adequate length for modeling, respectively). The purpose of this calculation is to show the effective capture of sediment behind the reservoirs, so to better understand the observed downstream channel responses after impoundment.

4.2.4 Planimetric change through time

Within the urban reach, historical aerial photography from 1935, 1951, and 2008 is rectified and the channel digitized to show planimetric change through time. Quantified average channel widths illustrate the degree of planform adjustment and compare with other downstream dam responses recorded in the literature. The timescale of transition from wide, compound channel to narrow, incised gully occurred within a few decades. The rapidity of planimetric adjustment elucidates the severity of spatial and temporal geomorphic responses to human action. The catalysts of adjustment include: hydrologic regime modification; sediment load reduction by dams; the removal of channel material by aggregate mines; the installation of the WWTP and addition of water mid-river; landcover conversions; changes in groundwater levels via wells and consequent changes in bank stability.

These catalysts, placed within the context of Santa Fe history, connect land management decisions and their effects on the river. Figure 4.A illustrates an example of changes in groundwater levels and flow directions. This process occurred in Santa Fe: groundwater levels have dropped throughout the watershed since the late 1940s, when public water supply wells first were installed (Figure 4.B). Falling groundwater elevations have adversely affected the riparian corridor in the downtown area, where naturalized Siberian elms (*Ulmus pumila*) are dying as the groundwater table drops and impervious surfaces increase (Bové 2008: personal communication).

Within the lower reach, this research contrasts present reach conditions with its pre- treatment plant form via 1936, 1951, and 2008 aerial photography. A braided channel devoid of riparian vegetation and reflective of high slope and sediment load in 1936 is replaced by the current form, dominated by different processes: low slope due to aggradation from upstream sand and gravel mines and a mono-flow regime of effluent create a very different cross-sectional geometry, planform, and riparian environment from the historical condition.

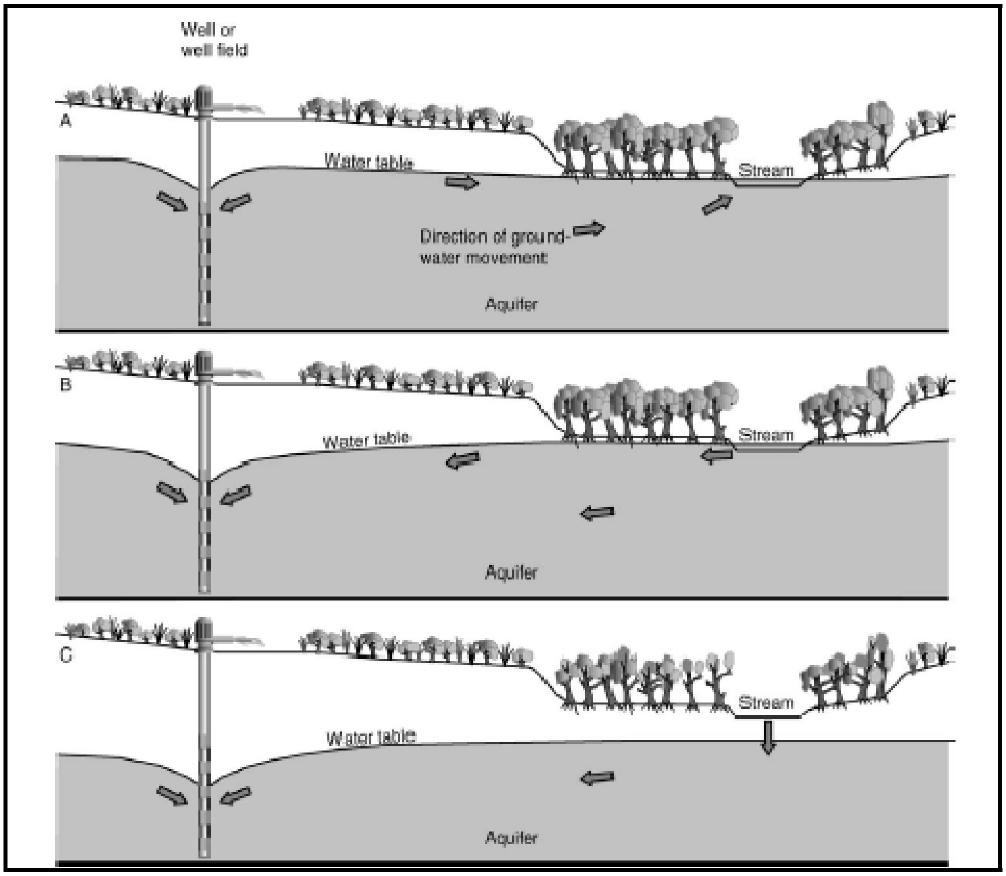


Figure 4.A. Groundwater responses to pumping
Source: Webb and Leake (2006)

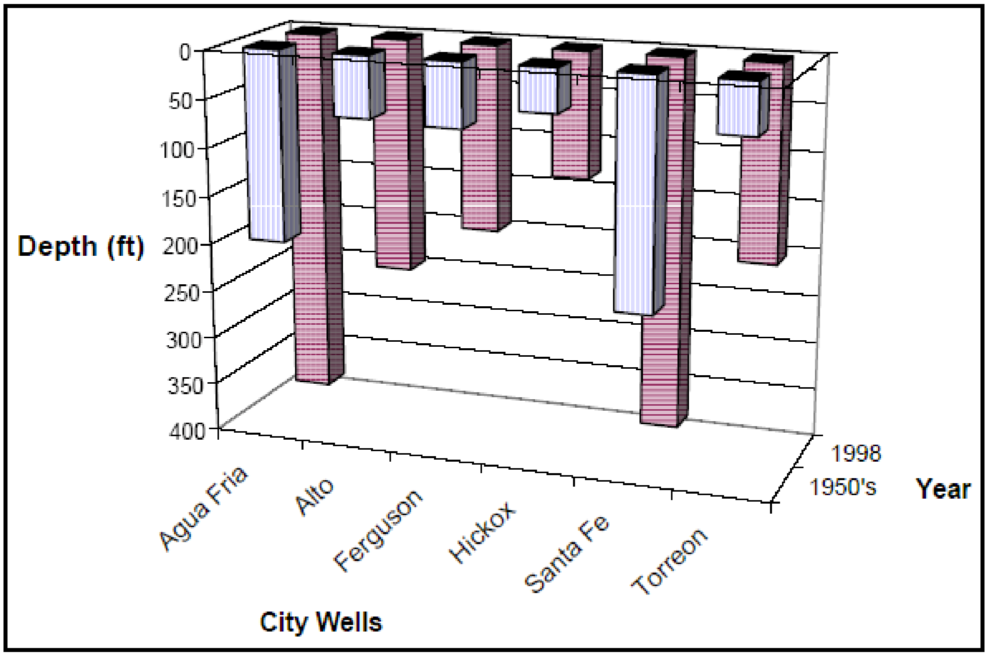


Figure 4.B. Water levels in Santa Fe City wells
1950s (blue) and 1998 (pink)
Source: Grant (2002)

4.3 SOCIAL SCIENCE RESEARCH METHODS

It is important to conduct physical system studies involving the influence of humans within the lines of established social science methods so to analyze data critically, and produce robust, confident results. During several months of fieldwork in the summers of 2005 and 2006, investigations sought existing information from a variety of historical (archival) and contemporary (interview) sources. The methods included snowball sampling for potential interview subjects, conducting interviews, and archival research. Note taking and information processing (coding and database management) occurred during and following interviews, respectively. Other research activities also included: (1) observing tourists and their behavior towards the river; (2) observing river restoration projects, taking photographs, obtaining project plans, and speaking with project engineers and coordinators; (3) interviewing persons in public positions including present and past employees of federal, state, county, local agencies, acequia commissioners and members, non-profit organizations, academics, and long-time watershed residents; and (4) attending public and private organizational meetings.[13] These activities came to be a cornerstone of this research.

4.3.1 Snowball Sampling and Interviewing

Before arriving in Santa Fe in June of 2005, I identified several individuals as a starting point for interviews. These individuals, mentioned in existing planning documents obtained via the World Wide Web, included Santa Fe Watershed Association members, the City of Santa Fe River Coordinator, and the USFS hydrologist for the Santa Fe National Forest. These individuals provided additional contacts in non-profit organizations, local, and federal governments, respectively. Through questioning, the interviews of key persons led to others. This process, called snowball sampling, is a type of convenience sampling used to identify effectively a list of target individuals, and has been used successfully by other social scientists (Bryman 2001; Beardsworth and Keil 1992). Snowball sampling is most effective when the researcher identifies key individuals, and queries these individuals for potential additions as research candidates (Bernard 2002). This method was successful during the preliminary investigation in Santa Fe because of limited local resource knowledge during the first field season. During this first season (after approximately two dozen interviews), the number of new recommendations began to drop. Ultimately, the list became saturated, and no new names surfaced (Bernard 2002). Thus, I questioned the entire population of the first season's interview subject list.

After several months of refining this research project, field investigations during the summer of 2006 expanded on the preliminary work. Snowball sampling continued to find individuals with relevant information pertaining to defined research objectives. The expanded list of interviewees reached saturation toward the end of the second field season (although phone interviews continued between 2006 and 2009 as mid-research questions arose). Saturation builds confidence in research "as it refers to the fact that no additional data can be found that contribute to the categories being considered. However, the major problem associated with this notion is that it assumes that researchers know in advance what categories can be used in a study" (Burgess 1984: 56). To deal with this problem, at the end of the interview, I asked each individual to identify additional persons, historical or contemporary documents, or datasets that would supplement the research. The suggested persons identified by the interviewees were then compared to the list of existing interview targets. As fewer names emerged, confidence grew that the snowball sampling of relevant individuals was reaching saturation, and was effective at identifying most players pertaining to the research question and subject matter. Flexibility was also important, and the addition of a few supplemental categories (i.e. individuals) at a later time did occur; however, it became important to constrain additional discovery to the research questions and objectives. Two additional visits to Santa Fe in November of 2007 and June of 2008 provided opportunities to conduct additional interviews.

After four years of research, the breadth and depth of interview subjects has expanded beyond initial expectations to include a relevant sample of over 80 individuals, representing public and private groups, and political and governmental entities on the local, regional, and state level. Many individuals were long-time residents of the watershed who had held jobs pertaining to the river's past management. A selection of commissioners and members acequia communities were interviewed. "Old-timers" in the Santa Fe area and Village of Agua Fria were met and questioned (often involving iced-tea under shade trees or slow strolls along long-dry acequias). I also questioned a sample of political actors who have an influence on water management and distribution in Santa Fe, including the mayor of Santa Fe and former lieutenant governor of New Mexico. Interviews with a larger sector of federal agencies included USGS, BLM, and USFS employees. Within the academic community, the present and former New Mexico state historians, archivists of the Museum of New Mexico, director of the School of American Research, and researchers housed in the Laboratory of Anthropology (located on Museum Hill in Santa Fe), proved to be sources of high-quality information. Other interviews also took place with current water system managers of the city's Sangre de Cristo Water Division, GIS department, stormwater manager, and river coordinator. I also questioned the water attorney for the City of Santa Fe and other lawyers specializing in western water law. Others interviewees included employees of the County of Santa Fe Parks and Recreation department, the City of Santa Fe Parks department, representatives of the Village of Agua Fria and La Cienega, employees of the Trust for Public Lands (State Land Office), Natural Heritage New Mexico (NHNM), employees of the Interstate Stream Commission and the Office of the State Engineer, private industry engineers and planners involved in current restoration projects, independent historians and anthropologists, and authors.

The interviews, conducted in a semi-structured style, followed an interview guide (prepared set of questions) to lead the interview in a clear direction (Bernard 2002). These questions allowed for the comparison of data between interviews, but encouraged flexibility in the process. Semi-structured interviews were most appropriate for this project; questions were tailored to the interviewee depending on their profession, subject matter, and area of expertise. Straightforward answers to the questions provided sources for further investigation, while many discussions followed leads and explored topics beyond the interview guide. During the interviews, I recorded the date, time and location, as well as the names of any other individuals present. Interviews began with introductions, and a request for relevant contact information (a business card, or the information generally contained therein). I then briefly described the project scope and the purpose of the interview, so to uncover all existing information on the river, including potential documents and additional interview subjects. The research instrument included both open and closed questions given orally to each identified subject. I recorded answers by hand. The interviewees were asked about two main topics: (1) the length of time living and working in Santa Fe to gauge their level of familiarity with the area and subject, and (2) their perceived affiliation with the research project. Questions then proceeded to further discussions on topics specific to the individual being interviewed.

4.3.2 Archival Research

Archival research occurred at several of the historical repositories in New Mexico: Museum of New Mexico's Palace of the Governors Fray Angélico Chávez History Library, the Center for Southwestern Research at the University of New Mexico, the New Mexico Office of the State Engineer's Library, the New Mexico State Archives and Record Center, the Library of the Laboratory of Anthropology (which houses the Spanish Archives of New Mexico (SANM)), and the Santa Fe Public Library. These resources house a wealth of primary and secondary source materials including maps and architectural drawings, newspaper articles, photographs, letters and diaries, audio tapes, hydrographic surveys, and existing plans. For this project, historical research located and accessed relevant information via archive, manuscript, and library traditions. These three traditions "have three different approaches to their material: the librarian classifies; the manuscript curator describes; and the archivist explains" (Burke 1997: 118). The manuscript tradition is closer to library system methods than to an archival system, because manuscript curators analyze and categorize the content of each manuscript to create searchable catalogs (now mostly searchable, digital databases). In contrast to both libraries with sophisticated systems of material classification and searchable manuscript collections, the archive tradition relies "on the system of provenance, which means that information does not reflect structures of universal knowledge…, but rather description reflects organizational structure and activities from which the information was created" (93). Thus, documentation of these activities occurs in a descriptive device known as an archival "inventory." Inventories are passive and simply describe what exists in a "general, narrative statement, with some statistical information," including dates and number of materials in the record housed in the archive (96). Despite these differences, several finding aids within archives and manuscript repositories are alike. These finding aids include: series; folder lists (in New Mexico these are referred to as vertical files); item lists; indexes; and calendars.

Regardless of the type of historical repository, when performing archival work in New Mexico, it was important to take advantage of all available resources. The meager documentary base pertaining to colonial New Mexico is limited given the villa's isolation and tumultuous history: no documents or materials survived the Pueblo Revolt of 1680,[14] and archivists and historians try their best to glean as much detail as possible out of the few documents that remain (Hordes 2009: personal communication). Thus, this historical research effort sought to exhaust all possible sources of information pertaining to the research objectives, and was not a sample of relevant materials. Each research institution in Santa Fe provided assistance to aid in the discovery of all relevant project information. Research staff was important because, as stated by Burke (1997: 101), archivists are "the most frequent user of archival records, and the finding aids to the records are designed to aid that research." Therefore, to produce the most effective research outcome, I described the project with each archivist and staff historian at length before research began, and conducted follow-up meetings during the months of investigation. The "staff does research to provide guidance to distant researchers and inform them of the existence of certain materials and their apparent pertinence to the question at hand" (*ibid.*). I sought the assistance of museum curators, archivists, and research librarians so that I might "be given every clue possible to the content and importance of [each] collection, [as] many clues will have been gained by the staff in the processing or arrangement stage" of archive construction (*ibid.*). After four years of research, I have established good rapport with archivists and historians at the Laboratory of Anthropology and SANM, both past and present New Mexico State Historians, and scholars at the School of Advanced Research, and have called upon them on occasion to gather, duplicate, and mail (or e-mail) archival materials referenced during the review of items collected during field residency.

In the summer of 2005, the Fray Angélico Chávez History Library was the primary focus of historical research. Part of the Palace of the Governors and New Mexico's oldest library (1851), the Fray Angélico Chávez History Library preserves historical resources from pre-Columbian times through the present (Palace of the Governors 2005). This institution applies a combination of library and archive traditions, and uses three catalogs: (1) SALSA, the New Mexico State Library online public access catalog; (2) the online archive of New Mexico; and (3) vertical files by subject. These general catalogs provided the first step in the research process: the search for records began by using approximately fifty keywords including, but not limited to, geographic place names, subjects, persons, companies, governmental agencies, or other keywords. "'Key words' searching is extremely simple in most of today's systems, because it relies only on explicit reference terms in the search field" (Burke 1997: 117). I also spoke with the history library curator to inquire about finding all potential source materials relating to this research project.

After the curator and I identified relevant collections, the second step involved reviewing the collection content description and identifying pertinent information. The curator then pulled the documents for review. Most collection materials were in their original formats, and required delicate handling and proper care (pencils only for note taking, white gloves when handling materials). Primary sources, including maps and diaries from the seventeenth century, required a duplication request. After reviewing the material, I documented any additional resources that surfaced in a field note tablet for future investigation. If the additional resource was housed within the current research location, the material was requested for viewing as well.

The secondary focus of research in the summer of 2005 was the Center for Southwestern Research at the University of New Mexico (CSWR). CSWR focuses on New Mexican interdisciplinary subjects like Spanish Colonial, Chicano/Hispano, and environmental history, and houses regionally focused rare, archival materials (University of New Mexico 2009). CSWR uses digital collections of online documents, an online catalog, and subject guides. This institution also is a portal to the Rocky Mountain Online Archive. To find relevant materials for this project, at this research institution I repeated the process described above using their various finding aids and archivist assistance.

After a year of reading and translating the gathered materials, and better formulating my research objectives, I divided most archival work in the summer of 2006 between the Chávez History Library, the Laboratory of Anthropology Library in Santa

Fe, the Spanish Archives of New Mexico, the New Mexico Office of the State Engineer's Library, and the New Mexico State Archives and Records Center. Unfortunately, a fire at the University of New Mexico library (which houses the Center for Southwestern Research) precluded further research at this location. At each location, archive and manuscript research began with the use of inventories, records, and the guidance of resident scholars, followed by the two-step methodology described above. In some cases, I was aware of and sought out specific documents, deeds, photographs, maps, or other materials not part of the keyword search.

In both summers, I used the libraries mentioned above for general research and access to historical newspapers on microfilm. The Chávez History Library has a large microfilm collection of *The New Mexican*, from initial publication in 1849 to the present. Oftentimes I was aware of specific events described by the newspaper and read specific issues with purpose. Otherwise, this research effort used traditional library finding aids (card catalogs), to look for keywords in materials within the stacks and microfilm via the Dewey Decimal System. I read each item returned via the search for additional leads to other materials: a method reflective of snowball sampling.

At the conclusion of this research effort, I have dedicated four years to exhausting all possible sources of information with some relevancy to the present project within archives, manuscript collections, and libraries of northern New Mexico. Two additional opportunities (November 2007 and June 2008) allowed for additional gathering of primary sources, and meetings with resident scholars at each archive, as well as the present state historian Dr. Estevan Rael-Gálvez. These meetings ensured that I was aware of any additional collection materials that may have enriched this research, but were acquired by the archive since field residency. Any relevant materials that may be housed within archives in Spain or Mexico are not reflected in this research; however, I believe that if materials exist in these locations, their contents would only add minute details to the history of the river, and would not change the overall findings of this research.

4.3.3 Field Notes and Information Processing

Field notes gathered during the summer research periods comprised of two types; a log, and descriptive notes. The log documented each day's activities, including interview schedules, time spent in libraries and performing archival activities, daily expenses, and bicycling mileage. Descriptive notes collected during preliminary investigations included many subjects; each were recorded in a different notepad. Several notepads contained interviews. Each interview spanned approximately one hour, with several pages of notes collected per interview. Additional notes and general observations, written at the end of each day, supplemented each interview. I added potential leads to new interview subjects or data sources to the log for further investigation the following day. All notes were taken by hand due to limited computer access (modern amenities such as electricity and running water were not available in the field). Other notepads contained subject-specific material including cross-sections and field measurements of river conditions, geographic coordinates of important features, potential data sources and their locations, descriptions to supplement photographs, visual descriptions of landscape conditions, and potential project ideas.

Transcribed and coded interviews aided content analysis and organization. In many cases, qualitative analysis begins with coding, and there are many approaches to doing so (Bryman 2001). Preliminary investigations in Santa Fe established general research themes and keywords. The "value of using your own codes is that they develop naturally from your study and you'll find it easy to remember them as you code your notes each day" (Bryman 2001: 380). A combination of keywords and codes categorized collected information and designated existing documents (E); interviews to cross-reference (C); potential data sources (D); potential interview contacts (I); and subjects to review (R). Procedures continually developed during fieldwork to include additional codes. These codes were entered on the left margin next to the relevant note, and used during interviews and while transcribing. Coded interview data allowed for better assessments of interview contents and provided references for quick retrieval. Coding interviews with keywords reduces interviewer bias, and although coding has its own potential for bias, the researcher objectively selected keywords based on their frequency of occurrence. Upon the completion of fieldwork, the use of a database for cataloging interviews also allowed for quick retrieval of records and quotations based on keywords recorded during the meetings. As the volume of field notes and documents increased, the need for organization became apparent. I organized all collected material from the summer 2005 field season by keyword in folders, and alphabetized in file boxes. Within each subject folder, the documents were alphabetized by author name. This organizational structure, also documented within the database, acted as both a finding aid and as a method to track collected documents. During the summer 2006 field season, I indexed all field notes using the established keyword list from the previous field season. Computer access was limited, so each paper note denoted the date collected, keyword, and source. By entering these notes into the database after fieldwork was complete, queried entries were quickly accessible. This system was flexible and could easily incorporate new keywords not encountered during the first field season.

4.4 DISSERTATION FRAMEWORK: A GUIDE TO METHODS

The methods employed to compose this dissertation are organized to guide the reader through the content and findings of the following chapters. A framework of topics presents these methods: hydrologic techniques (Section 4.1) provide a framework for Chapter 5, Santa Fe River Flow; Chapter 6, Santa Fe River Form, contains the methods inherent to fluvial geomorphology (Section 4.2); while a majority of the GIScience and qualitative methods (Section 4.3) are reflected in Chapter 7, Santa Fe River Function, and Chapter 8, the Living River. These latter two method categories benefit the entire project; thus, the results of which are found throughout the document. Each topic breaks new ground in Santa Fe: some methods are unique to this research, while others apply established techniques to gathered data for the first time in this location. The results elucidate previous unknowns and establish connections between historic events and environmental conditions within the basin. This research contributes new methods for the spatial reconstruction of historical acequia networks in arid environments of northern New Mexico (a GIScience technique), the estimation of irrigation land totals from the rectification of historical maps, and the correlation of streamflow (reconstructed from tree-ring data) to yearly irrigation potential.

SANTA FE RIVER FLOW

5.0 CHAPTER OVERVIEW

Four sections divide the discussion of Santa Fe River flow. The first section of Chapter 5 (5.1) describes river flow through space and time at the reach level. The purpose of this section is to clarify river flow geography within the context of Santa Fe history via modern quantitative techniques and descriptive materials. There has been significant debate amongst anthropologists, historians, and basin managers about the geography of river flow through time, and many scholars question whether the river indeed ran for its entire length throughout the year. Section 5.1.1 discusses elements of physical geography, and historical and current conditions influencing flow in the upper reach from its headwaters, downstream to several dams. The upper watershed is an important spatial component of this research. Flow is described here more thoroughly than the other reaches for two reasons: (1) to give context to the overall description, as most of the water flowing in the river comes directly from the upper watershed, and (2) a lengthy record of publicly accessible discharge data are available in this reach, but are absent in the other two. This section examines upper reach flows to quantify hydrologic change in the last century using a K-S test and an IHA two-period analysis. Section 5.1.2 describes flow in the urban reach. The discussion includes characterizing four-hundred years of river flow, from the dams to beyond the historic Village of Agua Fria. Quantitative findings and historical descriptions support the hypothesis of perennial flow *in most years*, from settlement in 1610 to the installation of dams in the late 1800s.

Section 5.1.3 describes flow in the lower reach, beginning at the current WWTP and continuing downstream to the river's confluence with the Rio Grande. Geology plays a defining role in the flow of this lower river reach.

Analysis in the second section of Chapter 5 (5.2) reconstructs major trends in river flow by applying linear regression to tree-ring derived precipitation values from the nearby Arroyo Hondo Pueblo. Using previously assembled tree-ring chronologies from Rose, Dean, and Robinson (1981), a framework of historic events in Santa Fe sets the tone for irrigated agriculture in the watershed. Reconstructing river flow adds a level of quantification to specific historic events that changed the colony and challenged the survival skills of Santa Feans. In some cases, results reveal the true causes of events, while others elucidate their previously unknown magnitude. Combining quantified results with historical materials paints a truer picture of the changes in river flow that have taken place over the last four-hundred years of Santa Fe's occupation.

The third section of Chapter 5 (5.3) elucidates the influence of irrigated agriculture on river flow. This research emphasizes the importance of vast water spreading on the Santa Fe pediment over a 300-year period. Calculations enumerate the subsurface flow feedback at work; contributions to river flow via shallow groundwater allow for agricultural expansion not otherwise possible under natural conditions. Remote sensing techniques quantify the amount of land in irrigation from historical maps and aerial photography. By relating the tree-ring predicted flow results with spatial areas in irrigation, this research quantifies the carrying capacity of the river (in acres) on an annual basis.

The fourth section of Chapter 5 (5.4) discusses the effects of dam installation on flow. Two statistical methods, IHA and linear regression, are applied to existing stream-gaging and precipitation data, respectively. A chronology of dam installation provides a framework for the IHA output. Linear regression identifies variability in regional climate patterns to show definitively that changes in river flow indicated by stream-gaging records are not a result of climate change.

Section 5.5 closes the chapter by reviewing the findings of the flow analyses. Human-induced changes within the watershed affect flow through the combination of landcover manipulation and dam installations. Chapter 5 findings explain some origins for the current perceptions of past and present river hydrology, and elucidate the reasoning for the elevated expectations placed upon flow restoration efforts. This section revisits the major findings of this chapter within the context of hydrology and human-induced change.

5.1 THE GEOGRAPHY OF FLOW THROUGH SPACE AND TIME

5.1.1 Upper Reach Flow

During villa site selection in the first decade of the 17th century, water filled the river in its upper reach: flowing steeply and freely from high in the watershed, exiting the metamorphic rocks of the Sangre de Cristo Mountains, and meandering through high terraces of gravel and sand into the valley below. The resource-laden upper watershed was another attractive reason to select this particular site. The ample timber, plentiful grazing lands, and abundant food sources of seeds, nuts, fish, and wild game became the means from which the population supplemented their agricultural endeavors (Figure 5.A).

Figure 5.A. Upper reach fishing, circa 1912
Photographer facing downstream
Source: Museum of New Mexico, negative #61587

In the Santa Fe watershed, the amount of precipitation received annually is more a function of elevation than latitude. Thus, the upper watershed receives more precipitation than lower watershed areas; however, local variability is also a function of a landscape's aspect, topographic features, and seasonality (Pratt and Snow 1988). The upper reach is a snowmelt-dominated system. Each winter's snowpack delivers water to the channel via surface and subsurface flow, and constitutes the majority of annual streamflow. Because of this melt water, the river is perennial from its headwaters to McClure reservoir. Few historical documents survive that describe river flow in the upper watershed, but references by Fray Francisco Atanasio Domínguez during his visitation of the missions in 1776, and by Señor Don Pedro Alonso O'Crouley in 1774, describe it as having exceptional water clarity, and as a “crystal clear river full of small but choice trout,” respectively.

In 1880, fire devastated the town and surrounding hillsides of Las Vegas, New Mexico, because there was no existing water source or water infrastructure to fight the blaze (Goldman 2003). To avoid a similar fate, Santa Feans began to build dams to protect their watershed from fire, to store water for times of drought, and to control seasonal flooding. In 1932, the U.S. Department of Agriculture (USDA) closed the watershed to all entrants and occupants to protect the public water supply from pollution and contamination from humans and livestock. As a result, there was a rapid resurgence in tree cover because of grazing and logging prohibitions and fire suppression. Paired aerial photography from 1936 and 2001 show the stark differences in tree densities (Figure 5.B).

Ecological assessments by the USFS have calculated tree densities at 800 to 1,200 per acre, instead of a more natural 100 to 200 per acre (Grant 2002). Scientists hypothesize that these dense stands, called doghair thickets, have reduced stream flow in the upper reach by up to 33 percent (Uday 2004). In relation to other land uses, forests are intensively water consumptive, and may reduce stream flow (Trimble *et al.* 1987). Covington *et al.* (1997) found similar results in western Ponderosa pine forests, where greater tree densities, higher transpiration rates, and smaller stream flows were the result of fire suppression. Snow ablation from the canopy of these dense stands may also reduce streamflow, as water fails to reach the ground to contribute to surface and subsurface flows (USFS 1998).

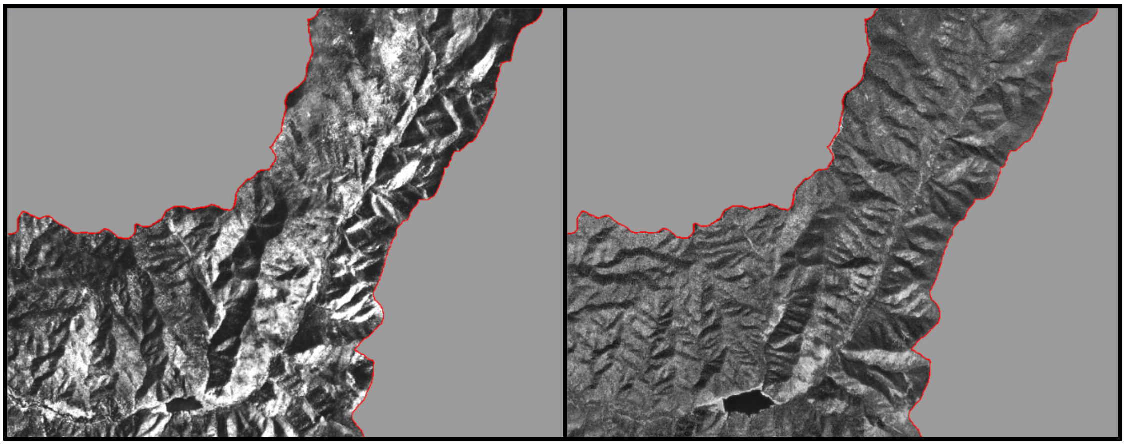


Figure 5.B. Resurgence in tree cover after watershed closure
Paired photography from 1936 and 2001
Source: maps by author; imagery USDA Forest Service (2005); USGS (2001)

Because the research citing this reduction does not clarify whether the effects of dams were removed from the analysis, statistics test the hypothesis that streamflow volume has reduced significantly since watershed closure, irrespective of dams. In 1913, the SRS stream gage began to capture unregulated daily mean flows from the upper reach, until the 1925 construction of Granite Point Dam (now known as McClure Dam) upstream. A second gaging station (SRM) installed in 1998 above all dams has recorded unregulated daily mean flows for the last 10 years (Figure 5.C). A K-S test examines daily mean flows (normalized by watershed area) between these two datasets to state definitively that there has been a reduction. Several findings led to the selection of this test. First, the data are not normally distributed, meaning that the mean and median are not equal, and parametric testing would be inappropriate. Typically, stream flow records do not fit the classic bell-shaped curve, but instead fit a lognormal distribution. A single high flow event may cause the mean to exceed the median, while the large number of average daily flows positively skews the dataset. Sometimes when a sample size is large, parametric tests are appropriate; however, in this case, the data are non-normal and to stress confidence in the results, this analysis applies the K-S test. The K-S test is non-parametric, and identifies significant differences between datasets without assumptions about the distribution. Results indicate a significant difference between the two distributions.[15] Streamflow in the last ten years is significantly different from streamflow in the early twentieth century, irrespective of dams.

Regardless of this careful statistical test selection, the results of this examination still require a cautious interpretation because of data limitations. Given the established relationship between precipitation and streamflow (Section 5.4.2), the temporal coincidence of these datasets with significant climatic departures from average conditions compromises the comparisons. The first dataset represents a statistically significant wet period while the second dataset represents a significantly dry period. Unfortunately, this scenario is unavoidable because these datasets are the only periods of publically available streamflow records uninfluenced by upstream dams.

In addition to the limited selection of available data, streamflow values between years are often temporarily correlated due to the influence of climate. When climatic events last longer than a single year, the likelihood is high that streamflow between years will be similar. If temporal autocorrelation exists between years, the results of the K-S test are not valid. To test for temporal autocorrelation within the examined datasets, correlograms plot calculations of autocorrelation against time lags for annual median flow for the two periods under investigation.[16] Neither of the plots illustrates autocorrelation at a confidence interval of 95 percent. The results of these statistics show that there is a statistically significant difference in streamflow volumes between the two periods, irrespective of the influence of dams and their water diversion for public supply.

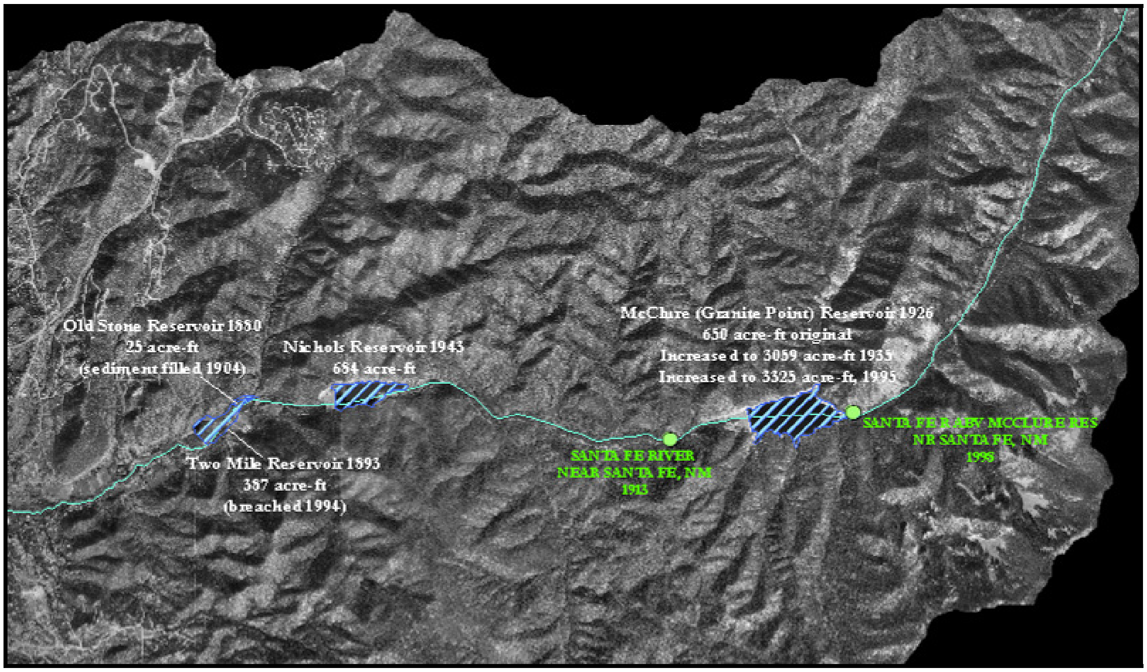


Figure 5.C. Reservoir and stream gage locations on the Santa Fe River
Source: map by author; imagery USGS (2001)

IHA two-period analysis run on the same datasets applied to the K-S test reveals temporal changes in individual hydrologic flow parameters. The resulting tabular output shows significant differences in some flow parameters between the periods (Table 5.1).[17,18] IHA effectively deals with the problem of non-normalcy in these data by parsing the data into individual hydrologic regime parameters (Appendix A). Via the application of a stationary, simple interrupted time series research design, IHA captures alteration in magnitudes and recurrence intervals not seen when examining each station alone (using the one-period linear regression option). The use of IHA two-period analysis on two different gages on the same system, normalized by watershed area, is a novel and elegant method of discerning flow differences between times, irrespective of dams. These stations are comparable because of the similarity of their watersheds: these basins are one and the same, yet the contributing basin to the upstream station (SRM) is simply one-third less the area of the other. The similar land covers, topography, elevation, and management histories makes them directly comparable.

Table 5.1. IHA Parameter Scorecard[18]
Santa Fe River near Santa Fe (SRS) and Santa Fe River above McClure (SRM)
SRS: Water Years 1913-1925 SRM: Water Years 1998-2008

PARAMETERS	**MEDIANS**		**COEFF. OF DISP.**		**DEVIATION FACTOR**		**SIGNIFICANCE COUNT**	
	SRS	SRM	SRS	SRM	Medians	C.D.	Medians	C.D.
Parameter Group # 1								
October	13.7	13.93	1.94	1.272	0.01698	0.3442	0.8699	0.5155
November	13.7	11.99	1.04	1.052	-0.1242	0.0119	0.5626	0.983
December	13.7	10.45	0.6	0.8981	-0.2373	0.4969	0.3383	0.2192
January	13.7	10.83	0.4401	0.7767	-0.209	0.7651	0.1291	0.07007
February	14.52	9.092	0.8208	1.666	-0.3737	1.03	0.2072	0.05906
March	31.23	21.67	0.693	1.688	-0.3062	1.436	0.4414	0.04204
April	79.43	47.39	2.134	1.861	-0.4034	0.128	0.5576	0.8118
May	175.3	116.1	0.7344	1.396	-0.3379	0.9007	0.3403	0.1622
June	104.1	37.72	1.237	2.471	-0.6376	0.9974	0.1431	0.1491
July	33.96	21.67	2.202	1.061	-0.3621	0.5182	0.3293	0.3453
August	33.96	17.8	1.121	3.174	-0.476	1.831	0.3514	0.08308
September	18.35	17.22	1.112	0.9832	-0.0619	0.1158	0.8819	0.8118
Parameter Group # 2								
1-day minimum	7.67	4.411	0.7141	1.158	-0.425	0.6215	0.3824	0.2462
3-day minimum	7.304	4.514	0.75	1.257	-0.382	0.6762	0.4805	0.2222
7-day minimum	7.513	4.974	0.7552	1.231	-0.3379	0.6296	0.4715	0.2863
30-day minimum	6.738	6.313	1.18	0.987	-0.06314	0.1637	0.8669	0.6737
90-day minimum	10.66	8.354	0.7253	0.7856	-0.2162	0.08313	0.6527	0.8539
1-day maximum	301.3	243.7	1.518	1.468	-0.1911	0.03289	0.6557	0.9419
3-day maximum	299.5	232.1	1.424	1.343	-0.2249	0.0567	0.6096	0.9049
7-day maximum	234.8	207.3	1.663	1.31	-0.1172	0.2122	0.7818	0.6827
30-day maximum	177.9	171.9	1.378	0.9687	-0.03347	0.2969	0.9069	0.6016
90-day maximum	135.1	105.5	1.318	0.9327	-0.219	0.2923	0.3433	0.6456
# of 0 days	0	0	0	0			0	0
Base flow	0.1084	0.1417	0.7991	0.9247	0.3075	0.1572	0.07808	0.8999
Parameter Group # 3								
Minimum date	273	276	0.2322	0.209	0.01639	0.1	0.9269	0.8779
Maximum date	146	207	0.1571	0.2459	0.3333	0.5652	0.07608	0.07007
Parameter Group # 4								
Low pulse count	4	4.5	1.375	2.167	0.125	0.5758	0.7578	0.2242
Low pulse duration	6	9.25	1	2.216	0.5417	1.216	0.1061	0.2503
High pulse count	3	2.5	1.167	1.2	-0.1667	0.02857	0.6076	0.9319
High pulse duration	9.25	14.5	4.757	1.345	0.5676	0.7173	0.2723	0.3804
The low pulse threshold is 13.15								
The high pulse level is 65.74								
Parameter Group # 5								
Rise rate	3.287	2.32	1.166	0.5838	-0.2942	0.4995	0.3293	0.2372
Fall rate	-4.383	-1.548	-0.6874	-0.6873	0.6468	4.951E-5	0.1802	1
# of reversals	62	106	0.2339	0.4151	0.7097	0.7749	0.004004	0.03604

By comparing the two stations on the same stream with vastly different periods, several differences are evident. All minimum flow parameters show that between these periods, low flows have decreased in volume; however, recent low flows of shorter duration have greater variability than their early twentieth-century counterparts, by up to 68 percent. Spring flows indicate that, in general, the seasonal pattern of snowmelt delivery is still consistent, although medians vary from year to year. For example, March results indicate a moderately reduced median flow (30 percent), but the variability increased by 143 percent (a highly significant difference). Perhaps warmer temperatures in the last decade have led to a few instances of earlier spring melts. May results follow a similar pattern, with a 34 percent flow volume reduction, but 90 percent increased variability. In contrast, although April's median flow is 40 percent less than it was 80 years ago, the variability of these flows has only increased by 12 percent. These conflicting results require further investigation, in particular, including the effects of temperature. Summer months show the greatest volume reductions, especially June, with a 64 percent reduction in median flow, and 100 percent increase in the variability of those flows. August flows are significantly different as well, with medians dropping by 48 percent, and variability increasing by an incredible 183 percent (the most statistically significant IHA result of this analysis). It is likely that Monsoonal variability heavily influences August flows. These results indicate a volume reduction and increased inconsistency in total water delivery to the stream, likely attributable to climate differences, including both modified temperature and precipitation patterns (wet period versus dry period). If landcover changes in the watershed were the only reason for the reduction in flows in the spring and summer months, C.D. variability would likely not be as high.

Despite the reduction in total water delivery between periods, some of the seasonal character of annual climate inputs is not substantially different. The least amount of change, in both flow volumes and variability occurs in September, October and November: dry months where the climate lacks inputs to the hydrologic regime regardless of the ENSO influence. The significance counts are high (close to 1.0) indicating there is little difference between the periods. The annual date of minimum flow also changed only minimally in both central tendency and variability, with a shift from September 30 to October 3.

For several variables, low significance counts indicate a highly significant difference between the periods. For example, the date of maximum flow has shifted 30 days later into the calendar year (perhaps an effect of climate change?); a low significance count of 0.07 (minimum value is 0) illustrates an extreme difference in the periods. Other parameters included in this category include the number of reversals and low pulse duration. Regardless of these few parameters, the differences between the two periods statistically confirm hydrologic regime changes in the upper watershed independent of dams. These results indicate that the resurgence in tree cover is not the only factor driving reductions in streamflow. Although these results correlate well with the K-S test results, this research shows synoptic and climatic variability can significantly affect hydrologic regime parameters, and that IHA can more specifically elucidate these changes beyond generalizations about total annual flow volume or data distribution changes. However, in Section 5.4.2 (Regional Climate Change and Effects on Flow) linear regression of precipitation anomalies by month reveal that no significant change in annual precipitation volume has occurred between 1850 and the present. These results indicate it is simply not the annual volume of precipitation determining flow in snowmelt-dominate hydrologic regimes, but the timing of its delivery. This research encourages pairing further hydrologic regime investigations with changes in watershed management (i.e. stand thinning), and the specific effects of synoptic and climatic influences, including temperature, ENSO and PDO. It is therefore likely that a combination of factors contributes to the differences in streamflow recorded by gages in the last century.

5.1.2 Urban Reach Flow

Before the influence of humans, the river likely would flow continuously *in the wettest years* from its origin in Lake Peak to its relative terminus at the Rio Grande. The river, in all probability, would have been ephemeral were it not for the geologic characteristics of the watershed and the vast agricultural applications of water to fields. The highly porous Ancha unit easily absorbed irrigation water, while the unconformity of the underlying Tesuque unit guided subsurface flow to the river. There are also faults that bisect the river in several places, and ramp groundwater from the Tesuque to the surface; thus, creating springs in a hydrologic daisy chain. Seasonal and climatic variations aside, the occurrence of water along the entire course is evident given the citations found in early documents and the historical farms that dot the corridor: their place names all indicative of the continued presence of water (Cieneguitas (*little marshes* near present-day Frenchy's Field park), Agua Fria (*cold water*), Cienega Grande (*big marsh*, i.e. modern-day La Cienega), and Cieneguilla (*little marsh*)). Even the place name of the abandoned pueblo in downtown Santa Fe that once housed Indians north of the river, Kaupoge, means "place of shell beads by the water;" bolstering the argument for the past presence of continuous flow. Figure 5.D shows the locations of these early *ranchos* and geologic faults. Evidence of agriculture and surface water at each location is present in the inset maps. The visual expressions of these faults are typically springs.

Scientists and historians do not debate the perennial nature of flow high in the urban reach, although it has not run regularly through downtown since the major dam constructions of the early 1900s. A virtually complete dewatering of the river has occurred from the Camino Alire Bridge to the city's WWTP. Presently, the only flows occupying the channel are from surface runoff generated by precipitation events, or surplus discharges from upstream dams after they meet their water allocation requirements. Prior to impoundment, however, flows extended downstream beyond the confluence with the Arroyo Mascaras, past Cieneguitas, and to at least Agua Fria even in the most meager years. The cienega and numerous springs in the downtown area, which included the Rio Chiquito (a spring-fed tributary to the river), supplemented urban reach flows. After dam installation and cienega desiccation in the early twentieth century, baseflow came primarily from groundwater contributions.

The historic Village of Agua Fria is a little more than 3.2 river km (2.0 river mi) downstream of Cieneguitas. The place name indicates the presence of cold spring water that originates from the Agua Fria reverse fault, which bisects the river and ramps water to the surface (dip is approximately -75°) (Figure 5.E). The fault is visible where it dissects the river course, as is the unconformity between the Ancha and Tesuque formations. Vegetation and moist sediments are upstream of the fault; downstream there is no vegetation and the surface sediments are dry. Before the aquifer drawdown that began in the 1950s, this spring added water to the river's baseflow and supplemented irrigation. Now, a well taps the spring and it remains a reliable source for the city's Sangre de Cristo Water Division. In historical documents, Agua Fria is referred to Quemado, or burnt pueblo. The fact that a permanent pueblo was located here indicates that this hydrologic connection has been present for hundreds, if not thousands, of years. Fray Francisco Atanasio Domínguez mentioned Quemado during his visit in 1776, as having "farmlands fertilized by the aforesaid river… [that] usually yield fairly good crops," indicating that river flows extended at least as far as the village on a regular basis (Adams and Chávez 1956: 41). After upstream dam installations, irrigation in Agua Fria decreased from an estimated 900 acres (3.6 km^2) (from historical aerial photography in 1936) to a mere 90 acres (0.36 km^2) of orchards, gardens, and hay fields today.

5.1.3 Lower Reach Flow

Lower reach flow begins at the city's WWTP, located 7.2 river km (4.5 river mi) downstream from Agua Fria. Due to daily wastewater discharges and spring contributions, the river is perennial from the plant to its confluence with the Rio Grande. Built in 1963, the city's Paseo Real Wastewater Treatment Plant has been upgraded to handle the current 13 million gallons per day (mgd) (equivalent to 11,607 acre-feet per year) inflow volume produced by 65,000 residents. The plant discharges an average volume of 5.8 mgd (0.255 cms, 9.0 cfs, or 5,179 acre-feet per year) to the river (City of Santa Fe 2009a). Significant spikes in water use and wastewater production occur each year during Santa Fe's heaviest tourist weekends, which include the annual Santa Fe Opera opening, Spanish Market, and Indian Market. During these events, an additional twenty-thousand visitors flood the city and increase pressure on water resources and on the wastewater system (Harwood 2006: personal communication). The effluent receives

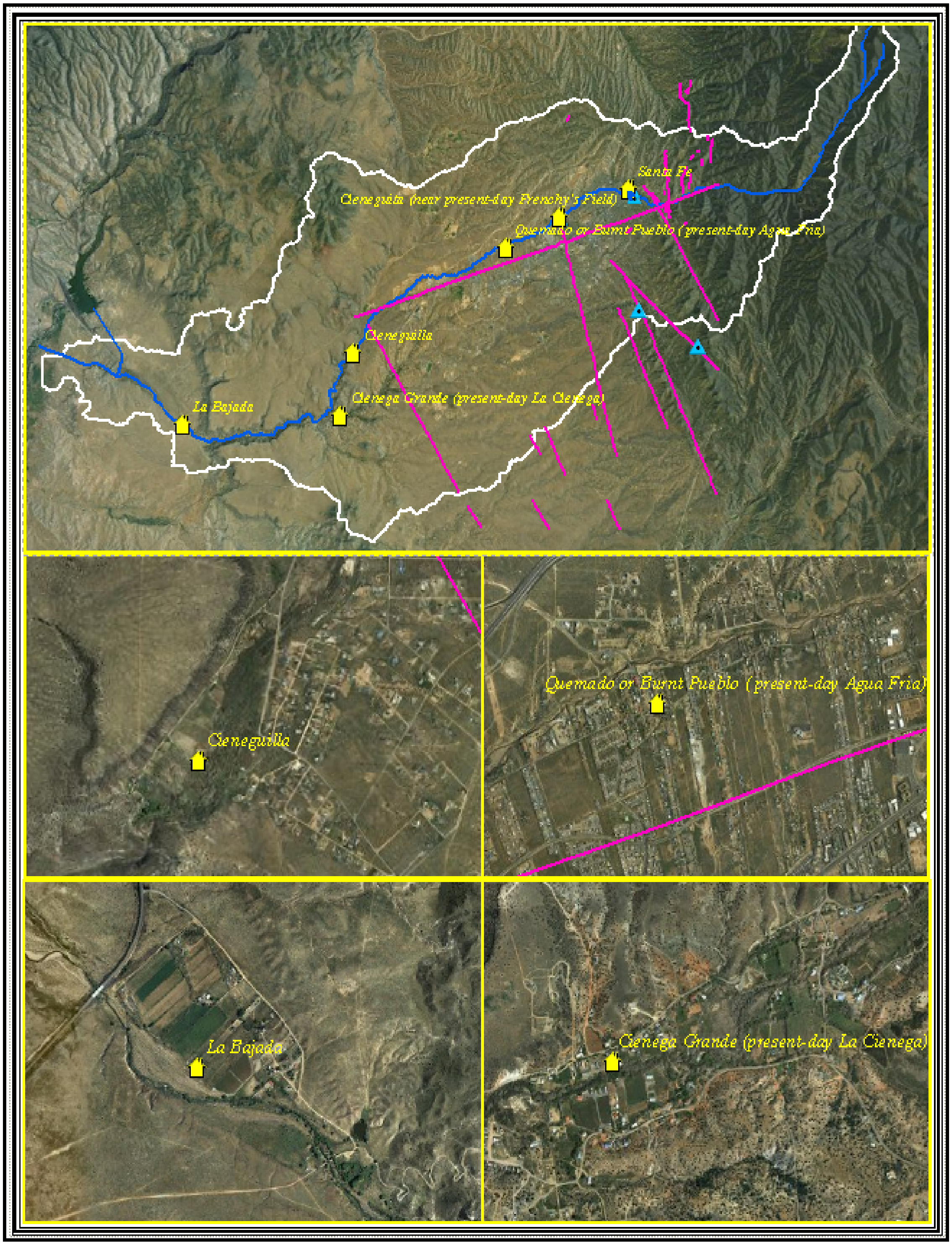


Figure 5.D. Early ranchos in the watershed with mapped geologic faults
Source: map by author; imagery ESRI ArcGIS Online (2009)

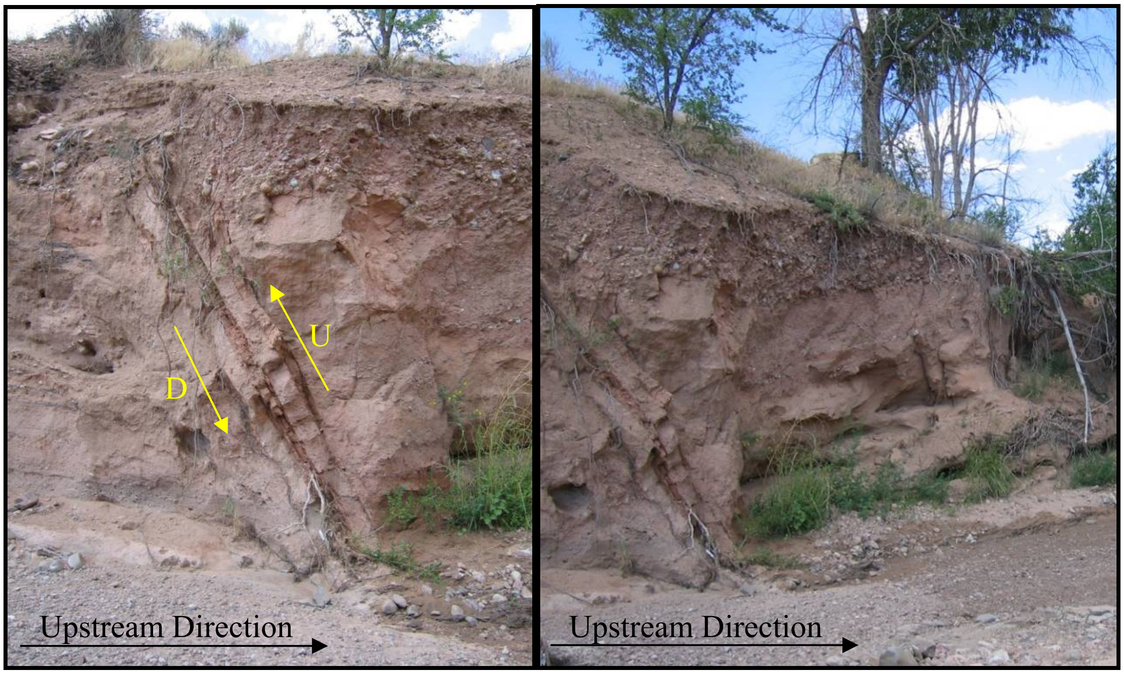


Figure 5.E. The Agua Fria reverse fault ramps water to the surface
Source: photos by author (2005)

secondary treatment: some is metered before it is discharged to the channel, while the remaining volume is sold via yearly contract to private companies for construction, dust control, compaction, and non-potable land applications, including local golf courses and sport fields (City of Santa Fe 2009a). The nitrogen and phosphorus-rich discharges support dense streamside vegetation (Figure 5.F), and over time, have caused the local water table to rise.

12.9 river km (8 river mi) downstream of Agua Fria, just before the river enters the basaltic canyon of La Bajada, it passes a place under irrigation by water in the river

> when it gets that far. A little below this settlement near the nooks between some little rock mesas, a number of springs arise (they are probably a resurgence, or outcrop, of the Santa Fe River) and run to the west in little ravines. Since this water flows down-hill between the rocks, they cannot change its course in order to use it for irrigation instead of the Santa Fe River. The water from these springs forms a river called Las Bocas… This settlement is called Cieneguilla
> (Adams and Chávez 1956: 41).

This observation by Fray Francisco Atanasio Domínguez in 1776 is still relevant today: Cieneguilla's water supply is primarily spring-fed. Geology plays an important role in keeping this area wet and adds to the river's baseflow. Approximately one river mile upstream from Cieneguilla, the Cienega Fault bisects the river. Springs abound from this planar fracture. Another river mile upstream of the Cienega Fault, the Santa Fe River Fault crosses the river. These two structures create important hydrologic features by creating barriers to groundwater flow (topographically driven in the upper units) and ramping water to the surface. Thus, groundwater contributions were a vital part of the river's perenniality. Figure 5.G shows a flowing river at Cieneguilla in 1910 and 2001. In modern Cieneguilla, the river course is more narrow, with invasive species (Russian-olive (*Elaeagnus angustifolia* L.)) obscuring views of any flow.

Figure 5.F. Dense streamside vegetation downstream of wastewater treatment plant
Photographer facing downstream
Source: photo by author (2005)

Figure 5.G. Paired photography - Santa Fe River at Cieneguilla, 1910 and 2001
Source: (1910) Rio Grande Historical Collections, New Mexico State University Library, Herbert W. Yeo Papers; (2001) Steven Tharnstrom

The confluence of Cienega Creek and the Santa Fe River is 6.4 river km (4 river mi) downstream from Cieneguilla, and 19.3 river km (12 river mi) downstream from Agua Fria. Cienega Creek is the only perennial tributary to the river, and contributes a reliable source of flow throughout the year (Grant 2002). A network of springs that originate from the Cienega Fault feed Cienega Creek. Tertiary intrusions, like the Cieneguilla limburgite, breccias, and flows of augite andesite can all be found in close proximity, and transport groundwater to the surface. Babiker and Gudmundsson (2004) documented the importance of fracture-related permeability in arid areas to deliver groundwater upward, thus making it more accessible. The Arroyo Hondo is an ephemeral tributary to Cienega Creek, and rarely contributes flow (Grant 2002). In 1776, the settlement within the small canyon called Cienega Grande (now modern-day La Cienega), relied on springs for irrigation, livestock watering, and daily use (Adams and Chávez 1956). The spring-supported acequia network in La Cienega was dug around 1719, and currently irrigates about 100 acres (0.40 km^2) (Figure 5.H; Scanlon & Associates, Inc. 1981).

The hamlet of La Bajada is 9.7 river km (6 river mi) downstream from the confluence of Cienega Creek and the river, and almost 23 river km (14 river mi) downstream from the WWTP. Currently, streamflow in La Bajada reflects the discharge pattern of the wastewater treatment plant because the plant is the reach's primary source; springs throughout the canyon supplement about 0.085 cms (3 cfs) to baseflow (Grant 2002). The waters are nutrient rich and algae cover the channel bed. Grazing cattle, which roam in the channel, are also a source of nutrients. This area has a long history of occupied *ranchos*: nearby archaeological evidence includes a prehistoric pueblo, a single-component historic Spanish home dated between 1650 and 1660, and a small, dozen-room compound that was still standing during the Reconquest but was not reinhabited (Laboratory of Anthropology 1962). These structures were located on a bluff on the north bank of the river approximately half the distance between the Rio Grande confluence and the hamlet. Field excavations by the Laboratory also uncovered evidence of animal husbandry, which was likely combined with acequia agriculture to sustain the small settlement. Springs were the primary water source for acequia agriculture in

Figure 5.H. Cienega Grande (modern-day La Cienega) spring-fed acequia
Source: photo by author (2006)

La Bajada prior to the installation of the WWTP, because upstream farms would bleed off most river water. Paired photography in Figures 5.Ia and 5.Ib show La Bajada in 1910 and 2001, respectively. This area remains one of the most unchanged landscapes in the watershed (Grant 2002). Historical aerial photography shows approximately 400 acres (1.6 km^2) in irrigation in 1936. Also visible is an acequia headgate about 1,000 m (3,280 ft) upstream from the main buildings, and a *tanque* (small reservoir) for water storage. Today, the reduced spatial extent of irrigation equals approximately 60 acres (0.24 km^2) (as estimated by aerial photography). The main headgate still diverts water for temporary storage through the Acequia Madre and into the local tanque. From the settlement history, the fields in irrigation, the tanque, and the acequia, it can be assumed that the supply of water coming downstream through the canyon was large enough to support a few hundred acres of irrigated fields, especially with the help of the small reservoir's storage. Field investigations in the summers of 2005 (a wet year) and 2006 (an exceptionally dry year) observed water in the channel. This lack of flow variability is due to the mono-flow of the upstream WWTP.

La Bajada means *the descent*. Prior to 1973, river flows descended through the canyon of basalt, exited the confines of its steep walls, and braided through an open savannah until joining the Rio Grande (Grant 2002). According to 1936 aerial photography, prior to the construction of Cochiti Dam in 1965, the confluence appeared to be a wide, braided alluvial delta interspersed with vegetated islands. Now, the river has a bifurcated mouth. An engineered channel began diverting all river flow into Cochiti Reservoir in 1973. In 1975, after ten years of construction, Cochiti Dam began its functions as flood and sediment control structure on the Rio Grande (Pueblo de

Figure 5.Ia. La Bajada hamlet, acequia and fields in irrigation, 1910
Source: Rio Grande Historical Collections, New Mexico State University Library, Herbert W. Yeo Papers

Figure 5.Ib. La Bajada hamlet, acequia and fields in irrigation, 2001
Source: Photo by S. Tharnstrom, September 2001

Cochiti 2009). The diversion now leaks, however, so seepage below it feeds the original river course. Minimal flows in the original river channel now join the Rio Grande south of the dam, amidst irrigated fields of Cochiti Pueblo.

5.2 SANTA FE RIVER FLOW RECONSTRUCTION

There are no flow records available on the Santa Fe River prior to 1913. Through linear regression techniques, tree-ring chronologies serve as a proxy for streamflow data. A direct relationship connects tree-ring derived precipitation and streamflow values during two known periods in time, and predicts river flow on an annual basis for years where no data existed. The modeled streamflow output relates wet and dry years to events in Santa Fe history recorded in historical documents. The modeled streamflow output also closely matches ENSO events. Hydrologic and statistical techniques categorize the magnitude and return interval of important flow events, including historical floods referenced by archival documents.

5.2.1 Tree-Ring Database and Correlation with Santa Fe River Flow

Rose, Dean, and Robinson (1981) assembled an extensive tree-ring chronology analyzing past climates at the Arroyo Hondo Pueblo. This classic period pueblo is only 6.4 km (4 mi) from downtown Santa Fe, and is located near the Arroyo Hondo, an ephemeral river tributary. The tree-ring chronology, developed from several local sources, was cross-referenced and rigorously analyzed using tested statistical methods and a lengthy modern precipitation record (Rose, Dean, and Robinson 1981). The lower-forest border species represented in this chronology are ideal for three-ring studies, as they are highly sensitive to moisture conditions, have the most consistent but variable ring-width response from year to year, and are known to produce only one ring per year (Fritts *et al.* 1965). Therefore, it is likely that this tree-ring chronology is highly reliable. The result is a long-range, high-quality representation of local climate in the area from 985 A.D. through 1970 A.D. (Rose, Dean, and Robinson 1981). After thorough analyses of response functions, Rose, Dean, and Robinson (1981) determined two useful variables for reconstructing precipitation from tree-rings in the Santa Fe watershed: (1) annual precipitation from the previous August through the current July, and (2) spring precipitation (March through June of the current year's ring).

There are limitations, however, to the river flow reconstruction from tree-rings. In a snowmelt-dominated river, such as the Santa Fe, streamflow records used to establish the correlation between annual precipitation and annual flow are more likely to reflect years when winter moisture is high. Winter storage conditions are highly influential on conifers in this region, and spring growth reflects moisture in the previous late fall and winter (Rose, Dean, and Robinson 1981). If the annual snowpack is large, the streamflow reconstruction likely will correlate well with actual hydrologic conditions. Given the relationship between ENSO events and winter moisture in northern New Mexico mountain environments, it is also likely that this model will more consistently represent warm ENSO than cold ENSO.

Another limit to this model includes the representation of years in which summer and early fall thunderstorms deliver the majority of precipitation to the annual streamflow total. In these years, flows will not be reflected in the annual growth ring, which introduces some error into the correlation. A clear example of this hypothesis occurs in October of 1767, when the earliest documented flood on the river appears in historical documents, yet it is not reflected in the predicted river flow value. The predicted volume for this particular year is close to the mean, and provides no evidence for any significant event. However, GIS analysis (detailed in this section below) and historical documents highlight the significance of this flow event to shaping the physical environment. A second example of this limitation occurs in 1904. In this exceedingly dry year, there was little snow in the upper watershed; an event heavily reported in newspapers and captured in Weather Bureau observations. The tree-ring data predicts 1904 streamflow to be greater than two standard deviations below the mean, which matches well with reports in the historical record. However, in late September of 1904 a monsoon-generated flash flood (likely a 50-year event) ravaged downtown Santa Fe and beyond. This important hydrologic event was influential to Santa Fe channel geomorphology, on subsequent dam operations, and drove river management decisions for decades. Yet, the predicted flow record does not reveal this event's occurrence. Rose, Dean, and Robinson (1981) indicate through verification analysis that the Santa Fe tree-ring chronology used here as a proxy for river flow is a better predictor of low precipitation than high, and that non-spring precipitation is less variable between years than spring (April, May and June) precipitation. It is also important to use caution when identifying periods of drought using tree-ring data: there is a limit to a minimum tree-ring size (zero-growth), and low precipitation reflected in zero-growth rings may not effectively describe the *degree* of precipitation stress.

The relationship between tree-ring data and streamflow is strong (r = 0.71), and tree-ring derived precipitation explains 51 percent of the variability in the modeled river flow.[6] Forty-nine percent of unexplained flow variability likely comes from monsoonal precipitation, groundwater contributions, landscape conditions and other factors. This result is comparable to other applications of linear regression for streamflow reconstruction in the literature for northern New Mexico rivers: Ni *et al.* (2002) reported a correlation coefficient of 71 within climate division 2; Woodhouse (2007) found a significant correlation (r = 0.725) on the Upper Rio Grande flow at Del Norte; Lewis and Hathaway (2002) obtained correlations of 0.54 to 0.68 for the Middle Rio Grande; results by Ackerly (1999) explained 56 percent of flow variability at San Marcial on the Rio Grande above Elephant Butte Reservoir.

A five-year moving average smoothes the scatterplot and highlights the major trends in flow (Figure 5.J). Visually, there appears to be a difference in the amplitude of flows between two periods: 1600-1749 and 1750-1970 (Figure 5.K). Z-scores reveal that between 1600 and 1750, the number of low-flow years (16, or 11 percent) is twice the number of high-flow years (8, or 5.3 percent) (defined as flow above and below one standard deviation). There is one year prior to 1750 (1685, or 0.7 percent) in which flow is beyond two standard deviations below the mean. During this 150-year period, there is also only one year (1747, 0.7 percent) in which flow exceeds two standard deviations above the mean. After 1750, flow amplitudes do increase: 31 years (14.4 percent) between 1750 and 1970 have flows that exceed one standard deviation, and three years (1849, 1920, and 1932, 1.4 percent) in which it exceeds two standard deviations above the mean. The percentage of flows below one standard deviation remains the same between periods (24, or 11 percent), but the number of extreme low flows increase: seven (3.2 percent) of these years (1773, 1836, 1890, 1899, 1904, 1925, 1934) exceed two standard deviations below the mean.

Some flows above and below the mean are coupled with warm ENSO and cold ENSO events, respectively. Gergis and Fowler (2009: 343) isolated signals of both phases to reconstruct a history of events from 1525 A.D., which includes the "most comprehensive La Niña event record to date. This annual record of ENSO events can now be used for independent verification of climate model simulations, reconstructions of ENSO indices and as a chronological control for archaeologists/social scientists interested in human responses to past climate events." After comparing these data to the Z-scores of predicted flows, findings conclude that between 1600 and 1970, 70 percent of years with flow above the mean were warm ENSO years, while 59 percent of years with flow below the mean were cold ENSO years (Figure 5.L). In a recent study, the National Oceanic and Atmospheric Administration's Climate Prediction Center found that while cold ENSO events typically induce below normal precipitation for New Mexico, this relationship weakens at higher elevations (NOAA 2009). In Santa Fe, modern (post-1950) cold ENSO events typically produce precipitation that is 86 percent of normal, while warm ENSO events produce precipitation volumes 150 percent of normal (NOAA 2009). The predicted streamflow values yield similar results: cold ENSO-year flows average 76 percent of normal, while warm ENSO-year flows average 120 percent of normal. These results would likely match the NOAA findings more closely were it not for the 49 percent of unexplained flow variability in the regression model.

Significant departures from predicted annual flow match several of the documented historic events found in the anthropogenic record. Meyer (1984: *x*) found that "[c]omparisons of the tree-ring analyses with the documentary evidence uncovered in the archives provide the kind of statistically valid independent verification that historians would love to have for other kinds of data," while Schwartz (1971) stated that the correlation between the archaeological record and tree-ring derived precipitation is so striking that the causal relationship between them must be inferred. Therefore, although no original documents prior to the Pueblo Revolt of 1680 survive, the tree-ring data provide a flow proxy, and assumptions about hydrologic conditions in the watershed are possible prior to, during, and immediately following the villa's founding. There is much debate among historians over the true date of settlement, with dates ranging from 1605 to 1610. For the purposes of this research, the assumed year of settlement is 1610. In 1596, 1597, 1603, and 1604, flows exceeded one standard deviation above the mean. These wet years lead to the conclusion that Peralta indeed saw a saturated and probably lush Santa Fe watershed. The predicted streamflow also reveal that the assumed year of settlement was above average (by one standard deviation).

Around 1620, the climate began to change and water availability went from a time of plenty to a time of want. However, community needs for water were still small, as only 48 soldiers and colonists were living at the settlement in 1617 (Twitchell 1925).

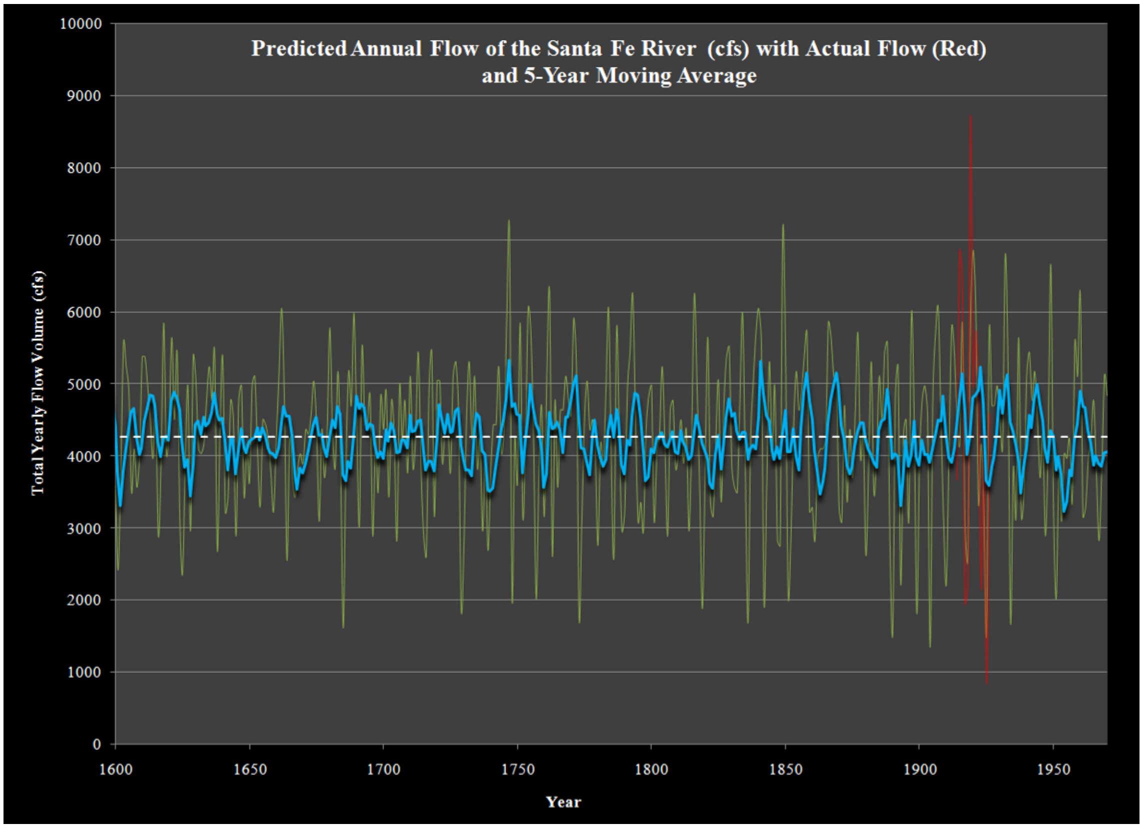


Figure 5.J. Predicted Flow of the Santa Fe River (cfs) from 1600 to 1970

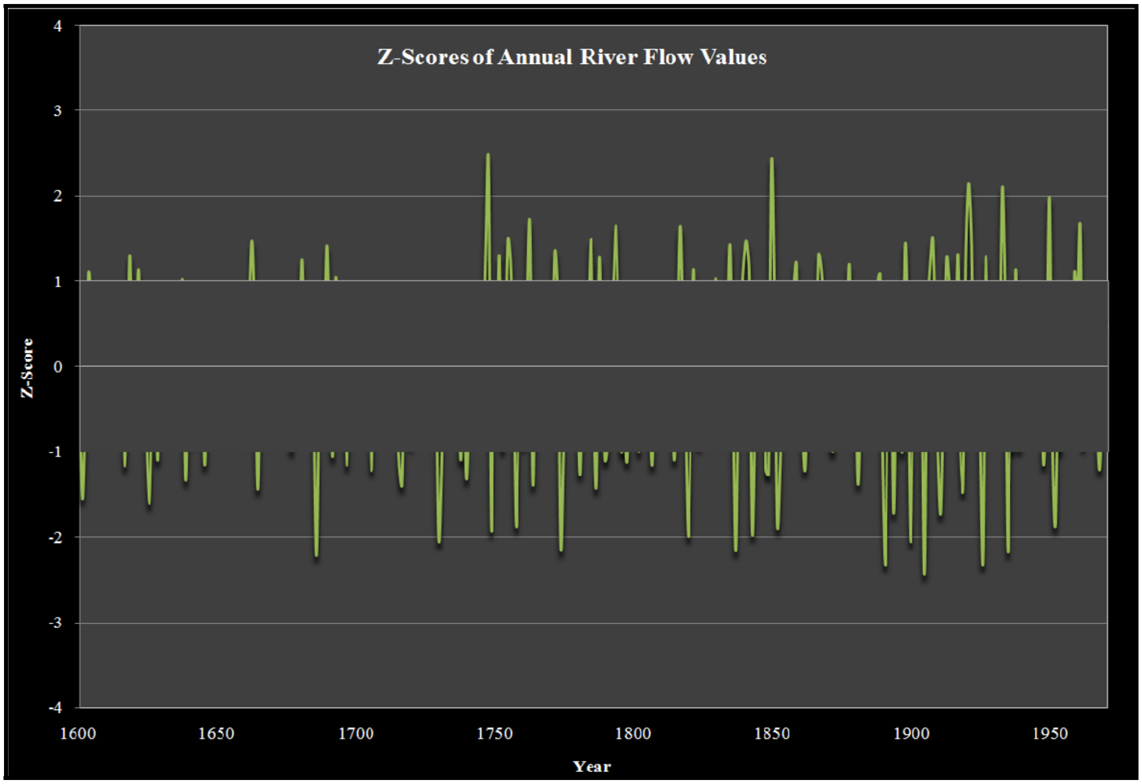


Figure 5.K. Z-scores for annual Santa Fe River flows from 1600-1970
Showing annual flows greater than +/- 1 standard deviation

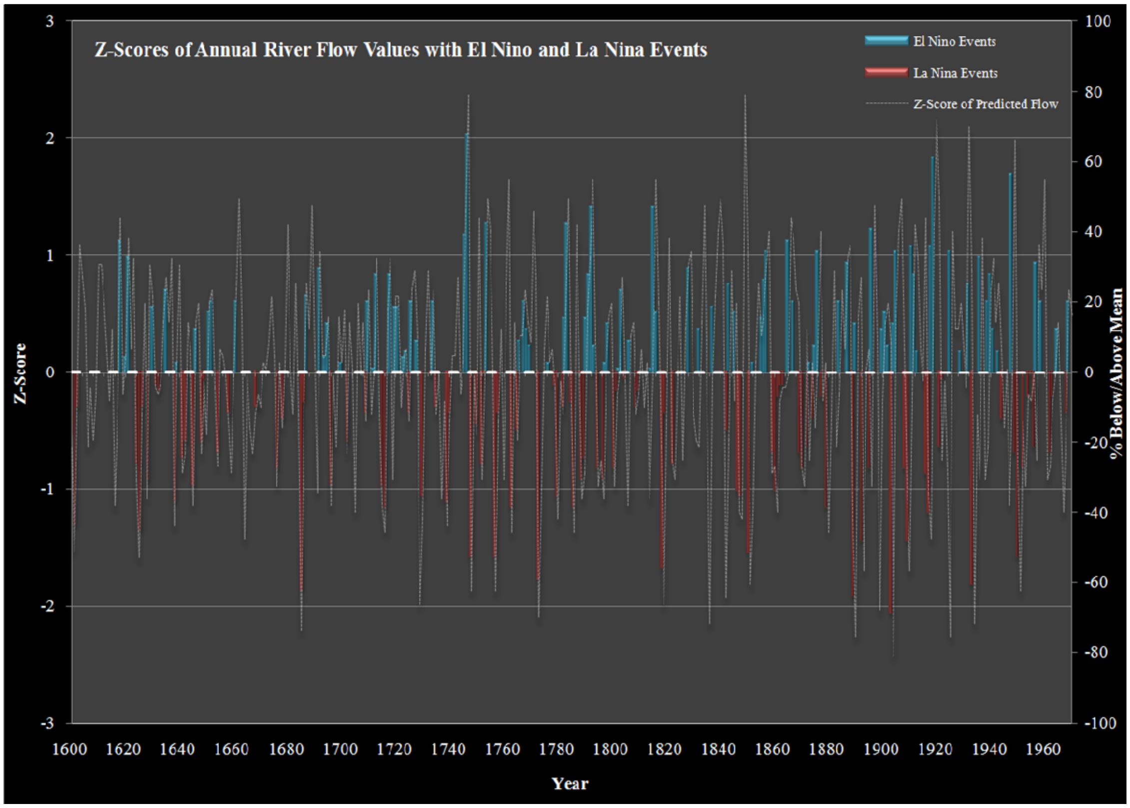


Figure 5.L. Warm ENSO and cold ENSO events mirror predicted streamflow

Because the settlement relied on the river for its main source of water for irrigation, years of exceedingly low flow tested the population's ability to survive. Through these early decades, a growing population (1,100 by 1630) put increased demands on local water resources, and the lack of river water meant a subsequent lack of food for the populace. Punctuated lows in 1624 and 1637 provided challenges for food production. With agriculture slowly expanding to lands up and down the valley, there was less water for more fields, and arguments over water allocations likely erupted. General trends from the predicted flow data show that the Spaniards likely had a difficult time sustaining their growing population for the first 150 years of settlement.

In the year 1666, Santa Fe had to import food and drought was the culprit. The friars in the missions throughout northern New Mexico developed a relief program. Missions least affected by drought in any given year supplied food to the missions and/or areas most affected (Scholes 1942). Not only do the predicted flow data support this conclusion, but they also reveal previous unknowns about the drought's severity: 1666 was known to be exceedingly dry (flow was below the mean), but so were seven out of the 10 preceding years. 1667 through 1670 also all have annual flows below the mean. Between 1645 and 1670, 17 years (63 percent) of flows were below average. This extended period of drought tested the Spaniards' ability to survive, put pressure on local Pueblo communities to meet their tribute requirements, and stoked the fires for the ensuing Pueblo Revolt of 1680.

In 1696, a few years after the Reconquest, the community petitioned the viceroy on June 20 in desperation: "we are on the point of perishing from our raging hunger… [e]verything that has been planted has been lost because of the great drought that has occurred. It has been necessary to dig wells by hand in the ciénaga just to provide drinking water for this villa" (Kessell, Hendricks, and Dodge 1998: 852). A very strong cold ENSO caused flow to fall below one standard deviation, which verifies why the community "reached the point of eating roasted cowhides, with no other food whatsoever, not even maize or wheat, since even *quelites* [wild greens] are absent from the countryside because of the lack of rain" (853).

By the mid-1700s, flow amplitudes began to increase, marked by a significant high between 1746 and 1760. Ni *et al.* (2002: 1645) postulated that this "might be linked to strong shifts from cold to warm El Niño-southern oscillation events and from a negative to positive Pacific decadal oscillation." As a result, high flow volume years became higher and low flow volume years lower. It is also likely that flows increased in their magnitude and destructive power. There are few references to river flows during this time, except for those made by Fray Francisco Atanasio Domínguez in 1776 during his description of the missions of New Mexico. After interviewing residents of the villa and surrounding ranchos, he reported that the Santa Fe River, with its crystalline waters, sometimes "in times of freshet" has run so swiftly that the current created damage, and that a stone embankment was constructed to "avoid further harm" (Adams and Chávez 1956: 40). Fray Domínguez was undoubtedly speaking of the flood of 1767. Because the predicted streamflow values do not pick up rainfall events, it is likely that there are many important hydrologic events early in Santa Fe history that are not captured until the arrival of the newspaper to Santa Fe in 1847. However, the documented flood of October 16, 1767, may have been a one-hundred year flood event, potentially capturing the Rio Chiquito, and making it deeper and wider as the river tried to change the position of its main channel. The river laterally migrates through the valley as it exits the mountains, and without man's interference, likely would have occupied the Rio Chiquito and converted this side stream to its main thread through time (Chapter 6, Section 6.2.2).

Spatial data in a GIS tests the hypothesis that this flow event constituted a one-hundred year flood. Old maps, historical accounts, and its conversion to modern-day Water Street aid the cartographic depiction of the Rio Chiquito's position. Within Figure 5.M, a digitized dashed line indicates the possible location of the new channel. The Federal Emergency Management Agency has preliminarily delineated the hazard areas for the Santa Fe River. The solid-hatched polygon indicates the areas deemed the 100-year floodplain. From the map, it is clear that the river occupied a majority of this floodplain if it had encountered the Rio Chiquito, showing the increased likelihood that this was a large-magnitude event with a low recurrence interval. This analysis reveals the earliest visualization of a flood event in Santa Fe prior to the invention of photography.

Important flow events, and predicted patterns of high and low flows in the last century (especially since statehood in 1912), are verified more easily because of weather record-keeping, stream gage installations, the daily newspaper, and a more literate society producing a greater percentage of surviving primary source documents. The first newspapers of Santa Fe tell many tales of floods and their toll upon the town: reports of violent thunderstorms, high water, and bridge washouts are ample in this record (Figure 5.N). Periods of extensive drought were also newsworthy. 1904, a year with flow predicted to surpass two standard deviations below the mean, is well known as being exceedingly dry via newspaper accounts.

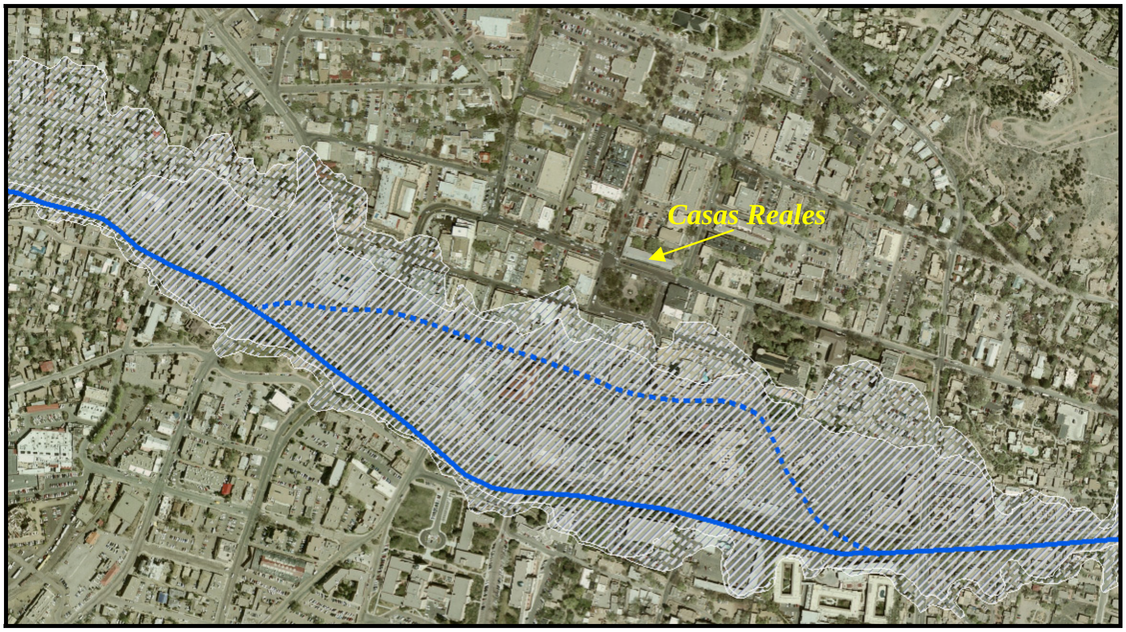
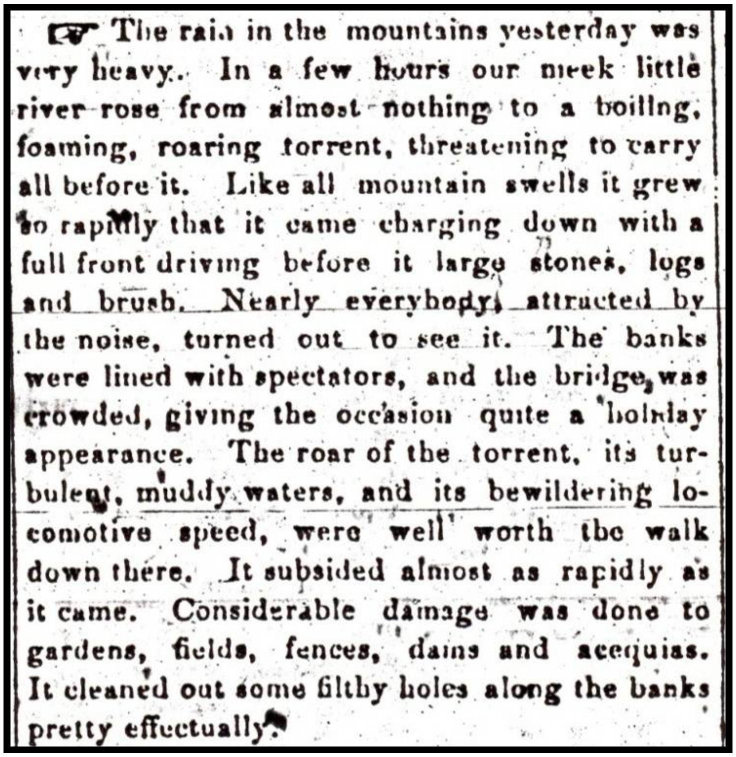


Figure 5.M. River, estimated Rio Chiquito capture, and FEMA floodplains
Source: map by author; imagery, City of Santa Fe (2005b); FEMA floodplains, NMRGIS (2009)

Ten out of the fifteen years between 1906 and 1921 had predicted flows above the mean: crosschecking the predicted flows with recorded streamflow data verifies the predictions. Construction of Granite Point dam occurred in 1926-28 in response to the above-average available supply and increasing population. Years of high flows, however, did not last. A significant predicted low in 1925 exceeds two standard deviations below the mean and reflects actual flow conditions: in that year, the lowest gaged volume of annual flow on record registered only 1,780 acre-feet. The 1930s were also dry, with six out of ten years' flows below the mean. Modern stream-gaging records also verify these data. With the population doubling in this decade (an increase of over 9,000 persons) and relying solely on the river for water, increased supply came from raising Granite Point (McClure) dam in 1935 (Goldman 2003). Between 1950 and 1957, the intense low of the predicted streamflow values matches the significant dry period in the historic record. 1950 in particular had an extremely dry fall and winter; an event reflected in the 1951 predicted flow value, which registers almost two standard deviations below the mean. Many newspaper articles illustrate the city's water struggles during this time; it was during this period that the city installed four municipal groundwater wells along the river.

Recorded events in modern times verify the predicted flow values from tree-ring data, and match known conditions well. This finding supports the use of these data to explain historical, undocumented flow in the river. These data provide a valuable resource to anthropologists and historians in Santa Fe for future research.



☞ The rain in the mountains yesterday was very heavy. In a few hours our meek little river rose from almost nothing to a boiling, foaming, roaring torrent, threatening to carry all before it. Like all mountain swells it grew so rapidly that it came charging down with a full front driving before it large stones, logs and brush. Nearly everybody, attracted by the noise, turned out to see it. The banks were lined with spectators, and the bridge was crowded, giving the occasion quite a holiday appearance. The roar of the torrent, its turbulent, muddy waters, and its bewildering locomotive speed, were well worth the walk down there. It subsided almost as rapidly as it came. Considerable damage was done to gardens, fields, fences, dams and acequias. It cleaned out some filthy holes along the banks pretty effectually.

Figure 5.N. Heavy rain generates flow event
Source: *The Weekly New Mexican*, August 5, 1852

5.3 THE INFLUENCE OF IRRIGATED AGRICULTURE ON FLOW

Centuries of vast water application and spreading on the landscape helped to maintain river baseflow. Today, water resource managers underemphasize the important role of irrigated agriculture in sustaining consistent flow conditions in the past. Acequia agriculture creates many positive benefits:

> the earthen acequia watercourse itself helps to recharge the local aquifer through the natural process of seepage. Aided by gravity flow, water that continues to flow in the ditch, in turn, serves to extend the stream to a new, wider landscape, resulting in a benign irrigation technology which helps to control soil erosion. Water that percolates down to the aquifer aids in the cleansing of groundwater. Seepage throughout the ditch system nourishes the cottonwood bosques as well as native shrubs such as plum, capulín, and willows, which, in turn, provide shelter for wildlife. Any unused waters are returned to the stream as *sobrantes*, or surplus waters, destined to support other values or users downstream (Rivera 1998: 32).

By the late 1800s, almost 300 years of acequia leakage and water application to fields had saturated the subsurface for tens of feet. The highly absorptive materials directly beneath Santa Fe soil horizons are sands and gravels of the Ancha formation, which conducts water efficiently to the aquifer unit (the Tesuque formation) beneath it. Despite evaporation and crop use, a great deal percolated and entered the aquifer, and fed the river. Irrigators applied an average of 2.7 trillion gallons of water to the land each year (assuming all river water was applied to fields). If multiplied by 300 years of water spreading, this monumental volume of water is equal to 1.1 cubic kilometers. Spiegel and Baldwin (1963) suggested that approximately 30 to 50 percent of water applied to the landscape contributed to river flow via gaining-stream conditions. Thus, the valley floor was considerably wetter than would have existed without cultivation, and contributions to river flow via groundwater allowed for agricultural expansion on the Santa Fe pediment not otherwise possible under natural conditions (Spiegel and Baldwin 1963). Acequia agriculture changed the physical character of the river by maintaining a higher volume of baseflow. The wetted river created elevated expectations in the minds of watershed residents as to what constitutes natural river conditions, and what flow restoration efforts might achieve. Despite the presence of upstream dams, without the reestablishment of thousands of acres of irrigated acreage, the river will never flow as it once had.

In recent times, the State Engineer has determined that the average application rate of water to Santa Fe fields is 4.5 acre-feet per acre (State Engineer's Office 1976). The predicted flow values generated in the tree-ring analysis can estimate the yearly supportable acreage by river flows. Converting the predicted flow in the upper watershed from cubic feet per second to acre-feet per year reveals the annual carrying capacity of the river. Total flow and water application volumes enumerate the feedback mechanism at work. Assuming a 40 percent gain from groundwater contributions via subsurface flow (the midpoint of the Spiegel and Baldwin (1963) estimate), the amount of acreage supportable from upper watershed flows is about 1,800 acres (7.28 km^2). The acreage values calculated and graphed in Figure 5.O reflect a 40 percent addition. Using predicted flow data from 985 A.D. to 1970 A.D., the upper watershed yields an average of 8,400 acre-feet per year. The predictions below, which describe the supportable irrigated acreage, include fields from the upper canyon area, through downtown Santa Fe. Downstream fields surrounding Agua Fria, Cieneguilla, La Cienega and La Bajada are not included in the total supportable acres because springs historically irrigated those areas, with only some supplementation from the river.

There are limitations to the application of these data for irrigated acreage prediction. As mentioned, because the tree-ring proxy does not account for the rainstorm-generated flows and the contributions of local springs, this analysis assumes that these additions allow the river to support 2,000 acres (8.09 km^2) each year (plus or minus 200 acres (0.81 km^2) to account for the unexplained variability). These estimates are annual statistics, which use total yearly-predicted flows, while irrigation only takes place during the growing season.[19] This analysis also assumes that all water in the river is applied to the land, regardless of the season, and does not account for other domestic and livestock usage.

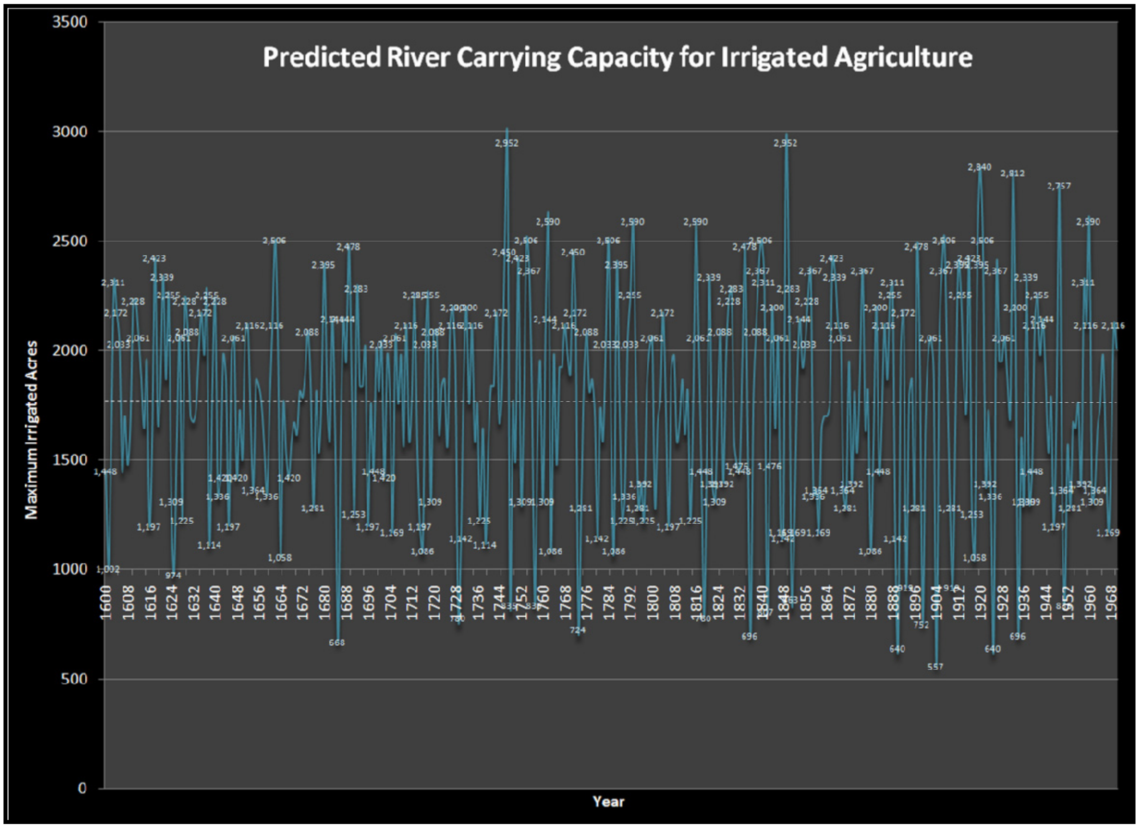


Figure 5.O. Annual river carrying capacity for irrigated agriculture
Predictions for 1600 to 1970

Z-scores elucidate historic extremes in supportable yearly acreages. When flows drop below one standard deviation, the supportable acreage is about 1,250 (5.1 km^2). When flows reach two standard deviations below the mean, the supportable acreage drops to 750 (3.0 km^2). These low amounts of supported acres in the driest years clearly show why irrigators would fight over water, and why a moderate drought could lead to failed crops and starvation. Flows reaching one standard deviation above the mean can support about 2,400 acres (9.7 km^2); while significantly wet years (flows above two standard deviations) support 2,800 acres (11.3 km^2). The year with the largest supportable amount of irrigated land is 1747, in which flow could support close to 3,000 acres (12.1 km^2). 1849 was also a good year for agriculture, with 2,952 acres (11.9 km^2) potentially in irrigation. If dams had not impounded upper watershed flows, 1920 and 1932 would have been excellent years for local crops, with flows able to support 2,840 acres (11.5 km^2) and 2,812 acres (11.3 km^2), respectively.

The lowest predicted flow year (1904) could only support 557 acres (2.3 km^2). Making matters worse, irrigators were already struggling with the water company, having received no allocations from upstream reservoirs (Acequia Madre de Santa Fe 1995). Because of incremental dam installations, acequia agriculture in Santa Fe virtually stopped. With no water in the river, the physical landscape of Santa Fe changed drastically (Chapter 7). The lowest year recorded before dam installation is 1685, when river flows could support only 668 arable acres (2.7 km^2). This low occurred after the Pueblo Revolt, during Indian occupation of Santa Fe, so the effect is unknown. 1836 also had exceptionally low flow with only 696 acres (2.8 km^2) able to be irrigated.

The carrying capacity of the river was exceeded early in Santa Fe history. The earliest surviving grievance occurs in 1716, when Captain Diego Arias petitioned to use cienega water to irrigate because "the scarcity of water that comes from the river is known" (SANM I: 169, Reel 8, Frame 151). By 1776, despite the supplemental waters provided by local springs, Fray Francisco Atanasio Domínguez mentioned that the river "is usually insufficient… because there are so many [farms] it does not reach the lowest ones" (Adams and Chávez 1956: 40). There were more fields in irrigation than available water to support them. Fields and ditches extended up and down the river valley: upstream beyond the modern-day dams and downstream beyond Agua Fria and the current WWTP, which far exceeded the 2,000-acre (8.0 km^2) threshold. The earliest known map of Santa Fe is the Urrutia Map of 1766. From this map, a GIS is used to calculate an area of 4,000 acres of farm fields (16.2 km^2).[20] Though it is likely an exaggeration of agriculture's true spatial extent, the map does indicate that a vast majority of the land was in fields. The Gilmer Map of 1846, the second earliest known surviving map of Santa Fe environs, shows an area of 4,600 acres (18.6 km^2) in fields, which is unlikely.[20] Even if Gilmer drew *half* as many fields as are included in his depiction around downtown, the river just barely would support them.

Modern times brought three significant changes to the river's flow regime. First, water withheld from the river behind dams was diverted for municipal needs. Second, acequia agriculture losses directly influenced the amount of water in the river by removing an important source of subsurface flow. The amount of land in irrigation declined significantly because of increasing reservoir storage: 1,200 acres (4.9 km^2) in 1917, to roughly 800 acres (3.2 km^2) in 1936, to about 650 acres (2.6 km^2) in 1951. Today, a few residents irrigate only about 100 acres (0.4 km^2) of orchards and gardens in downtown Santa Fe. Third, the city drilled wells along the river in 1946 and 1950. Large, public water supply withdrawals began to create cones of depression and change the direction of groundwater flow. The river was a gaining stream for centuries until modern pumping began. With these three changes happening in concert, the adverse effects on river flow were significant.

5.4 THE EFFECTS OF DAM CONSTRUCTION ON FLOW

5.4.1 Weather Observance in Santa Fe

To state definitively that dams have affected flows on the Santa Fe River, this research examines other sources of flow influences. Because there is a relationship between precipitation and river flow, long-term changes in precipitation must be ruled out (Figure 5.P). Acquiring and analyzing weather observations are required to identify long-term precipitation trends. As much of Santa Fe's history is explained through its continually changing governance, so is its weather data. Primary documents record many mentions of the weather, but no sequentially recorded, human-derived climatic record exists until 1849, when the U.S. Army ordered surgeons stationed at Fort Marcy to keep a weather log for their surgeries (Grice 2005). Between late 1871 and early 1938, the locations for observations changed 11 different times, though all were within one-quarter mile from the center of the Plaza (Grice 2005). However, from 1938 to 1941, the Weather Bureau moved the location of observation to the Santa Fe airport, 11.2 km (7 mi) southwest of the Plaza. Two years later, the weather station moved again to the newly constructed airport, 4.0 km (2.5 mi) farther west. Because precipitation varies dramatically with elevation in the Santa Fe watershed, it is important to treat data derived from these observatories with caution. The locations of weather observance through the years may introduce error into climate investigations, as the elevation of the collection stations ranged from 2,174 m (msl) (7,135 ft) at the second Fort Marcy, the Plaza at 2,131 m (msl) (6,992 ft), the first Santa Fe airport at 1,981 m (msl) (6,500 ft), and 1,920 m (msl) (6,300 ft) at Santa Fe's second airport. Despite the varying collection station geography, mining data sources for pieces of the climatological record has led to the assembly of monthly and yearly precipitation values from 1849 to 2006.

5.4.2 Regional Climate Change and Effects on Flow

To assess the effects of dams on the hydrologic regime, Williams and Wolman (1984) found it necessary to rule out any significant changes in the flow record that are a result of regional climate change. Regression equation generation occurred by applying a calculated precipitation anomaly value for this dataset to each month and year. Graphical results plotted average annual precipitation by each month over time, revealing visible trends (departures from the mean). For each month, the regression line varies in its slope, but there is no significant seasonal or long-term trend: no significant change has occurred in precipitation volumes since 1849 (Table 5.3). All R^2 values calculated through the regression analysis show no significant difference in precipitation volumes between 1849 and 2006, a finding mirroring McCabe and Wolock (2002). Because of the relationship established between precipitation and streamflow ($r = 0.786$), any recorded changes in stream flow volume are not a result of regional climate change (Figure 5.P).

Table 5.2. Linear Regression Equations and R^2 Values for Each Month, 1850-2006

Month	**Regression Equation**	**R^2 Value**
January	$y = 0.0019x - 0.1805$	0.0081
February	$y = -0.0045x + 0.7097$	0.0182
March	$y = 0.003x - 0.4296$	0.024
April	$y = 0.0005x - 0.0442$	0.0004
May	$y = 0.0025x - 0.243$	0.0125
June	$y = 0.0011x - 0.1991$	0.0033
July	$y = -0.0021x + 0.4552$	0.0065
August	$y = -0.0006x + 0.1111$	0.0003
September	$y = 0.0007x - 0.0006$	0.0007
October	$y = 0.0023x - 0.3271$	0.0134
November	$y = 0.0014x - 0.4413$	0.0048
December	$y = -0.0008x + 0.1842$	0.0018
Annual	$y = 0.0028x - 0.2489$	0.011

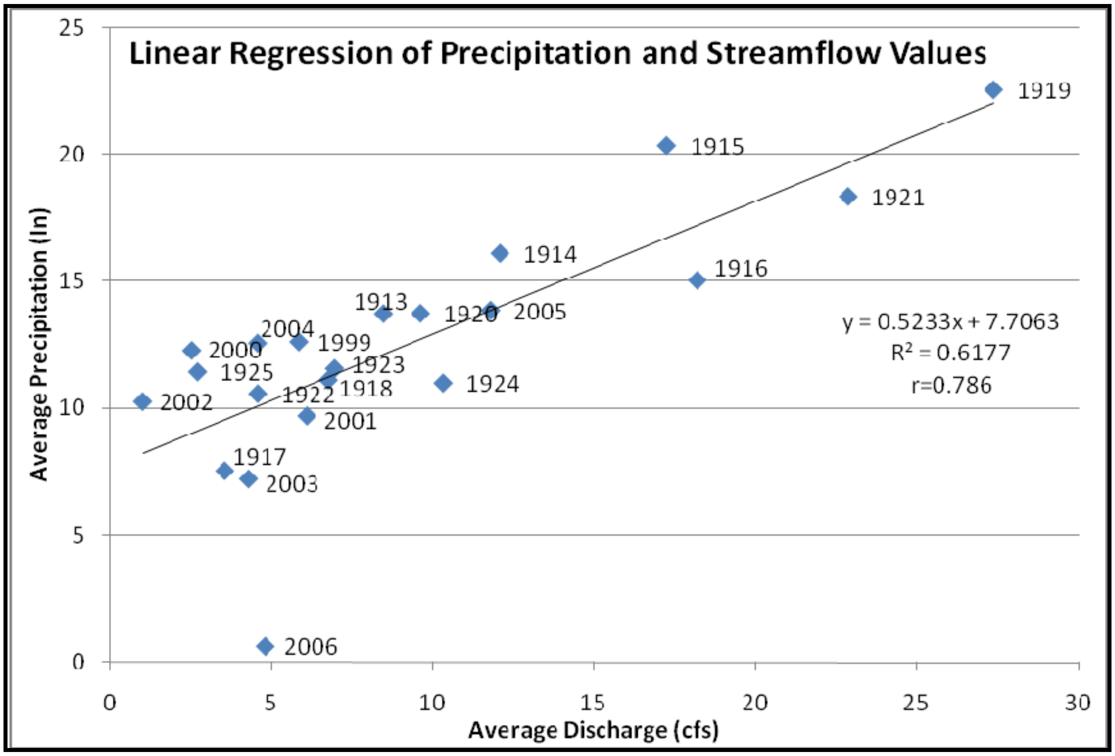


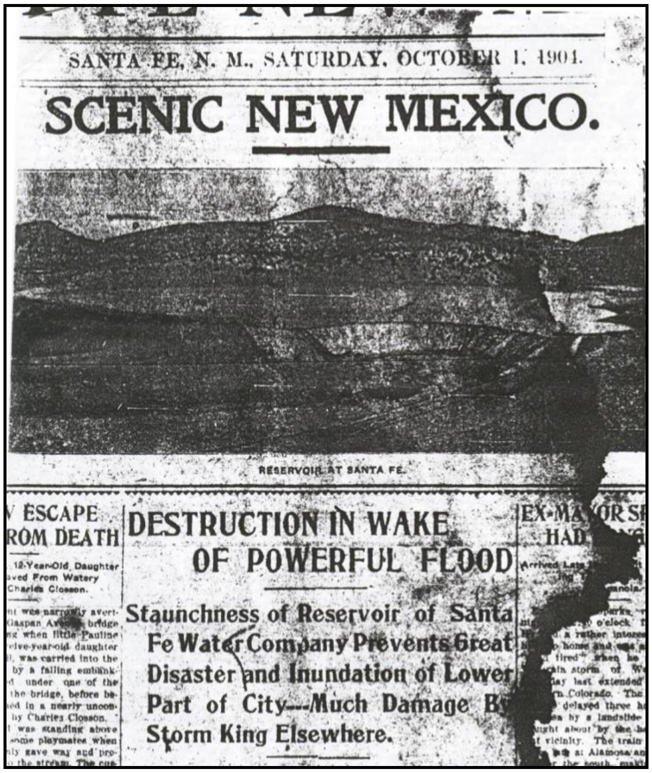
Figure 5.P. Precipitation-streamflow relationship

5.4.3 Modern Dams on the Santa Fe River

In the Kearny Code, laws written for the new territory specified that no acequias were to be disturbed, and that water rights were to remain intact. U.S. laws placed governance on the counties, however, and because Santa Fe went unincorporated until 1892, county commissioners made all decisions for the town. In 1870, the commissioners of Santa Fe County gave Santa Fe Water and Improvement Company the right to build dams, impound and distribute water, and create electricity (Chapter 7, Section 7.2.1.5).

Old Stone Dam was the first dam constructed on the river (in 1880), and held a mere 25 acre-feet of water (8 million gallons). Each year, the upper watershed generates an average volume of 6,173 acre-feet in the river (calculated from 96 years of USGS stream-gage data). Because the dam was so small, the effects on river hydrology were limited once the reservoir was full. The reservoir was also deemed too small for the growing town's water storage needs, and a second dam (Two-Mile) was constructed 0.46 km (1,500 ft) downstream of Old Stone in 1893. This dam held 387 acre-feet (126 million gallons), was significantly larger, and could impound six percent of the river's total annual flow. Residents noticed immediate changes downstream, both in the river's physical character, and in the volume of flow reaching acequias (Chapters 6 and 7, respectively). The river's hydrologic regime upstream from the dams, including variations in magnitude, duration, timing, frequency and rate of change of water flow events, continued to respond to the local climatic inputs, such as seasonal snow melt. Beaver (*Castor canadensis*) still built lodges in the channel, creating small areas of ponding, wildlife habitat, and groundwater recharge. Downstream, however, the river's hydrologic regime became significantly different (Section 5.4.4).

The flood of 1904 proved the "staunchness" of the new reservoirs, and showed their ability to protect the town from the floods that had endangered them for centuries. As a result of overgrazing grazing and logging activities in the upper watershed, vegetation was sparse and summer rainstorms easily mobilized exposed sediment. Sediment-laden floodwaters came writhing down the narrow mountain stream course, frothing with rock, sand, and debris. Upon reaching the first reservoir, the debris flow was immediately slowed by the reduction in slope, the widening channel, and the pool of Old-Stone. As a result, the reservoir immediately filled with sediment, and Two-Mile Dam held the major floodwaters at bay. *The Santa Fe New Mexican* reported on October 1, that "if the crest of the flood had struck Santa Fe, the entire lower portion of the town would undoubtedly have been inundated and many buildings washed out" (Figure 5.Q).



SANTA FE, N. M., SATURDAY, OCTOBER 1, 1904.

SCENIC NEW MEXICO.

RESERVOIR AT SANTA FE.

ESCAPE ROM DEATH

12-Year-Old Daughter aved From Watery Charles Closson.

DESTRUCTION IN WAKE OF POWERFUL FLOOD

Staunchness of Reservoir of Santa Fe Water Company Prevents Great Disaster and Inundation of Lower Part of City---Much Damage By Storm King Elsewhere.

EX-MA OR S HAD

Figure 5.Q. Water-damaged newspaper detailing 1904 flood
Source: *The Santa Fe New Mexican*, October 1, 1904

As the seriousness of the flood sank in, so did the realization that the dam had saved the town. The gravity of the potential damage raised awareness of the upper watershed's condition, and how maintaining it property was critical to Santa Fe's primary water source. The heavy grazing and logging since settlement came into focus, prompting the U.S. Secretary of Agriculture to close the upper watershed to all human entrants in 1932 to protect it from fire, erosion, and pollution.

As the local population quadrupled from 5,072 in 1910 to over 20,000 by the end of the 1930s, so did the pressure on local water resources (Goldman 2003). The Water Company responded by constructing Granite Point Dam (later renamed McClure) in 1926. The original structure could hold 650 acre-feet of water, and increased the total available storage behind dams to 1,035 acre-feet (337 million gallons), equivalent to approximately 17 percent of the river's annual flow. The spring snowmelt was retained behind the dams; once the reservoirs were full, water ran downstream. Less than a decade later, the height of Granite Point was raised to increase storage for the growing population and per capita water consumption. When completed in 1935, it could hold 3,059 acre-feet (997 million gallons). Now, over 50 percent of the average annual flow was retained. Nichols Dam was constructed above Two-Mile reservoir in 1943 in response to the population surge resulting from the Atomic Energy Commission project in Los Alamos. It added 684 acre-feet to the total water storage (Figure 5.C; Spiegel and Baldwin 1963). When construction was complete, in total over 60 percent of the river's flow was stored behind dams each year. This number is deceiving because it insinuates that 40 percent of the annual flow continued downstream. However, residents consumed water year-round, while water entered the pools in a seasonal pattern. For much of the year, usage exceeded inflows. Reservoirs were drawn down during the winter months, and during times when seasonal flow was high (due to the hydrologic regime), reservoirs maximized their storage. It is likely that water only flowed downstream when consecutive years' flows were above average. Thus, with these three structures in place, the acequias received very little water, if any.

5.4.4 The Indicators of Hydrologic Alteration Result Interpretation

The IHA analysis run on the SRS station includes pre- and post-dam flow alteration results (Table 5.3).[18] The IHA method presents clear evidence that several flow regime parameters have changed substantially since the 1926 installation of Granite Point (McClure) Dam. This investigation uses non-parametric analysis due to the limited number of years of continuous stream flow records prior to dam installation (less than 20 years). This factor limits the strength of the results, and therefore prompts cautious evaluation of the IHA output.

Table 5.3. Parameter Scorecard, Santa Fe River near Santa Fe (SRS)
Pre: Water Years 1913-1925 Post: Water Years 1929-2009

PARAMETERS	**MEDIANS**		**COEFF. OF DISP.**		**DEVIATION FACTOR**		**SIGNIFICANCE COUNT**	
	Pre	Post	Pre	Post	Medians	C.D.	Medians	C.D.
Parameter Group # 1								
October	2.5	3.6	1.94	1	0.44	0.4845	0.05405	0.1932
November	2.5	1.9	1.04	1.538	-0.24	0.479	0.5546	0.2713
December	2.5	1.7	0.6	1.318	-0.32	1.196	0.2523	0.01702
January	2.5	1.6	0.44	0.9375	-0.36	1.131	0.06006	0.03604
February	2.65	1.65	0.8208	1.333	-0.3774	0.6245	0.1211	0.1522
March	5.7	2.2	0.693	1.614	-0.614	1.329	0.08909	0.02703
April	14.5	5.4	2.134	1.463	-0.6276	0.3146	0.08108	0.5175
May	32	13	0.7344	1.773	-0.5938	1.414	0.0981	0.03203
June	19	10	1.237	1.075	-0.4737	0.1309	0.02503	0.7457
July	6.2	7.3	2.202	0.6096	0.1774	0.7231	0.4114	0.07808
August	6.2	6.4	1.121	1.008	0.03226	0.1009	0.8719	0.7858
September	3.35	5.2	1.112	1.188	0.5522	0.06795	0.006006	0.8749
Parameter Group # 2								
1-day minimum	1.4	0.8	0.7143	1.319	0.4286	0.8463	0.1281	0.04204
3-day minimum	1.333	0.8333	0.75	1.32	0.375	0.76	0.2232	0.05606
7-day minimum	1.371	0.89	0.7396	1.295	0.351	0.7515	0.2172	0.05506
30-day minimum	1.23	1.04	1.179	1.152	0.1545	0.02258	0.5205	0.955
90-day minimum	1.946	1.491	0.7007	0.865	0.2336	0.2344	0.2613	0.4444
1-day maximum	55	36	1.518	1.417	0.3455	0.06687	0.2202	0.8498
3-day maximum	54.67	34	1.424	1.221	0.378	0.1427	0.1151	0.6897
7-day maximum	42.86	29	1.663	1.296	0.3233	0.2211	0.1281	0.5756
30-day maximum	32.47	20.05	1.378	1.295	0.3823	0.0599	0.1041	0.8779
90-day maximum	24.65	13.19	1.318	1.042	0.4651	0.2097	0.05506	0.5956
# of 0 days	0	0	0	0			0	0
Base flow	0.1271	0.1331	1.08	1.049	0.04727	0.02915	0.8418	0.9379
Parameter Group # 3								
Minimum date	273	326	0.2322	0.2322	0.2896	0	0.1672	0.996
Maximum date	146	156	0.1571	0.1557	0.05464	0.008696	0.3894	0.992
Parameter Group # 4								
Low pulse count	4	2	1.375	1.5	0.5	0.09091	0.08208	0.7968
Low pulse duration	6	34	1	2.199	4.667	1.199	0.001001	0.06907
High pulse count	3	3	1.167	1	0	0.1429	0.6787	0.6446
High pulse duration	9.25	11	4.757	1.307	0.1892	0.7253	0.5616	0.07007
The low pulse threshold is 2.4								
The high pulse level is 12.0								
Parameter Group # 5								
Rise rate	0.6	0.3	1.167	2.708	0.5	1.321	0.2372	0.1672
Fall rate	-0.8	-0.4	-0.6875	-2	0.5	1.909	0.3714	0.05706
# of reversals	62	47	0.2339	0.4468	0.2419	0.9105	0.08609	0.01702

These IHA results exemplify the classic hydrologic regime responses to the operation of structures used primarily for public water supply and secondarily for flood control. The pre-dam data at the SRS station highlights the character of river flow in the upstream watershed before dams. River flow volumes prior to dam installation align closely with seasonal snowmelt responses. Post-dam, several flow parameters deviate significantly from their unimpounded condition; specifically, the seasonality of flows (timing), the magnitude of flows, and the duration of flows. Figure 5.R shows monthly alteration of median flow on an annual basis. In the spring months, flow is considerably lower than before dam installation, and is slightly higher in the summer and fall months. The dam reduces flow variability attributable to seasonal changes: the line indicating post-dam flow is substantially muted. The flattening of monthly mean flow over a yearly time-scale highlights a management strategy indicative of maintaining a viable volume of water storage for public consumption.

Parameter Group #1 includes the magnitude of monthly discharge conditions (Table 5.3). Five months show significantly lower median flow and C.D. values, compared to pre-dam conditions. May experienced a 60 percent decrease in median flow, with a 141 percent increase in flow variability around the median Figure 5.S). IHA found highly significant differences in March flow as well, where the median magnitude of flow decreased (61 percent), while the range of flow variability increased (133 percent) (Figure 5.T). In April, a 63 percent significant decrease in median flow occured after dam installation; however, flow variability increased, but not significantly (31 percent) (Figure 5.U). December experienced small decreases in the magnitude of median flow (32 percent), while the range of flow variability is quite significant (120 percent) (Figure 5.V). October and September flows increased significantly, although September's flow variability is virtually unchanged by the dam. August flows, both in their central tendency and variability are not markedly different between periods. These results indicate that much of the snowmelt-dominated flows are stored and diverted for public water supply.

Parameter Group #2 describes the magnitude and duration of extreme flow conditions (Table 5.3). Below McClure Dam, major flow changes include reductions of the 1-day, 3-day, and 7-day minimums, and highly significant increases in their variabilities. For example, the 1-day minimum flow rate (Figure 5.W) decreased in magnitude by 43 percent and increased in C.D. by 87 percent, highlighting the limiting, irregular nature of the dam's operating rules. The medians of 1-day, 3-day, 7-day, 30-day, and 90- day maximums are significantly lower post-dam, but their variabilities are not. The dam significantly alters the 7-day and 90-day medians of maximum flows. McClure Dam limits the magnitude of maximum flow events with the longest duration.

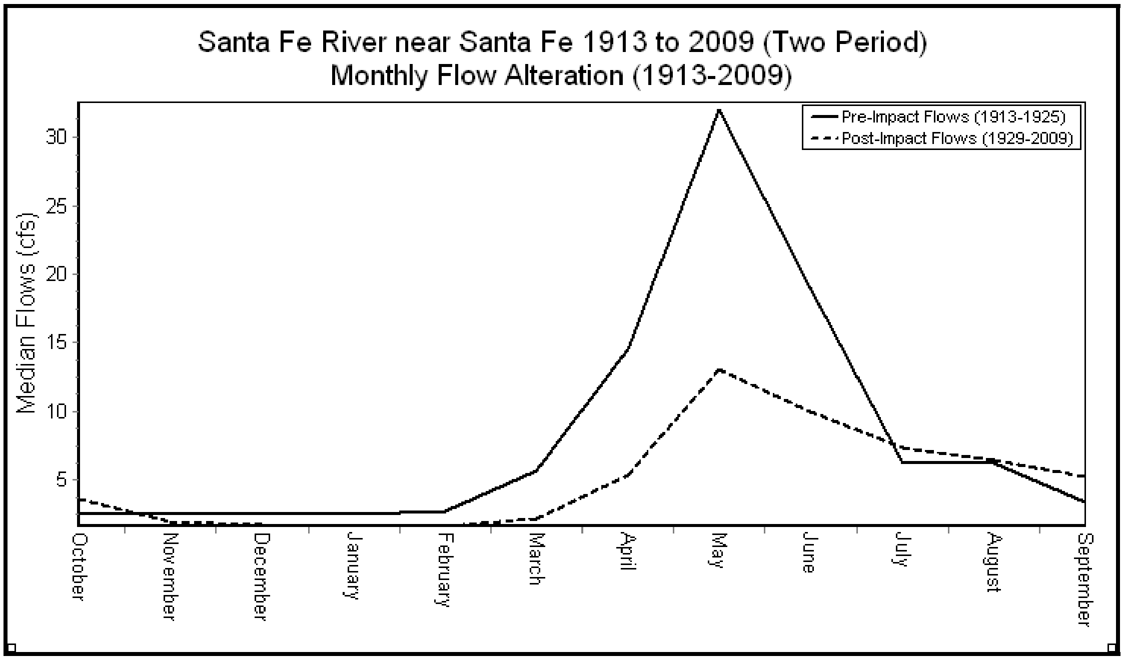


Figure 5.R. Monthly mean stream flow values (in cfs), pre- and post-dam

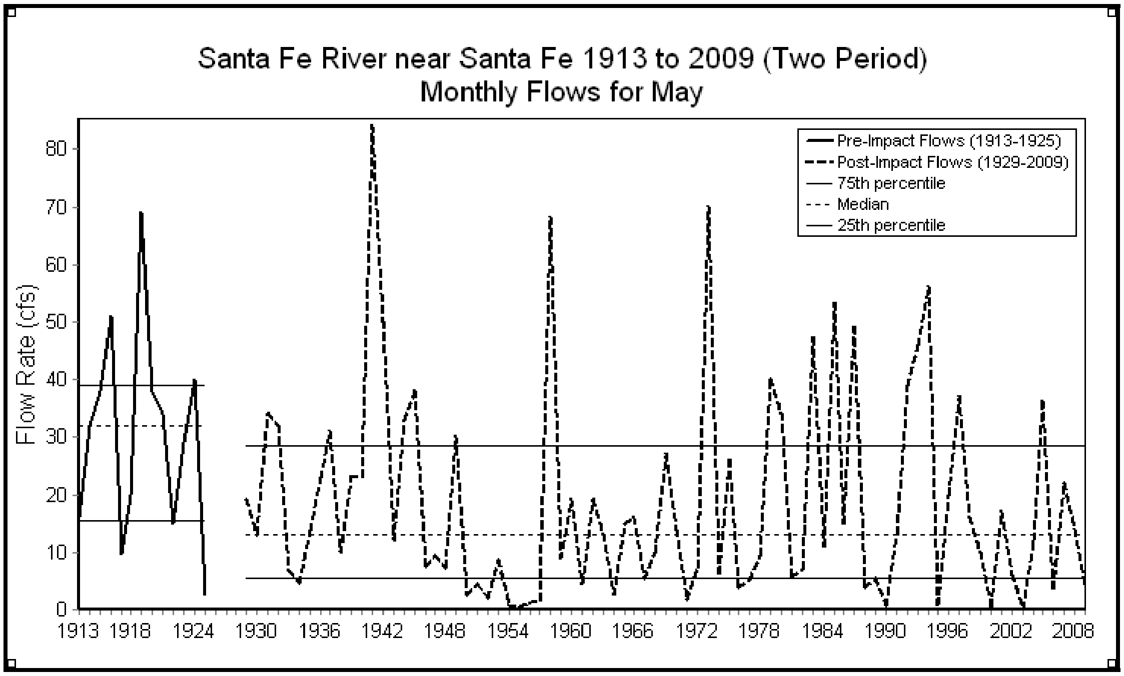


Figure 5.S. May monthly mean streamflow values (in cfs), pre- and post-dam

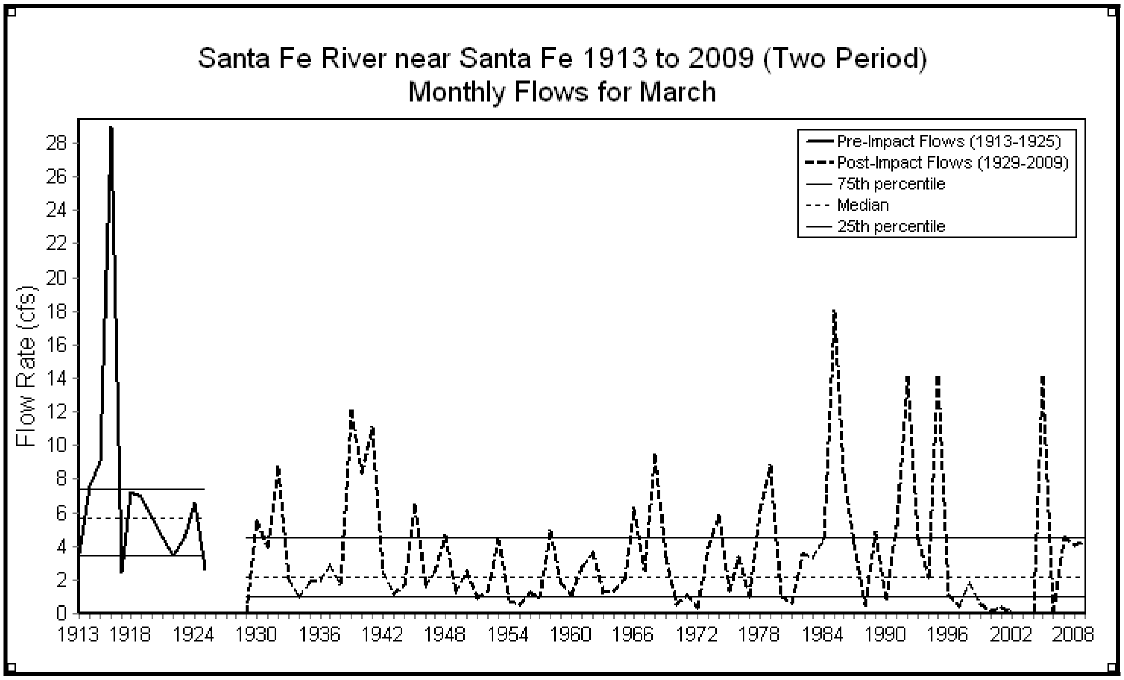


Figure 5.T. March monthly mean streamflow values (in cfs), pre- and post-dam

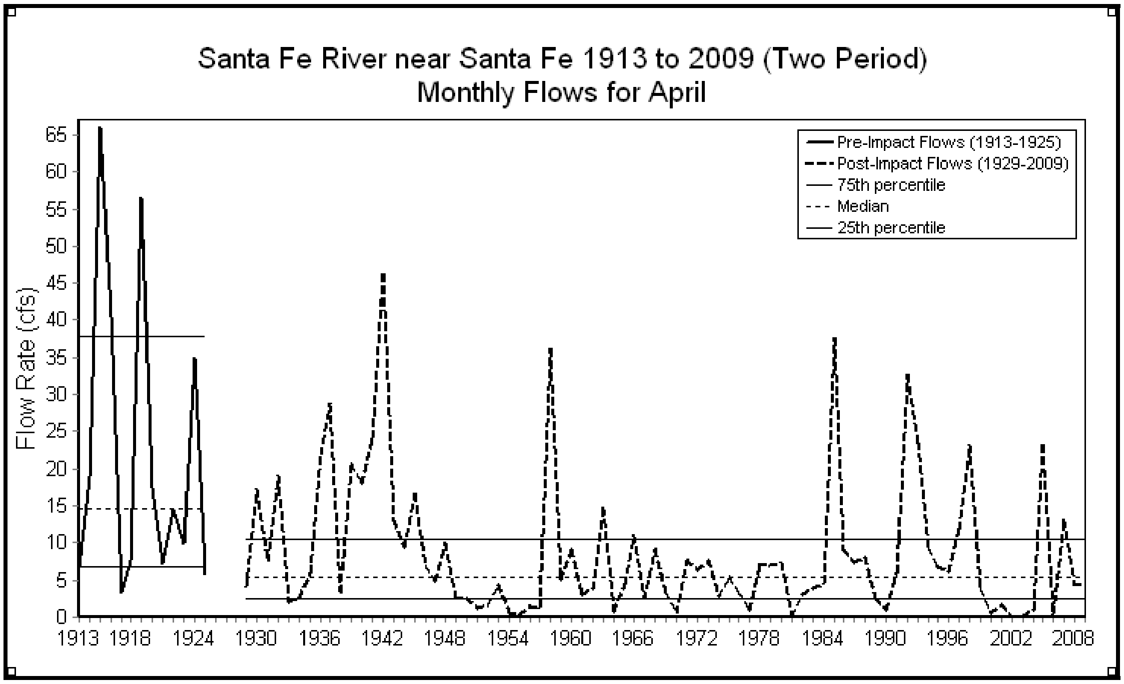


Figure 5.U. April monthly mean streamflow values (in cfs), pre- and post-dam

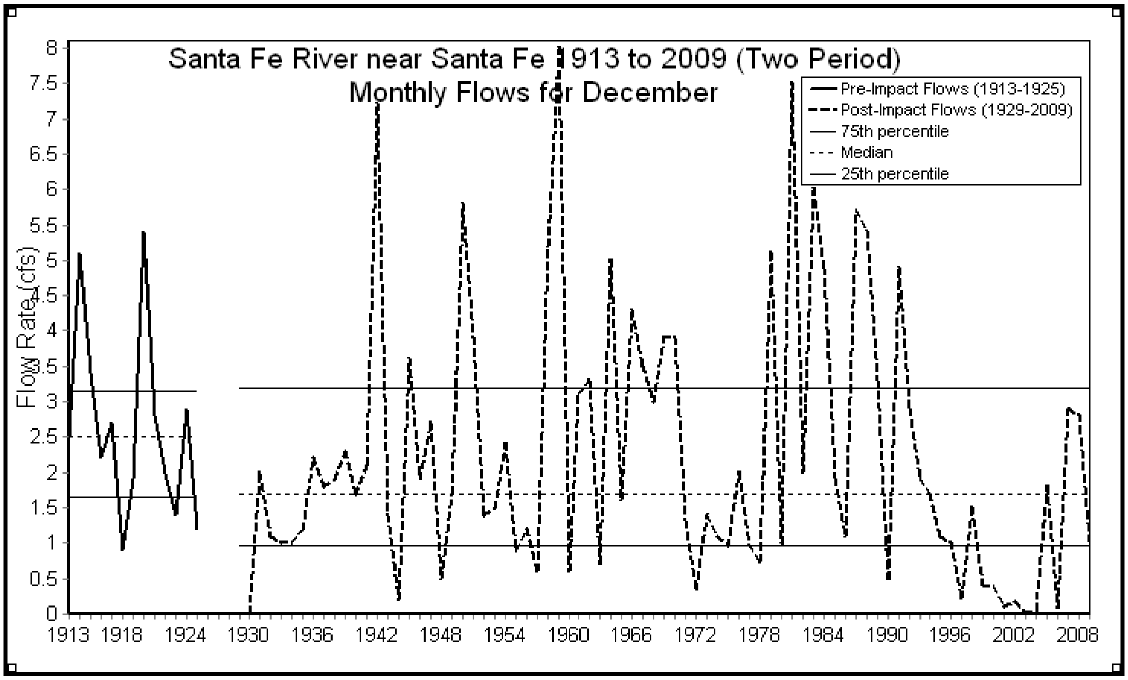


Figure 5.V. December monthly mean streamflow values (in cfs), pre- and post-dam

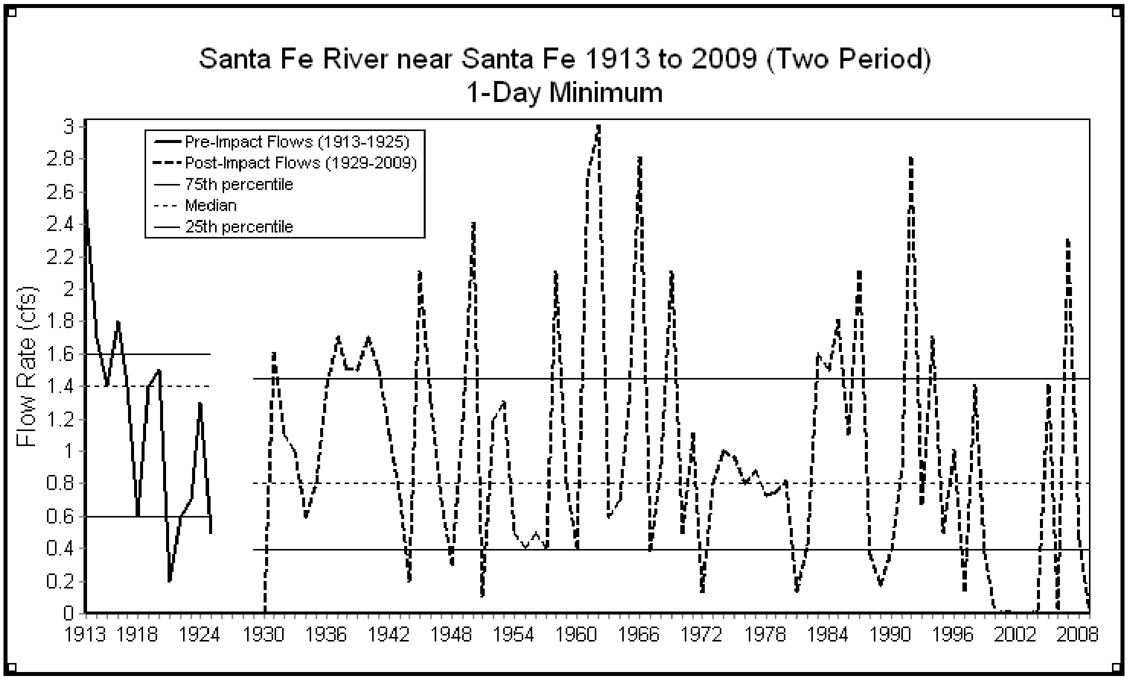


Figure 5.W. 1-day minimum stream flow (in cfs) for pre- and post-dam

Prior to dam installation, the duration of low pulse flow lasted an average of 6 days. After dam installation, low pulses lasted on average 34 days. The median increased by 466 percent, while the C.D. increased by 120 percent, and shows the striking increase in the length of low flows (Figure 5.X). The highly significant increase in low pulse duration is the most drastic change captured by this analysis. This result clearly indicates that the McClure Dam stores the majority of inflow, and releases very little, if any to downstream reaches.

Flow variance is a measure of statistical dispersion, and is calculated by IHA by month (in cfs), for pre- and post-dam flows (categorized by their percentile value). Here, variances for pre- and post-dam flows are plotted in a novel way (Figure 5.Y). The radial plot reveals details about changes in the variance of monthly flows by percentile range, and the timing of those flows. Dashed lines represent pre-dam flows; solid lines represent post-dam flows. The pre-dam distribution of maximum flows varied between

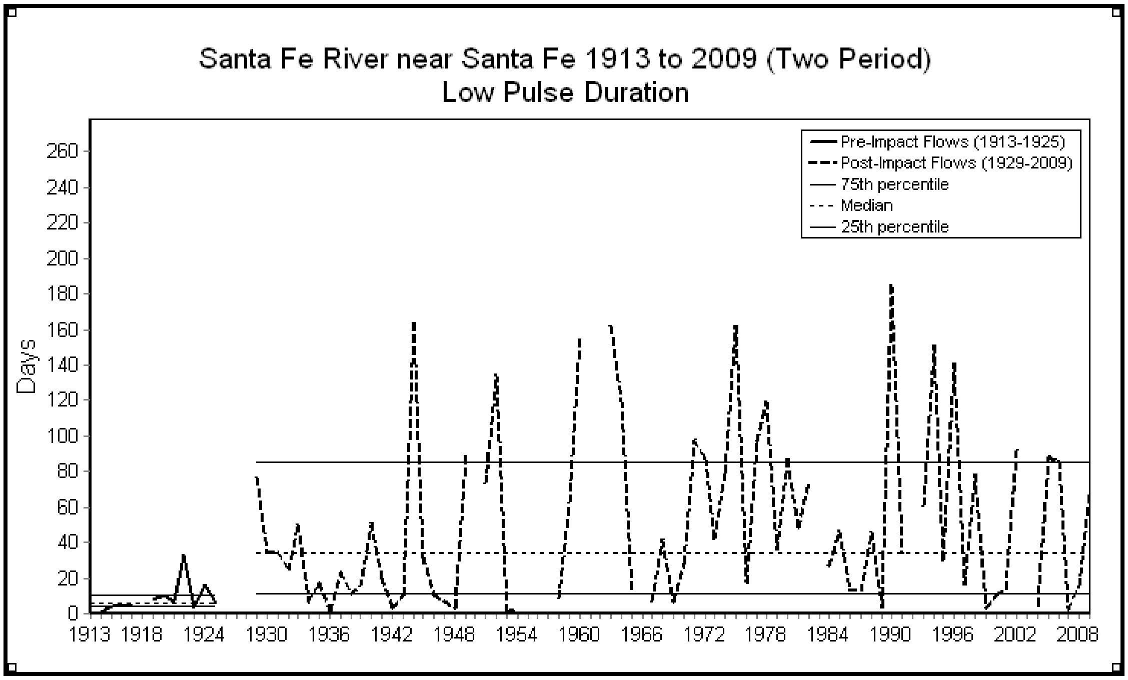


Figure 5.X. Low pulse duration for pre- and post-dam

April and August; however, post-dam flows are focused on May. Flows in the 75th percentile range before regulation by McClure Dam now match the timing and variance of 50th percentile pre-dam flows. Flows categorized in the 50th percentile pre-dam have similar results: these medians now match 25th percentile pre-dam events.

In summary, several hydrologic regime parameters have changed significantly since the installation of McClure Dam (Table 5.4). Monthly median flows for several months deviate from their natural condition. The dam increases variability. The flood control function of the dams reduces maximum values, while the significantly longer low pulse duration indicates the dominance of water storage in dam operations.

Table 5.4. IHA Result Summary Table
Significant Alterations from McClure Dam
Several monthly median flows show significant reduction from pre-dam flow.
Variability of some monthly median flows increase significantly.
Minimum flows volumes decrease while variability increases.
Maximum flows are reduced in magnitude.
Low pulse duration is significantly longer.

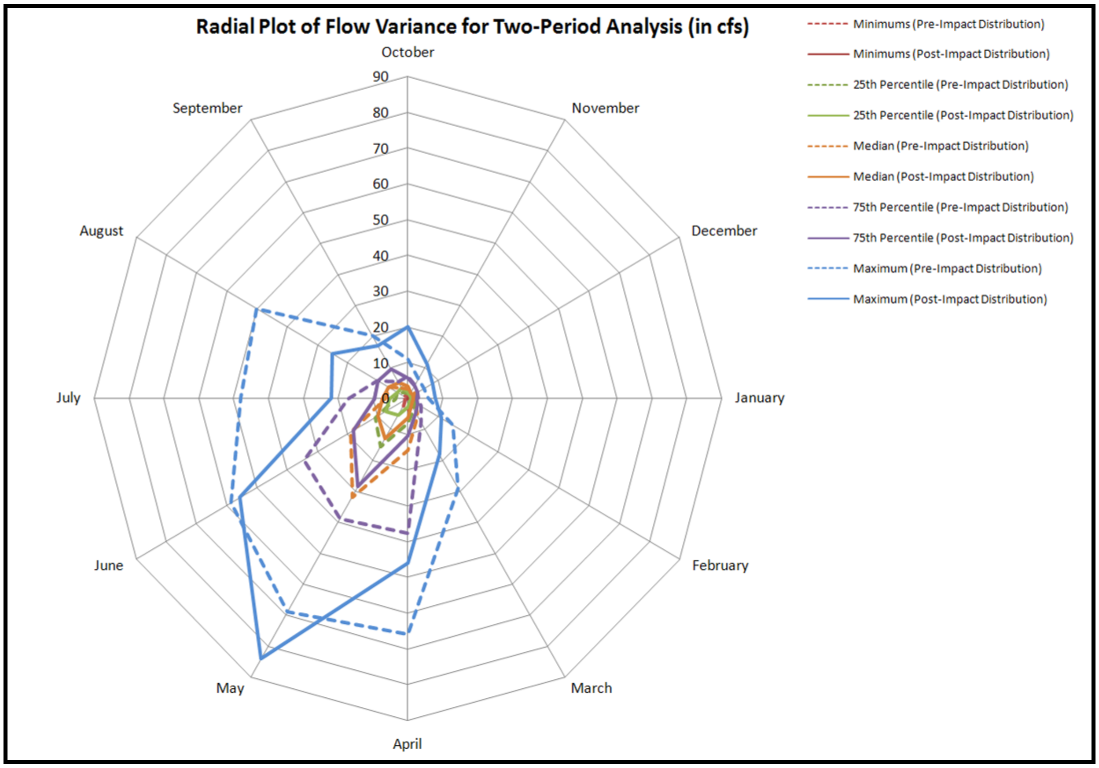


Figure 5.Y. Radial plot of pre- and post-dam flow variance by month (in cfs)

As substantiated by the IHA results, the effects of these dams on downstream flows, fluvial geomorphology, and acequias were immediate. Combined, these structures had the ability to withhold approximately 60 percent of the river's annual flow at one time. Reservoirs captured all incoming water: the local population used the water as their daily supply almost as quickly as it became available. Despite the presence of upstream dams, floods still threaten downtown Santa Fe. Increasing miles of paved roads directed stormwater into the river via curb inlets. Thus, as urbanization expanded in the watershed, so did the volume of runoff entering the river. Today, the river acts as a giant storm drain for the city. *The New Mexican* records examples of serious flooding events on August 4, 1910, August 24, 1957, and July 25, 1968, and illustrates that despite upstream flood control, the capacity for large storms to cause serious damage to infrastructure and human life in downtown Santa Fe increases as development spreads.

Creating stormwater detention opportunities, however small, are essential to the success of the different restoration efforts currently underway on the river (Chapter 8, Section 8.2.1).

5.5 CHAPTER CONCLUSIONS

Since settlement in Santa Fe, there have been continuous interactions between watershed residents and river flows. Prayers to *San Ysidro* (the patron saint of farmers and ranchers) for successful crops and to *San Francisco de Asís* (the patron saint of nature) invoked relief of drought. Perhaps Peralta knew when he properly named the villa that the harsh climate and river flow variability would play a predominant role in its history (Santa Fe's proper name is *La Villa Real de la Santa Fé de San Francisco de Asís*, or The Royal City of the Holy Faith of Saint Francis of Assisi). The Spanish tradition of irrigated agriculture transformed river hydrology: the volume of available flow and the timing of flows identified in this research guides anthropologists to understand better historical citations of farming success and surplus food or crop failure and near starvation. In times of drought, research findings give context to the length and severity of the struggle for survival, especially as the population grew, and flows increased in amplitude.

By reconstructing streamflow volume from tree-ring data, this research also elucidates the river's annual agricultural carrying capacity. As flow waxed and waned, so did the spatial extent of fields in irrigation. By converting annual discharge to the amount of arable land, the few historical descriptions of Santa Fe environs (and single map prior to U.S. territoriality) now translate to a spatial and temporal representation of landcover in the valley. Thorough and exhaustive research of the current literature indicates that this appears to be a unique method. Scientists may use the results of the annual flow reconstruction to answer previously unexplained questions about Santa Fe history, or translate the technique to other areas with similar datasets and landscape histories of irrigated agriculture.

Though humans were powerless to control water availability prior to dam installation, they were not a passive factor within the watershed. Unbeknownst at the time, the human-induced landcover conversion to irrigated agriculture revolutionized the character and volume of river flow. Despite rudimentary technology and methods, the sheer volume of water applied to the land over hundreds of years through the act of water spreading fed the river via subsurface flow, and kept it wet. By quantifying the influence of acequias and irrigated agriculture on river flow, this research illustrates the degree of hydrologic regime modification by the actions of humans prior to stream gaging. These changes were important elements in maintaining river flow throughout its course. Now, inflated expectations for river restoration are part of the current debate due to past spatial and temporal flow conditions induced by irrigated agriculture. The present community desires a living river, which in the minds of most people includes consistent flow; however, the desire to recreate the river of the past is not possible without being able to recreate the landscape conditions to support it. Today, homes and impervious surfaces cover much of the land previously in agriculture and thus prevent the recreation of past flow conditions.

This research also informs basin managers and the local community about the reality of the uncontrolled hydrologic regime. Santa Fe history often is idealized: the current fabricated landscape of stylized adobes that appear in harmony with the surrounding terrain reinforces the perception that residents of the past lived and worked in concert with a placid environment. These perceptions shift the focus toward the "restoration" of perennial, consistent, and acquiescent flows through the downtown reach. In reality, however, the flow regime was seasonal and oftentimes destructive, only to rapidly wane and leave many farmers struggling to effectively water their fields. Restoring a consistent flow to the river, by definition, is not "river restoration." Some human-induced change is beyond restoration, however. In the last 120 years, modifications to flow have been substantial: the upstream dams and downstream WWTP divide a once continuous system into three disconnected reaches. Despite flow reintroduction efforts, these constructions will continue to modify the hydrologic regime and the geography of river flow into the foreseeable future.

The findings of Chapter 5, Santa Fe River Flow, provide a foundation and segue to Chapter 6, Santa Fe River Form: human responses to flow events materialize as modifications to fluvial geomorphology. Hydrologic events transformed the physical landscape and built environment, as large flows modified channel planform, destroyed acequia headgates and *presas*, mangled adobe buildings, washed away bridges, and damaged ditches. The foundational information about flow events, coupled with the explanation of process-form relationships within the basin, oral traditions, and community efforts to modify river form materialize as a unique historical narrative.

SANTA FE RIVER FORM

6.0 CHAPTER OVERVIEW

River form is the direct result of landscape processes. These processes, driven by local geologic and climatic factors, dictate much of the Santa Fe River's fluvial geomorphology. As these dominant factors change in the downstream direction, so do channel geometry and planimetric pattern. The first human-induced channel manipulations were diminutive, consisting of small, mid-channel earthen berms built to direct water into acequias. With time, more sophisticated channel engineering included levees, elevated bridges, and small earthworks to protect the settlement; however, none were as altering to channel morphology as the dam installations in the late 1800s and early 1900s. Channel responses, including incision and bank armoring, continue to this day, and are further exacerbated by aquifer dewatering, ever-expanding impervious surfaces, and aggregate mining downstream. This chapter describes the fluvial geomorphology of the upper, urban, and lower river prior to the arrival of Spanish settlers, during the first three-hundred years of Hispanic settlement, and after the installation of dams. This research links geomorphic adjustment to human-induced changes within the watershed through the centuries.

Section 6.1 discusses upper reach form by first setting the stage with an explanation of upper watershed geology. The section segues into the effects of heavy resource use on the channel, discusses the current health of the riparian corridor, chronicles form response to dam installation and watershed closure, and closes with a dialogue on reservoir dynamics.

Section 6.2 addresses urban reach form. Section 6.2.1 describes fluvial geomorphology in the urban reach prior to human manipulation. It includes conclusions about probable river planform and channel type, made by applying a general understanding of geologic and climatic conditions, and GIS methodologies. Section 6.2.2 describes channel changes induced by Spanish colonists and later, Anglo settlers, between initial settlement and 1880. The most dramatic effects on channel form come from the installation of dams. Section 6.2.3 describes these effects and other modern human-induced changes. While referencing classic downstream responses to dam installation, quantitative techniques and descriptive materials place conclusions concerning channel adjustment within the context of Santa Fe history. Channel cross-sections establish baseline conditions for future restoration initiatives. Discussions of channel engineering and grade control structures occur within the context of degradation mitigation. Channel widths, digitized in a GIS using a multi-year sequence of historical aerial photography, quantify planimetric channel change. Descriptions from historical texts, interviews with retired city engineers and longstanding residents, and historical paired photography bolster conclusions.

Section 6.3 assesses channel form in the lower reach, which includes: quantifying the effects of aggregate mining (6.3.1), evaluating form adjustment induced by the installation and release of water from the WWTP (6.3.2), connecting channel metrics to vegetation composition and cattle grazing in BLM lands in La Bajada (6.3.3), and describing form adjustment associated with the construction of Cochiti Dam and consequent channel bifurcation (6.3.4).

Section 6.4 closes the chapter by revisiting the effects of humans on channel form. As local landscape processes changed with dam installation, landcover conversion, and direct river management choices by humans, the channel form responded as a function of its setting. This research presents knowledge of complex process interactions within the watershed based on the review of historical material and scientific study, and provides guidelines for restoration within physical system limitations. As with river flow, modern human perceptions drive aspirations to construct an archetypal river that fits within the current idealized, fabricated scene. Chapter 6 provides justification for overriding the human desire to recreate a “mountain stream theme” or some other classic meandering planform configuration that is inappropriate for the urban and lower reaches.

6.1 UPPER REACH FORM

A discussion of upper reach form comes from extensive work contained within existing studies, field observations, historical and contemporary aerial photography, and interviews with land and water managers. Over the last fifteen years, various groups have repeatedly surveyed and studied the condition of the upper watershed riparian ecosystem in preparation for a more active watershed management strategy (like the current thinning project underway in several subbasins (Chapter 8, Section 8.1.1)). By obtaining a permit from the USFS, upper watershed entry occurred for a two-day period during the summer of 2006. Field observations and hundreds of photographs taken during these visits compare stream conditions to existing study results within the upper reach. This research extends the current literature of the upper basin by presenting a more thorough examination of the upstream and downstream effects of dams.

6.1.1 Geology and River Form

Near the highest elevations of the upper watershed, the headwaters of the Santa Fe River begin in Lake Peak; a tarn that occupies a cirque last containing active glaciation during the Pleistocene. As the stream exits the lake, it begins its steep descent for several miles. In the upper watershed, the river has an average slope of 36 percent (see red line of Figure 6.A). At a local scale, the profile is a series of stair-stepped falls, pools, and riffles. This figure indicates an extremely steep, geologically controlled channel. Precambrian granites, schists, and gneisses underlie the channel of the upper reach and restrict potential degradation of the channel bed. In areas dominated by hard-rock geology, streams typically follow faults or bedding planes in the rock beneath the surface, as these are areas of weakness that steer flow directionality. The Santa Fe River Fault drives the placement of the river channel as it exits the mountain front because of the local areas of weakness created by this reverse fault (refer to Figure 2.A). In a few places, small tributaries contribute flow to the main stem, and the system reflects an elongated dendritic pattern.[21]

6.1.2 The Effects of Watershed Resource Extraction on Form

Prior to disturbance, the forested watershed would have had several factors acting at the atmosphere-lithosphere boundary layer during a precipitation event that would have limited runoff volume. The factors that would uptake and store moisture included evapotranspiration, infiltration, and groundcover such as dry soil and organic materials. Runoff was limited in the undisturbed watershed because the surface cover buffered precipitation intensity (Figure 6.B). Undisturbed landscapes also are less likely to generate excessive sediment due to hillslope stability and few erosive overland flows.

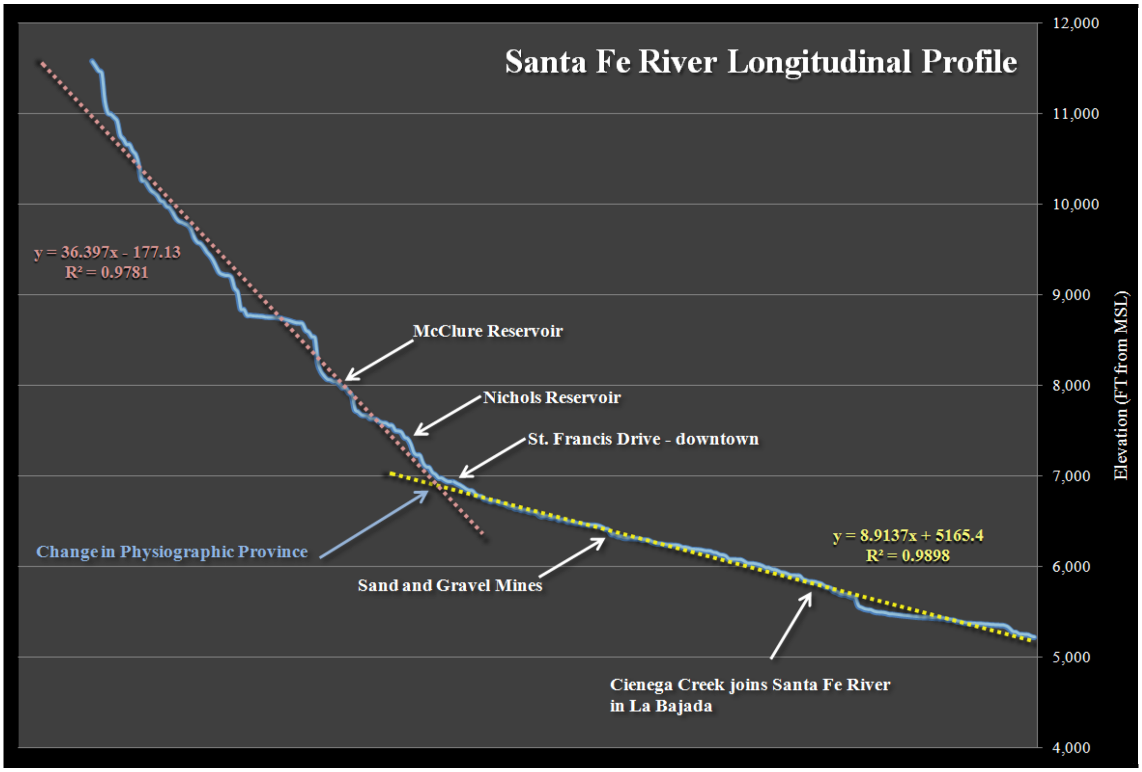


Figure 6.A. Longitudinal Profile of the Santa Fe River

Figure 6.B. Landscape cover intercepts precipitation and encourages infiltration
Source: photos by author (2006)

Human-induced landscape change has the potential to create serious degradation if runoff is uncontrolled. After three-hundred years of overgrazing and logging, the hillsides of the upper watershed were prone to unsaturated overland flow during precipitation events, as unstable soils and few trees replaced a dense canopy.[22] The raw, unprotected soil had neither vegetation to intercept, nor organic detritus to buffer the effects of intense rainfall (Figure 6.C). Adding these factors to sloping hillsides and the erosive forces resulted in water and sediment flowing downhill, often first in rills, then in gullies. The gullies enlarged over time via headward erosion and delivered sediment to the river and valley bottoms. Before watershed closure, hillslope processes were highly active. Newspaper articles from the mid-1800s document this common process in action. For example, within a two-month period of a single year (July and August of 1872), *The Daily New Mexican* notes four references to muddy, destructive flows from the mountains. The debris-filled flows, generated from the unsaturated overland flows during heavy rains, commonly carried “a torrent of muddy water and drift from the mountains” (*The Daily New Mexican* August 22, 1872).

Year after year, these moderate flows created problems for downtown residents, destroyed infrastructure, and affected channel form in the urban reach (Section 6.2.2). However, these occurrences paled in comparison to the front of the massive 1904 flood that completely filled Old Stone’s reservoir with sediment (Chapter 7, Section 7.2.1.5). The 25 acre-foot structure successfully captured almost 31,000 cubic meters of mud and debris (the equivalent of its entire volume) and buffered the brunt of the mudflow from downstream environments. After the flood, Two-Mile Reservoir became the only reliable water source for the city. Sediment transport and deposition via unsaturated overland flows from the surrounding hillsides threatened water quality in the remaining reservoir. This threat heightened the need for upper watershed management because settling was the only water treatment process before its delivery to users via pipe.

Figure 6.C. Unprotected soil easily mobilized by unsaturated overland flow
Source: photo by author (2005)

To impede hillslope sediment contributions, the water company constructed a "tin ditch" around the reservoir in 1930 (Goldman 2003). The three-foot high riveted-steel sediment fence flanked the northernmost slopes and kept hillside runoff at bay while it preserved reservoir storage capacity. This barrier was effective for local hillslopes, but did not address the sediment delivered via upstream inputs.

Additional investigation is necessary to quantify the volume of sediment that has sloughed from the hillsides of the upper watershed. 1936 aerial photographs clearly show raw mountainsides flanking each side of the channel for about 76.2 m (250 ft) (Figure 6.D). By 1951, vegetation is beginning to stabilize the canyon walls. In 2008, the canyon is nearly revegetated. Despite the resurgence of trees and land cover, some sediment previously delivered to the valley bottoms via hillslope processes has yet to stabilize, and appears to be migrating through the stream system, especially below McClure Reservoir. Photographic evidence during field reconnaissance captured this process (Figure 6.E). Given the reduced stream power below the dam, it will likely take longer for these sediments to stabilize within the floodplain, or to migrate downstream into Nichols Reservoir. Additional research is necessary to quantify this instream sediment volume. Regardless of the amount, high reservoir trap efficiencies will eventually capture these mobilized sediments (Section 6.1.4). The city may find further research on this topic worthwhile, as continued reservoir deposition will reduce storage capacities.

6.1.3 The Effects of Dams and Watershed Closure on Form

In 1998, the Institute for Conservation Science surveyed the upper watershed riparian corridor for the USFS to evaluate the hydrology, channel morphology, and streamside ecosystem (Tolisano 1998). It had been over sixty years since watershed closure. The evaluation sought information about both the health of the riparian system and the linkages at work between processes and forms in the upper reach. In its

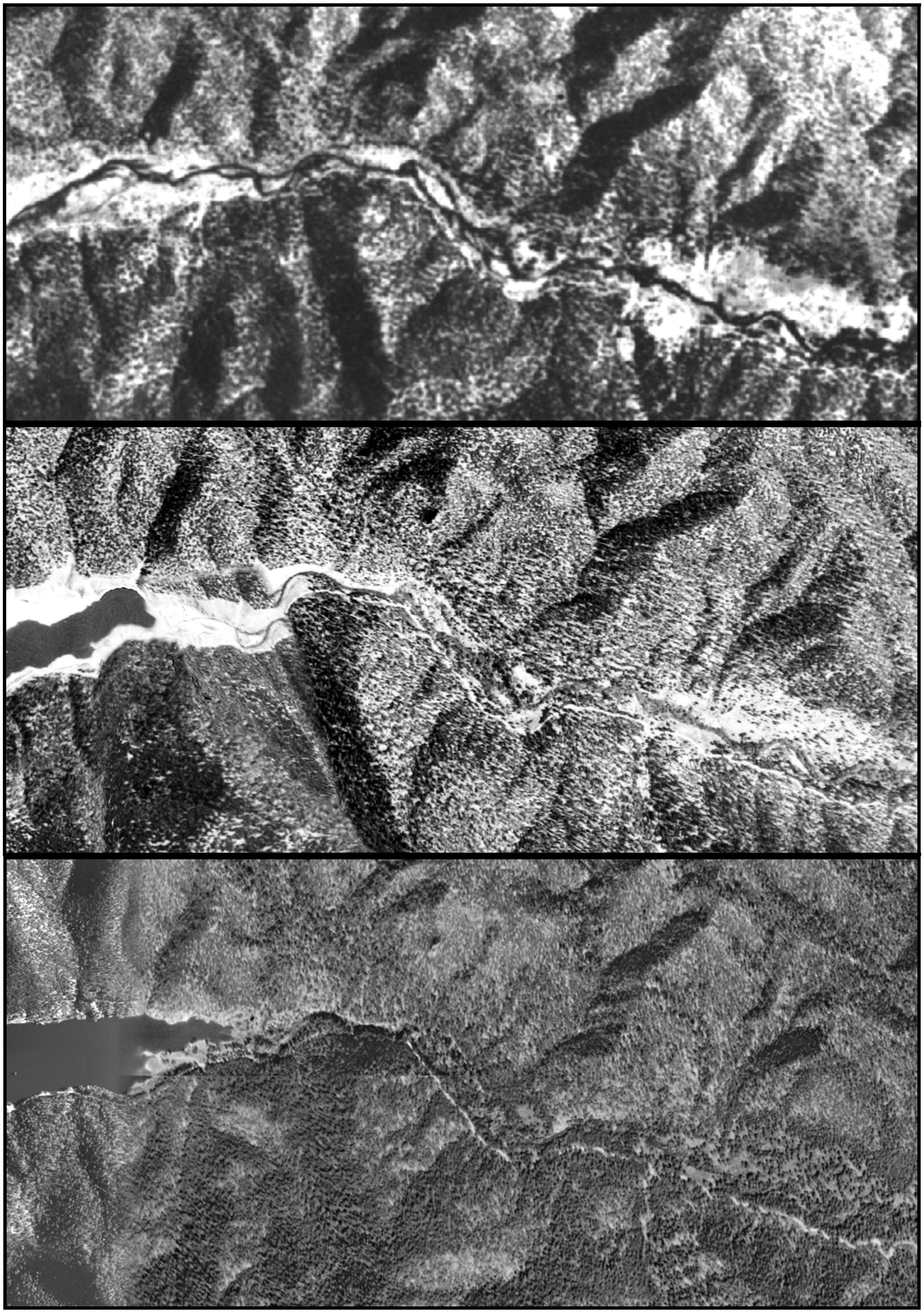


Figure 6.D. Repeat aerial photography of reach upstream from Nichols Reservoir
Landcover change in 1936, 1951, 2008
Source: top, USDA Forest Service (2005); center, City of Santa Fe (2005b); bottom, ESRI ArcGIS Online (2009)

Figure 6.E. Large woody debris captures and stabilizes mobilized sediment
Photo facing upstream
Source: photo by author (2006)

examination, the Institute applied the Proper Functioning Conditions method; an assessment technique developed by the BLM, to quantify and qualify the capability and potential of the riparian system (Tolisano 1998). Capability "is defined as the highest ecological status a riparian-wetland area can attain given existing political, social, and economic constraints;" while potential "is defined as the highest ecological status a riparian-wetland area can attain given no political, social, or economic constraints" (U.S. Department of the Interior 1999: 5-6). Categories for each functional condition score ecosystem health from 1 to 4: a score of 4 indicates an optimal system while a score of 1 indicates the system is non-functioning. The Institute evaluated eighteen river sample sites at 1.5 km (0.9 mi) increments, starting 100 yards (91.4 m) below the lake until reaching Nichols Reservoir. The study also categorized the river into three sub-reaches by apparent qualitative and quantitative differences in the sections. Stream flow and form were evaluated through a variety of river metrics including, but not limited to, channel cross-section analysis, measuring channel flow rate, substrate surveying and embeddedness evaluations, inventorying of large woody debris, calculating pool/riffle ratios, documenting evidence of overbank flows, and evaluating bed and bank stability (bank undercuts).

The first 9 km (5.6 mi) of stream included 6 sample sites. Due to the river's steep nature and massive bed and bank material size, the riparian corridor has limited width: with such a steep gradient, there are limited moisture storage opportunities within the banks (Figure 6.F). The hard-rock geology also restrains the creation of environments suitable for phreatophytic plants (Tolisano 1998). With such a narrow riparian corridor acting as a buffer, this channel reach also has the potential to be highly impacted by land disturbances, such as wildfire.

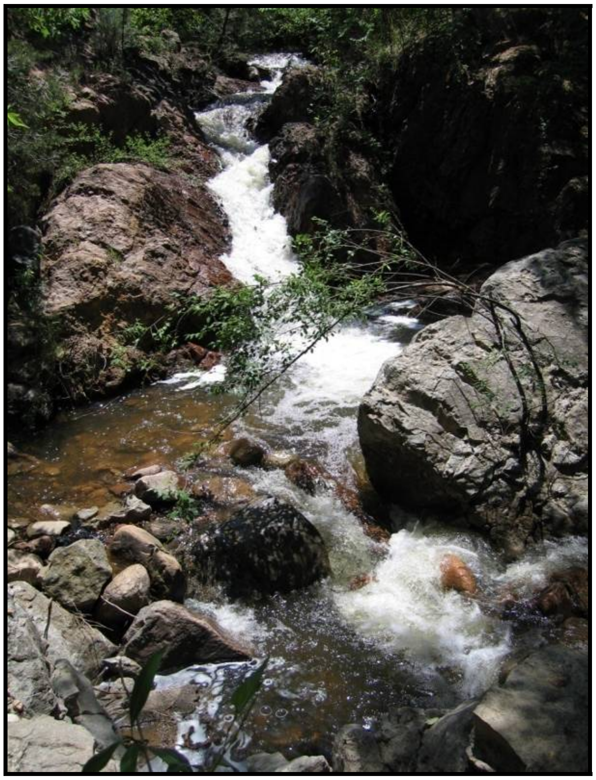


Figure 6.F. Geology controls channel form in the highest parts of the upper reach
Source: photo by author (2005)

Tolisano (1998) used geomorphic indices to evaluate the river form. Particle size assessments showed that there is no dominant class in particular, though boulders are the main particle component in the higher elevations of Reach no. 1 (*ibid*.). Of the samples in Reach no. 1 evaluated for embeddedness, sixty-two percent were less than twenty-five percent embedded. Embeddedness is a measure of the degree to which fine particles surround the coarser substrate on the streambed's surface (Sylte and Fischenich 2002). This low amount of embeddedness indicates that the river in the highest part of the upper reach is not carrying high sediment loads. This finding fits the landscape conditions: the upper watershed dense tree canopy is keeping soil erosion at bay.

The banks also are comprised mainly of a clay loam, instead of the rock materials more common farther downstream (Tolisano 1998). Low sediment loads from minimal hillslope mobilization and clay loam banks indicate that this part of the watershed was likely the least impacted by human activities prior to watershed closure, primarily due to both its steepness and remoteness. The even distribution of particle sizes within the channel support macroinvertebrate species. Low embeddedness values also correlate to high quality benthic habitat, macroinvertebrate abundance and diversity (Waters 1995; Angradi 1999; Lowe and Bolger 2000). Macroinvertebrate abundance and diversity are important indicators of ecosystem health. When embeddedness is low, there is likelihood for greater stream ecosystem health. High in the watershed, steep falls preclude cold-water fish species from upstream migration, despite the proper aquatic conditions in the pool and riffle environments to support them. All ten functional condition categories for the highest section of the river's upper reach received a rating of PFC (properly functioning hydrologic and ecological features); hydrologic indicators specific to channel form were rated at 3.47 out of 4, and approach optimal conditions from a geomorphic standpoint (Table 6.1).

Table 6.1. Mean Statistics for Hydrologic Indicators Only
Upper Santa Fe River Riparian Condition Assessment summarized from Tolisano (1998)

	Pool/Riffle Ratio	Large Woody Debris	Overbank Flows	Erosion	Bank Canopy Cover	Overall Condition Rating
Reach no. 1: Lake Peak to Black Canyon	3	2.5	4	3.83	4.0	**3.47**
Reach no. 2: Black Canyon to McClure Reservoir	2.71	2.57	3.57	3.57	4.0	**3.28**
Reach no. 3: McClure Reservoir to Nichols Reservoir	2.5	1.75	3.25	3.5	3.25	**2.85**

4: optimal functioning hydrologic features
3: properly functioning hydrologic features
2: hydrologic features functionally at risk
1: hydrologic features are non-functioning

In Reach no. 2, between 9 and 21 km (5.6 and 8.7 mi), river form changes as it exits the steep vale and begins to meander slightly through a wider floodplain. Within this section, there are areas where the floodplain can reach widths of 76.2 m (250 ft), which is a significant contrast from the zero to tens of feet in the headwaters. During field reconnaissance, evidence of frequent overbank flows included sediment and vegetation debris lines, and woody debris piled against upstream-side tree bases. These overbank flows support a highly diverse composition and structure of riparian vegetation (Tolisano 1998). The vegetation serves several important functions from the aspect of channel form. Large woody debris and vegetation stabilizes the banks, slows floodwaters, captures sediment, and induces meanders. There is a higher diversity of sediment sizes in the middle section (pebbles and cobbles are dominant) as compared to the first, and the bank material has a higher percentage of rock than the loamy banks of Reach no. 1. Field visits noted a few sections with bank undercuts. However, these sections are an exception in the overall stable system. The various distribution of particle size supports healthy macroinvertebrate and fish habitat. Field reconnaissance spotted trout (*Oncorhynchus mykiss* or *Oncorhynchus clarkii* x *mykiss*) several times (Figure

6.G). Their optimal spawning habitat (shallow gravel riffles) frequently is present. This middle section has more large woody debris and has the least amount of embeddedness (54 percent of sample sites were less than 25 percent embedded) than either of the other two sections of the upper river. Geomorphic conditions match the expression of fluvial processes at work during seasonal flooding from spring snowmelt. Overall, the fluvial geomorphology of this middle section of the upper reach is functioning properly. Reach no. 2 received a condition rating of 3.28 out of 4 (Table 6.1).

Figure 6.G. Santa Fe River trout
Oncorhynchus mykiss or *Oncorhynchus clarkii x mykiss*
Source: photo by author (2006)

The third section evaluated by the Institute, Reach no. 3, begins below McClure Dam and continues downstream beyond the outlet of Nichols Reservoir. This lower section has many of the same characteristics of the middle section; however, the regulating effects of the dams are evident in channel form. The floodplain widens even further between the dams. In a GIS, it measures a maximum of 198.1 m (650 ft) and reflects the gradual flattening of channel slope. The average slope in this section of the upper reach is about six percent (Tolisano 1998). Unlike the area directly above McClure reservoir, the floodplain of this inter-dam reach closest to McClure is not inundated frequently because the dam impounds most of the seasonal pulse. Streamside shade remains high; however, there is a mix of riparian and upland species within the floodplain, which reflects the managed releases and infrequent inundation from upstream reservoirs. The lack of flooding also reduces the toppling of streamside vegetation and limits the amount of large woody debris within the channel. Information about the hydrologic regime created by McClure dam is not disclosed by the Sangre de Cristo Water Division, but there is a maximum volume that the reservoirs can share between them (5,040 acre-feet). The reservoirs are managed to store this amount whenever it is available (Boychert 2006: personal communication).

Immediately below McClure Dam, the channel has entrenched itself. This entrenchment is a typical channel response to the lack of instream sediment in reservoir releases (Church 1995; Sanchez and Baird 1997; Knighton 1998). Because the dam's filtering effects remove sediment, the sediment-free waters attempt to rebalance the sediment regime by eroding the bed and banks. This response decreases with distance from the dam. However, at some point between the two impoundments the river process changes from degrading to aggrading: the excised sediment moves downstream and begins to accumulate within the channel bed. This aggradation may have taken place farther downstream were it not for the river encountering the upstream effects of Nichols Reservoir, which raises the local baselevel to match the elevation of the reservoir pool. There also is the likelihood that some of the volumes of unstable instream sediment are migrating downstream because of past hillslope processes (Section 6.1.2). Regardless of the sediment source, the low stream power and sediment transport capacity of flows released from McClure reservoir make the process of sediment migration a slow one.

Despite the reduced stream power and water volumes, Reach no. 3 closest to Nichols Reservoir has frequent overbank flows due in part to the aggradation. Thus, a gently meandering, aggraded reach with numerous wetlands and beaver-generated ponds has replaced the sinuous stream of the 1930s. These large beaver (*Castor canadensis*) populations construct lodges that trap much of the downstream-migrating sediment, recharge groundwater, and help to minimize the sedimentation in Nichols Reservoir (Figure 6.H).

Figure 6.H. Beaver activity attenuates floods and captures sediment
Photo facing upstream
Source: photo by author (2006)

6.1.4 Reservoir Dynamics

Reservoir managers learned of the consequences of flood mismanagement from the 1904 event. After Old Stone reservoir's sedimentation, storage losses, and adverse effects on water quality in Two-Mile, they allowed heavy flows carrying mobilized sediment to bypass the early impoundments. "The great washout, however, has worked a blessing, it is said washing the dirt out of the creek, and now allowing clean water to flow into the reservoir into which none of the tide was allowed to flow yesterday" (*The Santa Fe New Mexican* August 5, 1910). Thus, these erosive flows continued downstream and contributed to channel scour (Section 6.2.3). This newspaper statement also gives clues to the instream sediment migration and accumulation problems occurring in the early 1900s due to poor upper watershed hillslope conditions.

The management strategy changed with the installation of larger dams (Granite Point (McClure) in 1926 and Nichols in 1943), as neither structure has a bypass channel to divert unwanted flows. With water shortages and an increasing city population to supply, the water company wanted the water, regardless of the sediment it carried. Reservoir trap efficiencies of McClure and Nichols reservoirs quantify the percentage of transported sediment captured by the dams over time, as a ratio of drainage area and storage capacity.[23] A great deal of sediment accumulated behind the two reservoirs prior to land healing, although further research is necessary to measure the absolute volumes stored in the deposits. McClure reservoir likely received a larger volume of the sediment early in its history given that: (1) the watershed was early in its recovery from grazing and logging, (2) it was installed earlier in time and upstream from Nichols, and (3) its trap efficiency increased from 79 percent to 94 percent after it was raised in 1935 (Table 6.2). As total trap efficiencies increased in the late 1930s and early 1940s, so did channel incision downstream in the urban reach: the lack of instream sediment below the dams encouraged downcutting into the bed, thus necessitating engineering responses (Section 6.2.3). The two reservoirs acting in concert are able to capture close to 100 percent of the sediment migrating downstream because there is little flowthrough via spillways, and in arid areas, "the runoff per unit area is relatively low, and trap efficiencies are probably higher than those predicted by the function" (Graf 2002: 269). These results are consistent with the closest reservoir nearby, Cochiti, which withholds 99 percent of its entering sediment (Richard 2001).

Table 6.2. Reservoir Trap Efficiencies calculated from Moore *et al.* (1960)

Name	Year	Drainage Area (mi^2)	Storage (ac-ft)	Trap Efficiency (%)
Granite Point (McClure)	1926	17	650	79.3
Granite Point (McClure)	1935	17	3059	94.7
Granite Point (McClure)	1995	17	3325	95.1
Nichols	1943	22.8	684	75.0

Because of these high trap efficiencies, large deltaic deposits formed at the apex of each reservoir. Due to the low water levels in June of 2006, photographs taken during field investigations note several characteristics of the accumulated sediment in McClure and Nichols reservoirs. Typically, when water encounters the reservoir pool its velocity drops, and sediments will settle in a series of sorted layers called beds. The larger particles will settle out first, while incoming flows transport incrementally smaller particles downstream in a process called fining. This research visually examined the sediment patterns in the delta deposits: evidence of this layering process was evident, as were laminations along the shoreline indicative of past climatic and seasonal water level fluctuations and reservoir pool management. In Nichols reservoir, the exposed fines are remnant of a time when water elevations in the reservoir were higher (Figure 6.I). The channel bisects the silt and sand beds to expose larger materials beneath them (Figure 6.J). Clear evidence of a higher water elevation in the past also includes beaver lodges left high and dry (Figure 6.K). Baselevel fluctuations from changing reservoir elevations cause channel aggradation and degradation upstream to vary spatially, while destabilizing the shoreline and increasing sedimentation. Because of the short observation period, it is not known if enough fetch length is present in these small waterbodies to generate wave action that would manipulate the shoreline and create landforms (field reconnaissance did not observe waves or wind). Given the relatively smooth appearance of the shoreline, it appears that water level fluctuiations and topography have a larger influence on shoreline geomorphology than does wave action (Figure 6.L).

Figure 6.I. Flow dissection of Nichols Reservoir deltaic sediments
Photo facing downstream
Source: photo by author (2006)

Figure 6.J. Seasonal laminations and dissection of fines in Nichols Reservoir
Photo facing upstream
Source: photo by author (2006)

Figure 6.K. Beaver lodge reminiscent of a higher reservoir pool elevation
Source: photo by author (2006)

Figure 6.L. McClure Reservoir sediment deposit influenced by seasonality
Santa Fe River inflow at right
Source: photos by author (2006)

6.2 URBAN REACH FORM

6.2.1 Urban Reach Fluvial Geomorphology before Humans

By applying knowledge of geologic conditions, topography, and the hydrologic regime, it is possible to reconstruct some general characteristics of the river's fluvial geomorphology in the urban reach prior to channel manipulations by humans.

Downstream adjustments in slope, physiographic province, and stream discharge explain the longitudinal transitions in channel form from (1) single-thread stream within a dendritic network of the steep hard-rock mountains, to (2) meandering reach contained within the foothills, to (3) compound channel at the mountain front, to (4) wide, braided channel of the sedimentary alluvial fan that forms the open plain. These changes occurred on a downstream continuum, as the determinants of form adjusted throughout the urban reach.

Figure 6.A clearly shows the change in slope at the mountain front: the average abruptly changes from about thirty-six percent to roughly nine percent. At the mountain front, the rocks are closely faulted perpendicularly to the river and are deeply weathered in many places: these conditions produce large quantities of disintegrated rock. Tectonic movement of these faults has been the main control on sedimentation, as uplift continuously renews erosion in mountain streams by changing the local baselevel, and the abrupt reduction in slope at the mountain front encourages its deposition (Graf 2002). Rivers in highly faulted environments have a tendency to be structurally controlled, and follow weaknesses in rocks. The northeast trending Santa Fe River Fault and the northwest trending faults of the mountain front guide the river out of the mountains and west into the alluvial fan apex of the Santa Fe group, specifically the facies of the Ancha and Tesuque formations. “The Santa Fe group is largely a complex of alluvial fans that accumulated in the Rio Grande trough” (Spiegel and Baldwin 1963: 60).

Where the river first exited the Precambrian metamorphics of the mountain belt, it was confined within the foothills (called the Upper Canyon area in modern times), and began to meander through high terraces of Ancha formation alluvium. The river easily eroded the alluvium of unconsolidated sands and gravels, which led to local entrenchment and only minimal floodplain development (less than 61 m (200 ft wide)). River meandering and entrenchment within the alluvium terraces appears in historical photography prior to modern corridor revegetation (Figure 6.M). In this area, the Ancha formation is relatively thin (only tens of feet thick) and rests upon the much thicker (thousands of feet thick), less permeable sands of the Tesuque formation.

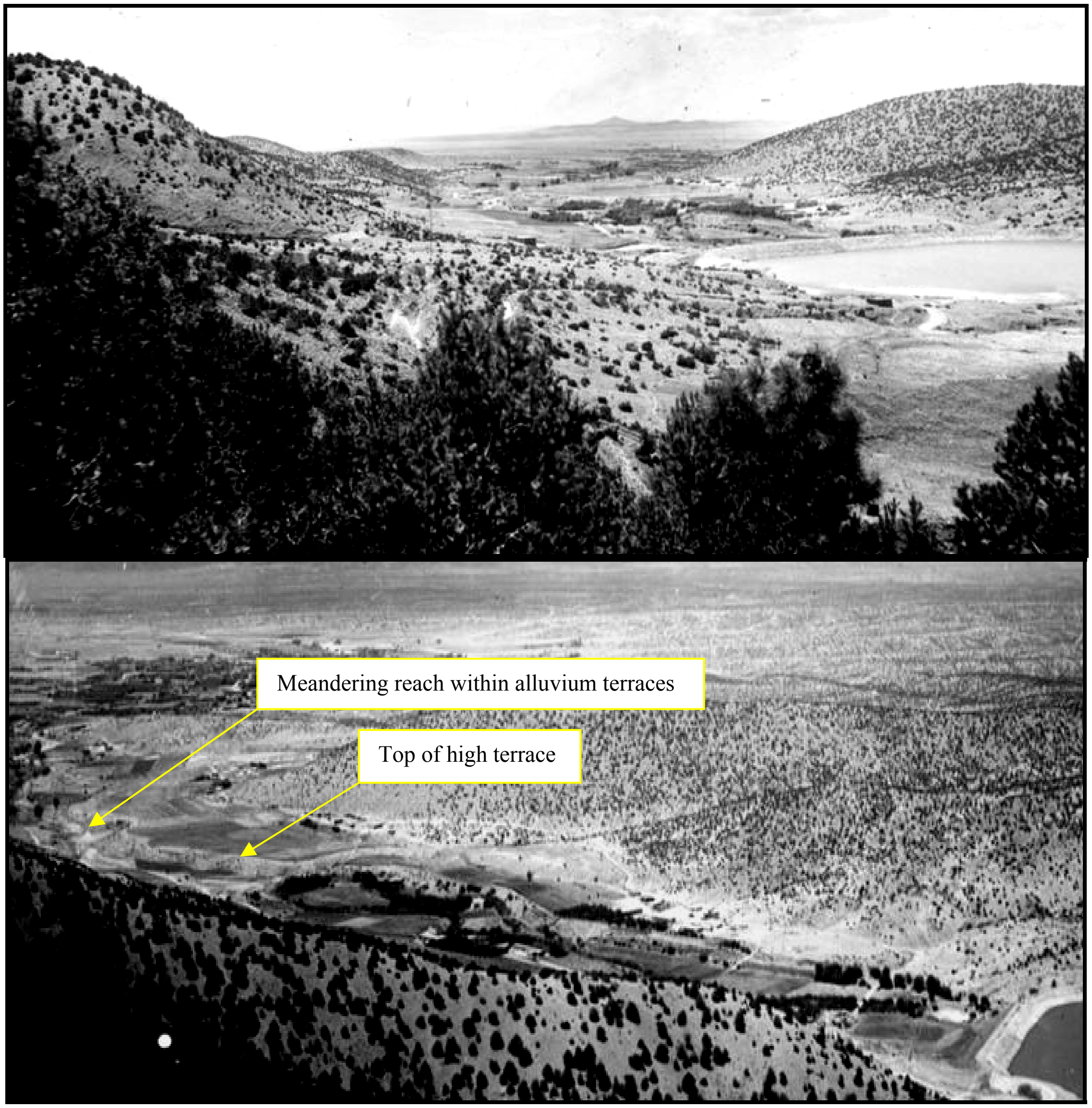


Figure 6.M. River meanders within high terrace alluvium of the Ancha formation
Before exiting the mountain foothills, circa 1910
Source: top, The Library of Congress (2009a); bottom, The Library of Congress (2009b)

A few hundred feet downstream, the river exited the canyon foothills and no longer was confined within the upper terrace alluvium. The channel now was free to migrate and widen. The river's planform changed from a meandering stream within a narrow floodplain to a widening compound stream, expressing characteristics of both meandering and braided systems. "Compound channels have two modes of operation: at low flow water occupies a single meandering channel while high flows occupy a wider 'braided channel'" (Graf 2002: 202). This section of river was in transition: it would become predominantly braided several miles downstream. The middle terrace of the Ancha formation restricted southerly movement, but there were no restrictions to channel migration to the north. The reduction in slope and channel confinement that occurred once the river left the canyon area and entered the villa, caused reductions in the velocity and transport capacity (stream power) of the river, and sediment fell out of suspension. This process has driven the creation of the Tesuque and Ancha alluvial fans for millennia. Although most braided rivers have characteristically high slopes, it has been shown that "slope is not an over-riding control" (Graf 2002: 202), as was the case in this section of the Santa Fe River. Figure 6.N shows the variety of sediment sizes and abundance of unconsolidated sediment in the wide, compound channel delivered from the upper watershed and upstream terraces during high flows.

The compound channel type best describes this section of transitioning form prior to human settlement because there were channel characteristics evident of both types in this reach. These channel types displayed themselves at different times in the year depending on the hydrologic regime. During periods of low flow, mostly during the fall and early winter months, and in times of drought, the channel likely meandered ever so slightly in a single thread through its wide, shallow floodplain; creating small pools, riffles, and glides that supported a riparian bosque, aquatic life, and recharged groundwater. Because the Tesuque formation is not very permeable in this area (Spiegel and Baldwin 1963), subsurface flow likely was perched atop the unconformity, and moved within the terrace alluvium of the thin Ancha unit. This process is the mechanism by which shallow local groundwater was available to be tapped so close to the surface by future Santa Feans, and the reason for the saturated conditions in the downtown cienega (Chapter 7, Section 7.2.3).

During periods of snowmelt, high bedload and high velocity flows filled the entire channel cross section and traveled more straightly through the reach. These high flows activated any present subchannels. The unconsolidated banks provided some additional sediment to the regime, although it is likely that the riparian vegetation helped to stabilize the channel. The periods of high flow would rework the bed sediments. After flow subsidence, the meandering stream component would have a slightly different configuration. This situation is especially true in areas where riparian vegetation would encourage sedimentation. During extreme events, the river would flood beyond its wide channel and potentially change its course, as was the case during the great flood of 1767 (Section 6.2.2). In the absence of humans and their infrastructure, the river naturally changed position for thousands of years between the middle terrace to the south and the surrounding hillsides to the north. Evidence of its movement is clear in the carved terraces that parallel its course, and the remnants of an oxbow that was to become an important feature in the history of Santa Fe (Chapter 7, Section 7.2.3).

About 3.2 km (2 mi) downstream from the foothills, the compound channel likely changed to a braided channel configuration. Evidence for this form change includes local slope and sediment supply increases: the sediment contributions of two arroyos and the unconsolidated banks of the alluvial plain drives planimetric adjustment and adds to the total bedload (Figure 6.A).

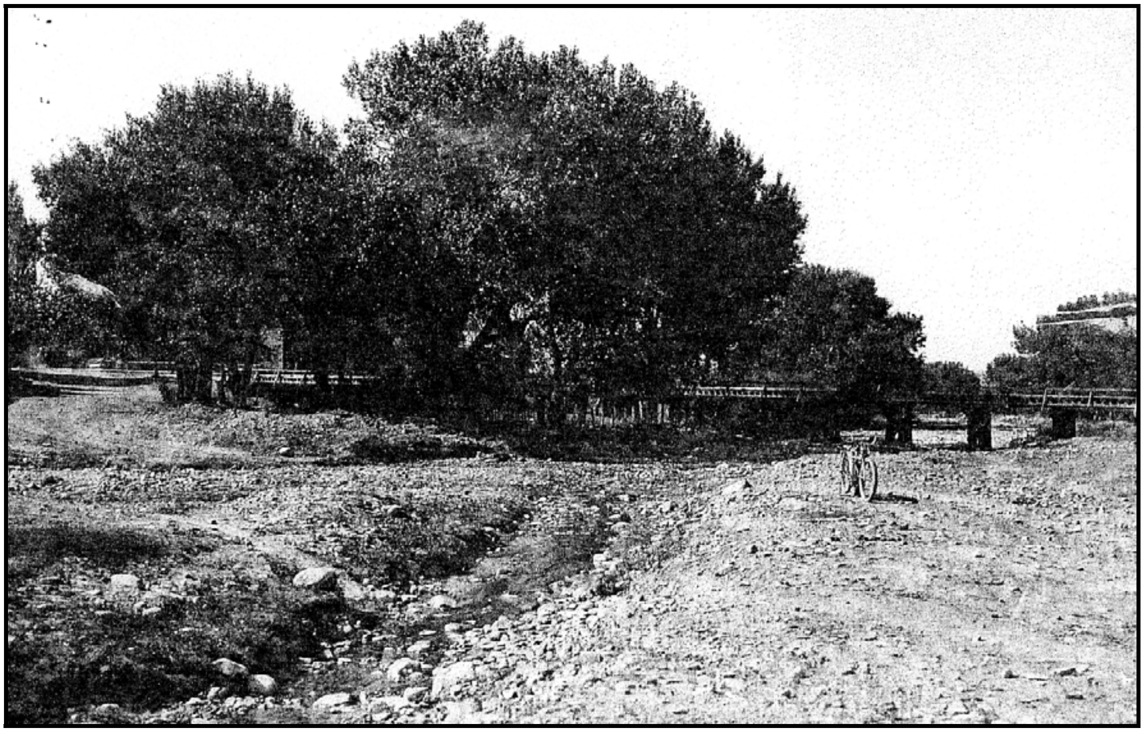


Figure 6.N. Compound channel, 1912
Small, nested stream within wider gravelly floodplain; bridge width indicates the span of large-capacity floods, photo facing downstream
Source: Museum of New Mexico, negative #61570

Despite the many intermingling channels, the braided stream was relatively straight. During high flows in braided streams, water will typically fill the entire cross-section. Aerial photography from 1936 shows the braided channel downstream of Santa Fe, and despite the presence of humans within the watershed, provides an idea of what the channel may have looked like prior to watershed habitation (Figure 6.O). The channel likely was wider and less stable prior to irrigation, except in areas where springs provided additional baseflow (locations later to become Cieneguita and Agua Fria). The saturated subsurface and vegetation roots at the spring sites were stabilizing features, and the channel narrowed at these locations.

Figure 6.O. Braided channel configuration with contributing arroyos, 1936
Source: USDA Forest Service (2005)

6.2.2 Urban Reach Form Changes from Settlement to 1880

As settlers made their way upstream to the site that would be developed for the villa, they likely saw the aforementioned braided channel peppered by areas of dense riparian vegetation at spring sites. 1692 Reconquest documents confirm this riparian scene. While on his way toward Santa Fe on the *Camino Real* (royal road), Don Diego de Vargas began to reassemble his troops after a night's rest somewhere near present-day Agua Fria. He wrote how he afforded "time for all the soldiers to gather, for …the forest was thick" (Espinosa 1940: 79). Only as they drew within one-quarter league of the settlement site (the equivalent of 1.2 km, or 0.75 mi) did the riparian vegetation decrease and the landscape change to "a meadow and open country" (Post and Snow 1992; Espinosa 1940: 79). Distance measurements indicate that 0.75 mi downstream from the

Plaza area is about the point where the Arroyo Mascaras and the Santa Fe River combine. There also was some riparian vegetation present in the downtown area, as Vargas also commented that from his camp on the south side of the river, he could see the *casas reales* being shaded morning and evening (Espinosa 1940).

The compound channel around the settlement site was ideal for the diversion of water into the newly dug acequias. The single-thread channel component could be manipulated via small modifications. Layers or heaps of logs, juniper brush, cobbles, and gravels were placed in the channel to create an earthen dam (*presa*) and contain the water enough to divert it into the inlet headgate (Rivera 1998). For example, the Acequia Pino, a ditch part of the Acequia Madre network, is documented as having received water "by the primitive method of training the river into it with use of earth, rocks and brush" (Snow 1988: 192). The ample source of unconsolidated cobbles and gravels from the compound channel made multiple dam replacements possible, as the high spring flows likely wiped out many, if not most, of these natural earthworks each year. The digital reconstruction of the historical acequia network demarcates 43 of these inlet works between the upper canyon area and the downstream reach beyond Agua Fria (Chapter 7, Section 7.2.2). Although these earthworks were numerous, from a geomorphic perspective, the changes to channel form they induced were small compared to the effects of modern twentieth century dams. There may have been some aggradation upstream from each tiny check dam, but the numerous pools likely created a configuration akin to the step-pool sequence more characteristic of the upper reach. At each diversion node, the dam diverted most of the available water into the acequia: dams slowed the water velocity and allowed the suspended and bed loads to settle, keeping most of the sediment out of the ditches and alleviating the problems excessive loads would cause to the ditch gradients and gravity-driven flow. Given the earthen nature of these dams, there likely was considerable seepage beneath each structure. The dams also may have induced some meandering if the *presa* did not cross the entire channel. Angled mid-channel berms likely acted as point bars and directed the undiverted portion of the thalweg towards the outside bank, creating some erosion. Modern evidence of this process still occurs at the Acequia Madre's mid-channel earthen berm in Santa Fe, although given the current subdued hydrologic regime and the influence of upstream dams on form (Section 6.2.3), the true reason for the cut bank is difficult to discern.

For the first few hundred years, these small channel modifications were the norm in Santa Fe. The locations of *presas* changed as the acequia network evolved, and new *presa* construction occurred periodically as agriculture expanded throughout the valley. This research is unable to deduce more about the pre-modern channel, as there are very few documents mentioning channel condition or placement. In actuality, historical materials mention the Rio Chiquito more often than the river: references in deeds and documents tracing back to 1692 solidify its role as an important physical landmark. Historians theorize that the Rio Chiquito was either an oxbow, a side channel (meander or braid bar), or the river itself. This research concludes that the Rio Chiquito was simply a small tributary to the river with its genesis in the cienega spring closest to the pond behind the convent (Chapter 7, Section 7.2.3). This hydrologic feature, however, was considerably important in the physical landscape and history of Santa Fe.

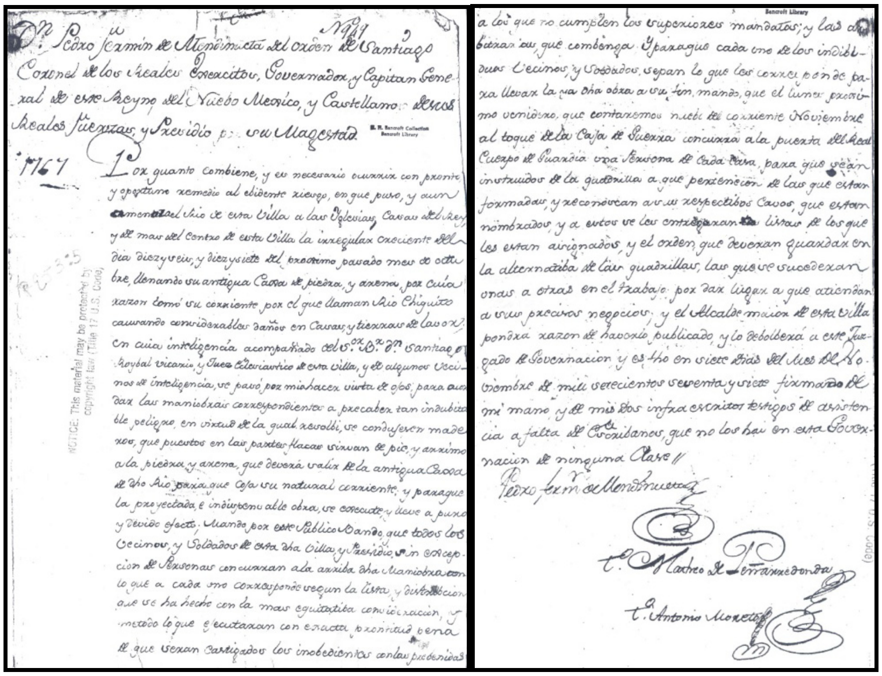
Despite the water resources within the Santa Fe valley, Peralta's site choice was a dangerous place for several reasons. In the villa's precarious position, it felt the wrath of seasonal flooding, suffered the effects of poor drainage, and had to fight a continued battle against the river's tendency to redirect its primary channel into the heart of the settlement. The river had changed position over millennia. Before the installation of upstream dams, there was nothing to stop its lateral migration throughout downtown. It is likely that the river tried to capture the Rio Chiquito during the 1767 flood event, thus rerouting its main course. Over the years, the tiny stream emanating from the small cienega seep had carried water downhill in a channel parallel to the main river, creating microtopography. It is unlikely that this side stream was part of the main river until the great flood, when flow exceeded the banks of the compound channel. Microtopography directed flow and concentrated it along the tributary path, likely creating incision and cutting a hydrologic connection between the main channel and the stream. After the flood, it took concerted local efforts to confine the river to its original path. During his visit to Santa Fe, Fray Francisco Atanasio Domínguez commented that the river's swift current "has done some damage, and although this was not extreme, measures have been taken to avoid further harm by installing a stone embankment" (Adams and Chávez 1956: 40). Fray Domínguez is undoubtedly speaking of this flood, which occurred nine years before his mission survey. One of the earliest surviving documents pertaining directly to the river is a *bando*, or edict by Governor Pedro Fermin de Mendinueta. The document reveals details about this massive flood, and about the earliest known major construction initiative on the river (Figure 6.P). Physical evidence of this event is long-gone; however, the havoc it wreaked was so severe that every resident of the villa was required to dedicate labor to channel restoration. The document describes the:

> Threat the river of this villa is to the churches, royal houses and others in the center of this villa, by its unusual crest the 16th and 17th of this past October,

> filling its ancient bed with stones and sand, for which reason its current took it into that which is called the Rio Chiquito, causing considerable damage to the houses and farm lands; … timbers be brought to be placed in the weakest spots that they might serve as footings and support for [against] the stone and sand where the river might leave its former bed, in order that it maintain its usual current; and in order that the projected and necessary work be done and carried to the desired effect, I order by this public decree that all citizens and soldiers of this villa and fort, with the exception of no one, heed the above stated work with whatever pertains to each the most equitable consideration and methods
> (New Mexico Records and Archives Center 1767).

At the time, it was important that the river remain in its original course. A permanent change in its location would put the *casas reales* in greater danger from flow events due to their new proximity to the channel (refer to Figure 5.L). Santa Feans tried to protect their homes and churches by constructing levees (*estacadas*). Levees artificially elevate the channel banks as an attempt to confine floodwaters (Knighton 1998). Photography from the late 1800s shows material on either side of the river that appears shaped like artificial levees designed to keep water from flooding the center of the town (Figure 6.Qa). Horizontal timbers, posts driven into the ground, and brush and stacked stone reinforce the banks of the river at the Galisteo Street Bridge, and provide a glimpse of the early riverworks fashioned to control channel position in downtown. This historical photography shows the bridges as causeways above the river course. Their average spans give clues to the channel width during larger flow events (Figure 6.Qb). Physical evidence of these early earthen control structures no longer exists today, as modern infrastructure has obliterated it.

From the Urrutia Map, the speckled pattern along both sides of the channel denotes the gravelly floodplain of the river (Figure 6.Ra). Urrutia drew a wide channel that maintains approximately the same width (about 15.2 m (50 ft)) from right to left, though he depicted a floodplain that widens in the downstream direction. This widening



N.o 949

D.n Pedro Fermin de Mendinueta del orden de Santiago Coronel de los Reales Exercitos, Governador, y Capitan General de este Reyno del Nuebo Mexico, y Castellano de sus Reales Fuerzas, y Presidio por su Magestad.

1767

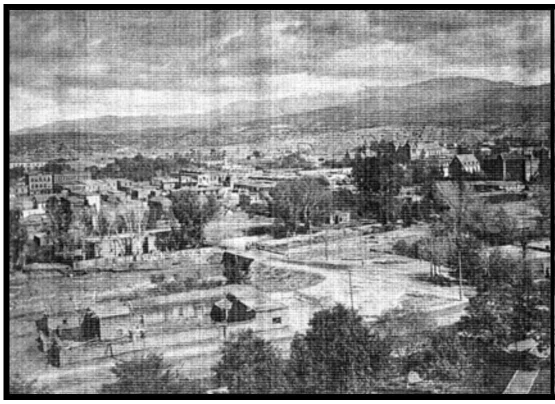
Por quanto combiene, y es necesario ocurrir con pronto y oportuno remedio al ebidente riesgo, en que puso, y aun amenaza el Rio de esta Villa a las Yglesias, Casas del Rey, y de mas del Centro de esta Villa la irregular creciente del dia diez y seis, y diez y siete del proximo pasado mes de ottubre, llenando su antigua Caxa de piedra, y arena, por cuia razon tomó su corriente por el que llaman Rio Chiquito causando considerables daños en Casas, y tierras de labor, en cuia inteligencia acompañado del S.or B.r D.n Santiago Roybal vicario, y Juez Eclesiastico de esta villa, y de algunos vecinos de inteligencia, se pasó por mi a hacer vista de ojos, para acordar las maniobras correspondientes a precaber tan indubitable peligro, en virtud de la qual resolbi, se condujeren maderos, que puestos en las partes flacas sirvan de pie, y arrimo a la piedra y arena, que deverá salir de la antigua Caxa de d.ho Rio para que tome su natural corriente, y paraque la proyectada, e indispensable obra, se execute, y lleve a puro y devido efecto, Mando por este Publico Bando, que todos los vecinos, y Soldados de esta d.ha Villa, y Presidio, sin excepcion de Personas concurran a la arriba d.ha Maniobra con lo que a cada uno corresponde segun la lista, y distribucion que se ha hecho con la mas equitatiba consideracion, y metodo lo que executaran con exacta prontitud pena de que seran castigados los inobedientes con las prevenidas a los que no cumplen los superiores mandatos; y las arbitrarias que combenga Y paraque cada uno de los indibiduos vecinos, y Soldados, sepan lo que les corresponde para llevar la ya d.ha obra a su fin, mando, que el lunes proximo veniedero, que contaremos nuebe del corriente Noviembre al toque de la Caja de Guerra concurra a la puerta del Real Cuerpo de Guardia una Persona de Cada Casa, para que sean instruidos de la quadrilla a que pertenecen de las que estan formadas, y reconoscan a sus respectibos Cavos, que estan nombrados, y a estos se les entregaran listas de los que les estan asignados, y el orden que deveran guardar en la alternatiba de las quadrillas, las que se succederan unas a otras en el trabajo por dar lugar a que atiendan a sus precisos negocios; y el Alcalde maior de esta villa pondra razon de haverlo publicado, y lo debolbera a este Juzgado de Governacion y es d.ho en siete dias del mes de Noviembre de mil setecientos sesenta y siete firmado de mi mano y de mis dos infra escritos testigos de asistencia a falta de escribanos, que no los hai en esta Governacion de ninguna Clase //

Pedro Fermin de Mendinueta

t.o Matheo de Tierrarredonda

t.o Antonio Moreto

Figure 6.P. Rare surviving document, edict for labor to repair Santa Fe River banks
Source: New Mexico Records and Archives Center (1767)



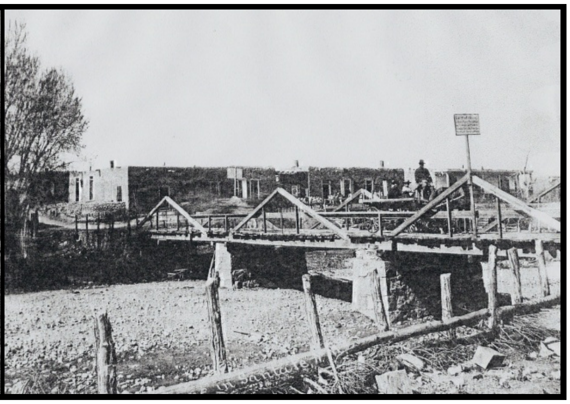


Figure 6.Qa. Constructed levees on the Santa Fe River, likely around 1880
Figure 6.Qb. Elevated bridge over Guadalupe Street, circa 1890
Source: left, Museum of New Mexico S. Loomis Collection, Box 135, Folder 2, Image #21943; right, Museum of New Mexico negative #15328

gravel is indicative of the longitudinal transition from a compound to a braided channel. This map provides the earliest reference to indicate that the river in this area was indeed a wide, gravelly compound channel that transitioned to braided longitudinally. Urrutia's map confirms the findings of this research concerning the geometry of the early channel form (derived from an understanding of process-form relationships). Urrutia's map also elucidates the magnitude of channel change in modern times. In a GIS, a visual comparison between Urrutia's map and preliminary predicted flood inundation areas generated by the Federal Emergency Management Agency (FEMA) in May of 2006 visually compares and contrasts past and present floodplain extents. The 100-year flood inundation polygon demarcates where large-magnitude flooding events would affect the downtown area both today and in the past (Figure 6.Rb). These are relatively the same upstream of the Guadalupe Street Bridge: the northern spatial extent of inundation may be *slightly* reduced in modern times due to increased channel storage in this section of the reach (due to the ~3 meters (~10 feet) of incision that has occurred between the original channel elevation and its current depth). However, downstream from the bridge, the modern floodplain width decreases by 90 percent. It is likely that this 100-year floodplain would continue downstream to match with the gravelly floodplain of the 1776 depiction, were it not for the ~10 meters (~30 feet) of incision that has occurred downstream of the bridge as a result of river management decisions within the last fifty years (Figure 6.Rc).

Two research findings of historic import result from this GIS analysis. First, it is clear that the *casas reales* were constructed beyond the 500-year floodplain, but whether Peralta was aware of the floodplain's extent during villa planning is unknown. The second finding relates to a feature commonly interpreted as an acequia. Noted on Figure 6.S, this hatched line materializes in the middle of several farm fields and continues in a northwesterly direction until it connects to the river. Although scholars believe this line is an acequia (Snow 1988), from a hydrologic perspective the spatial arrangement is puzzling, given the need for gravity flow when directing water away from the river. Frankly, this feature is going in the wrong (i.e. uphill) direction. After overlaying the rectified Urrutia Map in a GIS, it becomes clear that this feature is the upper terrace, and that the linear hatching aligns almost perfectly with the small bluff that parallels the river.

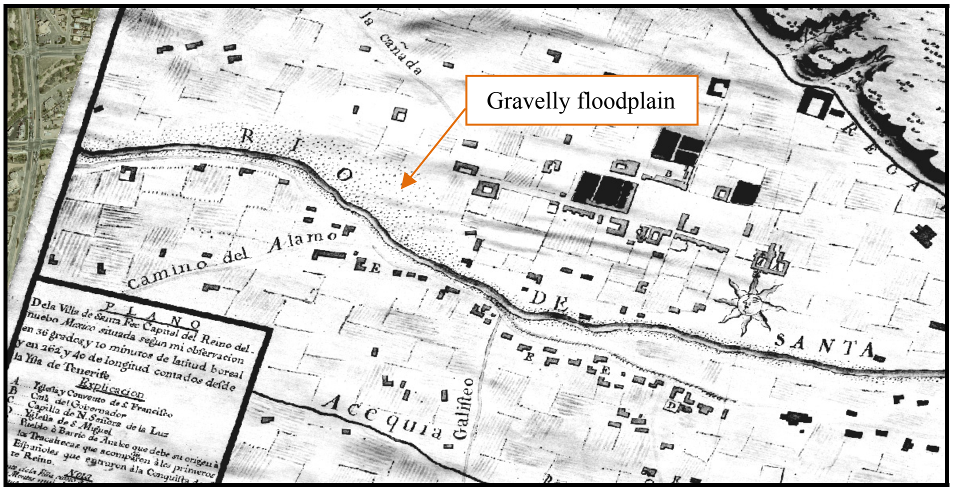


Figure 6.Ra. Rectified Urrutia Map of 1766 with gravelly floodplain
Source: Museum of New Mexico, negative #15048

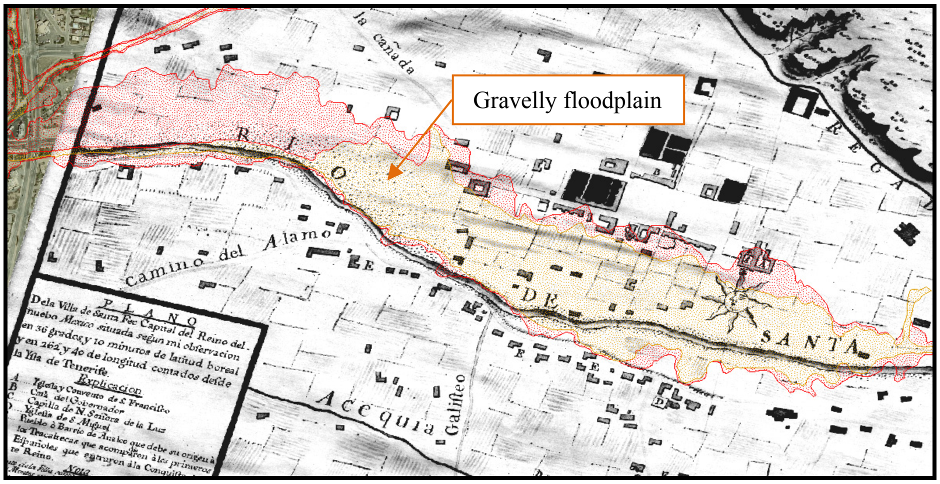


Figure 6.Rb. Urrutia overlain with modern FEMA floodplains
100-year floodplains (orange), 500-year floodplains (red)
Source: Museum of New Mexico, negative #15048, floodplains NMRGIS (2009)

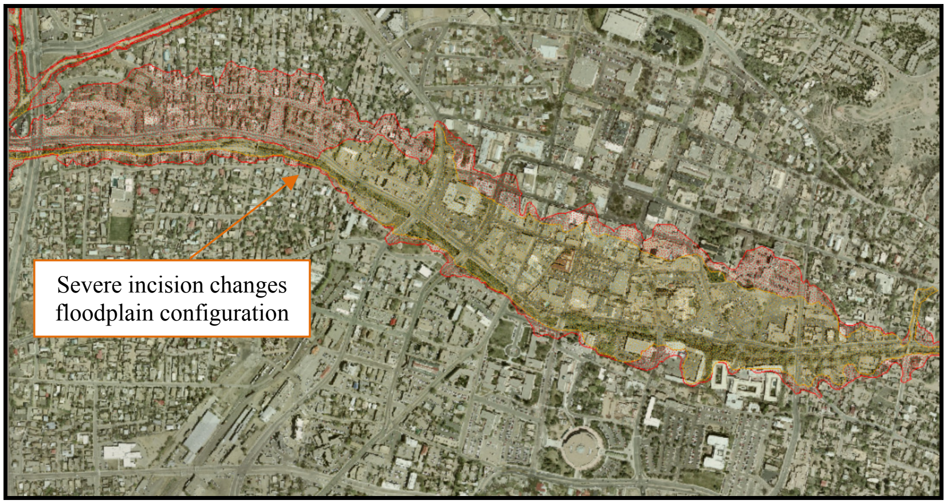


Figure 6.Rc. Modern aerial image of Santa Fe with FEMA floodplains
Source: floodplains, NMRGIS (2009); imagery, City of Santa Fe (2005b)

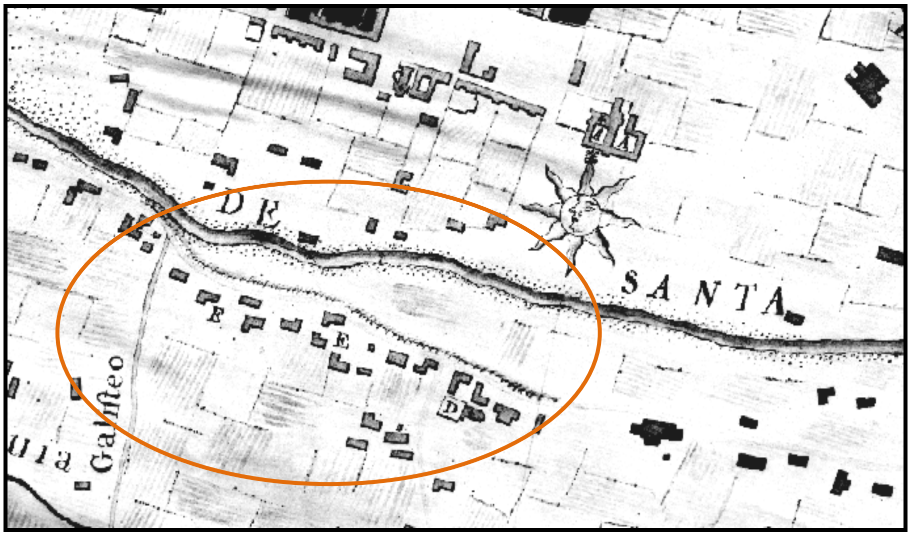


Figure 6.S. Detail of Urrutia Map showing the upper terrace bluff
Source: Museum of New Mexico, negative #15048

The historical literature contains only a few additional descriptions of channel form prior to the installation of dams in the late 1800s. Most of these descriptions relate to incidents of flooding. Largely they concern the condition of bridges spanning the waterway. A few of them note channel condition directly. For example, on June 28, 1879, *The Daily New Mexican* mentioned the need to widen passages in the river to improve flow, and that sheep and goat herding should be prohibited in the streambed. Perhaps the channel was aggrading due to the downstream migration of sediment from the upper watershed, or the animals were the direct cause of reduced channel conveyance from bank trampling and destabilization. The 1877 Plat of Santa Fe confirms the transitioning form through the urban reach. It depicts the shallow channel as a wide swath that broadens in the downstream direction, near where slope begins to increase and arroyos contribute to channel discharge and sediment load (Figure 6.T). The plat also shows the expanses of irrigated agriculture on the landscape and the presence of prairie to the south: an indication that grasslands were once a dominant landcover of the Santa Fe watershed. While assessing the Santa Fe River in 1907, Yeo described the river as flowing “in a shallow channel through a level plain for some 15 miles,” obviously not yet affected by the incision induced by upstream dams and downstream sand and gravel mines (Yeo 1928: 54). The small compound stream transitioning to a braided system is starkly different from the future channel form induced in the years to come by dam installation, the decline of irrigated agriculture, increases in impervious surfaces, and aquifer drawdown.

6.2.3 The Effects of Dams and Other Human-Induced Changes on Urban Reach Form

Dams introduce an artificial terminus into a gradually sloping river. The structures collect water behind them for later release, trap sediment as it migrates downstream, and perform several functions beneficial to humans. In Santa Fe, the canyon dams currently store 40 percent of the city’s water supply, act as flood control structures, and hold water available for fire protection in the upper watershed. The nature of the dams’ operating regime dramatically has influenced river flow (Chapter 5), river form, and river function (Chapter 7). The historical record captures some of the effects of the first dam, Old Stone, on river flow and function (Figure 6.U). The small structure had only a small influence on the flow regime once reservoir filling was complete; however, its influence on acequia agriculture was great. This precursor to future dams was an indication of the widespread changes ahead for the farmers and their traditional way of life.

In terms of river form, however, it has not been possible to identify documented downstream channel changes directly resulting from the 1880 Old Stone Dam construction. By applying an understanding of downstream geomorphic responses to dam installation, however, it is clear that the first form changes likely occurred in the urban reach section closest to the dam. It is likely that initial responses included some bed and bank incision: despite its small size (only 25 acre-feet), Old Stone's reservoir pool still filtered sediment. But prior to statehood, there is limited evidence of landscape change in the historical record, regardless of the subject matter. The few maps that exist are so small in scale that they depict the river only as a swath through town; thus, little can be gleaned about minute changes occurring in downstream channel form from these historical sources.

In 1898, cartographers were not yet depicting changes in channel form induced by dam installation. The land ownership map (Figure 6.V), drawn eighteen years after the completion of Old Stone and four years after Two-Mile Dam was complete, shows a river that still widens through downtown as it transitions from compound to braided; planimetrically similar to the Urrutia map of 1766 and the 1877 City plat (Figure 6.Ra and Figure 6.T). Extensive archival searches found no historical photography of the river between 1880 and 1893. Writings that describe landscape conditions are limited to major events documented in newspapers: small amounts of riverbed incision for tens of feet

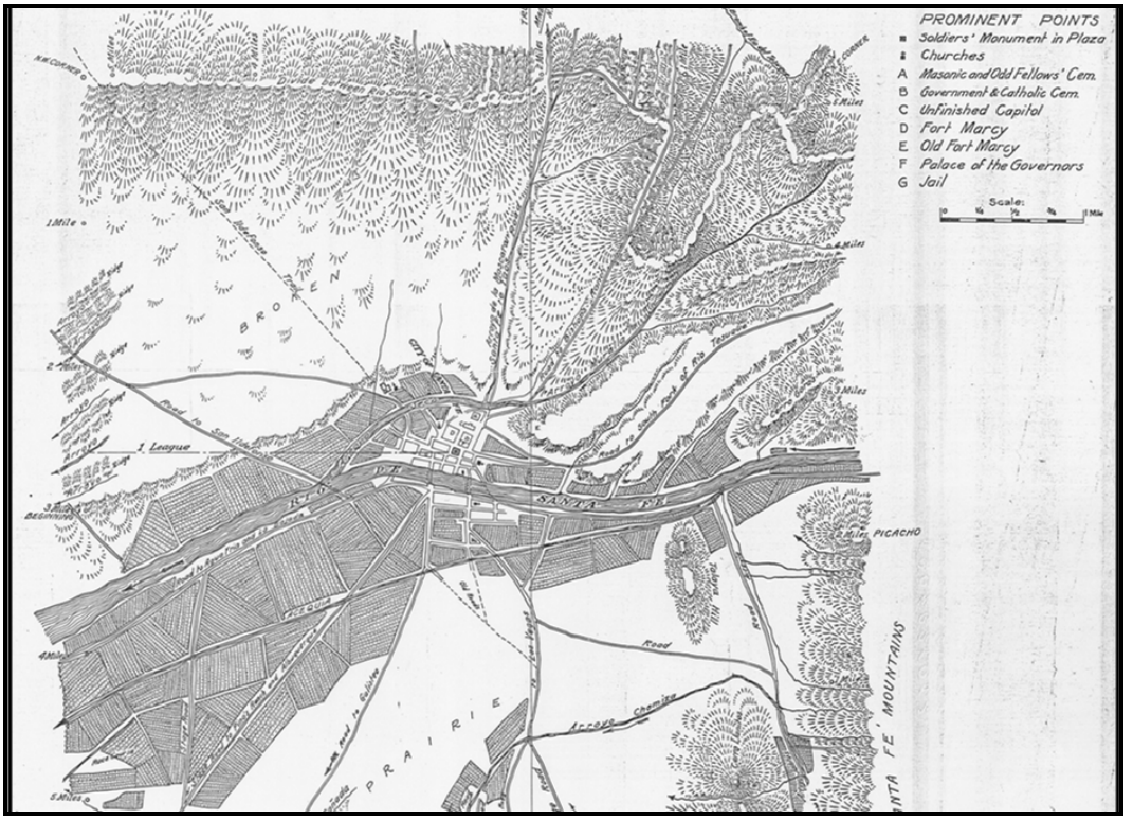


Figure 6.T. City of Santa Fe Plat, 1877
Source: Museum of New Mexico (1877)

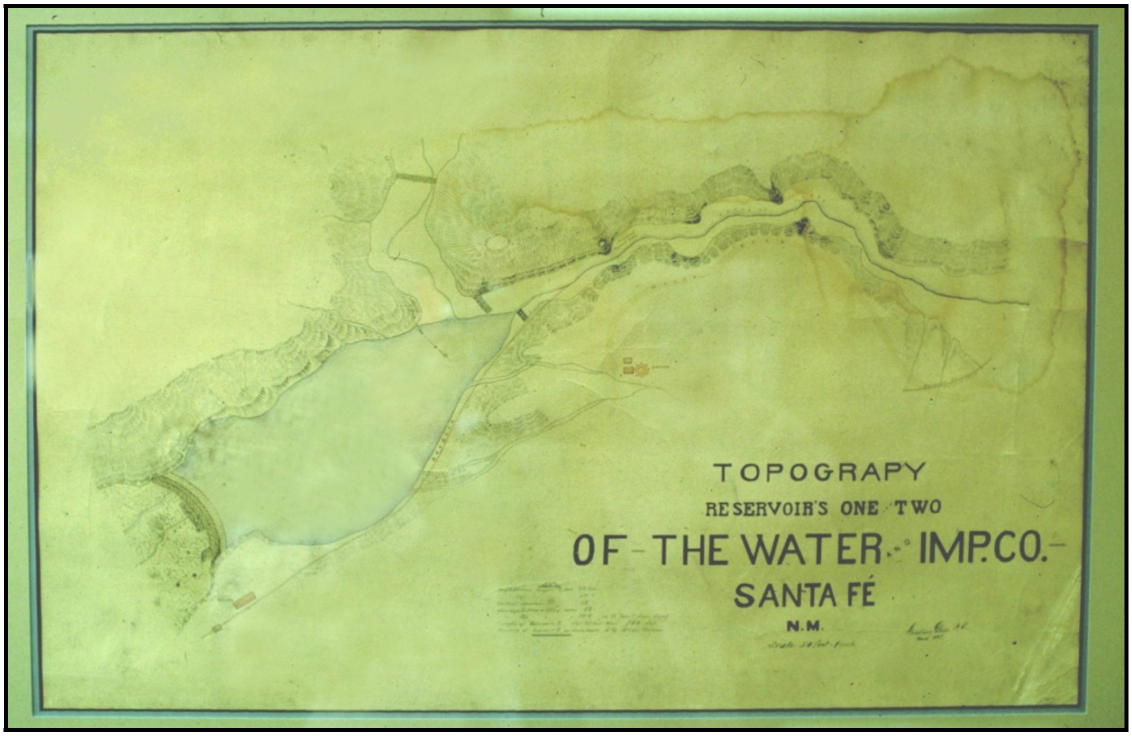


Figure 6.U. Blueprint of Old Stone Dam, 1889
Source: Courtesy of The Nature Conservancy, Santa Fe (2005)

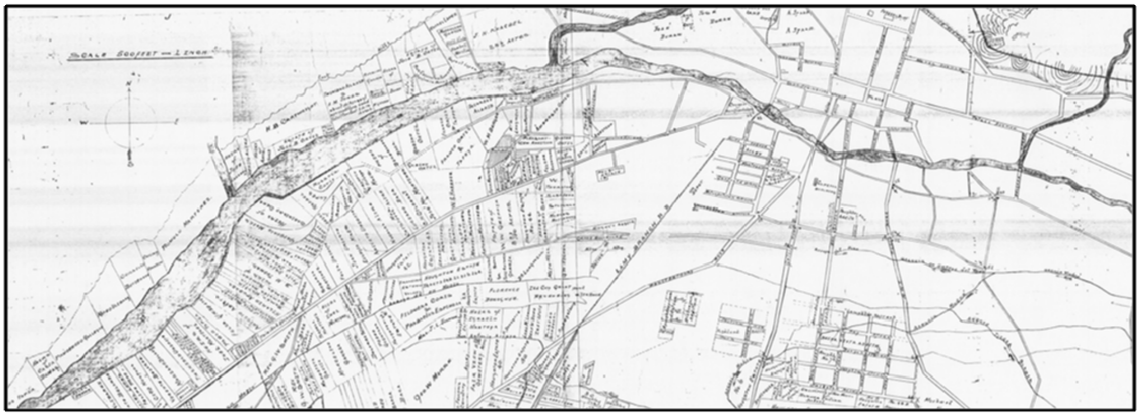


Figure 6.V. 1898 Ownership Plat shows widening river emerging from downtown
Source: Museum of New Mexico (1898)

near the dam were hardly newsworthy. Given the more recent understanding of the widespread effects of dams by geomorphologists, perhaps residents did not attribute changes like bed incision to the dam, and thus their effects were not discussed as such. Perhaps farmers were more concerned with surviving the harsh climate than with documenting their experiences in it: in the late 1800s local farmers were largely illiterate, and there are no known personal journals from Santa Fe agrarians describing the river. There was also no public forum for Hispanos that noticed the effects of the dams to discuss them. After 1880, the newspaper stopped printing its Spanish language pages. In English, *The Santa Fe New Mexican* continually championed the water company and their efforts, and repeatedly attacked the acequia mayordomos for their objections to water storage. Given the blatant boosterism for the dams and water works, it is unlikely that the newspaper would write anything negative about their downstream effects.

The construction of Two-Mile Dam in 1893 likely obliterated any channel incision occurring directly downstream from Old Stone Dam: five-hundred yards of channel directly downstream of Old Stone were covered by the reservoir pool of Two-Mile. Within two decades of the construction of this much larger structure (over fifteen times the storage capacity of Old Stone), maps and photographs begin to reflect the downstream effects (channel narrowing and bed incision) on channel form. Paired photography captures the beginnings of channel incision by 1914 (Figure 6.W).

Figure 6.W. Paired photography showing channel incision, 1910 and 1914
Source: left, Museum of New Mexico, negative # 61466; right, Museum of New Mexico, negative # 11051

Dams change downstream channel form by altering channel slope, sediment load, and discharge. Below the Santa Fe dams, the character of channel form reflects the conditions induced by dam operations prioritizing water storage and flood attenuation. The sediment load reduction caused by the dams was instrumental in changing downstream channel form through and beyond the downtown area. The typical response to sediment removal by dams is channel incision below the structure. Dams commonly remove over 90 percent of the total load from flows, and trap all of the larger fragments (Knighton 1998). Thus, the river acquires sediment to regain balance between discharge and total load first by entraining from the bed. Finer materials like sands, silts, and gravels are picked up and removed first from the river's bed, and then from its banks. Although Williams and Wolman (1984) found that bank erosion downstream of dams is not a foregone conclusion, the river banks in Santa Fe were excavated due to their high level of erodibility. Despite the stabilizing effects of riparian vegetation and saturated subsurface flow from irrigated agriculture, the river's path took it through the unconsolidated sands and gravels of the Ancha formation, which are highly mobile. The removal of fines from between the cobbles and boulders subsequently reduced bed embeddedness. The river below the dam has reduced discharge frequency and volume: minimal stream power lowers available energy to entrain and carry sediment, and the small volume of water released by the dams is not powerful enough to mobilize the riverbed.

Over time, the removal of fines creates an armored condition of non-transportable particles. The river simply does not have enough energy to pick up and carry the remaining cobbles and boulders that line its bottom, and channel roughness increases compared to the pre-dam condition. With time, this effect translates downstream. Knighton (1998) described the narrowing of rivers due to the incision process, where wide, braided channels have a tendency to have reduced widths and paths that are somewhat more sinuous. This response appears beyond the downtown area in Santa Fe. The once predominantly braided channel now is deeply incised and confined within its banks. Width-to-depth ratios are calculations that summarize channel shape, and can change quite drastically due to the effects of dams. Low value ratios calculated from channel cross sections ranging from 8.2 (180 yards downstream from the Palace Avenue bridge) to 4.4 (between the Don Gaspar Avenue and Galisteo Street bridges) now replace the likely pre-dam ratios characteristic of braided channels of 40 and above. Flooding also exacerbates incision, as was the case in 1910, when a large August rainstorm generated a flow event large enough to mobilize the bed armor, and incision began anew: removing exposed finer particles until a second-generation armor formed. Between 1912 and 1930, the downtown roads were paved with concrete, and flooding in downtown

Santa Fe increased as a direct result of unsaturated overland flows generated by these newly impervious surfaces (Lang 2006: personal communication). The river became the city's main conduit for stormwater removal.

Researchers hypothesize that a period of frequent regional storm events and severe flooding, exacerbated by livestock grazing, induced downcutting and episodic arroyo development during this period (Turner *et al.* 2003; Cooke and Reeves 1976; Graf 1983). Concentrated flows cut narrow arroyos. The creation of which is followed by channel widening. Figure 6.X details the process of arroyo downcutting and subsequent riparian responses. It is possible that the episodic arroyo development occurred on the Santa Fe River and its tributaries. As mentioned above, 1910 was the year that dam managers allowed a large flood to bypass the upstream dams and scour the channel. This degradation coincides temporally with the period of episodic arroyo development (1880 to 1940); but on the Santa Fe River, the downcutting is more likely result of upstream dams, the consequent baselevel changes, increasing impervious surfaces, and channel adjustment to a changed hydrologic regime and sediment load. There is no evidence of channel widening on the main stream during this period (a characteristic of episodic arroyo development). Episodic arroyo development may explain some of the down cutting on the tributaries to the Santa Fe River, which have experienced it to some degree without the effects of upstream dams. Historical materials cannot identify the timing of this downcutting, however. Depths of tributary incision visible today (5+ meters) are only a fraction of those on the main channel (30+ meters).

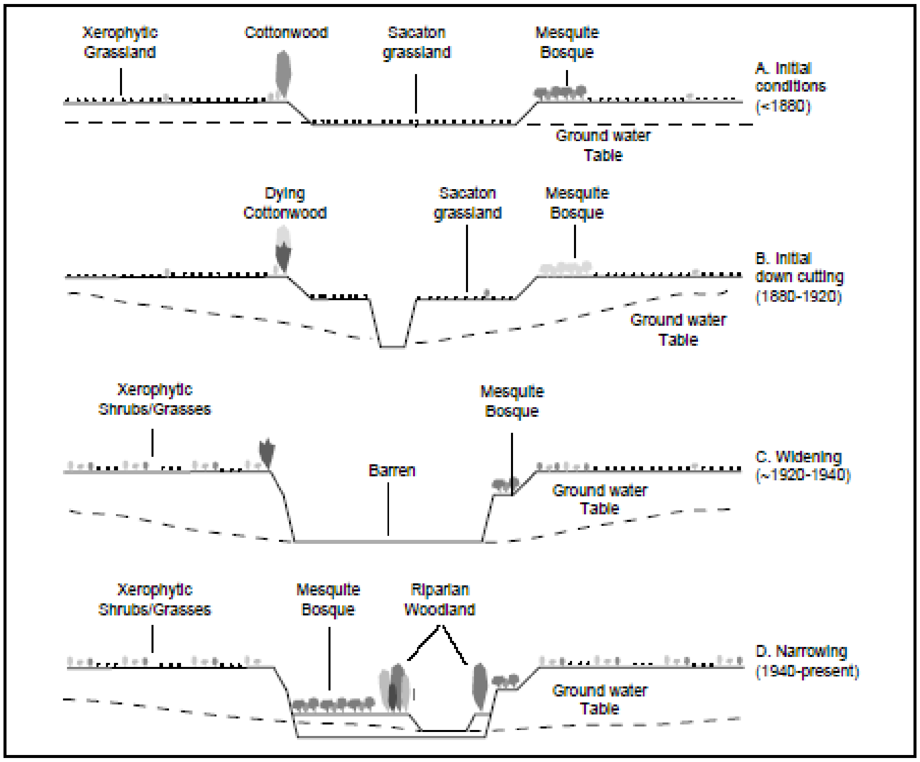


Figure 6.X. Arroyo downcutting with riparian responses
Source: Webb and Leake (2006)

When all dams were complete, the daisy chain of impoundments could store over a year's worth of river flow. Over a period of a few decades, the river planform in downtown Santa Fe changed from a transitioning system with a wide, compound – to – braided channel, with large volumes of sediment and seasonal floodwaters, to an incised and narrow single-thread stream without a sediment source or a reliable water supply. As incision worsened from the lack of upstream sediment delivery, the citizens of Santa Fe saw the changes in the river's banks and tried to stabilize them. President Franklin Roosevelt's second New Deal created the Work Projects Administration (WPA) to provide employment for people struggling during the Great Depression. In the late 1930s, the WPA began a Santa Fe River channelization project. Laborers employed for masonry work constructed low concrete bridges across the river (Chávez 1985). The workers also deepened the riverbed and laid more stable walls of concrete and stone to protect the banks from erosive lateral cutting. The masons also installed a few grade control structures; serving multiple purposes in addition to bed degradation control, like aesthetics, plunge pools for fishing, swimming, and ice-skating (Figure 6.Y). Wall construction contained the river flows, decreased the channel's width-to-depth ratio, forced a formerly compound system to run more swiftly through a straight chute, and focused the river's energy onto its bed. As a result, the increased velocity at the bed easily cut the formerly cohesive substrate of sands and gravels, once held together by a high water table and the roots of vegetation. Incision then worsened and flood conveyance increased. In meandering compound channels, several factors contribute to flow conveyance: "(1) sinuosity of the main channel; (2) relative roughness of the floodplain boundary compared with the main channel; (3) aspect ratio of the main channel; (4) meander belt width relative to total floodway width; (5) relative depth of flow on floodplain compared with main channel; (6) the main channel cross-sectional shape, including the side slope of the banks of the main channel; (7) flood plain topography, and in particular lateral slope of floodplains sloping toward the main channel" (Ervine *et al.* 1993: 1383). All of these factors changed to some degree because of channel engineering activities.

Aside from spring dam releases that occur when the reservoirs have reached their capacity, the dams held all seasonal flows, and there was very little water in the river for the acequias. If it was a dry year, *all* water was held behind the dams to ensure the public water supply was maintained, and so water was not "wasted down the Santa Fe river bed" (*The Santa Fe New Mexican* July 9, 1946). To exacerbate the problem of channel incision, irrigated agriculture was in decline because of increasing reservoir storage and the changing economy, as were the stabilizing effects subsurface flow provided for channel banks. The severe drought of 1946 left the water company and the city scrambling for water: geologists began a search for well sites in the unknown geology of Santa Fe, "prepared to drill as many holes as necessary… to get the water we need" (*The Santa Fe New Mexican* July 16, 1946). Desperation for water spurred the drilling despite the understanding that "short surface water also means short subsurface water" (*ibid.*). Wells sited along the river began to draw water down and away from the river, reversing flow direction for the first time and creating a losing stream. Decades later, the visible effect of withdrawing public water supply from these wells is drastic (refer back to Figure 4.B). Typical groundwater levels before pumping were 15.2 to 30.5 m (50 to 100 ft) below the surface; in 1998, no groundwater is closer than 45.7 m (150 ft).

Through the first half of the twentieth century, increasing expanses of impervious surfaces such as houses, paved roads, and parking lots with low permeability began to replace the fields once planted with hay, corn and wheat. As a result, unsaturated overland flows directed to the river exacerbated the narrowing and deepening. It was not until the 1950s that stormwater management became part of subdivision regulations (Lang 2006: personal communication). The WPA construction efforts, "while originally intended to minimize the likelihood of flooding, actually contributed to several floods during the 1950s and 60s. Debris carried by heavy runoff would get clogged where the river channel was constricted by bridge buttresses and inadequate culverts, thus contributing to the already high river overflowing its banks" (Santa Fe River Committee 1985: 15). In 1953, a 2.5-inch rain brought a "wall of water" down the chute, and the river "boomed out of its banks midway in the storm, but receded quickly," indicative of the decreased time of concentration and change in hydrograph shape (Chapter 5; *The New Mexican* 1953: p.1).

A flash flood on August 25, 1957, would become the catalyst for future channel management because it destroyed bridges, damaged roads, and did some considerable cutting within the river and its tributaries. For example, water mains once "four feet deep in the bed of the arroyo were exposed" (*The New Mexican* August 25, 1957: p.1 c.1). The damage induced by these overbank floods convinced city engineers that the channel needed to be as deep as possible to protect infrastructure: a deeper channel allowed floods to be contained within it. As land values in downtown Santa Fe increased, so did the desire to develop the parcels adjacent to the river (Lang 2006: personal communication), and as the riverbed continued to incise, so did the ability to develop safely to its edge. Meanwhile, the city asked the ACOE to evaluate the flooding problems and to make recommendations. The agency endorsed channelization of the river and Arroyo Mascaras (Santa Fe River Committee 1985). Although the city accepted and implemented the Arroyo Mascaras findings, they rejected the river portion in favor of restudy.

In addition to these issues, commercial aggregate mines began removing large volumes of sand and gravel from the riverbed in the lower reach, near Agua Fria. Aggregate removal initiates erosion by creating pits, which oversteepen the upstream gradient within the longitudinal profile, and initiate what is called a knickpoint. This base level change leads to slope adjustment in the upstream direction. As flows move downstream, headward erosion actively dissects material from the bed and banks and subsequently carries it downstream. Sand and gravel mining created several nicks in the continuous river slope. As a result, the process of entrenchment began in earnest (Section

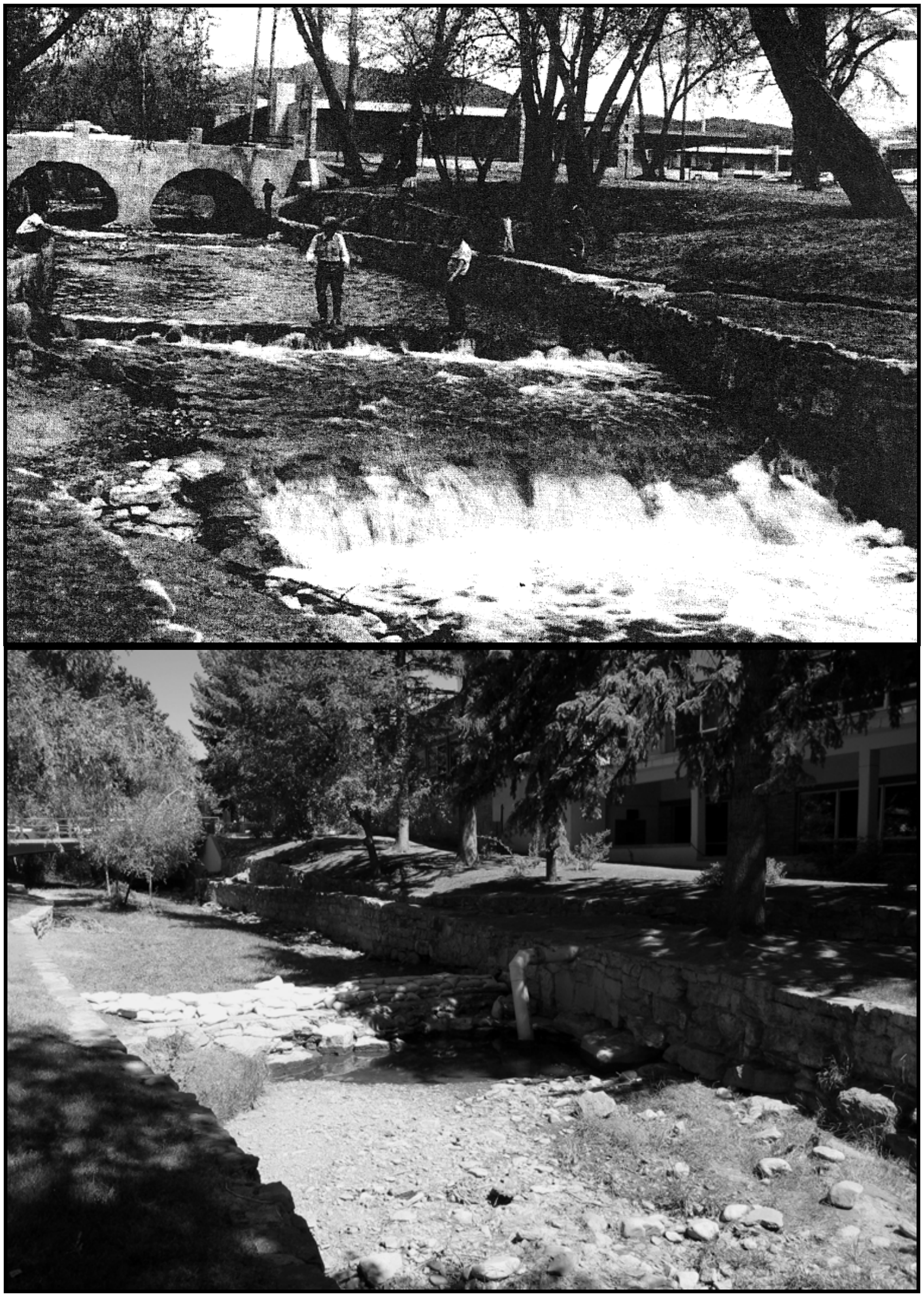


Figure 6.Y. Paired photography downstream of Old Santa Fe Trail Bridge
Circa 1960 and 2008
Source: top, Museum of New Mexico, negative # 120315; bottom, photo by author (2008)

6.3.1). This mining is one of the main factors leading to the extreme cross-sectional and planform changes evident in the river today upstream and downstream from Agua Fria.

The effect of the largest sand and gravel mine is so severe that the slope adjustment knickpoint is evident in the basin-wide longitudinal profile (Figure 6.A).

Prior to mining, the riverbed was near flush with the surrounding landscape and braiding was an active process within the wide, gravelly channel. As knickpoint migration began to spread upstream from the aggregate removal points, the river entrenched itself in several locations by over 9.1 m (30 ft). Further alterations from this process include lateral instability and bed coarsening (Kondolf 1994). Over a period of a few decades, the formerly braided channel narrowed to a single-thread, deeply entrenched arroyo (Figure 6.Z). Removing massive quantities of materials from the riverbed has adversely affected the streambed's equilibrium profile, channel planform, and has contributed to further degradation of the riparian corridor by lowering the water table (Chapter 7, Section 7.3.1). The river no longer interacts with its floodplain. Near the aggregate mines, groundwater has dropped between 3.0 m (10 ft) and 4.6 m (15 ft) (Vasquez 2001). In several locations, entrenchment reduced width-to-depth ratios to values around 1.0, and the channel resembles a vertically-oriented rectangular chute. This chute has no point bars or mid-channel bedforms to induce meandering: fluvial forms such as these would combat the negative feedback mechanisms at work in the entrenchment process by slowing erosive stormflows generated upstream in the urbanizing watershed, encouraging deposition and bed aggradation necessary for aggregate mining recovery, replenishing groundwater, and creating environments conducive for riparian habitat.

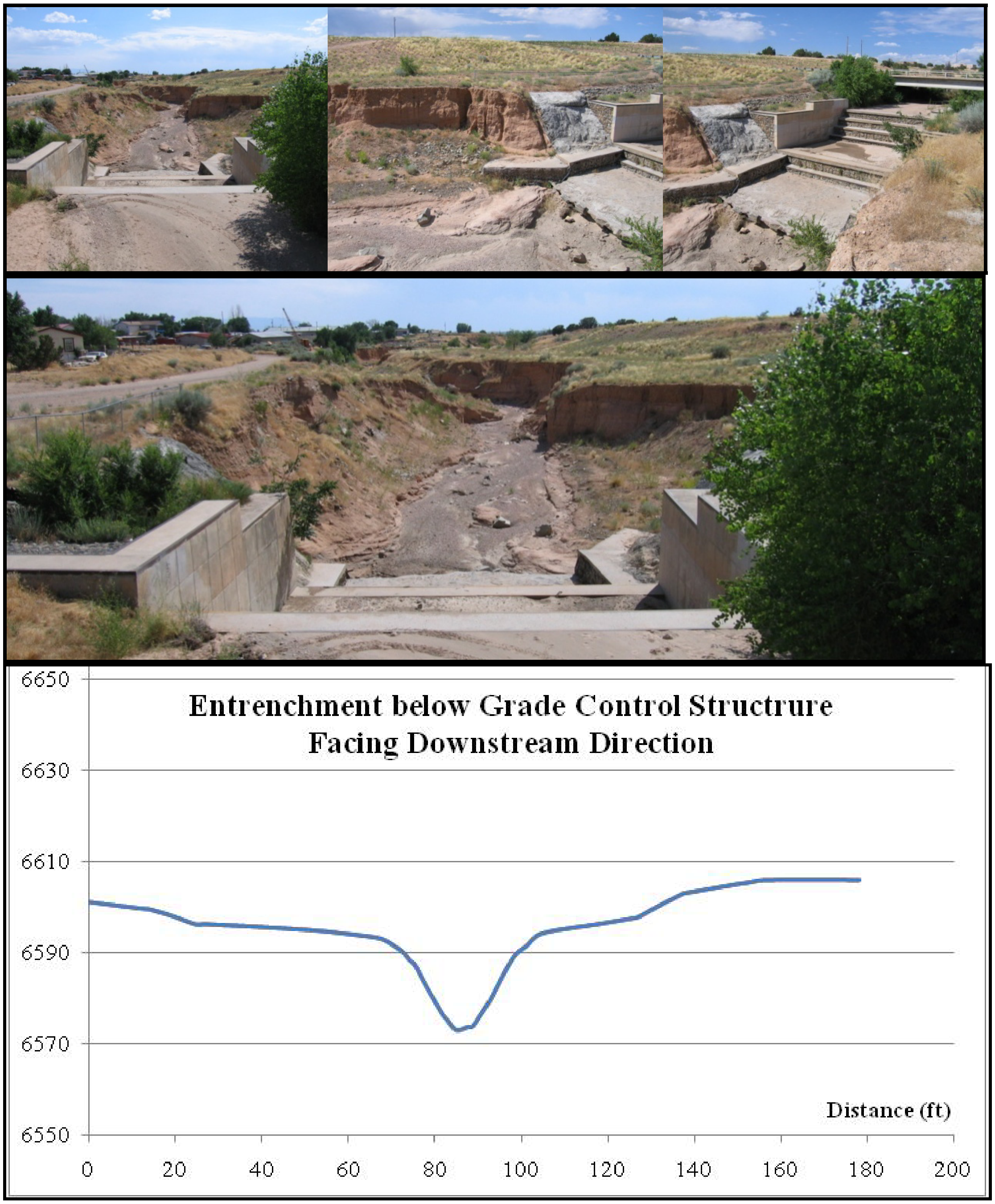


Figure 6.Z. Entrenchment graph shows degree of incision paired with photo above
Source: photos and graphs by author (2006)

If springtime flows reach the lower sections of the urban reach, they typically have low discharge volumes and velocities. Discharges such as these have reduced stream power able only to carry only the finest materials; thus, leaving behind the gravels and cobbles to create a channel armor impacting not just form, but the traditions of Santa

Feans. Before the presence of channel armor, residents of Agua Fria trained their horses in the finer sands of the channel (Romero 2006: personal communication). Today, the only things ridden in the channel are all-terrain vehicles. Field reconnaissance in the summers of 2005 and 2006 confirmed the disproportionate amount of larger sediments, lack of finer sands, reduced embeddedness, and the ATV tracks mentioned by Mr. Romero during the interview (Figure 6.AA).

Figure 6.AA. Gravels and cobbles dominate materials in incised channel bed
Photo facing downstream
Source: photo by author (2005)

Cross-sectional geometry was not the only form change to occur on the river. The planimetric adjustment in the urban reach between 1936 and the present is striking: changes in land use and land cover, sediment load, discharge, and progressive entrenchment caused the channel to adjust its planform quickly. In contrast to meandering channels, there are few relationships in braided environments that connect channel metrics and geometrical properties (mainly due to the short-term inconsistencies in the degrees of braiding) (Knighton 1998). Therefore, this research identifies changes in channel width in aerial photography over time to elucidate the widespread changes occurring within the urban reach channel form. After channel digitization from 1936, 1951, and 2008 aerial photography in a GIS, total width is measured in each year at 500-foot intervals from the St. Francis Drive Bridge downstream to the Caja de Oro Grant Road crossing in Agua Fria (a stream distance of 0.4 km (5.25 mi); Figure 6.BB). In 1936, the average channel width, from right to left bank (facing downstream) is 71.0 m (233 ft). In 1951, the average distance is 61.9 m (203 ft), a reduction of 13 percent. By 2008, the average distance is 15.2 m (50 ft). Between 1936 and 2008, the channel has decreased in average width by 79 percent, and the conditions needed to induce and sustain braiding (high stream power, slope and sediment load) are no longer present.

These results are not surprising, given that "[c]hannel narrowing after water management is most extensive along formerly wide, shallow, braided channels" (Friedman, Scott, and Auble 1997: 58). Other western dams have induced similar responses. Nearby, the Rio Grande below Cochiti Dam has narrowed 66 percent since dam closure (Richard 2001), while the channel directly below Elephant Butte Dam has narrowed and entrenched itself (Lagasse 1980), only to aggrade downstream near El Paso by 13 feet due to tributary sediment contributions (Reinhardt 1937). The Bill Williams River below Alamo Dam narrowed 71 percent between 1953 and 1987 (Shafroth *et al.* 2002b). Channels downstream from Jemez Canyon Dam near Albuquerque, John Martin Dam on the Arkansas River in Colorado, Fort Supply Dam on Wolf Creek and Canton Dam on the North Canadian River in Oklahoma, have reduced widths of 17 to 50 percent (Williams and Wolman 1984), while the Trinity Dam in California induced a 20 to 60 percent reduction in pre-dam width (Wilcock *et al.* 1996). Although channel width reduced significantly, the channel thalweg is relatively unchanged: braided channels are relatively straight, and because the Santa Fe River did not adjust its thalweg, the low-sinuosity, entrenched channel continues the negative cycle of incision, able to neither dissipate energy by meandering within its narrow confines, nor distribute floodwaters beyond its banks.

The New Mexican touted the "worst flood in 20 years" had hit Santa Fe on July 25, 1968. After this event, incision in downtown and beyond quickly got out of control. In 1974, the city intentionally removed the decades-old grade control structures installed by the WPA in the downtown area, to make room for additional flood storage. By 1976, scour action was progressing upstream, as was the "stated objective of the City Engineer" (Heggen 1997: 10). Between 1970 and 1990, the river has incised over 10 m (30 ft) near the Guadalupe Street crossing. Figure 6.CC provides visual scale of the incision with a 5-meter staff. The fence indicates street level (and the original riverbed's elevation); while a pipe shows the method of stormflow conveyance to the channel via curb inlets. The incision created an abundance of unforeseen problems: WPA walls were undercut, subsequently failed, and fell into the channel. City engineers began to respond hurriedly to the severe incision by installing rock gabions (wire mesh-covered retaining walls) against the newly exposed channel banks in an attempt to stabilize them. "At risk of oversimplifying a body of laws and procedures, the concept of 'emergency response' permeates the engineering" of the river, and a "lack of consensus regarding cause leads to local, short-term, and inefficient engineering" (Heggen 1997: 2, 27). Thus, as the river continued to erode into its bed due to increased flood conveyance and stream power, it undercut the gabions. The river also undercut wire baskets of rock installed below Camino Alire. After having to bear all of the weight of the rock contained within them,

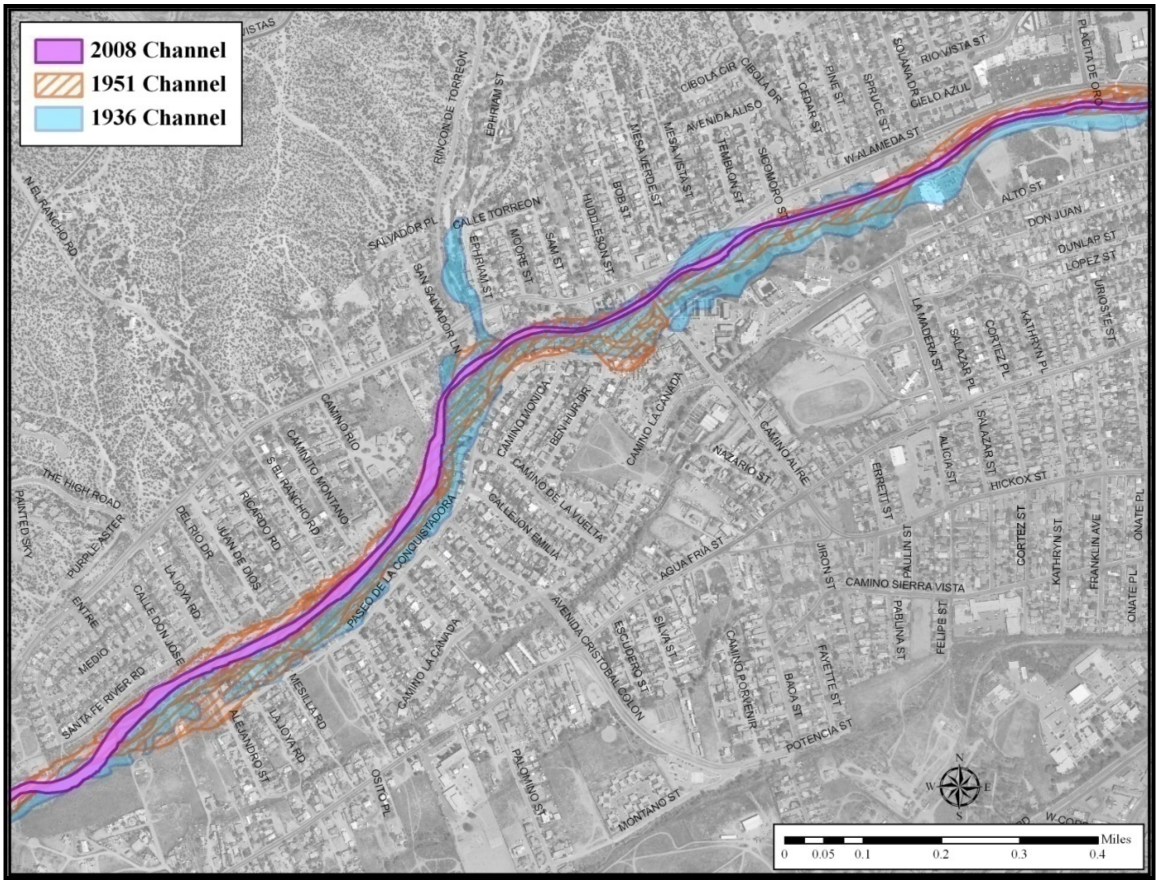


Figure 6.BB. Planimetric adjustment and channel narrowing
Digitized from 1936, 1951, and 2008 aerial photography
Source: map by author; imagery, ESRI ArcGIS Online (2009)

they later failed (Figure 6.DD). As a city engineer for sixteen years, Chuck Lang designed and constructed several of the emergency engineering responses to channel degradation (like the wire baskets). He said during an interview that encouraging river incision "destroyed it really, and the best we can do is dress it up a little" (Lang 2006: personal communication).

The city was still removing stabilizing structures "one rock at a time" and increasing channel capacity in May of 1983 (Heggen 1997: 10). Despite the success in increasing flood conveyance capacity through downtown, there is no longer a floodplain within the channelized river. Removing the grade control structures negated any positive floodplain effects, and therefore did not rectify flooding vulnerability in the city. Five months later, the Santa Fe City Council and the public quickly rejected the Army Corp of Engineers' River Channelization Design Proposal (Santa Fe River Committee 1985). If implemented, the plan would have called for a complete concreting of the channel in a style reflective of the Los Angeles River in California. Both the City Council and the public agreed that these measures would destroy what natural character was left in the river, and were simply too intensive and drastic. Within six months of the proposal's rejection, Mayor Louis Montano created the Santa Fe River Committee, which began to meet in December of 1984. Committee recommendations, printed in 1985, marked the beginning of the living river movement in Santa Fe. Chapter 8, the Living River, highlights a selection of river "restoration" initiatives from 1985 to the present.

Figure 6.CC. Severe channel incision with reference scale
Source: photo by author (2005)

Figure 6.DD. Gabion failure from undercutting
Photo facing downstream
Source: photo by author (2005)

6.3 LOWER REACH FORM

After a review of likely channel form prior to the influence of humans, Section 6.3 assesses the present channel geomorphology in the lower reach, which includes: (1) quantifying the volume of material excised by aggregate mining-induced erosion, (2) documenting planform adjustment after the installation of the WWTP, (3) evaluating current channel geomorphology and the effects of cattle access to the channel in the BLM grazing lands in La Bajada, and (4) describing channel engineering and planform change via historical aerial photography at the bifurcation associated with the construction of Cochiti Dam. Generalizations about lower reach channel planform and geometry prior to the widespread effects of humans are possible, and originate from process-form relationships developed from research in undisturbed locations with similar climatic and geologic conditions (Rosgen 1994). Both of these determining factors change in the downstream direction, although geology plays a more dominant role in determining channel form in the lower reach than it does in the urban reach.

Prior to human modification, the river continued uninterrupted from the urban reach. Water laterally migrated through the subchannels within this braided section as it flowed through the wide, sandy floodplain until reaching La Bajada canyon. Planimetric pattern and cross-sectional geometry adjusts at the canyon entrance, as local geologic controls induce process changes (Figure 6.EE). As faults ramp groundwater to the surface, sediment cohesion and riparian vegetation begin to stabilize the sands and gravels migrating downstream. Upon entering this gorge cut by the river over several thousand years, the river's ability to spread widely in a braided form lessens because of its confinement between steep walls of thick basaltic rock. The igneous intrusion limits downcutting, slope decreases, and the volume of malleable sediments are reduced as bed and bank material changes from highly erodible terrace alluvium, and sands and gravels of the Ancha and Tesuque units to more resistant Quaternary basalt flows. The conditions needed for braiding, including highly erodible banks and high bedload, no longer are present. At some locales the rivercourse is structurally controlled (Figure 6.FF). In La Bajada, the meandering pre- contact river creates bed and bank forms as it moves sediments downstream: clear geomorphic indicators of flow, including bankfull discharge and a low terrace, demarcate past and present flow conditions. As the river exits the gorge it no longer is confined and slowly widens, exhibiting characteristics of braided channel form. Erodible sediments become more available within the Rio Grande trough. After gradually increasing its slope over 11 river kilometers (7 river miles), the river joins the wide, braided Rio Grande after winding through a grassy plain.

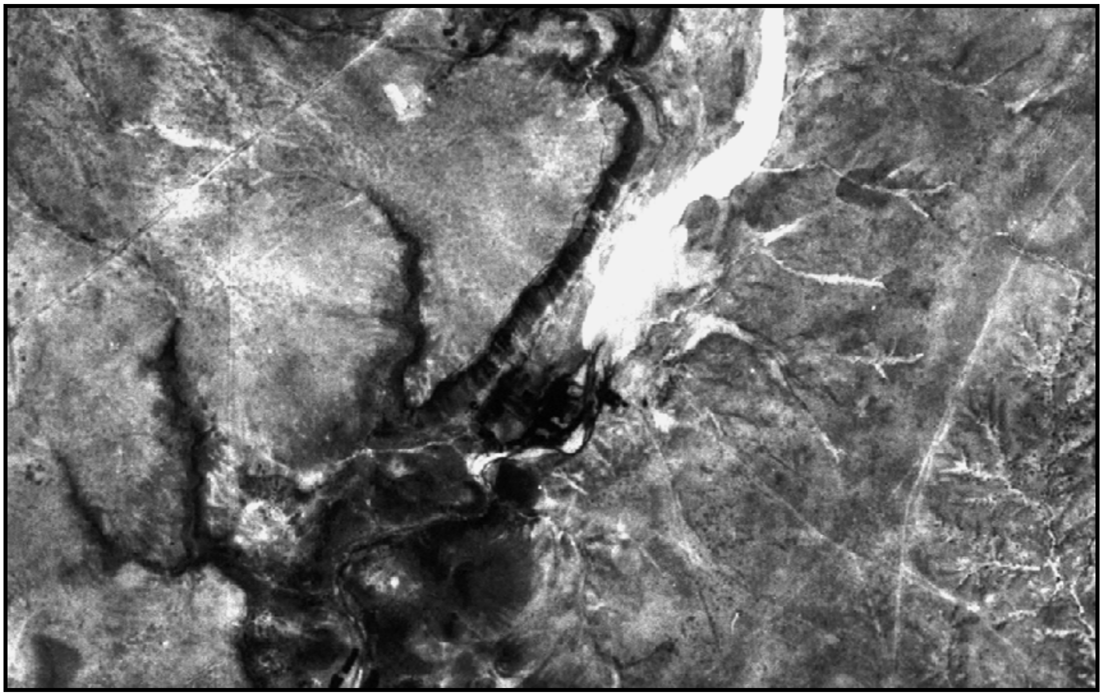


Figure 6.EE. Form adjustment from braided to meandering
River entering La Bajada canyon, 1936
Source: USDA Forest Service (2005)

Figure 6.FF. Point bar development at base of basaltic flows
Streamflow encounters structural controls, photo facing downstream
Source: photo by author (2005)

Since watershed settlement, humans have modified the lower reach to varying degrees by their direct and indirect activities. Upon settlement, the acequia agricultural practices in Cieneguilla and La Bajada led to channel modifications that divert water into fields and small storage impoundments. The acequia diversion in La Bajada, still actively used, serves as an excellent example to illustrate the minimal effect that these diversions have on channel form. A small backwater effect extends upstream from the *presa* for about 15.2 m (50 ft) as the earthen berm reduces flow velocity for redirection. Downstream of the diversion, there is slight narrowing of the channel; evaluating additional effects of the earthen diversion is not possible due to the disturbance by the four-wheeled vehicle crossing that uses this area (strategically placed to take advantage of decreased channel width and flow depth).

6.3.1 The Effects of Sand and Gravel Mines on Upstream and Downstream Form

A major factor in urban reach form adjustment is the severe channel incision between the downtown area and downstream, beyond Agua Fria. This research indicates that the process of extracting sand and gravel from the riverbed is the direct cause of much of this degradation (Figure 6.GG). Although the mines did not take all of the material, much of the process originates with their actions. GIS analysis estimates the amount of material excavated from the river through the process of headward erosion. A 3-D surface model TIN (triangulated irregular network) generated from LiDAR data is used to model cross-sections at 152.4 m (500-ft) intervals along the channel from the St. Francis Drive bridge downstream to the Caja de Oro Grant Road crossing in Agua Fria (a stream distance of 8.4 km (5.25 mi)). Measurements downstream from this point were not included because the city-provided LiDAR data continues only to its jurisdictional limits, and due to the terrain, traditional surveying methods were impossible without sophisticated devices (Figure 6.Z). Using the base of the lower terrace to estimate the original channel bank top elevations, these measurements indicate that on average, the channel has incised by 4.6 m (15 ft). After examining the longitudinal profile and conducting field reconnaissance, channel aggradation is evident at the WWTP, and continues downstream for several river miles (Section 6.3.2). This research assumes that sand and gravel mine activities gathered much of material removed via erosion, while the remaining fraction aggrades the riverbed.

The digitized 2008 channel polygon from the planimetric adjustment analysis estimates the volume of sand and gravel removed from the channel. Historically, sand and gravel miners that withdrew materials directly from the bed and banks benefitted greatly from the channel and watershed management decisions made upstream in the urban reach. The source of sediment must have seemed like an endless supply. As noted above, the city allowed the channel in downtown to dissect its bed and banks to make room for floodwaters: these sediments were deposited downstream. As mining exacerbated headward erosion, sediments dissected from channel bed and banks both below and above Agua Fria too were deposited downstream. These two processes working in concert delivered at least 1,900,000 cubic yards of sediment to downstream areas, and a great deal went into the backhoes and dump trucks of the sand and gravel companies. Although sand and gravel mines have not gathered *all* materials (given the aggradation downstream), this volume is the equivalent to over 116,500 dump trucks worth of aggregate (assuming each truck carries 16 cubic yards; Figure 6.GG). Chapter 7 and Chapter 8 describe sand and gravel mine disruptions of Santa Fe River function, and the county restoration efforts, respectively.

6.3.2 Wastewater Treatment Plant-Induced Form Changes

Immediately downstream of the sand and gravel mines is the city's wastewater treatment plant. Discharges from the plant induce significant form adjustments that diverge from earlier channel cross-sectional geometry and planform of the area. Prior to treatment plant installation, this section of the lower reach was a wide, braided channel with high sediment supply and little riparian vegetation. Now, the channel is a narrow, meandering stream with dense streamside vegetation (Figure 6.II).

Figure 6.GG. Aerial photography of sand and gravel mine activities, 2001
Source: City of Santa Fe (2005b)

Figure 6.HH. Sand and gravel mining activities affect channel form
Source: photo by author (2005)

Figure 6.II. Panorama of wastewater treatment plant confluence
(left) upstream of plant, (center) dry channel and effluent confluence, (right) effluent-filled channel
Source: photos by author (2005)

The braided channel was relatively straight and wide, and based on bank to bank incremental measurements every 152.4 m (500 ft) for 4.0 river kilometers (2.5 river miles) downstream from the Paseo Real crossing, the 1936 aerial photography shows an average width of 99.7 m (327 feet). By 2001, this same streamcourse has an average channel width of 4.9 m (16 ft), which is a 95 percent reduction. Cross-sectional geometry is much different. The change in planform results in a reduced width-to-depth ratio. Although historical measurements of channel depth are unavailable, it is likely that ratios around 40 were typical of this braided reach. Since the channel has become a meandering, single thread reach, the width-to-depth is reduced to 6.4. Sinuosity, a measure of the degree of meandering, is calculated by dividing channel length by straight-line valley length (Knighton 1998). Sinuosity is an important indicator of river stability because it is dependent on shear stress, flow velocity, stream power, and sediment transport capacity (Graf 2000). Sinuosity is a measure that provides geomorphologists with estimates of river planform, sediment load, and channel configuration. Hydrologic regime change affects these variables, compromises river stability, and causes adjustment. In 1936, the braided reach under investigation had a sinuosity of 1.02, which is a ratio very typical of this channel type. According to Rosgen (1994), braided channels commonly have a sinuosity of less than 1.1. In 2008, sinuosity for the same reach is 1.26, an increase of 81 percent, and is a value in alignment with typical meandering streams (typified by Rosgen (1994) as greater than 1.2). Material migrating downstream from the mining action has caused aggradation of the channel bed, evidenced in field reconnaissance and the longitudinal profile, thus reducing the slope necessary to support braiding (Figure 6.JJ and Figure 6.A). To combat the aggradation, Santa Fe County has had to construct earthen berms to confine floodwaters within the channel to protect roads and several homes (Johnson 2004).

Braided rivers typically require highly variable discharges: the WWTP discharges a constant 0.255 cms (9 cfs) to the channel, and the mono-flow regime causes little disturbance, except during heavy rainfall events. As a result, the channel position has little lateral movement. The channel thalweg, digitized from 2001 and 2008 aerial photography, illustrates the minimal channel migration. This geomorphic response is unexpected in an environment where unconsolidated sand and gravel dominate the constituents of bed and bank material; here, channel behavior should include dynamic shifting (Figure 6.KK). Two factors may explain this behavior, however: (1) there are few larger flow events to create diversity in bedforms and induce meandering, and (2) most of the streamside vegetation planted by the non-profit group Forest Guardians has had a 95 percent survival rate (Johnson 2004; Chapter 8, Section 8.1.3).

Figure 6.JJ. Channel aggradation and fine sands downstream of WWTP
Source: photo by author (2005)

Fluvial geomorphic science accepts that bankfull discharge, the dominant discharge typical of a two-year flow, is the prominent factor in creating channel change. Bankfull discharge *may* occur in this section of the lower reach (although there are no gage data to substantiate its presence and geomorphic indicators are disturbed by restoration activities and the treatment plant mono-flow); however, the extreme densities of planted riparian vegetation render this flow ineffective in creating significant channel change. Therefore, this reach needs to experience larger events to induce bed and bank forms and lateral movement (last known to occur in 1996 and 1997) (Johnson 2004). Between 1996 and 2004, hundreds of bundles (equating to thousands of stems) of Fremont Cottonwood (*Populus fremontii*), New Mexico Olive (*Forestiera neomexicana*), Boxelder (*Acer negundo*), Coyote Willow (*Salix exigua*), and other species were planted

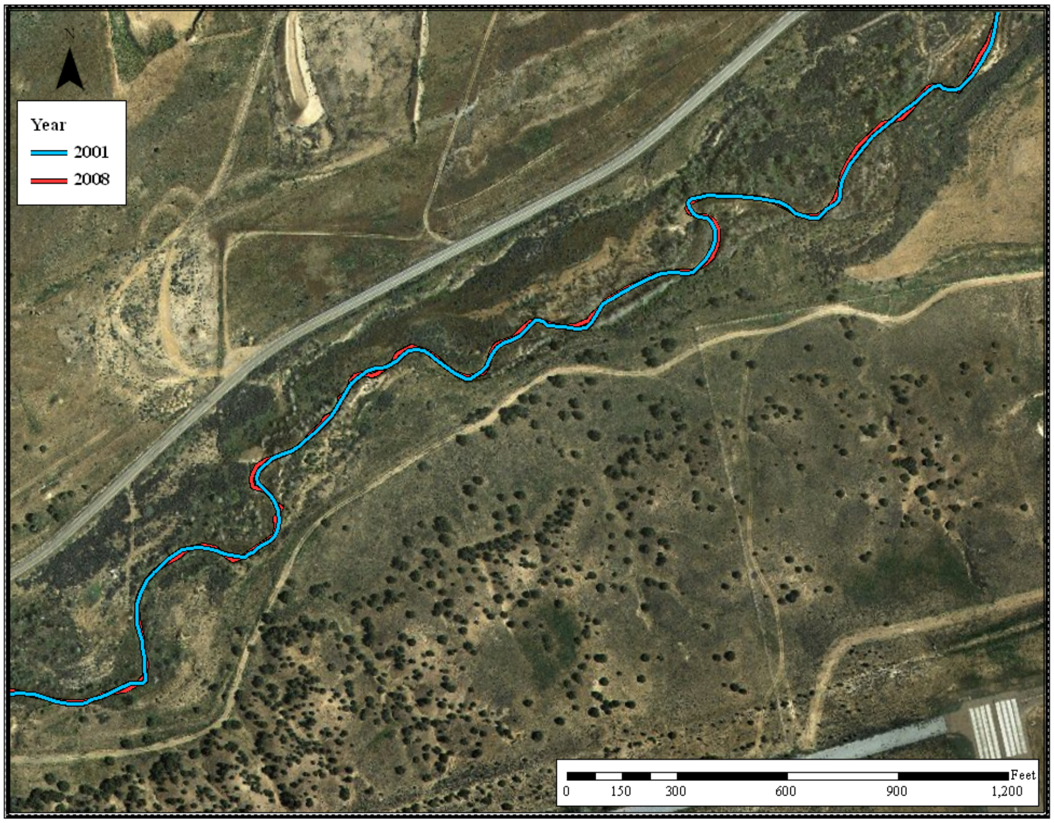


Figure 6.KK. Seven years of channel migration illustrates little movement
Source: map by author; imagery, ArcGIS ESRI Online (2009)

in this reach close to the river and in the floodplain. This native, although unnaturally dense, riparian vegetation thrives in the nutrient rich effluent downstream of the treatment plant. Forest Guardians restoration managers were unaware at the time that their seedling and sapling survival rate would be so high, and planted densely to account for dieback and flood wasting (Matison 2005: personal communication). Some dieback did occur in 2001 when, during a drought, the city contracted wastewater effluent to other users; however, riparian vegetation was not present in such densities in historical aerial photography in 1936 or 1951.

Braided rivers also typically have a high bedload. Although the unconsolidated channel materials are present, flow velocities of treatment plant effluent are not great enough to transport the abundant gravels and cobbles necessary to support a braided planform. Treatment plant flows have the transport capacity to move sand, the primary fraction in the aggraded reach, to downstream environments (Figure 6.JJ). The thick algal mat on the channel bed also deters entrainment of sediment, as the nutrient-rich waters have created an environment conducive to growing algal beds (Figure 6.LL).

Figure 6.LL. Dense algae deter sediment entrainment
Source: photo by author (2006)

6.3.3 Geomorphic-Biologic Connections in La Bajada

In the summer of 2005, research efforts paired with Natural Heritage New Mexico (NHNM), a division of the Museum of Southwestern Biology at the University of New Mexico, to survey the channel in La Bajada and create connections between their biological assessments and fluvial geomorphology (Figure 6.MM). NHNM biologists are interested in assessing the recovery of streamside vegetation after the exclusion of grazing, while this research is interested in assessing the geomorphic conditions of the lower reach. In exchange for two days of surveying assistance, NHNM received the cross-section data, geomorphic inventory forms, and interpretations.

The scientific community accepts livestock grazing as one of the most pervasive and degrading land use activities to influence riparian environments in the southwestern U.S. (Belsky *et al.* 1999; Fleischner 1994; Ohmart 1996). Livestock frequent riparian areas for water, shade, and forage. In doing so, they degrade water quality, destabilize channel banks, cause landscape-level erosion and stream morphology disturbance, and damage riparian soils (Belksy *et al.* 1999). Belksy *et al.* (1999) also found that cattle reduce biodiversity and species composition, and damage riparian vegetation, aquatic biota, and other wildlife. To determine if this conclusion is relevant for the Santa Fe River, NHNM established baseline conditions in 2003 by surveying vegetation composition and abundance along seven transects spanning the floodplain for 3.2 river kilometers (2.0 river miles) within an active BLM grazing allotment. Cattle had been frequenting the riparian area for forage, as dry conditions limited vegetation elsewhere. In 2004 and 2005, ranchers made concerted efforts to restrict cattle from the channel. Milford *et al.* (2007) correlated the data provided on geomorphic indicators with vegetation transitions along each transect and assessed the riparian response to the removal of grazing pressure. In most transects the transition from mesic herbaceous wetland (Creeping Bentgrass-Knotgrass Mesic Herbaceous (*Agrostis stolonifera-Paspalum distichum*) to upper herbaceous wetland (Tall Fescue-Alkali Muhly Upper Herbaceous (*Festuca arundinaceae-Muhlenbergia asperifolia*)) occurred at the point of bankfull discharge. By 2008, results showed evidence of habitat recovery, including taller and denser herbaceous vegetation, and statistically significant increases in aquatic macroinvertebrate species richness (Milford, Muldavin, and Beck 2009). Indicators of channel stabilization and morphology improvements also indicated that riparian ecosystem structure and function follow the exclusion of grazing. Visit Natural Heritage New Mexico via the World Wide Web for additional information about their continued monitoring efforts on the Santa Fe River.

Seven channel cross-sections in this reach are used to calculate key geomorphic metrics, which average the following: width-to-depth ratio 26.3, floodprone width 9.3 m (30.5 ft), floodprone cross-sectional area 19.9 m^2 (214.4 ft^2), bankfull width 4.7 m (15.4 ft), bankfull cross-sectional area 0.84 m^2 (9.04 ft^2), entrenchment 1.8, bankfull depth at the thalweg 0.32 m (1.05 ft), channel gradient 0.006 percent, and sinuosity 1.22. Using these average geomorphic metrics, the Rosgen (1994) stream classification characterizes this section of the lower reach as a meandering B4. The dominant bed material is large gravel, with large basalt boulders strewn throughout the channel and floodplain. The channel and floodplain interact during high flows, and the transition between the mesic floodplain and upland terrace is abrupt. Vegetation debris caught against boulders and trees is evidence of overbank flows. Terraces on both sides of the channel indicate a floodplain level of the past. The river meanders through a 27 meter-wide (90 foot-wide) floodplain, alternating between runs, glides, small riffles, and a few pools. In a few locations, the underling basalt redirects flow laterally, which undercuts the banks. Some areas where grazing is active also suffer from bank instability. Grazing also contributes to water quality issues: disturbance increases sediment and adds nutrients to the water, which is evident in the algae on the channel bed. “Organic input from old dung and urine still present in the floodplain may take years to be absorbed and flushed from the system” (Milford *et al.* 2009: 7). Large woody debris is rare, and streamside shade covers less than 10 percent of the entire reach. Compared to upstream environments, this reach is geomorphically viable and functional.

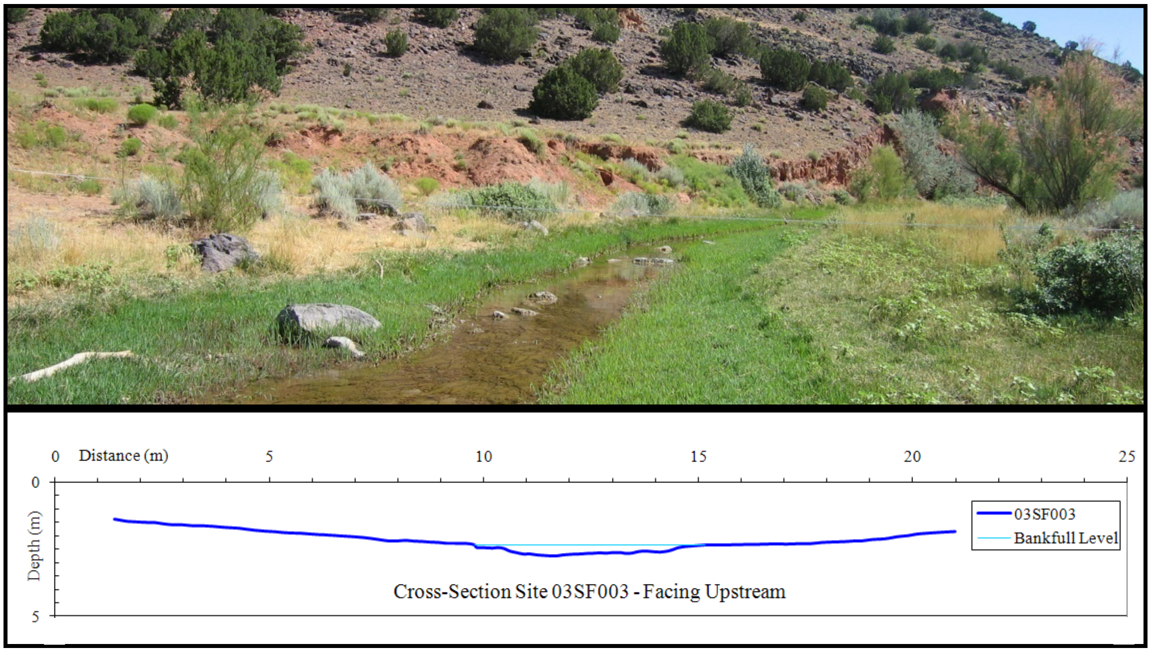


Figure 6.MM. Photograph and cross-section with bankfull level indicators
Site 03SF003, photo and cross-section facing upstream
Source: photo and graph by author (2005)

6.3.4 Channel Bifurcation to Cochiti Reservoir and Rio Grande Confluence

Prior to 1965, the river would exit La Bajada canyon and flow freely to its confluence with the Rio Grande. In 1936 historical aerial photography, the river appears braided in two distinct sections, divided by a basalt flow that initiates a short reach of meandering within the geologic confinement (Figure 6.NN, top). The river then joins the braided Rio Grande amidst Cochiti Pueblo farm fields and acequias. As with many dam construction projects, engineers take advantage of geologic features that confine rivers, and strategically place infrastructure at structurally secure locations. The Cochiti Dam diversion modifies the original rivercourse by diverting flows into the reservoir through a constructed channel that begins at the base of a massive earthen berm positioned at the geologic constriction (Figure 6.NN, bottom). The berm also creates an intermittent pool

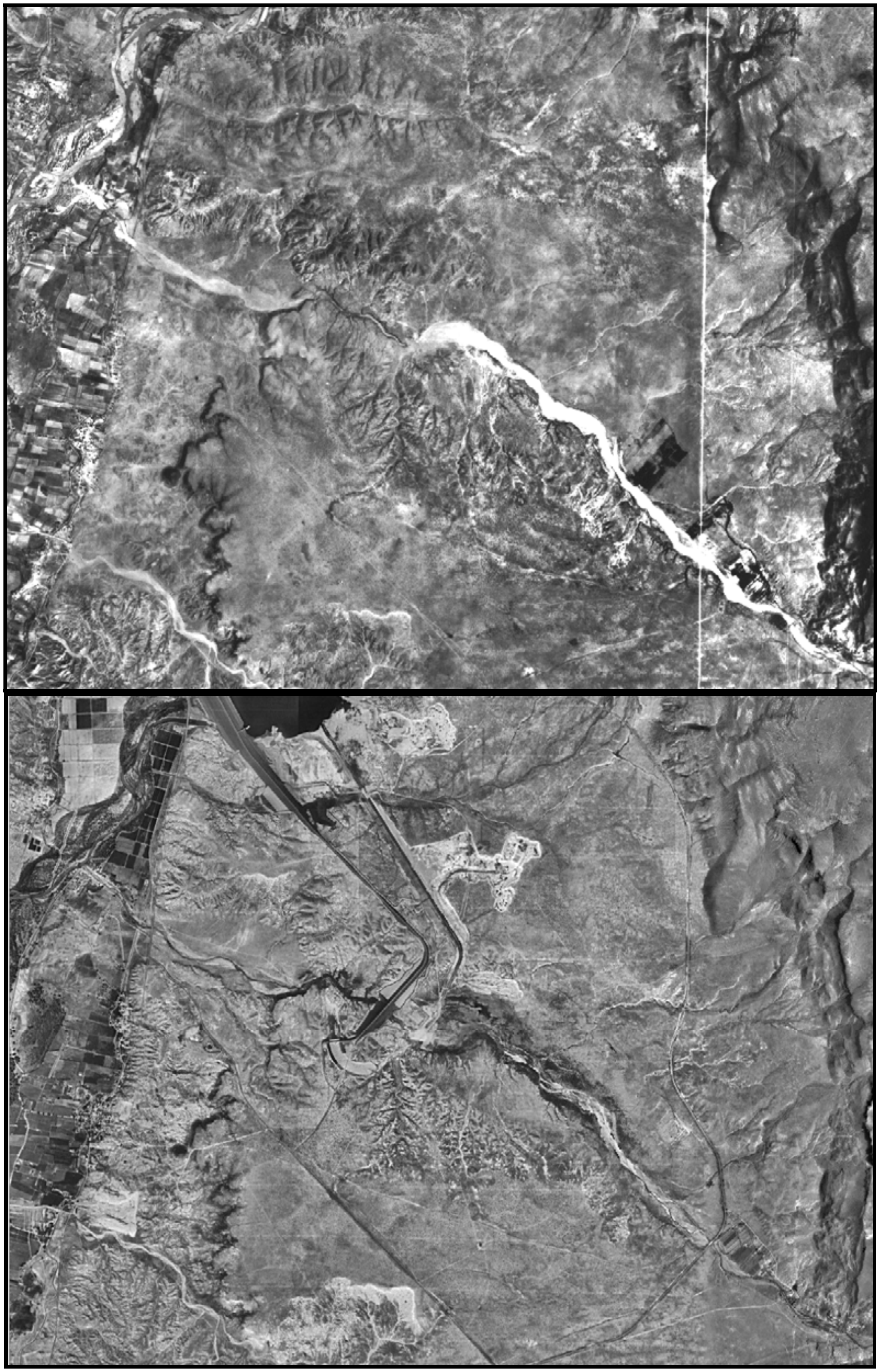


Figure 6.NN. Paired aerial imagery, pre- and post- Cochiti Dam diversion
(top) 1936, (bottom) 2008
Source: USDA Forest Service (2005); ESRI ArcGIS Online (2009)

at its base and captures the sediment load of the river before waters reach the diversion channel, thus protecting reservoir water quality. Here, lush wetlands stabilize sediment in an area that historically was void of most vegetation. The majority of river flows are volumetrically small, however, and pond above the diversion, percolating to groundwater instead of flowing into the reservoir. As a result, water seeps beneath the diversion and flows in the river through its original channel. Downstream of the diversion, reductions in bedload, and discharge variability result in a planform adjustment from braided to single thread. Pockets of riparian vegetation and invasive species (Tamarisk (*Tamarix ramosissima*) and Russian-olive (*Elaeagnus angustifolia* L.)) flank the entrenched reach until it joins the Rio Grande, where it no longer supplies water to acequias.

6.4 CHAPTER CONCLUSIONS

This chapter deconstructs the process-form relationships responsible for Santa Fe River fluvial geomorphology from Santa Fe Lake to the Rio Grande confluence. Prior to the arrival of humans, local climate and geology set the stage for at-a-station cross-sectional geometry and planform configuration, which adjust longitudinally with changes in slope, sediment load and vegetation. When Spanish colonists arrived in the watershed, their river form and landscape modifications were too minimal to substantially alter planform or cross-sectional geometry. The effects of humans in modern times, however, are significant and pervasive. This chapter elucidates the transformative nature of upstream dam installation, downstream aggregate mining, groundwater pumping, land cover conversion, and channel engineering decisions to fluvial geomorphology, while emphasizing that a combination of these factors, *not just the dams*, contributed to the present, degraded channel condition. Over the last century, process-form relationship modification occurred to such a degree that the current physical landscape can no longer support the historical channel configuration. Through quantitative measurements of channel planform and geometry and the presentation of historical materials, the narration of form evolution elucidates the complex nature of basin modification within the context of governmental and technological change.

Now, the modern channel in the urban and lower reaches is significantly different from its predisturbed state. As a result, river managers looking to restore it often have been unsuccessful because they lack guidance as to the channel form most appropriate for modern conditions. Their efforts follow neither historical relationships nor present conditions; instead, their guide is a perception of an idealistic form that is out of place for the modern landscape processes at work (Chapter 8, Section 8.1.2.5). This research enlightens local residents, managers, and scientists as to the present process-form relationships within the basin, and sets the stage for more informed decision-making when returning stability and functionality to Santa Fe fluvial geomorphology.

SANTA FE RIVER FUNCTION

7.0 CHAPTER OVERVIEW

The Santa Fe River has many functions: domestic and irrigated agricultural water source, recreational opportunity, surface manipulator, revenue producer via water, important regenerator of groundwater, supporter of wildlife habitat, and corridor for waste disposal. From the upper watershed, through downtown Santa Fe, past the wastewater treatment plant, to its junction with Cienega Creek and beyond, the Santa Fe River's role changes with its downstream geography. River function also has changed temporally with human advances in technology, governmental jurisdictions, and land uses. The purpose of this chapter is to highlight the functions of the river as foundational to Santa Fe history. This chapter explores river history from a resource perspective, chronicles the decline of Santa Fe's acequia communities, and creates new knowledge by reconstructing the acequia network and cienega complex in downtown.

Section 7.1 details the functions of the river in the upper reach. As it flows through the water-generating region of the Santa Fe watershed, the primary function of the upper reach, from a human perspective, is to deliver water to downstream users. This reach has many other roles however, and its treatment here includes: (7.1.1) summarizing upper reach historical use, thus creating a context for the discussion of its management, (7.1.2) establishing connections between upper reach function and upper watershed management (or non-management) prior to dam installation, and (7.1.3) discussing the changes affecting upper river reach functions between the mid-1800s and the mid-1900s.

The discussion of the urban reach (Section 7.2) is divided further into three subsections that highlight some of the significant contributions of this research, including: (7.2.1) the examination of Santa Fe River's history from the perspective of acequia communities (including the effects of dams and water infrastructure installation), (7.2.2) the digital reconstruction of the Santa Fe acequia network via GIS and remote sensing modeling techniques, and (7.2.3) the presentation of definitive evidence for a saturated Santa Fe, as detailed in hypotheses for the formation of the cienega complex and the Rio Chiquito. The functions of the lower reach have changed most noticeably in modern times, as human activities within the watershed have moved from an agrarian society to one based on civil service and tourism. Section 7.3 discusses the changing functions of the lower reach, which specifically include: (7.3.1) the mining of sand and gravel from the riverbed, (7.3.2) the river as a corridor for waste disposal, and (7.3.3) the effects of uranium mining in La Bajada.

7.1 UPPER REACH FUNCTION

7.1.1 Upper Reach Historical Use Summary

The upper reach flows through the water-generating region of the watershed, and has several important environmental functions. Albeit narrow due to geologic conditions, prior to intensive human use of the upper watershed, the river supported riparian vegetation along its banks. Dense streamside vegetation stabilized the channel banks, shaded the channel, and supported cold-water fish. This riparian environment filtered sediment from overland flows and maintained pristine water quality. The river supported beaver colonies and their dams, which subsequently created upstream wetlands, natural sediment filters, and flood control. These natural impoundments increased corridor biodiversity by creating additional habitats for fish, amphibians, and birds, and helped to recharge both shallow and deep groundwater reserves in the crystalline Precambrian rocks that underlie this area (Grant 2002). Large woody debris generated by flood flows and beaver action created natural pools, which acted as localized grade control structures, provided for sediment storage, and supplied additional cover for native fish.

From the vantage point of a watershed resident, the primary function of the upper reach always has been to deliver the water deposited as snow during the winter months to downstream users for irrigation and domestic needs. Prior to damming and upper watershed closure, this reach also offered recreational opportunities including fishing and swimming, and supported picnicking, camping, and wildlife viewing (Santa Fe National Forest 2001). The river provided the necessary water to support livestock grazing within the upper watershed. It was the domestic water source for homesteaders (and a bordello), powered sawmills, gristmills, and carding machines, and allowed opportunists to pan for gold and trap beaver (Lewis 1996; Santa Fe National Forest 2001). The first documentation concerning upper watershed use occurs in 1744 with the establishment of the Santiago Ramirez Grant, though its many resources likely were utilized since occupation (Martine 1998). When reporting on the villa in 1776, Fray Francisco Atanasio Domínguez called attention to the important natural resources of the upper watershed, specifically how "the sierra that lies to the east of this villa abounds in firewood and timber needed by the population. …There is trout fishing above in the canyon" (Adams and Chávez 1956: 40).

7.1.2 Upper Reach Function and Upper Watershed Management (or Non-management)

For the first few centuries of habitation in Santa Fe, it is likely that the resources of the upper watershed seemed limitless to downstream residents. The "abounds of firewood and timber" described by Fray Francisco Atanasio Domínguez were more than the tiny community could deplete. Population pressures on the watershed increased slowly for the first centuries of habitation. There were fish in the creek and timber on the hillsides. When the Santa Fe Trail connected Missouri and Santa Fe in 1821, contact between the U.S. and the west increased, and the population began to grow. Timber logging occurred more aggressively to meet fuel wood and construction needs (Figure 7.A). Due to the popularity of felt top hats manufactured from beaver pelts, these animals were trapped in the watershed in great numbers and exported eastward. Recreation in the upper watershed increased, and manmade fires exacerbated ground cover removal. Before 1846, the number of people accessing the watershed remained below a few thousand, yet the number of sheep and goats was astronomical. Baxter (1987) estimated that there were tens of thousands of sheep grazing the watershed in the 1830s alone. Despite the importance of grazing to the traditions of New Mexicans, this activity was detrimental to the landscape (deBuys 1985). Animals denuded the understory, trampled the riparian corridor, removed soil-stabilizing vegetation, and waded through the upper reach while accessing the water, consequently contaminating it.

By the late 1800s, the health of the watershed had reached a critical point, and these activities severely affected the subsequent health of the upper reach. The surrounding landscape conditions threatened its main function of water production and delivery. Most of the trees had been removed from the lowest slopes for fuel wood, and

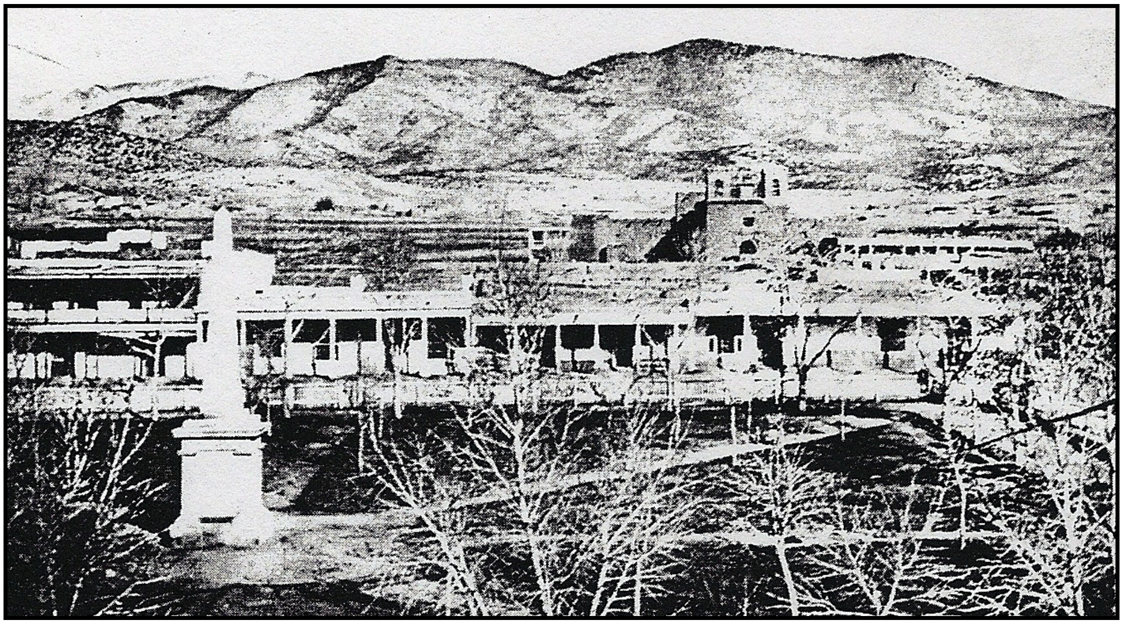


Figure 7.A. View of the denuded Sangre de Cristo Mountains from the Plaza, 1868
Source: Museum of New Mexico, negative #011252

the extensive grazing had removed all understory vegetation (Figure 7.B). The sheep and goats removed the stabilizing effect of grasses and other plant roots, thus there was no protection for the instable slopes from thunderstorm action and erosive overland flows. Sediment flowed freely from the hillsides into the river, creating deep rills (Figure 7.B) and degrading water quality. Decades of heavy trapping of beaver colonies left few lodges and wetlands to filter out the sediment and control flood flows. Heavy grazing had removed the riparian vegetation as well, and the filtering effect of this protective corridor was gone. As a result, flashier seasonal flows carried higher sediment loads, and their erosive forces were increasingly damaging to acequias and downstream infrastructure. *The Daily New Mexican* recorded such an event on July 20, 1874, when the Santa Fe River, “with its rolling, bounding, breaking, dashing waters carrying in its wild rampage the debris of the mountain, fences, boards and logs, and occasionally a stalk of green corn or wheat appearing for a moment above the surface of its turbid waters.”

Figure 7.B. Paired photography of the Santa Fe River in 1916 and 2000
Surrounding hillsides denuded of vegetation, trees, and gullied slopes compared to modern-day tree-covered hillside.
Source: (left) Blanchard (1916), USFS Santa Fe NF, photo # 33559A; (right) S. Tharnstrom (2001)

7.1.3 Changes Affecting Upper River Reach Functions: mid-1800s to mid-1900s

By 1880, the population in Santa Fe reached 6,600 (Goldman 2003). In this same year, the first dam construction occurred on the river. The negative downstream effects of subsequent dam installations on flow (Chapter 5), form (Chapter 6), and function (Section 7.2.1) of the urban and lower reaches are substantial. Yet, these dam installations set into motion a series of events that would change land management in the upper watershed and yield many positive responses in the upper reach.

It was the massive flood in late September 1904 that brought the greatest attention to the condition of the upper reach. Because of the denuded landscape, this flood brought a wall of mud and debris raging down the canyon at high speed, and upon encountering Old Stone reservoir, immediately filled the impoundment with sediment. Just downstream, Two-Mile reservoir stopped the remaining floodwaters. The dams performed well as flood-control structures, but Old Stone was irreparably filled; thus, 25 acre-feet of water storage was lost. Also of considerable concern was water quality: the diversion of potable water occurred from the top of Two-Mile reservoir, and with the addition of turbulent floodwaters, the reservoir needed time to settle (Lewis 1996). This turbidity was a potentially reoccurring problem in the water system's design, so managers looked to target the source of the sediment. In a 1926 cooperative agreement between the USDA and the New Mexico Power Company, sheep and cattle grazing, and the logging and gathering of forest products were limited to designated areas (Santa Fe National Forest 2001). Within one year, sheep and goats were expelled from the city's jurisdictional lands within the canyon. 1929 brought additional restrictions to bathing, camping, picnicking, and fishing in the river, reservoirs, and watershed. By November 1932, the Secretary of Agriculture closed the watershed to all public entry (Figure 7.C; Lewis 1996; Santa Fe National Forest 2001; Goldman 2003).

The closure order marked a significant change in the management of the upper watershed, and the effects on upper reach functions were almost immediate. The upper watershed, which no longer was a community-owned resource, went from a landscape of overuse to complete non-use. Resurgence in vegetative cover in the decades following closure was encouraged by a shift in climate pattern that favored shorter, more intense rains (Leopold 1951). Beaver (*Castor canadensis*) populations rebounded and their lodges once again captured the sediment migrating downstream (Figure 7.D). Water quality improved after the recovery of the riparian corridor and increases in soil stability. Less sediment now enters downstream reservoirs.

The single upper reach function that was affected negatively by upper watershed closure, from a human's perspective, is water quantity. Discussed in Chapter 5, multiple factors led to a reduction in total flow delivered to downstream reservoirs. The benefits of increased soil stability are likely to outweigh the increased consumption by vegetation due to the invaluable benefit of decreased sedimentation to the downstream

UNITED STATES
FOREST SERVICE

NATIONAL
AUDUBON
SOCIETY

CLOSED
TO THE PUBLIC

NO PARKING

The Santa Fe Watershed was closed to unauthorized access in 1932.

The Purpose of Strict Enforcement of this Closure follows:

Fire Hazard – The Watershed is extremely vulnerable to Wild Fires caused by careless behavior of Trespassers. This is especially true during dry conditions.

Drinking Water Protection – Visitation creates the introduction of contamination borne by Pets and People.

Heavy Traffic creates additional erosion which adds to treatment costs and sedimentation of the Reservoirs.

VIOLATORS WILL BE PROSECUTED.

Violation is punishable by a fine of not more than $5,000 or imprisonment for not more than 6 months, or both Title 16 USC, Section 551.
Violators may be prosecuted under 36 CFR 261.53(e) and/or State Criminal Trespass Law under Article 14-[illegible]-14-1.

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CITY
OF SANTA FE

Figure 7.C. Santa Fe watershed is closed to all public entry in 1932
Source: photo by author (2006)

Figure 7.D. Beavers create impoundments that capture sediment and control floods
Source: photos by author (2006)

reservoirs (Speigel and Baldwin 1963). Spiegel and Baldwin (1963) discussed two types of vegetation change within the context of streamflow reduction: (1) grass, shrub and deciduous-tree seedlings in meadows, marshes, and valley bottoms; and (2) growth in forest undergrowth. The increased plant growth increased the capacity for soil moisture-retention, increased the direct use of water by these vegetative communities, and decreased runoff. In 1963, these authors noted the need for additional research to determine the effects of vegetal changes on upper reach water yield; some study has been completed within the last ten years (Chapter 8, Section 8.1.1.2).

Watershed managers saw the conditions caused by overuse and responded with the opposite management strategy of complete non-use. The highest portions of the watershed were designated as part of the Pecos Primitive Area in the 1930s, and by the 1950s, were part of the Pecos Wilderness (and subject to the same regulations as other National Wilderness Lands) (Santa Fe National Forest 2001). As was common with other overused areas in the West, upper watershed forests were preserved in a state of complete non-use. From scientific gains in modern forestry, we now know that non-management and complete fire suppression equates to mismanagement. Fire suppression and grazing restrictions began in the watershed around the same time: without these two activities, dense stands that could funnel fire to the crowns replaced the groundcover that sustained low-intensity ground fires and established a scenario for disaster. Despite the benefits of stabilized sediment, doghair stands containing thousands of 80-year old trees that are only a few inches in diameter are not only unhealthy ecosystems, they are extreme fire hazards. With the devastation of Los Alamos's water system in the Cerro Grande Fire of 2000, the focus of Santa Fe watershed management shifted from passive to active; with the health of the upper reach at the core of new sustainability measures (Chapter 8, Section 8.1.1.2).

7.2 URBAN REACH FUNCTION

For approximately the first three-hundred years of Santa Fe history, the urban river reach provided several important functions: a water conductor for irrigation and domestic needs via acequias, livestock watering, recreation (swimming, fishing, and ice skating), power for grist and saw mills, water and ice for breweries and distilleries, ice for food preservation, groundwater recharge, and riparian habitat (wildlife corridor) (Snow 1988; Santa Fe National Forest 2001; Sanborn Mapping Company 1886; Grant 2002). With the installation of dams and modern infrastructure, the river also provided a source of running water piped into Santa Fe homes, and electricity (about 100 kilowatt hours) after the construction of the first hydroelectric plant adjacent to the river in 1895 (Goldman 2003). This research extends the current historical literature by examining the river's history from the perspective of acequia communities, digitally reconstructing the Santa Fe acequia network, and presenting definitive evidence for a wet Santa Fe. Given the current landscape of concrete, asphalt, and adobe-style buildings, it is difficult to envision a Santa Fe once saturated to such a degree that springs gushed, and "mists of known and evident detriment" rose from the cienega. Through the presentation of physical and historical evidence coupled with the application of modern geographic techniques, this research presents hydrologic connections between the river, the physical landscape, and residents of Santa Fe that is unlike any other in the current literature.

7.2.1 Acequia Agriculture: Water, Irrigation & their Defining Roles in Santa Fe History

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When the settlers of Santa Fe arrived at the site chosen by Governor Peralta for the new villa, they undoubtedly saw a small river surrounded by a lush, green corridor and a cienega, or swamp, which kept the land moist. One reason for Peralta's site selection was its close resemblance to the description required by the *Recopilacion de Leyes de los Reynos de las Indias,* or Laws of the Indies. In this royal decree, King Philip II, in 1573, set laws for settlement establishment in New Spain, including the distribution of cropland and water to its residents. The presence of a reliable, clean water source was one of the many requirements for villa site selection:

> having water close by which may be conducted to the *pueblo* and the tillable lands, disposing the same, if possible, for its better use and for the materials necessary for buildings, farm lands, agricultural and grazing… and in the event of building along the banks of a river, the settlement should be laid out that the setting sun falls first upon the *pueblo* and then upon the water (Twitchell 1925: 35).

These water sources were the means to keep the villa sustained in the arid climate, while irrigated agriculture was the way. Long-established Spanish irrigation methods translated well to the dry landscape, and even were recognized by American Indians who also practiced community-based irrigation. Technical and legal aspects of Spanish irrigation come from the Romans and Moors. Though the Romans developed irrigation infrastructure, the Moors were influential in water law development; their foundations originating in Islam and "the law of thirst, which granted to all living things completely free access to all waters to satisfy this need, derived directly from the teachings of the Prophet" (Clark 1987: 9). Irrigation in practice dictated the need for established rules. Though variations occurred, "all recognized beneficial use as the basis for granting the right initially and assuring its continuation" (*ibid*.). These ideas, established over 1000 years ago, are the foundations of contemporary water laws in practice in the western U.S. today. Applying water for beneficial use and limiting waste, establishing rights to water through initial and continued use, and the appropriation of water are rooted in this tenet of Islam.

Earliest communities in the Spanish Colony were isolated; farmers governed themselves in the first water democracies, or acequia communities. Given their straightforward nature, rules in acequia communities passed between generations orally (Figure 7.E). Each ditch, or acequia, has its own community of irrigators and their families. Overseeing each acequia is a mayordomo. Elected to a one-year term by his peers, this water superintendent oversees ditch maintenance, water distribution, and handles grievances between irrigators such as water theft and cattle damage. Irrigators who fail to follow established rules and found guilty by the community are commonly given ditch maintenance work (or *tareas*) to settle the issue. Members of acequia organizations attach feelings of pride, identity, and community to the group and to the land. Organizations perform social and political functions by providing local government below the county level. Acequias give community members a sense of place; many describe where they are from by the name of the ditch they use. Harsh natural conditions in Santa Fe made for a challenging agricultural existence, and the community effort of ditch maintenance bound the people together.

7.2.1.1 Irrigated Agriculture in pre-Revolt Santa Fe

Although historians debate the exact year of Santa Fe settlement, the first construction undertakings are not. The acequias were dug first, before the construction of public buildings, churches, or houses, so that fields of beans, corn, and hay would produce in their first year. Logistically, digging acequias was also necessary for building construction, because the mortar used to cement adobes together must be mixed with water where it is used (Snow 2009: personal communication). The Viceroy ordered Peralta upon arrival at the new location that farming "must be started at once in that land;

and he shall be sure that the colonists bring tools and other necessary implements for farming" (Hammond and Rey 1953: 1087). Orders of the Viceroy aside, lessons learned from food shortages at their previous settlement, San Gabriel, taught the settlers to plant crops before all else. They arrived early in the year to clear fields, dig acequias, and plant crops, ensuring a viable food supply for the coming year.

Figure 7.E. Acequia farming: oral tradition passed between generations, circa 1940
Source: Museum of New Mexico, negative #58868

A combination of many factors shows how difficult surviving in Santa Fe would have been for the average farmer. Within the watershed, the growing season length and frost-free period is highly variable; therefore, the timing of planting is critical to the success or failure of each season's crop. Because growth typically does not occur below 40-42 degrees Fahrenheit, the Santa Fean agriculturalist would need to time the planting of his crop after the last killing frost, and leave enough time for the crop to mature (about 120 days for corn) before the first killing frost in the fall (Pratt and Snow 1988). Farmers had about 154 days on average to plant, grow, and harvest their corn crop to avoid failure. Native corn was a major crop from prehistory through the twentieth century: first for Native subsistence, and later as a source of animal fodder for the Spanish colonists (Pratt and Snow 1988). Spaniards (or their servants/slaves) were also growing wheat and a variety of beans, including garbanzos among other crops, while Pueblo-speakers still relied on the *milpa,* a field where the prehistoric triumvirate of corn, pinto beans, and squash grow together symbiotically. All grew introduced crops such as apricots, peaches, and melons. Wheat imported by the Spanish, unlike native corn, could not survive without irrigation.

To irrigate, an earthen berm or small dam (*presa*) of logs, brush, and stone diverts water from the river into acequias. Once in the unlined main ditches (*acequia madres*), water flows from a higher elevation under gravity through a series of unlined main ditches. After potentially traveling a half-dozen miles, and changing direction several times, it moves through laterals and smaller ditches (*sangres*) and is directed to specific fields by opening and closing wooden (and in more modern times metal) gates (*compuertas*) (Figure 7.F). Once the water enters a field, and is spread across the landscape under gravity, the farmer helps the water reach all the furrows and farthest corners of his field by moving clods of dirt with his shovel (Figure 7.E).

Settlers had help constructing the first ditches in Santa Fe. Acequia farming is difficult and tiresome work; Indian servants or slaves provided a majority of the labor for digging, clearing, planting, irrigating, and harvesting. After about two years of construction, the established villa likely had acequias snaking throughout the landscape, delivering water to fields and households, and supporting the small population of clergy, agrarians, governmental and military men, craftsmen, and artisans. Santa Feans were apportioned "two lots for house and garden, two contiguous fields for vegetable gardens, two others for vineyards and olive groves, and in addition four caballerias [about 133 acres] of land; for irrigation, the necessary water" (Noble 1989: 28).

Figure 7.F. Metal Gate on the Acequia Madre, Acequia Madre Street
Source: photo by author (2005)

7.2.1.2 The 1680 Pueblo Revolt and 1692 Resettlement

Acequias played a pivotal role in the Pueblo Revolt. When Indians blockaded the Spanish settlers inside their compound, they cut off the acequia providing their water supply. In later describing the attack Otermin wrote, "… When dawn came more than 2,500 Indians fell upon us in the villa, fortifying and entrenching themselves in all its houses and at the entrances of the streets, and cutting off our water…" (Hackett and Shelby 1942: 170). After two days without water, the settlers were forced to abandon the settlement. For twelve years, Santa Fe remained in control of Tano Indians, who modified the existing structures within the villa, worked the surrounding fields, and used the acequia network.

In 1692, Spaniards returned to Santa Fe to reclaim their villa in the same manner that had once been their downfall: they severed the acequia supplying the compound, and denied the Indians a water supply, forcing their surrender. Within the year, approximately 1,500 people were residing within the walls of the compound. Homes and churches were rebuilt, any fields or acequias allowed to fallow by the Indians were reestablished. By the end of the seventeenth century, farmers had settled both sides of the river for several leagues downstream, as far as present-day Agua Fria.

7.2.1.3 Water and Acequia Agriculture in Santa Fe 1700s to 1850s

Each season's success depended directly on the amount of water in the river. Feast or famine was often the case. During the annual snowmelt, the river would swell beyond its banks and easily damage the adobe homes. Often residents in the direct path of its fury would tie their doors, shutters, and furniture to the roof and leave until the waters had subsided. Heavy summer rains often brought a torrent of water and mud downstream with a roar, causing damage to acequias and gates, and filling the ditches with debris. But water shortages would strike as well, and only every so often would there be enough for every field. "[T]he scarcity of water that comes from the river is known," states a petition arguing the use of cienega water for irrigation in 1716 (SANM I: 169, Reel 8, Frame 151). When Fray Francisco Atanasio Domínguez visited the Santa Fe environs in 1776, he noted that the river would flow downstream beyond the villa in only the wettest years. He wrote, "although it carries enough water to be called a river, it is not overabundant. Indeed, it is usually insufficient, and at the best season for irrigating the farms, because there are so many of them it does not reach the lowest ones, for the first, being higher up, keep bleeding it off with irrigation ditches, and only in a very rainy year is there enough for all. In such seasons ranchos 5 leagues downstream benefit as much as the rest" (Adams and Chávez 1956: 40). Five leagues equates to approximately 21 km (13 mi): during wet years the flowing river would extend past Agua Fria, beyond the modern-day WWTP, and would join the spring-fed areas in La Bajada Canyon.

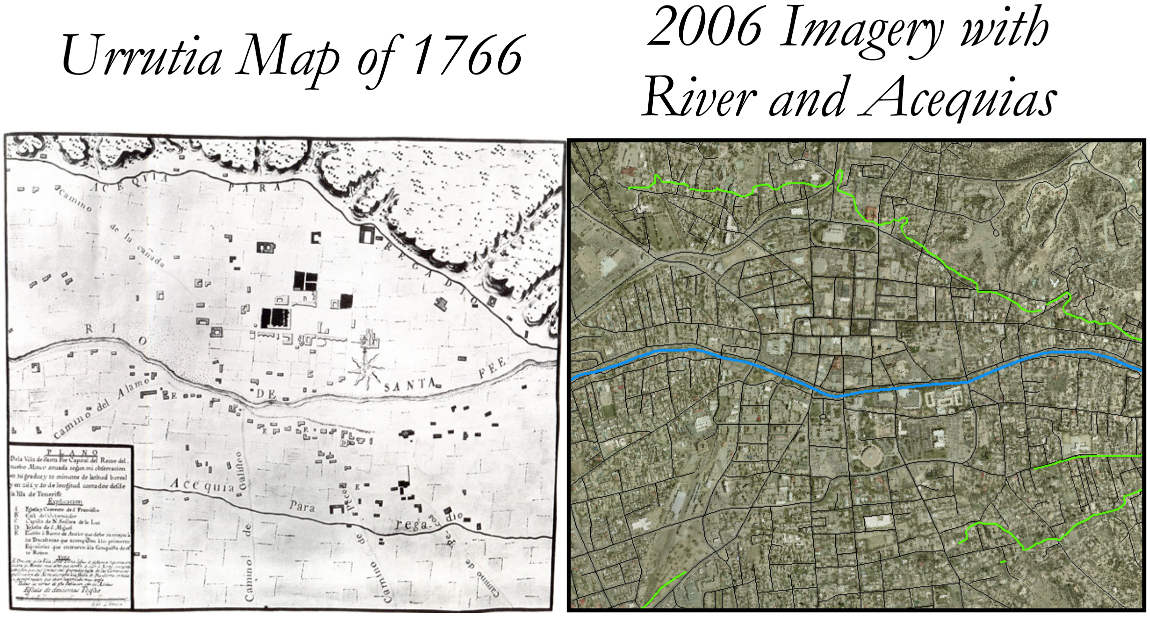
Joseph de Urrutia captured the earliest surviving depiction of irrigated agriculture in Santa Fe in 1766-68 (Figure 7.G). This map shows the royal buildings, churches, and individual homes. It also shows the river flowing from right to left, its gravelly floodplain, two irrigation ditches, and a possible lateral. A patchwork of fields covers an expanse of approximately 4,000 acres (16.2 km^2). Urrutia uses cartographic license in his depiction: modern stream-gaging and water application calculations indicate that the Santa Fe River, on average, could support approximately 2,000 irrigated acres (8.1 km^2), or about half of what is drawn. Urrutia simply filled the landscape with fields to an extent that is unrealistic. However, this map is our best estimate of the early settlement.

Several important features are not shown; including, the cienega, the springs and gardens on the convent property, the Rio Chiquito, or the ditch from the bishop's springs. The reason for their omission is unknown. Urrutia's portrayal also includes a gravelly floodplain, an early characteristic of this river that was a result of the large deposits of sand and gravel that it entrains as it flows, and later deposits, downstream. Many of the features matched well with modern landscape features after rectification in a GIS.

Irrigated fields were planted upstream and downstream beyond the map. Fields flanked the river and filled the floodplain upstream from the villa beyond present-day McClure Reservoir (Figure 7.H). Farms downstream in Cieneguita (near present-day Frenchy's Field), Quemado (present-day Agua Fria), Cienega Grande (present day La Cienega), Cieneguilla, and La Bajada Canyon relied on springs, and the river in wet years to water their crops of beans and corn (Figure 7.I). In these places, Fray Francisco Atanasio Domínguez observed fields of "wheat, maize, legumes, and green vegetables, and also fruits such as melon, watermelon, and apricots, of which there are small orchards" that fed a population of about 2,000 (Adams and Chávez 1956: 41).

7.2.1.4 Under United States Control: Agriculture in the Territorial Period

In 1846, U.S. General Stephen Kearny began the occupation of New Mexico in Santa Fe. Kearny ordered lawyer members of his Missouri volunteers to begin drafting a code of laws for the new territory. In the Kearny Code, water laws were to remain unchanged and established irrigation ditches were not to be disturbed. New Mexico became a territory of the U.S. in 1850. In 1851 and 1852, the New Mexico Territorial Laws, or *Leyes Generales del Territorio de Nuevo Mexico*, crystallized oral traditions into codified laws for the first time. These laws were “significant because they reduced to writing and in perpetuity the acequia practices that had evolved in the former Spanish-


Urrutia Map of 1766

2006 Imagery with River and Acequias

Figure 7.G. Urrutia Map and modern landscape comparison

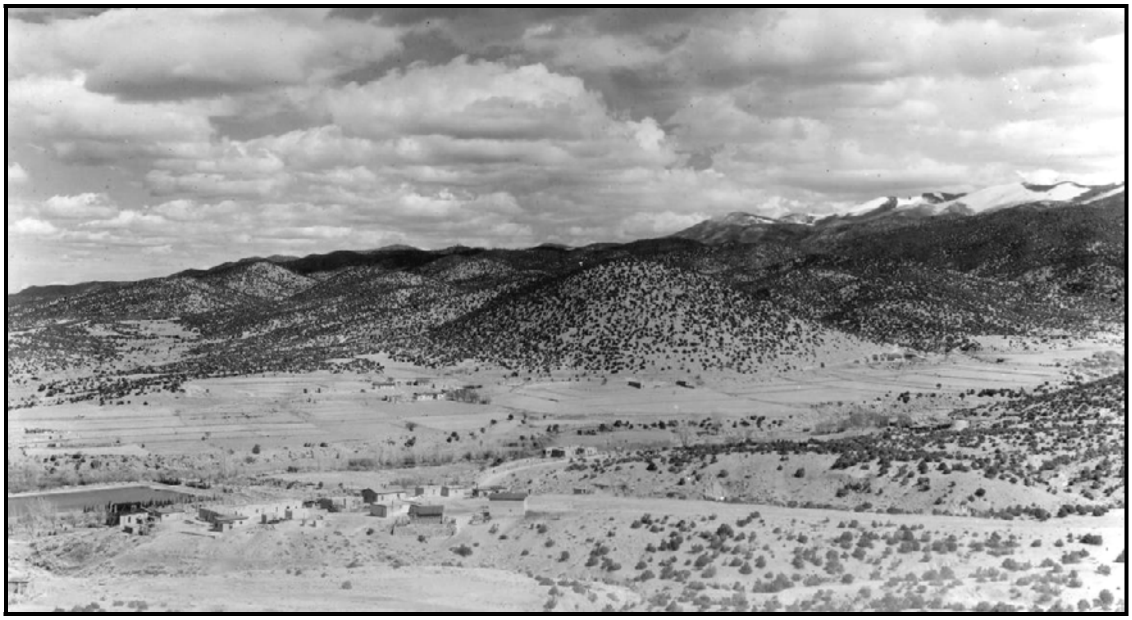


Figure 7.H. Irrigated fields fill the valley upstream from town, circa 1920
Source: Museum of New Mexico, negative #011125

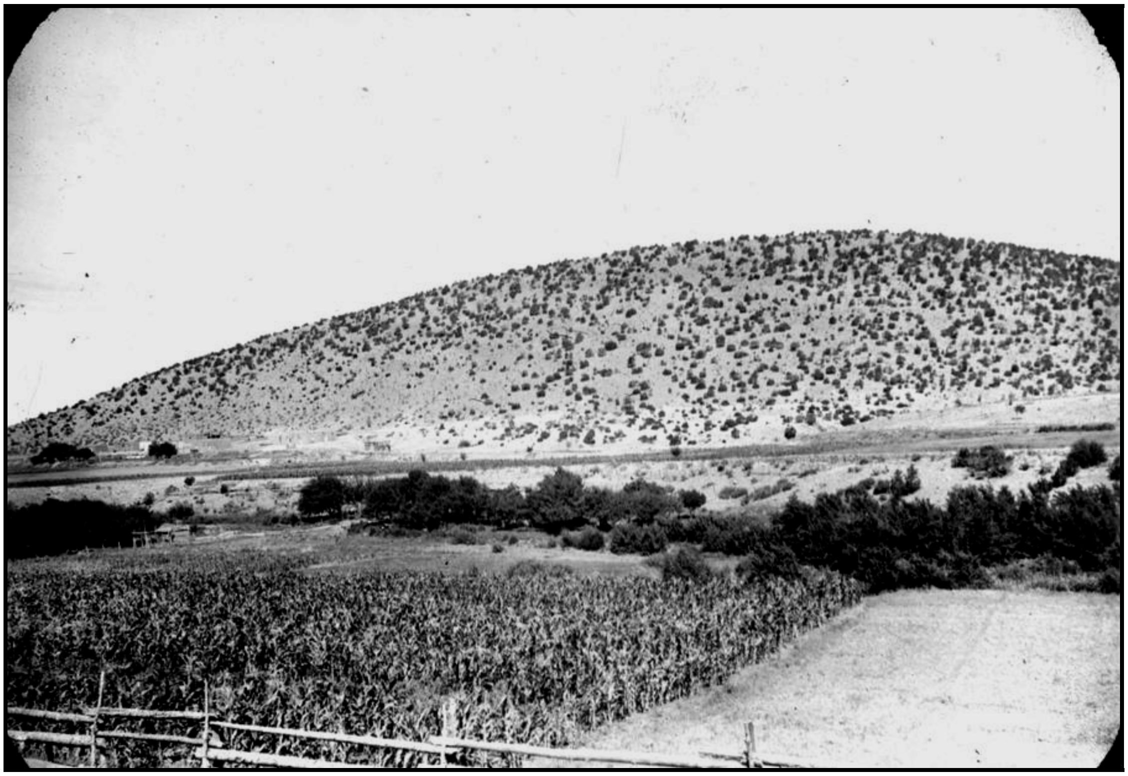


Figure 7.I. One of the staples grown with irrigation in Santa Fe was corn, circa 1910
This field is upstream of downtown, near Upper Canyon Road
Source: Library of Congress (2009c)

Mexican province for two and a half centuries" (Rivera 1998: 50). These laws reflected important aspects of New Mexican life: "the primary dedication of water to agricultural purposes and the clustering of water usage around the institution of the community acequia" (Clark 1987: 25).

Lt. Jeremy F. Gilmer created his map after U.S. occupation and shows Santa Fe of the 1850s. He drew existing structures and cultivated lands, as well as ditches leading from the cienega, the parochial lands, and the Rio Chiquito. The Acequia Muralla to the north and the Acequia Madre to the south were now joined by a complex network of canals. Gilmer drew the Acequia Muralla, and a second main northerly ditch that diverted water from several different sources to water the fields north and west of the governmental buildings. Historians believe this acequia is perhaps the root of the famed lateral that was cut by American Indians during the Pueblo Revolt. The Rio Chiquito is also a significant feature of Gilmer's map. Historians dispute the source of this feature; either a small side-channel of the Santa Fe River or a man-made ditch supplied by the Bishop's Garden springs (further discussed in Section 7.2.3). Despite the source, the channel carried water with enough frequency to give Water Street its modern name. Like Urrutia, Gilmer also filled his map with 4,600 acres (18.6 km^2) of cultivated land, an extent too large to be irrigated by the meager river, even with the help of plentiful springs.

The uncontrolled river and variable climate continually subjected Santa Fe irrigators to its cycle of have and have-not. On June 14, 1870, *The Daily New Mexican* reported, "[s]o long have our farmers been without rain that the want of it is becoming to be quite seriously felt in this valley. … The past winter, so unusually dry both as to snow and rain, is the occasion of a very small supply of water in the creek from which the irrigating acequias are supplied, wherefore the rivalry between the planters to obtain the use of the water is quite lively just now." Only two years later, on August 5, 1872, the paper described "rain in the mountains yesterday was very heavy. In a few hours our meek little river rose from almost nothing to a boiling, foaming, roaring torrent, threatening to carry all before it. Like all mountain swells it grew so rapidly that it came charging down with a full front driving before it large stones, logs and brush. … It subsided almost as rapidly as it came. Considerable damage was done to gardens, fields, fences, dams and acequias. It cleaned out some filthy holes along the banks pretty efficiently."

7.2.1.5 The Rise of Modernity in Santa Fe

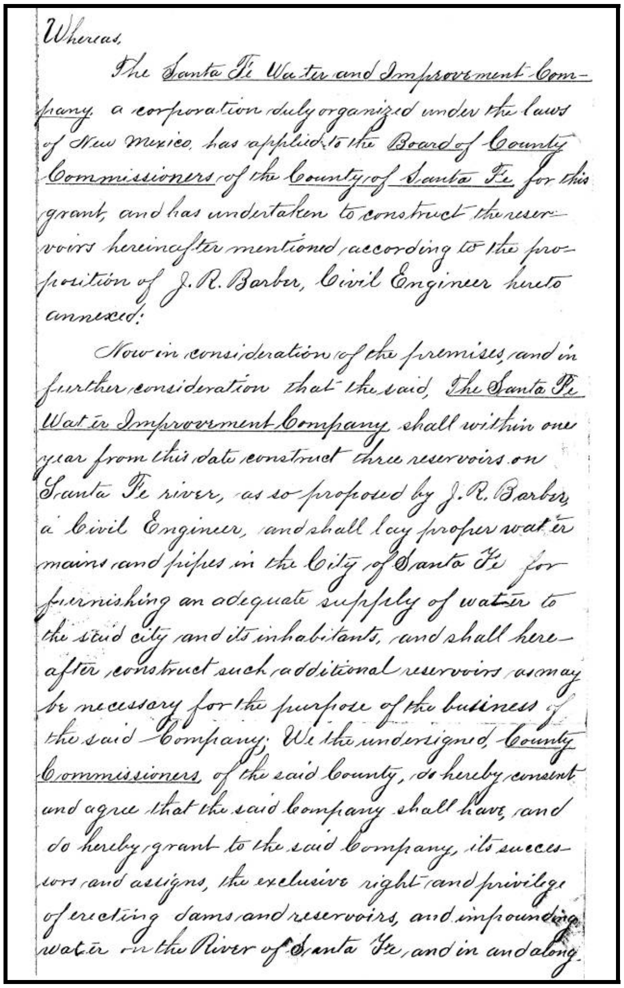
By the 1880s, Santa Fe's population had exceeded 6,600. Anglo-Americans brought new ideas and modernization to the isolated city. A newspaper, mail service, and railroad marked changing times during the first decades of U.S. occupation. Electric and water utilities were soon to follow; beginning with a dam, the catalyst for Santa Fe urbanization. On December 29, 1879, the Santa Fe Water and Improvement Company founders submitted a certificate of incorporation to the County of Santa Fe. In the certificate, the Company declared their intention to supply water to Santa Fe and its vicinity "for all purposes for which the same may be used in the streets, houses, buildings, and fields" (Santa Fe Water & Improvement Company 1880: 1). Under the Territorial Laws of New Mexico, the Commissioners of Santa Fe County gave the Water Company the "exclusive right and privilege of erecting dams and reservoirs, and impounding water on the River of Santa Fe" (Figure 7.J). "The commissioners felt that a water system would be beneficial to Santa Fe's image through its civilizing effects" (Lewis 1996: 11). However, this act was a direct deviation from the rules that had governed water distribution in Santa Fe for almost three centuries. The Laws of the Indies established water as a public resource to be shared among all users for the public good, not a commodity to be purchased and delivered via pipe.

In 1880, the company changed hands, and erected the first dam on the Santa Fe River in Santa Fe Canyon, a little more than 3.2 km (2 mi) upstream from the plaza. Old Stone Dam was constructed of stones stacked 8.5 m (28 ft) high, creating an 800-foot long reservoir that held about 25 acre-feet of water (over 8 million gallons). An acre-foot represents the volume of water needed to cover one acre of land with one foot of water. This dam was Santa Fe's first attempt to control the river and to store snow meltwater, and served many purposes: public water supply reservoir, source for fire protection, and flood control structure. The Santa Fe River had plagued the downtown area for centuries, with documented floods wreaking havoc on manmade infrastructure; acequias, bridges and buildings. Despite all the trouble the river caused, public opposition to the dam included vandalism and altercations during construction. Opinions differed on water rights between the newest Santa Fe residents, and the older families and acequia mayordomos.

In June 1881, *The Santa Fe New Mexican* printed the following objection to water impoundment:

> We, the majority of the people of Santa Fe, declare and maintain that whereas we have been entitled to the water in the Santa Fe River since the conquest of this country, have used it for the purpose of irrigating our fields and quenching the thirst of our families, that the water has been given to us by the sublime will of God… Resolved that the people of Santa Fe will by all legal means cause the said water works company to stop abusing and appropriating the rights belonging exclusively to the people, will prevent their converting the same to their own pecuniary welfare, leaving the community helpless and subject to their charity, and depriving them of all the sacred rights which nature has given them merely to satisfy ambition... (Sanborn 1982).

Old Stone Dam was too small to control the river. Once the reservoir was filled, water commonly flowed through acequias as it had in the past because river volume greatly exceeded its storage capacity. Sometimes it behaved as it had in the past, as on April 20, 1886, when *The Santa Fe New Mexican* reported that “high water in the Rio Santa Fe broke through several acequias in the western suburbs of the town last night and this morning the fields south and west of the residence of Hon. T. Alarid presented the appearance of a vast lake. It is well that the crops had not been planted.” According to the 1890 ownership plat of Santa Fe, Trinadad Alarid’s property was located on the river floodplain now occupied by the Alto Youth Center, between Alto Street and the river.



Whereas,

The Santa Fe Water and Improvement Company, a corporation duly organized under the laws of New Mexico, has applied to the Board of County Commissioners of the County of Santa Fe for this grant, and has undertaken to construct the reservoirs hereinafter mentioned, according to the proposition of J. R. Barber, Civil Engineer hereto annexed:

Now in consideration of the premises, and in further consideration that the said, The Santa Fe Water Improvement Company, shall within one year from this date construct three reservoirs on Santa Fe river, as so proposed by J. R. Barber, a Civil Engineer, and shall lay proper water mains and pipes in the City of Santa Fe for furnishing an adequate supply of water to the said city and its inhabitants, and shall hereafter construct such additional reservoirs as may be necessary for the purpose of the business of the said Company. We the undersigned, County Commissioners, of the said County, do hereby consent and agree that the said Company shall have, and do hereby grant to the said Company, its successors and assigns, the exclusive right and privilege of erecting dams and reservoirs, and impounding water on the River of Santa Fe, and in and along

Figure 7.J. Document grants Water Company exclusive rights to impound river, 1880
Source: Santa Fe Water & Improvement Company (1880)

Meanwhile the more affluent Santa Fe residents began to enjoy the benefits of running water. If they could afford the up-front cost, landowners received reimbursements after installing connective piping from the public water mains to their homes and properties.

With its minimal storage potential, Old Stone reservoir quickly became too small to supply the growing community, and in 1893, the construction of Two-Mile Dam began. By now the Anglo population "…predominated among merchants, military personnel, and governmental officeholders… their role in agriculture was almost nonexistent" (Lehmann 1974: 22). The Water Company was a political force and town residents were anxious for running water. The opposition, by this point, either had accepted the dams, or were acquiescent; no known vandalism or outward protests occurred. Acequia communities were encouraged by the promise of surplus water from the new reservoir; enough to water 1,000 acres (4.0 km^2) of orchards. After its completion, the 85-foot high earthen structure created a reservoir that increased storage by 93 percent to 387 acre-feet (more than 126 million gallons). Flow into acequias was immediately disrupted. The Water and Improvement Company tried to work with irrigators, as stated on March 14, 1893 in a letter filed with the County Clerk's Office and addressed to la Acequia del Cerro Gordo. In the letter from water company president L.A. Hughes, he stated:

> The Water and Improvement Company wishes to advise you that it has obtained from the County and by purchase of individuals the right of all surplus water in the Santa Fe River... That the present work they are doing now is not with the purpose of interfering with your Acequias… The quantity of water supplied from the River to the Acequias will not be lessened, only the manner of taking the same will be changed,... this company wishes to act always in harmony with you and with all others to have rights in Acequias and will always work together with you with the purpose to make the water reach in all possible ways to all persons entitled to the same and with as less cost as possible (Hughes 1893: 1).

Changes to laws also accompanied physical changes to the river. Beneficial and significant acequia legislation that defined "community ditch," "acequia," and their legal status was passed on February 28, 1895. Acequia communities became corporate entities, were given legal standing, could now sue and be sued, collect fees, and were required to publicize rules and regulations and elect ditch commissioners. These were important changes for acequia communities in Santa Fe because now the groups had legal standing to fight the water company for control of their water rights. Senior water rights are granted to a user who is the first to establish and continually use the resource on a particular stream. This user has priority to the water over others who establish their right later in time. The appropriation doctrine, or prior appropriation, is best explained by the phrase ‘first in time, first in right.’ Acequia farmers were ‘first in time’ to use river water, therefore they were ‘first in right.’

Two-Mile Dam, constructed just several hundred feet downstream of Old Stone, soon became the only reservoir for the growing city after a catastrophic flood of September 30, 1904, filled the old, smaller reservoir with sediment. A newspaper headline the following day hailed the success of the dams: “Destruction in Wake of Powerful Flood: Staunchness of Reservoir of Santa Fe Water Company Prevents Great Disaster and Inundation of Lower Part of City” (Figure 5.P). Two-Mile Dam protected the town and reinforced the argument for additional dams. The flood of 1904 also brought attention to the health of the Santa Fe watershed, and its role in sustaining the public’s water supply. Centuries of grazing and logging had left the landscape largely devoid of vegetation. Rainstorms brought raging torrents of mud and debris downstream to fill acequias, fields, and streets of downtown Santa Fe. In order to protect the water supply, the watershed was closed to public use in 1932 by the U.S. Secretary of Agriculture.

The state legislature of New Mexico established the Office of the State Engineer in 1907, and mandated a survey of existing waters, and the adjudication of all water rights. Adjudication is a legal process settling all water rights claims on an entire stream system. Citizens of Santa Fe (many of them acequia farmers) petitioned the State Engineer in 1914 with the hopes that adjudication of the Santa Fe River would confirm their water rights (some beginning ‘time immemorial and prior to 1680’), and force the owners of upstream dams (at the time, the Public Service Company of New Mexico or

PNM) to release impounded water downstream into the river and acequias. The State Engineer compiled a hydrographic survey of the Santa Fe River during these early adjudication efforts. The Hydrographic Survey of 1919 includes a census of each acequia by number and geographic position, including lists of irrigators, monthly discharge to the ditches during the growing season, maps of the irrigated plots and their acreages, and crops grown. Thirty-eight ditches were irrigating about 1,200 acres (4.9 km^2) of green gardens, orchards, wheat, oats, alfalfa, and corn in 1914. With an average application rate of 4.5 acre-feet per acre, 1,200 acres (4.9 km^2) would use 5,400 acre-feet of water to sustain the planted crops during the 1914 growing season. The Santa Fe watershed generated 8,800 acre-feet that year, mostly during the snowmelt of April and May, and during the rainy period in July and August. Because water use in Santa Fe was not metered until 1930, the amount of water withheld each day by the Water Company is unknown. However, between 1904 and 1926, the Water Company continuously stored approximately 400 acre-feet of water and delivered this water to Santa Fe residents for household and irrigation uses. As the population quadrupled from 5,072 in 1910 to over 20,000 by the end of the 1930s, more residents connected to the water system. As water demand increased more and more, it flowed into acequias less and less.

7.2.1.6 Reservoir Feast, Acequia Famine

The water company slated more dams for construction. McClure Dam (previously Granite Point) was built 5.6 km (3.5 mi) upstream from Two-Mile in 1926-1928. Originally, the reservoir stored 650 acre-feet, but after being raised in three stages to 3,325 acre-feet, the reservoir held more than half of the river’s typical annual volume. Now very little water reached acequias. Despite earlier promises, reservoir storage received priority and many acequia families relied on mayordomos to petition the Water Company for releases into the ditches.

Acequia farmers were still battling for water releases when the U.S. entered World War II. As the men went to war, only the young and old remained to fight for the acequias. An army hospital built in Santa Fe put increased demand on the water system. As a result, the water company constructed Nichols Dam between Granite Point and Two-Mile in 1943. The three dams could now store more than 60 percent of the water that the Santa Fe River produces in an average year. No minimum flow requirement or water provision existed for the acequias. After returning from war, most veterans found dry fields. With the majority of water being stored behind reservoirs and little chance for releases to the ditches, the men found other jobs in manufacturing, construction, and tourism. The memory of acequia farming remained fresh in their minds however:

> To my certain and personal knowledge, the crops grown on the farm… were irrigated 1888-1890 by surface waters of the Santa Fe River diverted onto the land from the Canyon Road Community Ditch: a part of the Acequia Madre Community Ditch: the irrigation of these crops continued uninterrupted until the 1950's when water was no longer available in the Canyon Road Ditch.
>
> Fred Valdez, Sr., 1975 (in Snow 1988)

> My recollection is that there was always plenty of water during irrigation season in the Canyon Road Ditch until at least 1939 when I went into military service. However, when I returned to Santa Fe in 1946, there was rarely any water available in the Canyon Road Ditch for irrigation purposes.
>
> Ignacio L. Vigil, 1976 (in Snow 1988)

With reservoirs storing essentially all river water behind them, the amount of land in irrigated agriculture dropped sharply. Black and white aerial photographs of Santa Fe in 1936 show approximately 800 acres (3.2 km^2) being irrigated (USDA Forest Service 2005). Aerial photography from 1951 shows the area irrigated dropped to about 650 acres (2.6 km^2) (Figure 7.K). In 1977, seven functioning ditches were irrigating 61.68

acres (0.2 km^2) (State Engineer's Office 1976). Between 1948 and 1990, the Acequia Madre Ditch Association and others requested numerous times that water be released into their ditches. PNM simply believed that they were within their rights to impound all water, as granted by their permit from the State Engineer.

The adjudication process occurred haphazardly for several decades, never truly being completed. An order issued by the Santa Fe District Court in 1975 directed the State Engineer's Office to survey all claims to river waters. "In March 1990, the Acequia Cerro Gordo and the Acequia Madre went to court and asked for interim relief because the adjudication had gone on for 15 years and there was no end in sight" (Acequia Madre de Santa Fe 1995: 3). On June 22, 1990, the First Judicial District Court of New Mexico found in favor of the acequias. In this case (*Henry Anaya, et al. v. Public Service Company, et al.,* SF 71.43,347), the court ordered PNM to release water into the Santa Fe river for acequia distribution. The court interpreted the 1880 deed from the Santa Fe County Board of Commissioners as granting PNM the authority to collect, store and deliver water. However, PNM does not own the water rights themselves. PNM had overstepped its rights by categorically denying water to downstream users for over 100 years. In a letter to both parties, District Judge Art Encinas states, "the preservation of these water rights is important to the vitality of a culture over three centuries old. The people, the land and the water are intricably bound together and will be until Santa Fe is entirely paved over. It is this culture which is our greatest pride and not without considerable value, though not measurable directly in dollars" (Bové 1999: 5).

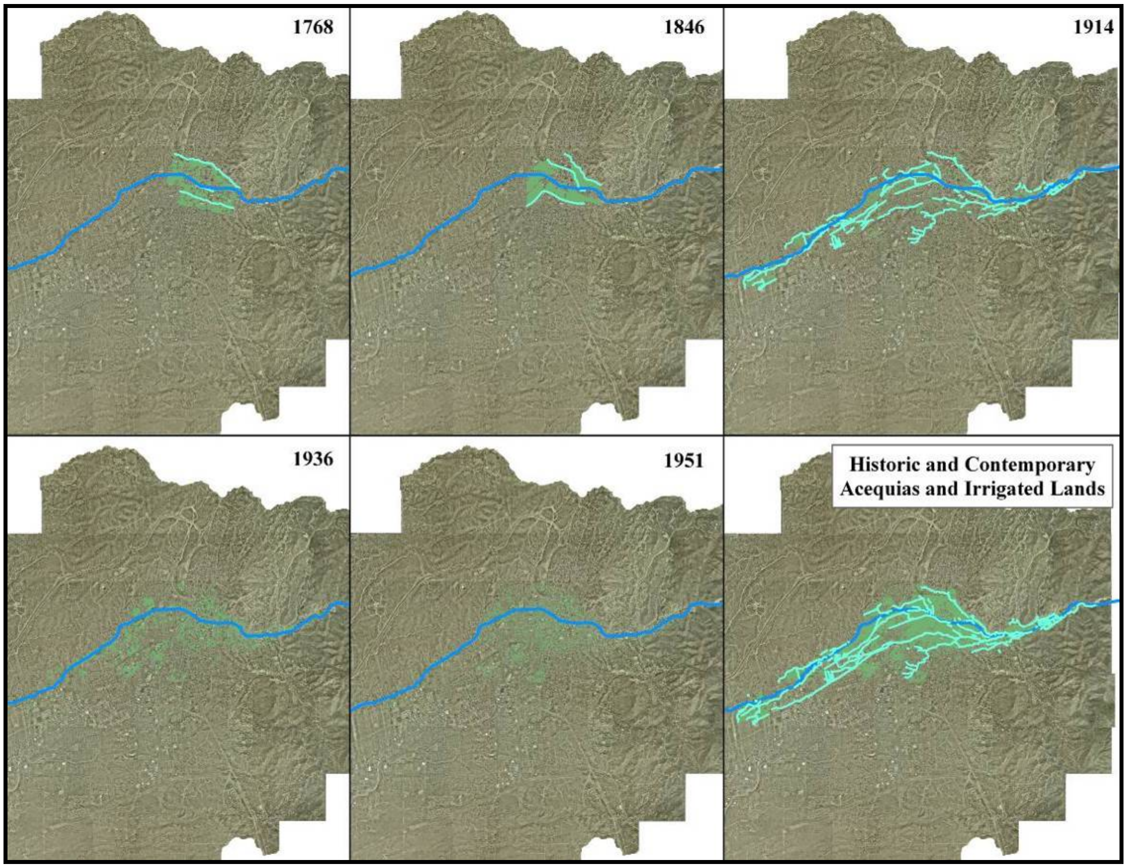


Figure 7.K. Comparative map sequence through time
Historical and contemporary acequias, and irrigated agricultural lands
Source: map by author; imagery, City of Santa Fe (2005b)

7.2.1.7 Today

Acequias are a vital element of New Mexico heritage; these cultural treasures deserve protection and preservation. Founded in 1990, the New Mexico Acequia Association leverages their unified voice for acequias throughout the state. The importance of acequias in Santa Fe is paramount: imagery depicting acequia farming decorates buildings and infrastructure (Figure 7.La and 7.Lb). In downtown Santa Fe today, there are four functioning ditches and associations: Acequia Madre, Acequia Cerro Gordo, Acequia Muralla, and Acequia del Llano, together totaling 2.9 linear miles (Figure 7.M).

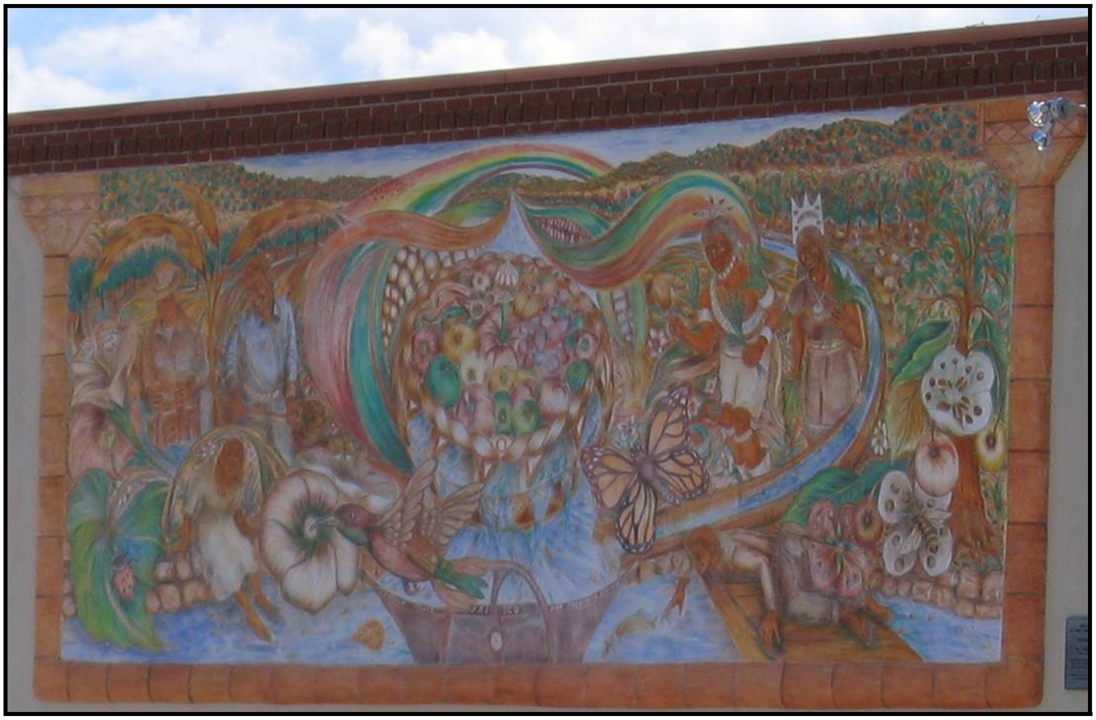


Figure 7.La. Mural on the side of Acequia Madre School
Shows Hispano and American Indian farmers joined by water and acequias, and cornucopia
Source: photo by author (2006)

Figure 7.Lb. Reminiscent of times past: mural of an irrigated field
Decorates the side of a grade-stabilizing structure in the Santa Fe River near Agua Fria
Source: photo by author (2005)

The Acequia Madre is on the National Register of Historic Places and is recognized by the Historical Santa Fe Foundation, and delivers water to approximately 100 acres (0.4 km^2) of hay and green gardens throughout the city. The City of Santa Fe now owns and operates the water system, and has the right (as declared by the State Engineer) to 5,040 acre-feet of Santa Fe River water annually that they may store and distribute. 66.8 acre-feet must be allocated to the Acequia Madre Association and 8 acre-feet to the Cerro Gordo Association annually. Any remaining water is released to the river. Others acequias downstream from Santa Fe continue to irrigate crops using traditional methods. About 100 acres (0.4 km^2) are currently irrigated in La Cienega and La Cieneguilla.

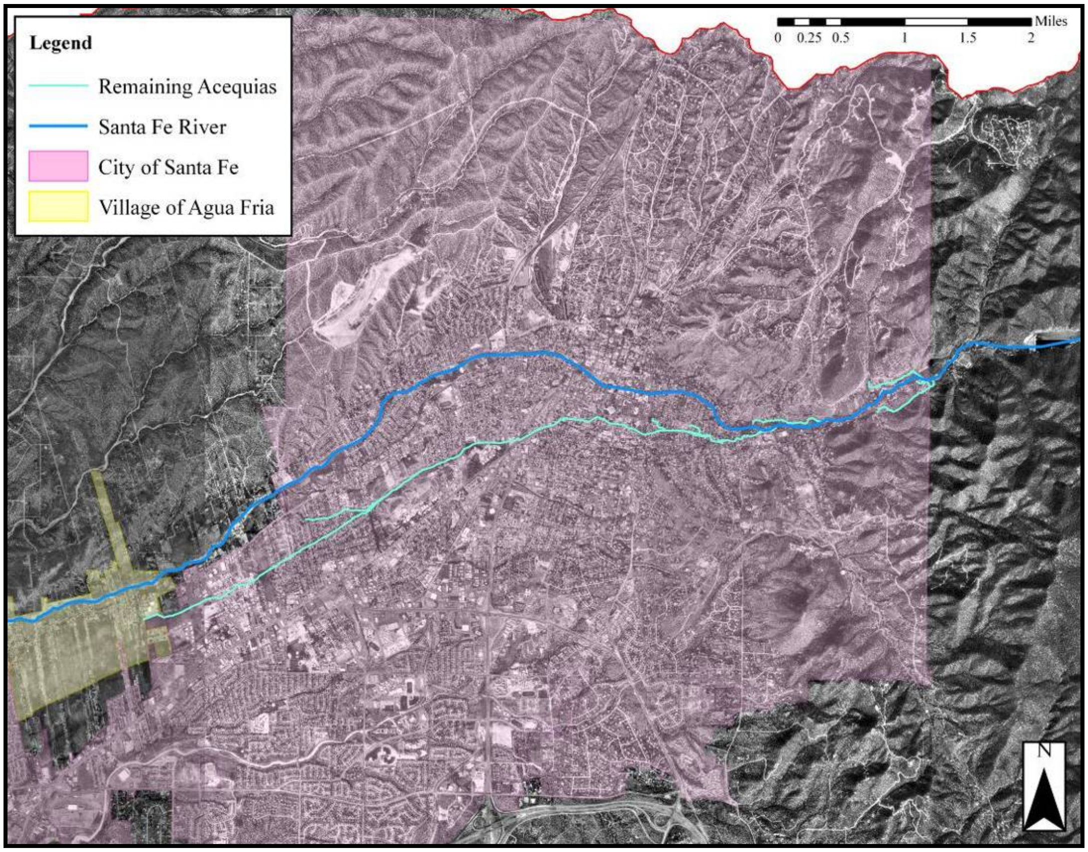


Figure 7.M. Current acequias in Santa Fe total 2.9 linear miles
Source: map by author; GIS layers, City of Santa Fe (2005b)

Santa Fe acequia communities continue to fight for their interests in future water and land planning. Through their tireless efforts, the small remaining legacy of Santa Fe acequias will live on. These ditches sustained the community for over three centuries. Now, as Santa Fe turns 400, it is time to pay tribute to the acequias, their communities, and their defining roles in Santa Fe history.

Table 7.1. Remaining Santa Fe Acequias and their Date of Predication

Acequia Name	**Predication Date**
Acequia Madre	Time immemorial and prior to 1680
Acequia de Muralla	Prior to 1766, but after 1680
Acequia Cerro Gordo	Prior to 1877, but after 1766
Acequia del Llano	Prior to 1907, but after 1877

7.2.2 Reconstructing the Santa Fe Acequia Network

In 1988, renowned Santa Fe archaeologist David Snow conducted a field inventory of acequias, during which all identifiable segments of former ditches were mapped. His work combined the field findings with an extensive oral history provided by long-time acequia community members. The result includes a series of 17 map plats that include forty-one individual ditches and land in irrigation from the base of the current reservoirs, downstream beyond Agua Fria. Ditches in Cieneguilla, La Cienega, and La Bajada are not included. 1977 updates of the 1914 hydrographic survey done by the State Engineer served as basemaps on which Snow's acequia remnants and their headgates by ditch number, name, and construction date were plotted atop roads, topography, property boundaries, structures, and land use (Snow 1988). Invaluable information on the maps also includes the fields in cultivation, with specific information about the crops under irrigation (orchards, corn, wheat, oats, alfalfa, plowed ground). Each map was scanned, and rectified to modern landscape features using a first-order polynomial, while insisting on a root mean squared error (RMSE) of less than 2.0. This level of accuracy was attained easily because of Santa Fe's slow-changing nature. "Santa Fe remains the ultimate expression of the city planning ordinances of the Laws of the Indies on the soil of the United States. Probably this is because of the city's isolation and poverty which made speculative development and rapid change a minor part of the history of the city" (Crouch and Mundigo 1977: 398-406). This statement is a keystone of this research, as many of the historical maps and documents concerning the river, acequia agriculture, cienega, and the Rio Chiquito would not have been possible if Santa Fe had been a dynamic and responsive city to changing governmental and technological advances.

After rectification, digitization, and attribution with their name, ditch number, and construction date, the headgates were snapped to the river-acequia junction to show their specific diversion locations. Because the dates of some ditches are known, the incremental growth of the partial network can be represented through time (Figure 7.N). A few small *tanques* also were captured to indicate past areas of water retention in the valley, including two in Agua Fria on the north side of the river, one in Cieneguita on the south side of the river, and one near the junction of ditches 16 and 22, between modern-day Cibola Drive and Cedar Street. The fields in irrigation were also digitized, and attributed with their production crop.

This digital network captures all acequia sections where verification of the ditches is possible through field reconnaissance. The network is incomplete however, because acequias that are no longer visible are not captured. Two additional techniques using GIS and remote sensing modeling techniques are applied to available data, identifying the probable locations of the pre-Revolt acequias, and generating missing sections of the acequia network. These include: (1) the classification of LiDAR-generated flow accumulation grid cells to reveal nuances in microtopography and postulate acequia positions,[8] and (2) unsupervised classification of black and white aerial photography from 1936 and 1951 to identify linear features of saturated land and to connect missing segments of the network. The number and positions of the 1610 acequias of Santa Fe are unsubstantiated, given the lack of historical documentation (the Pueblo Revolt of 1680 destroyed most documents) and archaeological testing in the downtown historic district. Speculations about the villa, its buildings, fields, ditches and daily life are gleaned from Otermín and Vargas journals, supplemented by a few 1692 Reconquest documents that reference the pre-Revolt landscape (Ellis 1976). Despite missing evidence concerning their placement, their general locations can be deduced by using modern GIS and remote sensing technologies, and by applying an understanding of landscape topography, hillslope processes, and Spanish ditch engineering techniques. The process of ditch construction in New Spain has been accepted for centuries; the basic irrigation engineering technologies involved in Santa Fe are the same as those brought by the Moors to the Iberian Peninsula when they invaded centuries earlier. Acequia agriculture has also been part of the cultural identity of Spaniards since Moorish rule in the early 700s (Section 7.3).

Ditch construction begins by building a mid-channel berm of boulders, cobbles, and brush within the river to raise the level of the water enough to divert water out of the streamcourse and onto the land. Once it leaves the channel, water is allowed to follow the natural topographic flow lines of the landscape, and the ditch then is channeled

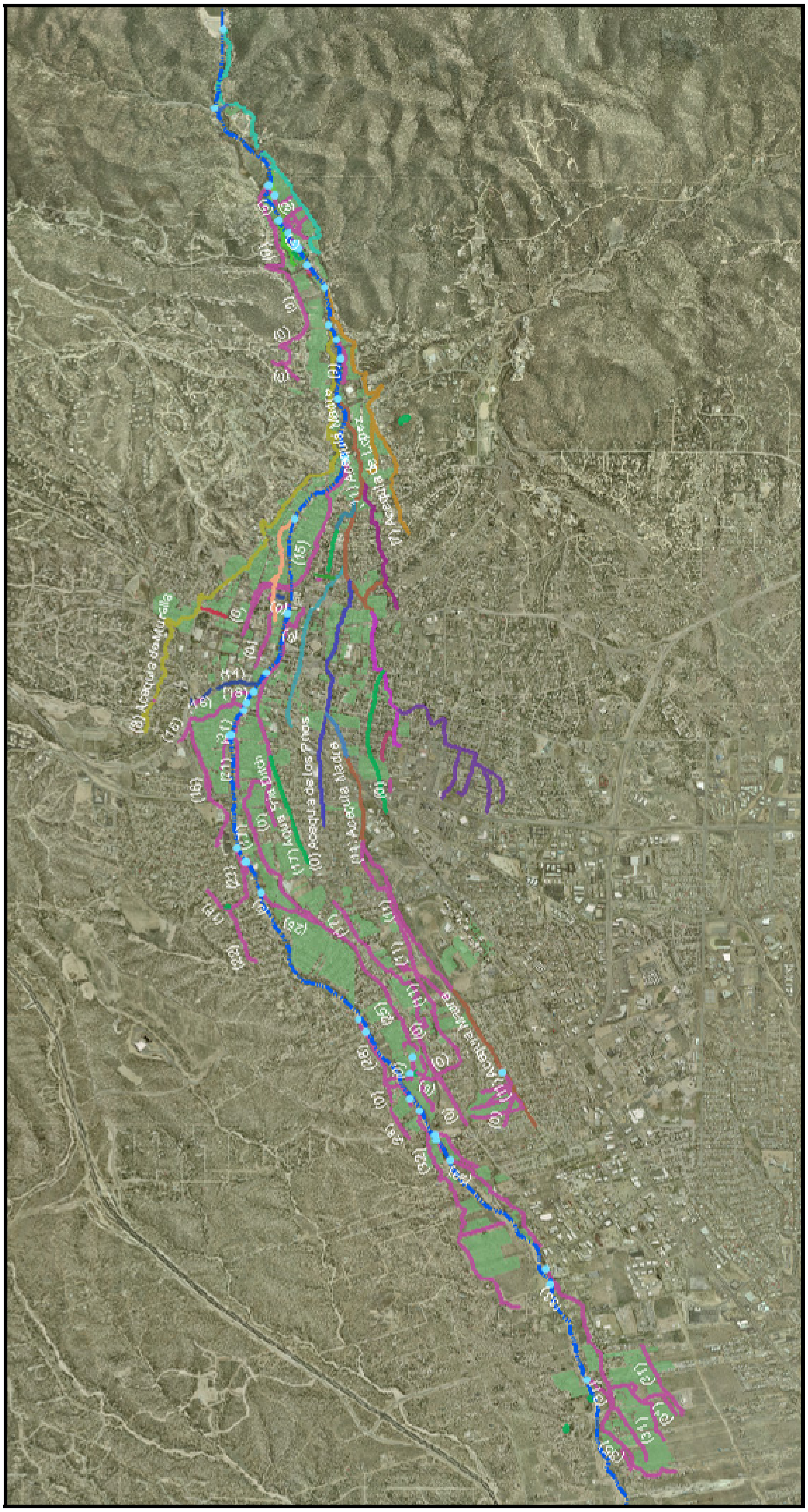


Figure 7.N. Digital reconstruction of acequia survey
Includes headgates (blue dots), and 1914 irrigated lands
Source: map by author; acequias, Snow (1988); irrigated land, State Engineer's Office (1917)

consequently (Rivera 1998). At this location, a main headgate, or *compuerta*, would be built to control the entry of water into the ditch. The Acequia Madre's earthen berm (*presa*) is still evident today in the river slightly upstream of the intersections of East Almeda Street and Canyon Road. Once the gate is opened, water then flows through the main gate into the mother ditch (*acequia madre*) under the force of gravity. If a topographic obstacle, like an arroyo or area of lower land must be crossed to connect fields of equal elevation, a flume (*canoa*) of timber is constructed and is used to span the gap.

There is a specific balance to the grade that must be established and maintained in order for the ditch to remain an efficient conductor of water. If the ditch is dug too steeply, the bottom will be eroded due to the shear stress placed on the bed, and the ditch will incise. If the ditch is dug too shallowly, sediment and debris will accumulate, and the ditch will be clogged. Ditches delivered water from the river to nearby fields, but they also collected additional water from surrounding hillslopes. Overland flow adds a small amount of water to the total acre-feet available in the ditches each year, but may potentially cause problems with ditch incision when violent cloudbursts add uncontrolled volumes of water and sediment to the unlined channels. The disequilibrium in the main acequias generated by these events "could result in more than a casual change of the surrounding landscape… [and] over a period of years could erode into a deep barranca, or canyon, not only permanently altering the topography but rendering itself useless for irrigation purposes and requiring the opening of still new lands" (Meyer 1984: 19). It is speculated that many sections of Santa Fe acequias were abandoned and redirected due to flood-generated incision, which explains why there are so many acequia sections that direct water to the same area.

To place these pre-revolt acequias on the landscape, one must first examine Santa Fe topography. As in many cases with this research, the fortunate fact that Santa Fe has remained virtually unchanged for centuries allows for the modern topographic landscape model generated from 2001 LiDAR data (donated to this project by the City of Santa Fe GIS office) to correlate closely with features in historical maps. Even many of the modern roadways of Santa Fe began as footpaths along acequias, which gives the city the look of unplanned sprawl that some locals term a "plate of spaghetti." To test the application of this technique, the positions of some of the known acequias are compared spatially with the smallest channels of the modeled overland flow. The flow microtopography grid was created in a GIS through widely accepted hydrologic modeling process steps.[8] Due to the basic principles of their engineering, several acequias match quite well with the smallest flow accumulation cells (values ranging from 0 to 20). The cell size of the generated DEM limits this model, however. It is also important to evaluate the results carefully, and to consult as many possible archival materials describing the ditch in question, as many linear features may be remnants of modern-day infrastructure.

Santa Fe's first acequias likely included ditches that supplied water from the cienega to the *casas reales* and its surrounding fields, ditches that extended water from the Rio Chiquito to fields between it and the river, and the Acequia Madre on the south side of the river. At the time of settlement, royal laws specified that American Indian servants and slaves were not to cohabitate with Spaniards. These individuals were relegated to the south side of the river, in an area that came to be known as the *Barrio de Analco*. The southern Acequia Madre supplied water to the American Indian fields, or milpas of San Miguel that were so fruitful they were called the breadbasket of the villa. Although Snow found some sections of these acequias during field reconaissance (the Acequia Madre is still a functioning ditch), much of their lengths can be reconstructed with the microtopography model.

One particularly strong example of the model's application includes the placement of the Palace Ditch. There is much evidence to support this ditch as one of the first acequias (also the ditch likely severed by American Indian invaders during the Pueblo revolt), as being a spring-fed ditch from the cienega that flows down palace avenue, directly in front of the *casas reales* (specifically the Palace of the Governors) and then turning south to rejoin the river. A historical document written in 1697-1698 specifically mentions the acequia's placement in relation to the post-Revolt church and convent: "which borders on the north side with the water ditch that passes in front of this Villa" referring to the *casas reales*, and more specifically the Palace of the Governors, with "its water drawn from a marsh above" (Pedro Rodrigues Cubero in Chávez 1949: 85). The microtopographic model and substantiated historical account bolsters the position of this acequia. When the model is symbolized using the lowest valued cells, a tiny arroyo results that passes almost perfectly down Palace Avenue, directly in front of the Palace.

After the field survey (Snow 1988) and microtopographic model combine in a GIS, a third technique completes the acequia network reconstruction: unsupervised classification of black and white aerial photography from 1936 and 1951 identified linear features of saturated land and connected missing segments of the network.[9] In arid environments, black and white images clearly identify areas of saturation with low-valued pixels. This third process effectively reconstructed over 8 km (5 mi) of additional acequias. Many segments appear as though they may connect; however, without confirmation from the microtopography model or image classification they were not joined. Although only 4.6 total kilometers (2.9 miles) of functioning acequias water the landscape of Santa Fe today, a total of 80.5 kilometers (50 miles) of acequias have been reconstructed in the historical network via the three techniques described above (Figure 7.O and Figure 7.P). Draping the final product on a 3-D landscape model shows the expansiveness of the network and its relationship to the terraces that parallel the river (Figure 7.Q).

Figure 7.O. Example of 1936 image analysis result
Source: imagery, USDA Forest Service (2005)

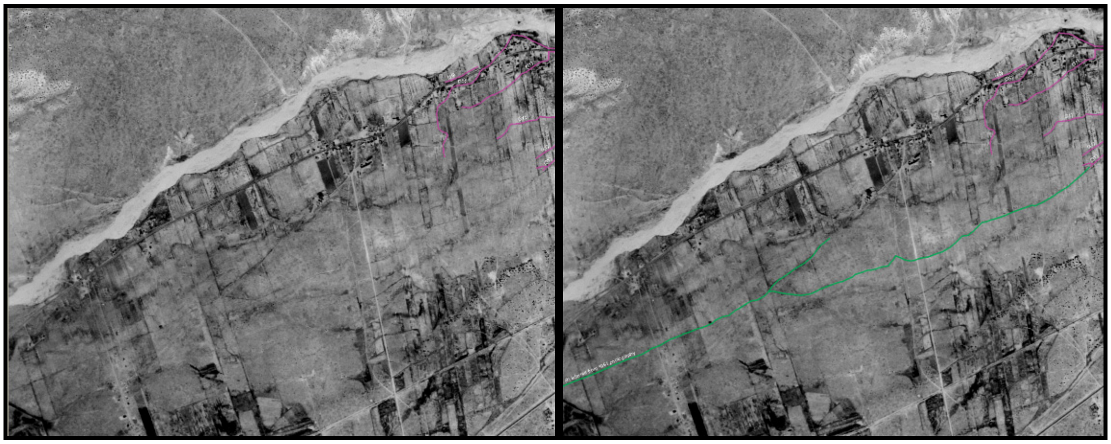


Figure 7.P. Example of 1951 analysis result
Source: imagery, City of Santa Fe (2005b)

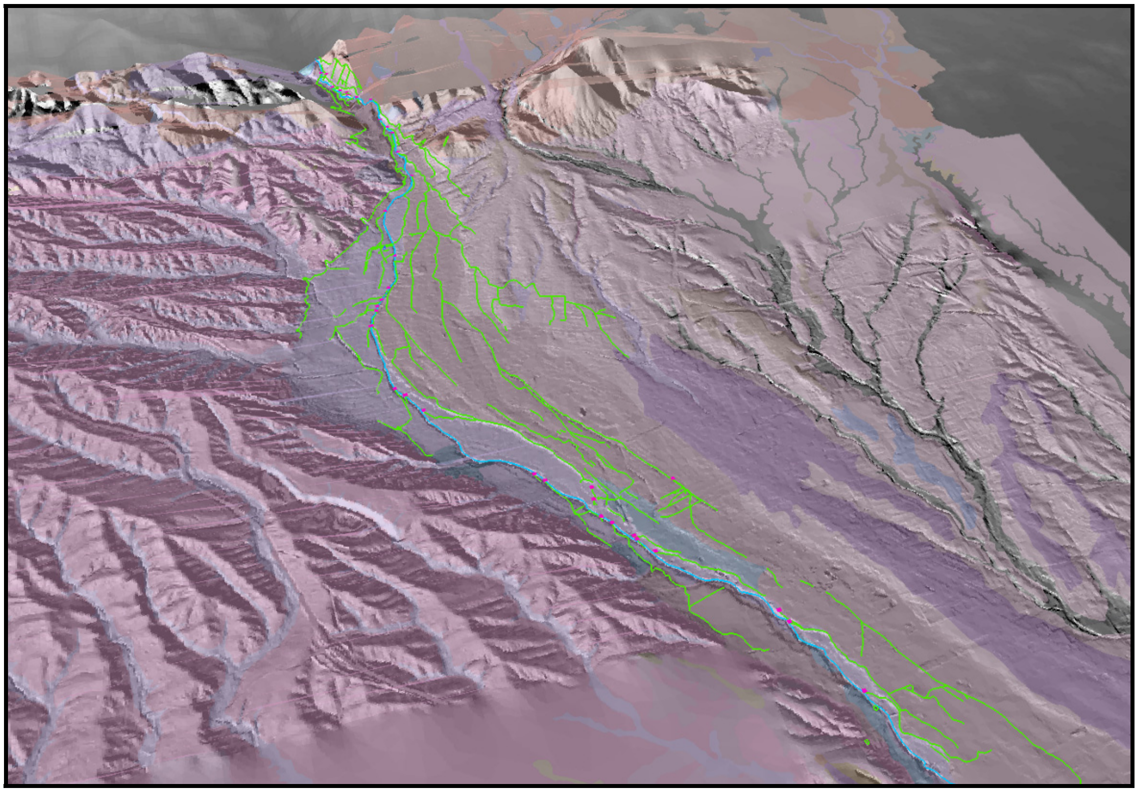


Figure 7.Q. Final result of acequia network reconstruction in 3-D GIS
Source: surface generated from LiDAR, City of Santa Fe (2005b); geology digitized from Spiegel and Baldwin (1963)

7.2.3 The Cienega Complex of Downtown Santa Fe

Existing literature discusses the cienega in downtown Santa Fe as a communal resource for grazing and hay cultivation (SANM I: 169), as the focus of an early land ownership dispute (Ebright 1994), and as a source of water to local fields (Museum of New Mexico 1846; Read 1927). To date, no other works have presented a collection of evidence to illustrate the physical origin of the cienega, or the interconnectedness of its features and the river. This research presents physical evidence to support the hypothesis that the cienega lies in an abandoned channel, or oxbow, of the river. A discussion of the cienega is relevant here because it was a hydrologic extension of the river, and it had important functions in the development of water resources in Santa Fe. In this research, the idea of a cienega complex is presented, along with its role in initial site selection, its relationship to historical landscape features (such as the Bishop's pond and surrounding acequias), and its genesis of the Rio Chiquito. This chapter discusses temporal changes in this important feature in the context of river decline, as well as the problems that the cienega "swamp muck" continues to create to this day.

In 1610, Governor Don Pedro de Peralta chose the villa's location for its water abundance, its favorable farming conditions, its lack of American Indian occupants, and its similarities to the ideal New World settlement sites described in the 1573 royal decree, *Recopilacion de Leyes de los Reynos de las Indias*. The river was flanked by a bosque or forested floodplain, wide and flat river terraces ideal for farming, and a nearby cienega or marshland later used as a community-owned pasture for settlers' and royal livestock, and hay cultivation. One of the most significant landscape features in the watershed from a resource perspective was the cienega (not to be confused with Cienega Grande or La Cienega, the small settlement several miles downstream). Translated as *marsh* or *swamp*, this wetland likely exceeded 38 acres (0.2 km^2) north of the river in 1610. It was a seminal water producer throughout the history of settlement until the early twentieth century, when references to its existence no longer appear in documents, newspapers, or on maps. Today the location once covered by lush grasses and gushing springs is a landscape of parking lots and buildings. The cienega's only modern-day reference occurs in the street name (Cienega Street) that bisects its past locale, lending little credence to its importance in the evolution of the city's physical layout and in settlement survival.

The river exits the steep slopes of the Sangre de Cristo Mountains guided by the Santa Fe River Fault. The river follows this plane of weakness until it departs the Precambrian schists and gneisses and beings to meander through the thick, high terraces of Quaternary alluvium that rest atop the Pleistocene alluvial fan deposits of the lower Tesuque formation (Spiegel and Baldwin 1963). At the canyon's egress the valley widens (around the point where East Palace Avenue meets Canyon Road), and the river turns slightly northward as it begins to wind through lower terrace alluvium. It is within the bounds of the lower terrace that the current channel meanders. The higher terrace limits river movement to the south; thus, any change in planform would occur northward. The physical divide between the high and low terrace is clearly visible on the landscape. As discussed in Chapter 6, the river meandered throughout the lower terrace to adjust to the stark change in slope at the mountain front. At some point in pre-Santa Fe time, the river flowed through the area that was to become the cienega, as there is no topographic or geologic barrier to inhibit the river from taking this course. To illustrate this point, rectified and digitized geologic units and faults are overlain on a LiDAR generated DEM in 3D-GIS software (Figure 7.R). An oxbow formed after the river abandoned this channel for another path. The geometry of the 1610 cienega mapped by Tigges (1990) (green polygon) would match precisely with the position of the abandoned river's floodplain if it had not turned southward some 150 m (492 ft) upstream from the Delgado Street bridge crossing. Physical evidence of a former riverbed near this location strengthens the hypothesis that the river once took this path through the cienega. Snow (1988: 22) reports on "a recent pipe-line excavation along East Alameda Street, just west of Delgado Street, running perpendicularly to the river, disclosed a gradual slope to the original ground surface from about 2.5 to 3 feet, from north to south. At a point some 60 feet north of the present sidewalk, the old river bed, covered by several feet of silt, indicates a fairly wide former channel at this point." A green star added to Figure 7.U indicates the approximate location of Snow's observation.

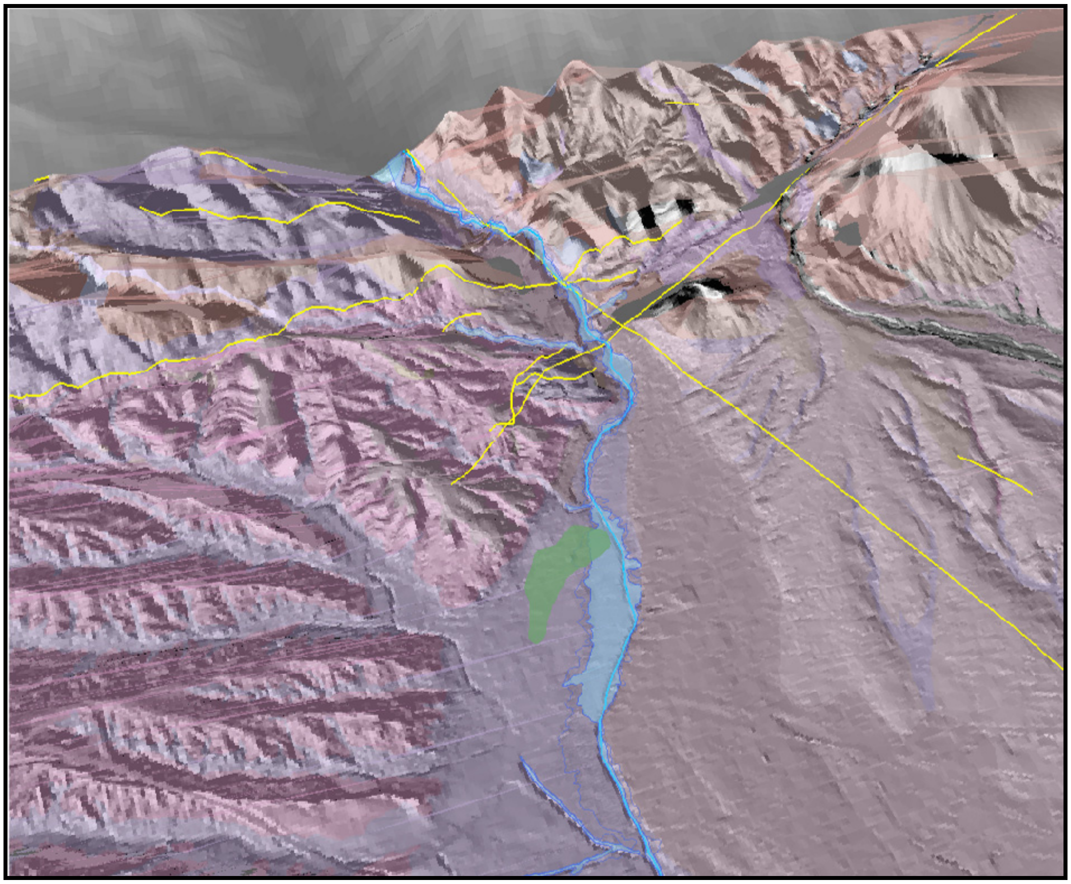


Figure 7.R. Geologic and hydrologic features modeled in 3-D GIS
Source: surface generated from LiDAR, City of Santa Fe (2005b); geology digitized from Spiegel and Baldwin (1963)

After changing position to reflect its present course, the abandoned oxbow filled with sediments and organic detritus over time. The bluffs to the north and east deposited sediment into the oxbow via hillslope processes, while the river's overbank flows contributed finer silts and clays. As wetland plants colonized the area, a large amount of organic material accumulated because the saturated conditions did not encourage decomposition. The troublesome "swamp muck" formed as a result. Speigel and Baldwin (1963: 139) believe the cienega springs "probably represent discharge of the water in terrace-gravel lenses that were interbedded with impermeable carbonaceous swamp deposits." Recent soil tests in downtown Santa Fe in the former cienega show the highly organic upper layer of the "swamp muck" at the base of the pit (Figure 7.Sa). The right image (Figure 7.Sb) shows a close-up of the alluvial strata beneath the clayey muck. Redoximorphic features laminate these silts and sands: oxidized root channels are indicative of a high water table for at least part of the year. This series of geomorphic processes is not unique to Santa Fe: the Pecos River (also in the Sangre de Cristo Mountains) has similar landforms (Figure 7.T).

Figure 7.Sa. "Swamp muck" under modern construction fill
Figure 7.Sb. Redoxamorphic features within alluvial strata below "swamp muck"
Source: Museum of New Mexico (2009)

The cienega was not simply a result of hillslope runoff infiltration at the base of the nearby bluffs as Vargas believed in 1693, when he described how "the waters gather from the surrounding mountains and mesas" (Twitchell 1925). Seepage from this process may have contributed to the total volume of water emerging from the cienega, but were it not for the existence of a past river oxbow, groundwater would have flowed westward in a sheet following general topography, and the plaza, *casas reales*, and convent would have been sited elsewhere. The pre-historic Kaupoge pueblo found in recent excavations beneath the newly constructed Santa Fe Convention Center in 2007 also sits beyond the wetland's limits; construction activities found no wetland soils or evidence of reducing environments (Figure 7.U). It is probably not a coincidence that the original plaza's spatial extent surveyed by Peralta in 1610 (although its exact dimensions are speculative) fits neatly between the Rio Chiquito and Palace Avenue, bounded on the north and east by the cienega. It is also remarkable that after rectifying the Urrutia Map of 1766 in a GIS, that the cienega polygon fits neatly within all of the mapped buildings (Figure 7.V).

The highly erodible, unconsolidated lower terrace gravels are also highly permeable (Spiegel and Baldwin 1963), conducting groundwater towards the cienega as it exits the canyon. The Tesuque formation has low permeability beneath the lower terrace in this particular locale; thus, water is perched atop the unit, and confined within the gravels (*ibid.*). The shape of the cienega is also important: the previous rivercourse created a substructural guide for groundwater flow. The wide base near the river indicates the majority of water feeding the cienega comes from river-generated subsurface flow, not simply the surrounding hillsides. Although the main source of cienega water was river-generated subsurface flow, it is highly likely that the unlined Acequia Muralla, which follows the base of the bluffs around downtown Santa Fe (shown in Urrutia's map of 1766 as the northern *acequia para regadio*), also contributed water to the cienega via seepage of ditch water downslope (Figure 7.V).

Peralta undoubtedly foresaw the usefulness of the cienega. First, the cienega acted as a supplemental water resource to the river. Undoubtedly, the river was the major water source for the settlement, but the springs of the cienega should also be given credit for attracting settlers to this site for several reasons. Spiegel and Baldwin (1963) believed that it was the cienega, and not the river, that was the main attractor to settlement. They note that throughout the rest of the watershed, settlements occurred where there were significant marshes and springs. The availability of water in the river for irrigation in dry years was limited, and the cienega sustained irrigated agriculture for many of the surrounding family fields north of the main watercourse. Gilmer's map in 1846 clearly depicts evidence of the cienega's use as an irrigation source: a spring and irrigation canal appear radiating from the center of the swamp (Figure 7.Y).

Second, the cienega was the primary source for hay and pastureland for royal livestock (SANM I: 169, Reel 8, Frames 145-160). deBuys (1985) discussed the importance of community lands in the customs of New Mexican settlers. The idea of communal sharing of natural resources was deeply ingrained in Spanish traditions, and for centuries, dominated the management of land and water in the Sangre de Cristo Mountains. Evidence of its use in this regard in Santa Fe is found in primary documents

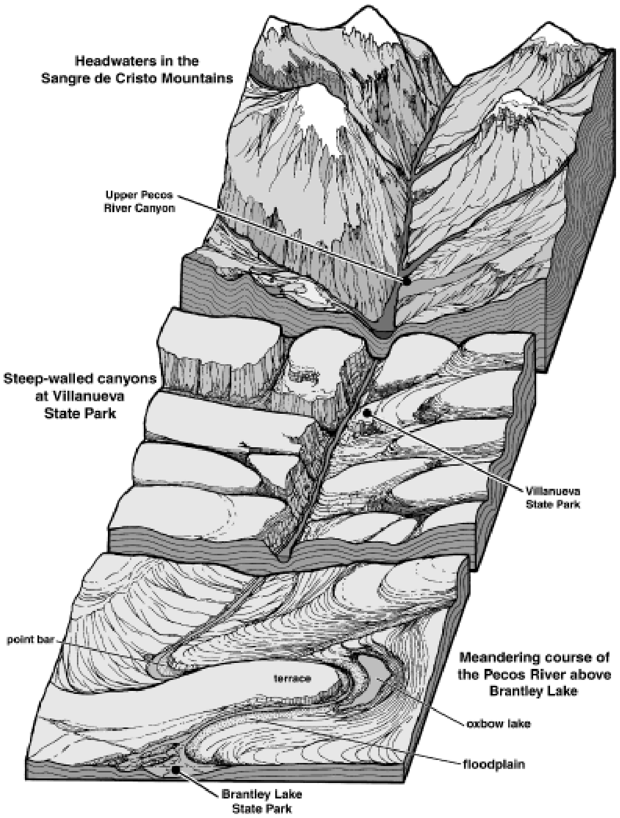


Figure 7.T. Process of oxbow lake formation, base of the Sangre de Cristo Mountains
Block diagram of the Pecos River south of Santa Fe
Source: New Mexico Bureau of Geology & Mineral Resources (2009)

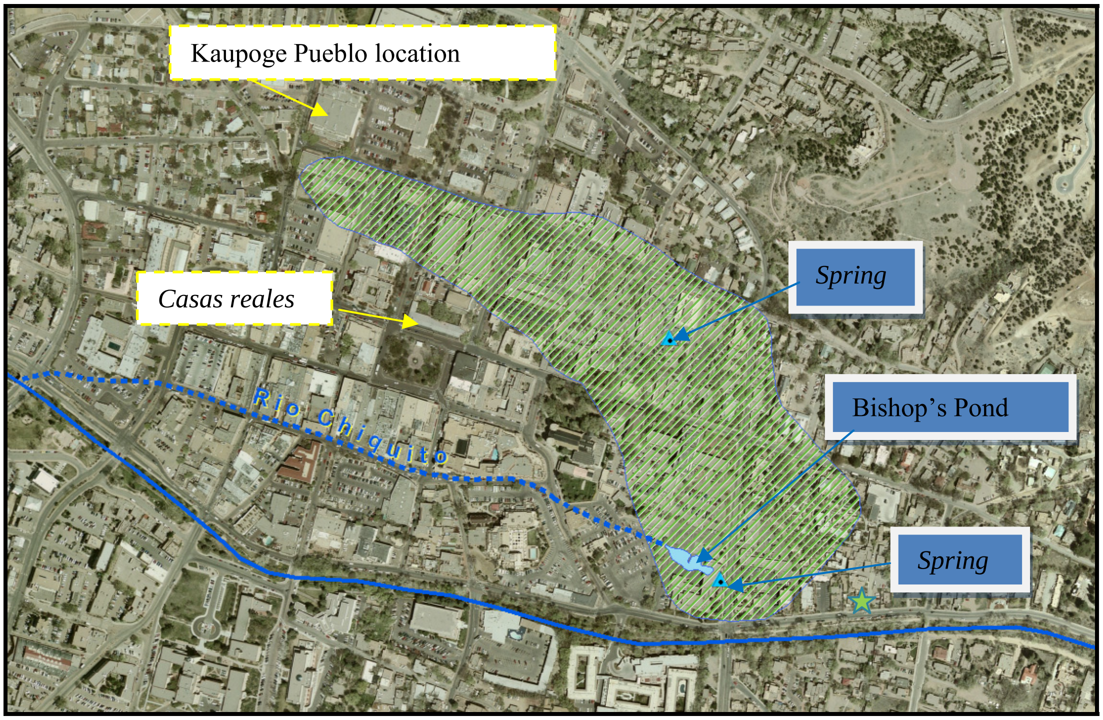


Figure 7.U. 1610 cienega extent, with springs, Bishop's Pond and Rio Chiquito
Source: Cienega extent rectified and digitized from Tigges (1990); other features by author; imagery, City of Santa Fe (2005b)

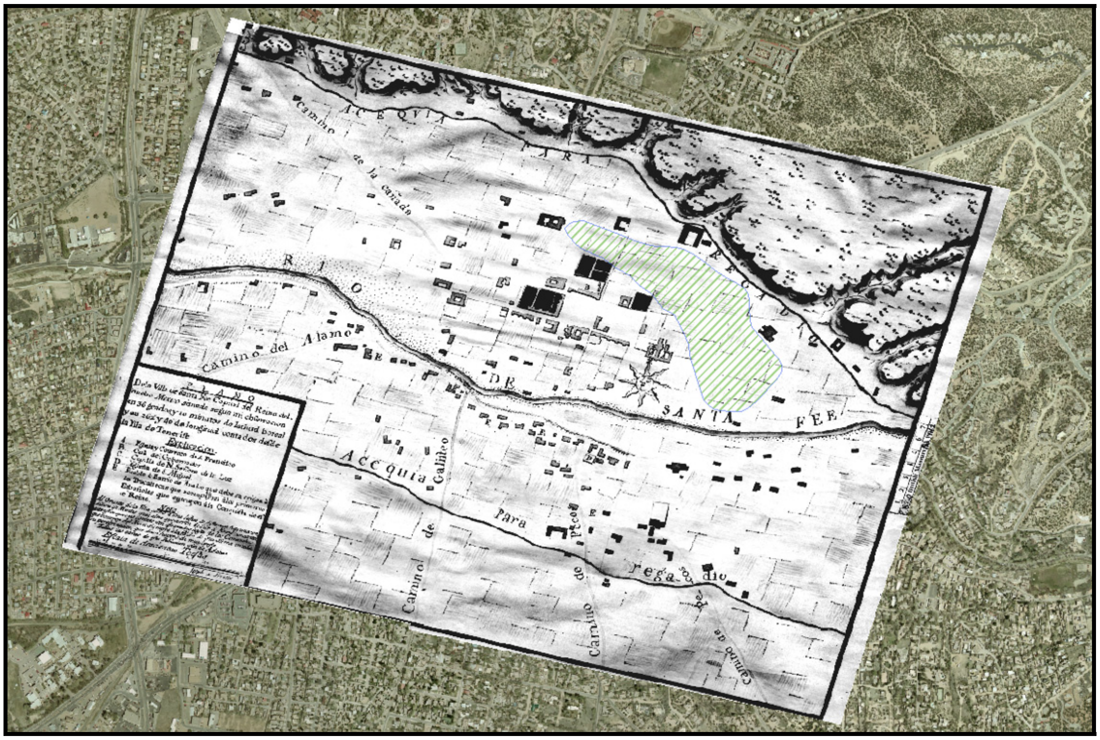


Figure 7.V. 1610 cienega extent on rectified Urrutia Map
The cienega remarkably fits within all structures
Source: Cienega extent rectified and digitized from Tigges (1990); Urrutia Map, Museum of New Mexico negative #15048; imagery, City of Santa Fe (2005b)

from 1716 (SANM I: 169, Reel 8, Frames 145-160), and chronicled by Ebright (1994). Community grazing land appears in mid-nineteenth century photographs before it disappeared; for "it is true that from said cienega the horses of the soldiers and citizens are maintained" (SANM I: 169, Reel 8, Frame 159). The cienega remained in community ownership until being sold around 1828, and despite private ownership, remained an open area for grazing well into the early twentieth century as evidenced by paired historical photography (Figure 7.W; Tigges 1990). In the lower left corner of Figure 7.Wa, a depression that was once a pond still has a wet center, and was likely centered on one of the cienega springs. There appears to be an acequia in the earlier photograph that cuts through the cienega from upper left to lower right. The saturated ground is evident in the darker grasses. Houses replaced the cornfield in the foreground within a few decades (Figure 7.Wb). In the second image, horses are seen grazing in the open area mid-left, and the early footpath to become Cienega Street bisects the wetland. The area once a pond is now vegetated. The marshland was also a popular duck-hunting site until its dewatering (Snow and Snow 1991).

Third, the cienega acted as a natural barrier for defense. The expansive 1610 cienega, as discussed above, followed the topography of the surrounding landscape, curved convexly from north to west, and created a deterrent to invaders from the surrounding hillsides. A bosque, watered by the cienega, likely created a thick deterrent to invaders from the north (Snow and Snow 1991). The cienega's presence was not always viewed positively, however. In 1693 during the resettlement, Vargas reported to the Viceroy that the original site was "cloudy and abounding in water, with heavy frosts and ice, and due to its shade and thick fog and mists of known and evident detriment, the said place is unsatisfactory" (Twitchell 1925). Ultimately, his request to move the *casas reales* to a different location was denied; however, the climatological explanation for the mists of "known and evident detriment" begins with the extreme diurnal temperature changes in Santa Fe due to its altitude, and the semi-arid environment rapidly radiating heat through the dry, thin atmosphere (Spiegel and Baldwin 1963). Because water heats and cools less rapidly than air, the water in the cienega would remain warmer through the nights when the air above it cooled. Localized fog formed above the cienega when the water began to evaporate. After being cooled by the cold air above it, the moisture condensed and formed the "thick fog and mists" that Vargas deemed unsatisfactory. Reflecting on the written account that the cienega created detrimental mists, archaeologist David Snow (2008: personal communication) believes that after the Reconquest, the cienega was used as a dumping ground for refuse in order to decrease its spatial extent. He believes adobes and historical "trash" from deconstruction of the pueblo built atop the *casas reales* during American Indian occupation, and from other demolished buildings over the centuries was used as landfill.

Also part of the cienega complex were several long-standing springs that surfaced within the wetland and functioned as perennial, reliable water sources for the villa (Figure 7.X; Museum of New Mexico 1946; Reed 1927). Captain Miguel Thenorio de Alva was interviewed in July of 1716, and swore under oath that around 1650 there were three springs in the cienega, and that he knew of their locations "because the pressure of the veins was such that they gushed" (SANM I: 169, Reel 8, Frame 160). The other predominant spring was located in the southern part of the cienega complex on the convent property. This spring, which fed the Bishop's pond, was referred to in 1716 as “the old one behind the convent,” and must have been a long-standing landscape feature, and present prior to the Pueblo Revolt in order to be referred to as *old* in 1716 (SANM I: 169, Reel 8, Frame 160). This spring had two important functions in the history of Santa Fe: (1) source of water for the Bishop’s pond, and (2) source of water for the Rio Chiquito.

The Bishop’s pond was not a natural feature. It was likely created in the cienega on parochial property prior to the Pueblo Revolt due to the 1716 reference that it had “been for a long time open, behind the *convento*” (SANM I: 169, Reel 8, Frame 151). The earliest mention of the pond is in 1705 (SANMI I: 169). The pond was a physical landscape feature for centuries until the early 1900s, when it was filled prior to the construction of St. Francis School. Although not included on Urrutia’s Map in 1766, it must have been present due to the chronology of older references. Gilmer drew the pond and spring on his 1846 map, but the orientation of the feature is wrong, and because of his cartographic error, the proper spatial size, position, and orientation of the pond misled archaeologists for decades (Figure 7.Ya and Figure 7.Yb).

This research presents the proper placement of this important hydrologic feature using modern GIS techniques.[24] The finished product provides the first correct glimpse of the Bishop’s pond and convent spring in decades. The siting of the pond also explains an important hydrologic connection between the pond and the Bishop’s Garden acequia, a relationship that was only an inference up to this point. Although several references to this ditch exist in the historical record (Horgan 1975, State Engineer’s Office 1914), this research establishes a clear connection between the pond’s outlet and the ditch surveyed by Snow (1988), and confirms the Bishop’s pond’s function as an alternative source of water to the acequia network (Figure 7.Zb). Refer to Snow (1988) for historical details of each individual Santa Fe acequia. The pond provided an important function for the Archdiocese. The Catholic Friars used the pond for aquaculture: on Fridays and during the Lenten season, Catholics abstain from consuming meat, and the pond provided the fish for their meals (Snow2006: personal communication). The species of choice was carp (*Cyprinus carpio*), as indicated by a notation on the 1887 photograph (Figure 7.Z).

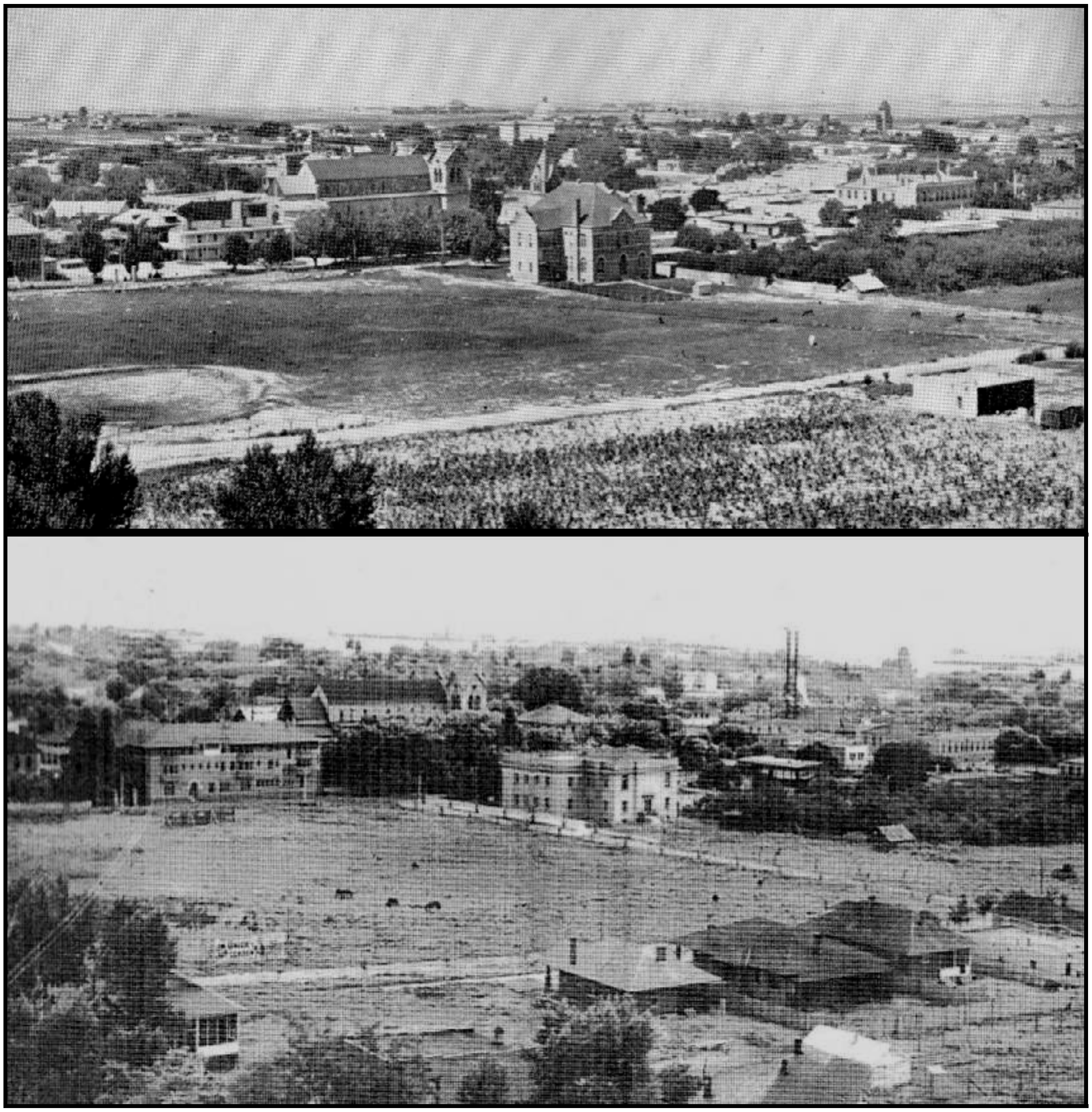


Figure 7.Wa and 7.Wb. Paired photography of the cienega area, downtown Santa Fe
In 1895 (a), and early twentieth century (b)
Source: a, Huntington Library Collection in Beck 1962; b, Museum of New Mexico S. Loomis Collection, Box #135, Folder 2, Image 21945/21942

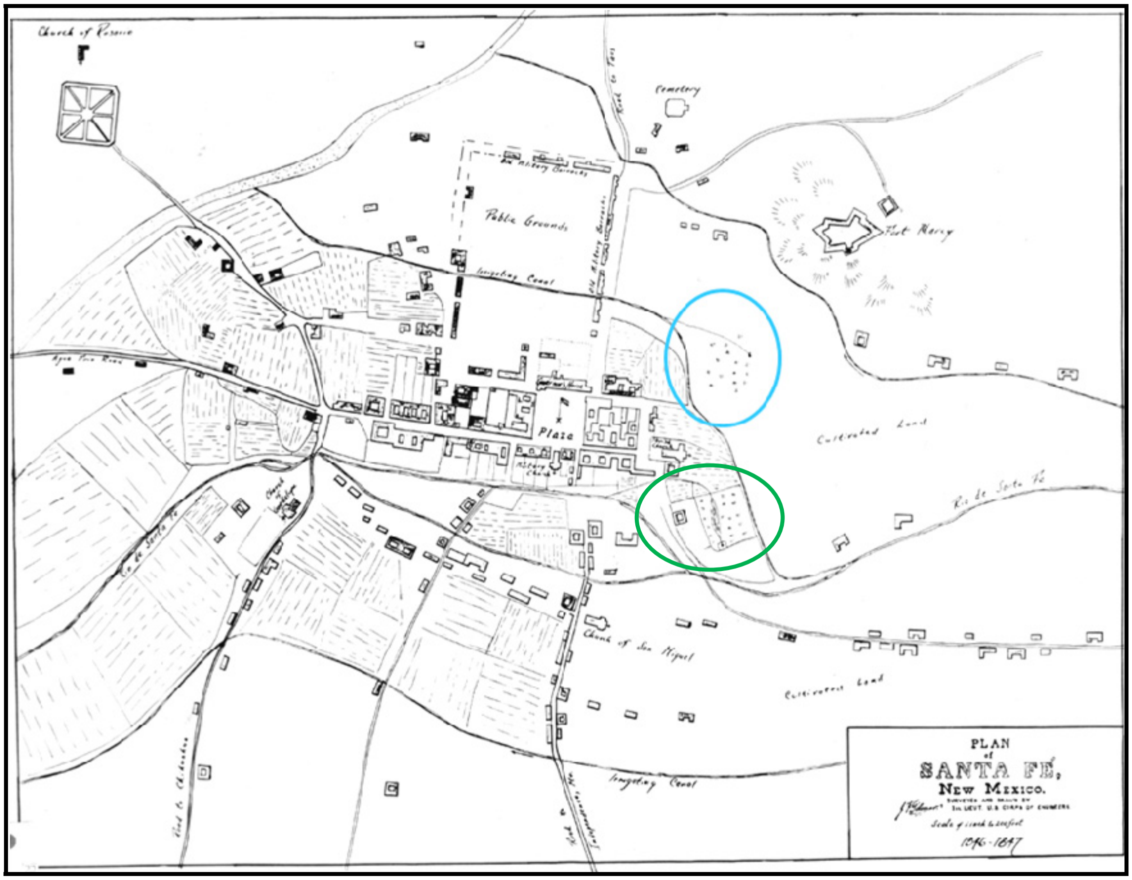


Figure 7.X. Gilmer map of 1846-47 with highlighted features
Cienega (blue circle) with spring, and irrigating canal within it; Bishop's pond and spring indicated with green circle
Source: Museum of New Mexico (1846)

Cordelia Snow (anthropologist at the Laboratory of Anthropology in Santa Fe) theorized that whiskered fish caught in the river in the late 1800s were actually escaped carp from the Bishop's pond. Snow believes that carp traveled through the acequia network (or Rio Chiquito) and into the river, and these references were not to a native species of catfish (Snow 2008: personal communication).

The Rio Chiquito was one of the most important hydrologic features in Santa Fe. Its genesis was the Bishop's Garden spring near the southeastern most corner of the convent property (Figure 7.X). This watercourse was part of the cienega complex, and a tributary to the river. The tiny channel functioned as a water source for irrigating the fields between it, and the river to the south. It was also one of the earliest referenced, most important landmarks in Santa Fe, and acted as a property boundary; listed in many land claims post- Revolt (Snow 1992). Although no references to this feature appear in the historical record prior to 1697, there is speculation among anthropologists that prior to the Pueblo Revolt, the Rio Chiquito formed the southern boundary of the original Plaza (Snow and Snow 1991; Snow 2006: personal communication). Before the desiccation of the cienega, it is likely that the Rio Chiquito also acted as an open sewer, conducting wastes downstream to the river. After its disappearance, the previous channel was fittingly named Water Street (Figure 7.AA).

The watercourse has been hypothesized as having been a side channel, an acequia, and the main channel itself (Snow and Snow 1991). From a geomorphologic perspective, a "side channel" would be a braid bar or meander cutoff; however, Chapter 6 discussed the compound nature of the channel in downtown Santa Fe, and these hypotheses do not fit with the physical evidence. Present findings indicate that this "side channel" hypothesis originated with the Gilmer Map of 1846-47, on which he drew the Rio Chiquito as though it was connected to the main channel (Figure 7.X). This map is the singular piece of evidence that indicates such a hydrologic connection ever existed. After examining the local topography, GIS-modeled flow accumulation grid, historical documents, maps, conducting interviews, and perusing the literature, I believe that the Gilmer map has incorrectly persuaded current opinion to include this connection as a viable hypothesis. Without the depiction of a Rio Chiquito connected to the river in this map, I believe that this idea would never have entered into the minds of historians. All other known references in textual documents indicate that the Rio Chiquito was a tiny stream that flowed down slope from the Bishop's garden spring, until it contributed to the river near the Guadalupe Church. I believe that information on the Gilmer map should not be used to make conclusions about the physical geography of Santa Fe because: (1) of the incorrect placement and orientation of the Bishop's pond and spring, (2) the river and Agua Fria street are transposed in the western portion of the map, and (3) the original Emory and Gilmer plat of 1846 (the precursor to the Gilmer map) makes no physical connection between the Rio Chiquito and the river (the Rio Chiquito is not even present). This research refutes the idea that the Rio Chiquito was ever part of the river in the last four-hundred years, aside from its contributions as a small tributary. As discussed in Chapter 6, it is likely that the river tried to capture the Rio Chiquito during the 1767 flood

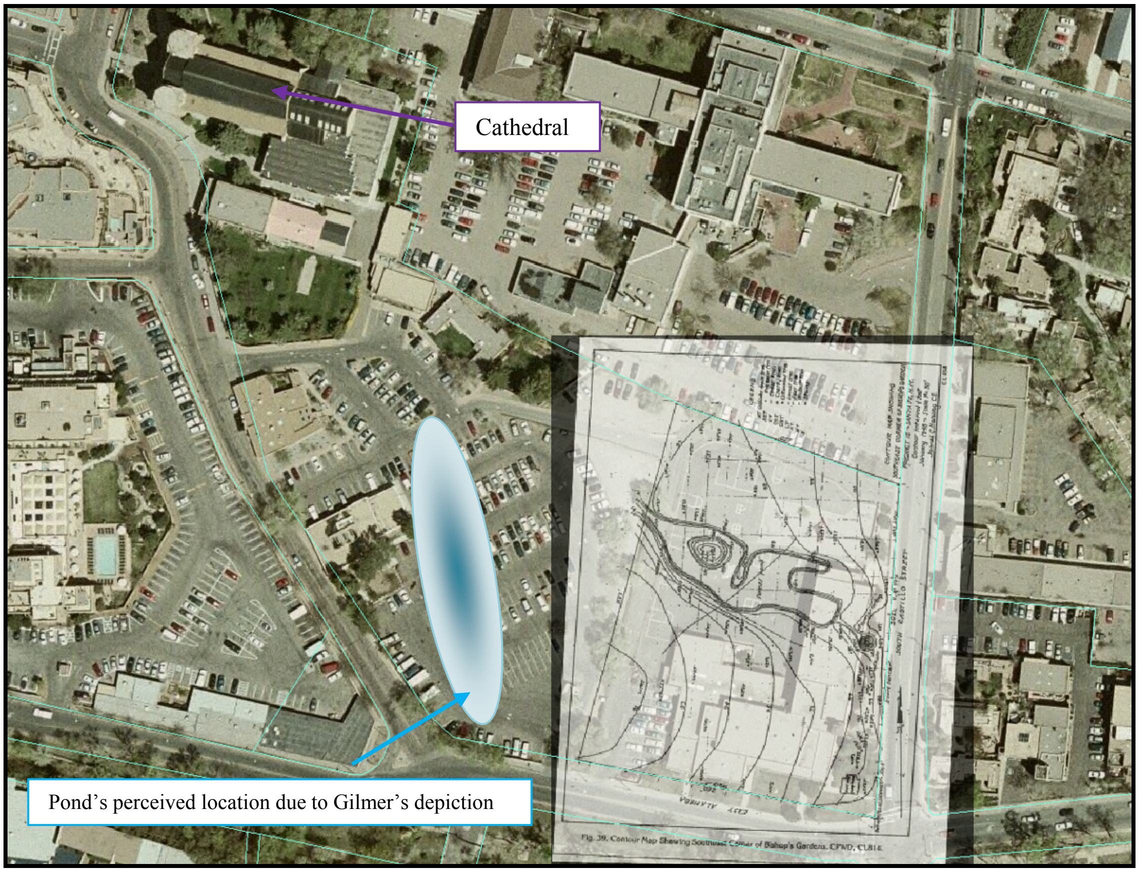


Figure 7.Ya. Rectification of Bishop's pond survey and placement of Gilmer pond
Source: Plat, Snow (1988); imagery and parcels, City of Santa Fe (2005b)

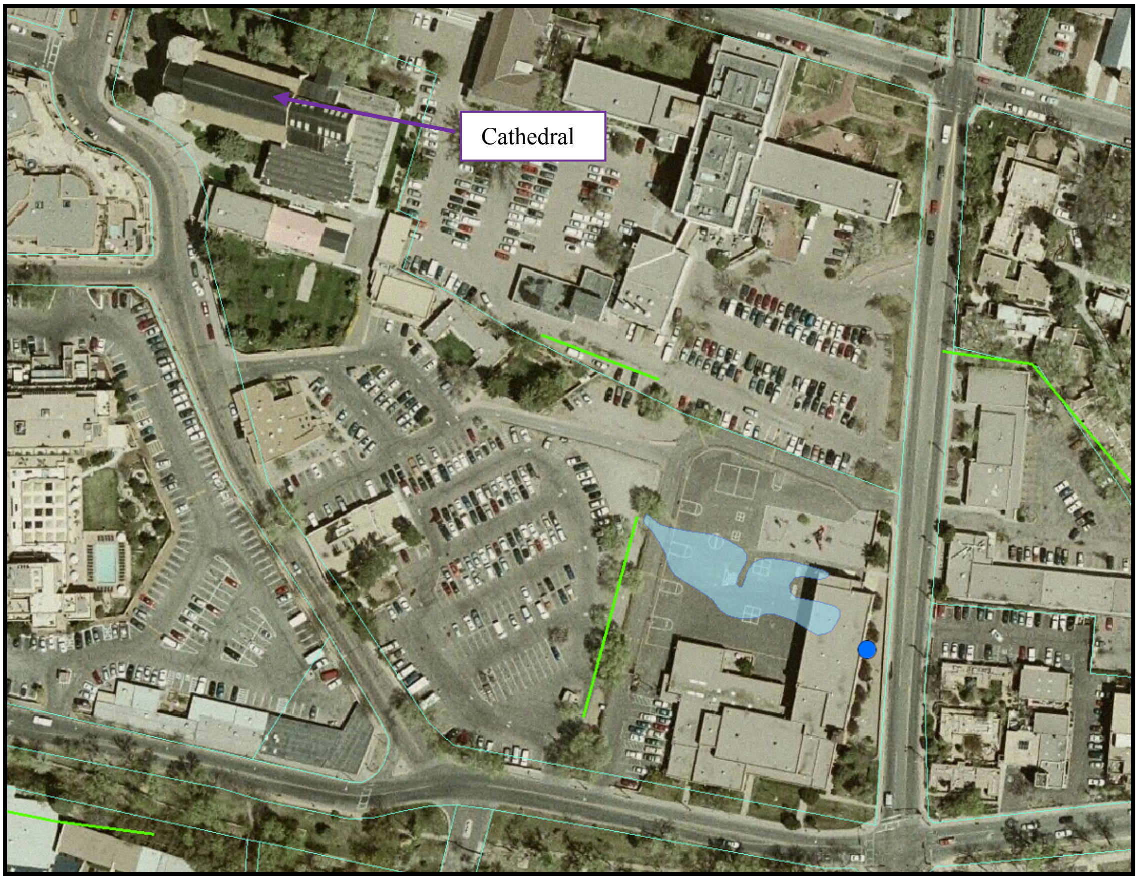


Figure 7.Yb. Proper size, shape, and orientation of Bishop's pond and spring
Acequias are green linear features
Source: imagery and parcels, City of Santa Fe (2005b)

Figure 7.Z. Paired images of carp pond in the Bishop's Garden, ca. 1887 and 2008
Source: Museum of New Mexico, negative #15264; photo by author (2008)

event, thus rerouting its main course, but local efforts confined the river to its original path. Snow (1988) noted that the sediments found in the pipeline excavation near Delgado Street might have been the place where the Rio Chiquito split from the main channel (marked with a green star on Figure 7.U). This research has shown however that these river sediments were likely part of the previous channel that flowed through the cienega.

Figure 7.AA. View of Water Street today, facing "downstream"
Source: photo by author (2006)

The conversion of Rio Chiquito to Water Street occurred sometime in the late 1800s. Efforts to modernize Santa Fe included street improvements to the muddy swale. On March 23, 1881, a report in *The Santa Fe New Mexican* mentioned, "…Water Street cannot be made straight, but when the commissioners and committee get through with it, it will be vastly improved" (Ellis 1976: 226). Sanborn Maps in 1883 show Water Street as a roadway. Sometime after December in 1890, an electricity-generating steam plant capable of producing 25-kilowatt hours was constructed on Water Street (Sanborn Mapping Company December 1890; Santa Fe National Forest 2001). By 1898, Sanborn Maps show the steam plant at 224 Water Street as a one-story structure "built for elect. light plant" with one boiler not in use, and listed as vacant. The steam plant reportedly used local (perhaps Rio Chiquito or Bishop's spring) waters to generate a small amount of electricity, but was run "at intervals" after 1895 after the construction of a new hydroelectric plant on the river, capable of producing 100-kilowatt hours (Figure 7.BB; Santa Fe National Forest 2001; Sanborn Mapping Company 1898). The Water Street Steam Plant continued to expand over the decades to provide additional electricity during times of low flows on the river (Sanborn Mapping Company 1898, 1902, 1908, 1913, 1921, and 1930).

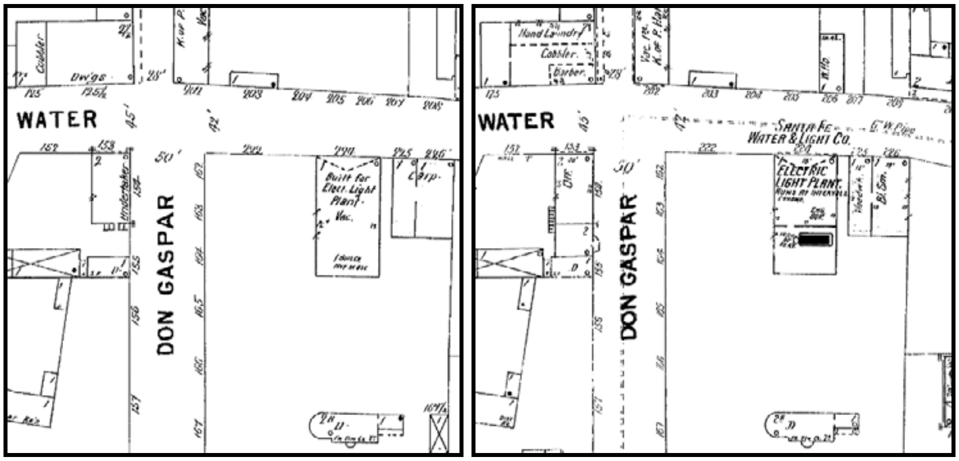


Figure 7.BB. Water Street Steam Plant on Sanborn Fire and Insurance Maps
June 1898 vacant electrical plant (left), December 1902 plant expansion (right)
Source: Sanborn Mapping Company (1898), (1902)

Given the current landscape of downtown Santa Fe, with its large expanses of impervious surface and adobe-style structures, it is difficult to envision a saturated Santa Fe. Because the groundwater in the thin terrace sediments of the cienega complex are hydrologically connected to the river, once changes to river hydrology and dewatering began in the late nineteenth century, water in the cienega springs, Bishop's pond, and Rio Chiquito was not recharged and the features disappeared. The diversion of shallow groundwater into cones of depression via well pumping around downtown exacerbated the drawdown of the aquifer.

However, the drying of the cienega increased the expanse of developable land within walking distance to the Plaza. To take advantage of the increasing land values in the late twentieth century, engineering techniques further drained the area; boulder-filled trenches were dug to the river in attempts to conduct moisture out of the cienega (Spiegel and Baldwin 1963). Despite the dewatering, the “swamp muck” has continued to create problems with modern construction and at times, seeps have made their way into several downtown basements (Snow 2006: personal communication). Around 1990, when the Inn of the Anasazi on Washington Avenue was under construction, workers encountered a spring, and the “dense, gunky muck” created problems for the typical piled-foundation parking garage planned for the site. As a result, engineers changed the parking garage design to a “floating” type garage: the foundation, constructed of a concrete and EPS-foam sandwich, has a lightweight floor that literally floats on the ground surface (Snow 2008: personal communication; Quadriga 2009). The malleable muck has frustrated Public Works engineers on countless occasions: sections of Washington Avenue now rest on a geo-textile fabric. In parts, the muck as been excavated and replaced with sand, and on the southernmost end of the street, replaced with massive chunks of concrete (Tigges 1990). Despite many contemporary efforts, as the organic-rich sediments of the cienega continue to degas, the rigid impervious surfaces above it will continue to crack and buckle.

7.3 LOWER REACH FUNCTION

Until modern times, lower reach functions included conducting water and sediment downstream, recharging groundwater, supporting riparian communities and wildlife. As discussed in Chapter 5, springs supplemented lower reach flow at particular locations, and any harvestable water in the river was used for irrigation. The river also watered livestock, and to this day, cattle wade into the lower reach throughout most BLM lands in La Bajada. Classified as a marginal cold-water fishery and warm water fishery, the lower reach is suitable for secondary contact recreation such as fishing or boating (Whitworth 1995). Section 7.3 moves beyond these traditional roles to discuss the contemporary functions of the lower reach, including: (7.3.1) sand and gravel mining from the riverbed, (7.3.2) the river as a corridor for waste disposal, and (7.3.3) uranium mining in La Bajada.

7.3.1 Sand and Gravel Mining

Water is not the only product that generates revenue from the river. At some point between 1951 and 1960, sand and gravel mining of the dewatered riverbed began in earnest below Agua Fria (Grant 2002). Aerial photography from 1951 does not show definitive evidence of the practice; however, aggregate removal from the channel on a limited basis was possible despite no telltale signs of stockpiling or equipment access points. The adverse effects of this practice are discussed in Chapter 6; however, there are negative impacts on other river functions as well. The remaining riparian flora and fauna have been destroyed by heavy equipment operation. Water withdrawals used to wash materials on-site and to control dust have drawn down the local water table, affecting local residents who rely on well water (Vasquez 2001). These environmental changes have encouraged the growth of invasive species, like Tamarisk (*Tamarix ramosissima*) and Russian-olive (*Elaeagnus angustifolia* L.). Residents also attest to a reduction in the aesthetic qualities of the river due to equipment noise, air pollution from dust and diesel fumes, and river flows that resemble mud due to the unconsolidated sediment in the disturbed channel bed (Salazar 2002).

Despite the obvious physical and human impacts, the sequence of events that led to river sand and gravel mining are vague. Archival research, interviews with local residents, county and state officials, and historical aerial photography investigations assemble only a partial timeline. Newspaper accounts note the practice has been happening since 1962 (McKee 2002). Owners of land flanking the river leased land to miners, and several parcels were purchased for aggregate removal. Sometime between the mid-1960s and mid-1980s, Santa Fe County began the practice of issuing permits. In 1991, the county passed a mining ordinance, establishing designated zones for the practice; mines not situated within the designated zone were eligible for grandfathering if an application was filed (McKee 2002). Aside from the mining permits, there has been very little regulation and oversight of the practice. Despite removing massive volumes of material from the channel bed, and operating heavy machinery within the channel, no state or federal permits are required. New Mexico state law does not cover aggregate mining, and Section 404(a) of the federal Clean Water Act only applies to dredge and fill materials, including incidental fallback from equipment (Blodgett 2004; *National Ass'n of Home Builders v. U.S. Army Corps of Engineers*, No. 01-0274 (D.D.C. Jan. 30, 2007). There is no law against *removing* material from a waterway, especially since the material is not being stored. Litigation between the county and M & R Mining Company (the last in-stream miner) continued until 2004, when upon reaching a settlement, the county put the land into conservation easement included in the San Ysiedro Park restoration. Without this proactive action, material removal would have continued to threaten the multi-million dollar channel restoration work done downstream of San Ysiedro crossing (Chapter 8, Section 8.1.2).

7.3.2 Waste Disposal Corridor

Humans have been using rivers for waste removal since antiquity because their unidirectional flow continuously moves unwanted substances downstream (Knighton 1998). It is likely that the river has transported human-generated wastes downstream since settlement. Peralta considered waste removal via the river during settlement and villa planning, for he insisted, "buildings that cause filth be placed on the (opposite) side of the river… below the town" (Chávez 1985: 2). There is historical documentation of tanneries west of the plaza in the 1630s through the 1830s dumping their waste streams directly into the river (Snow 2009: personal communication). The Rio Chiquito is theorized by some anthropologists to have acted like an open sewer (Snow 2008: personal communication), and although the disposal of waste into acequias was against community rules, it inevitably was done (Rivera 1998). Sanitation in Santa Fe created problems over the years: until the mid-1900s, hundreds of privies dotted the landscape, and the poorly managed wastes caused numerous outbreaks of typhoid and cholera (Snow 2009: personal communication). After the incremental installation and raisings of upstream dams in the late 1800s and early 1900s, flow through the urban and lower reaches were limited to stormflows and contributions from springs. The lack of in-channel water meant residents could no longer rely on the river as a waste remover.

The first wastewater treatment plant (by today's Gonzales Elementary School), constructed in 1923, had two lagoons for settling and was used to irrigate the state prison farm (Lang 2006: personal communication). By 1924, the earliest known sewers were directing their wastes to this small facility (Snow 2009: personal communication). The second treatment plant, upstream from Camino Alire, consisted of two Imhoff tanks that clarified the sewage by settling, sedimentation, and anaerobic digestion (Lang 2006:

personal communication). These tanks discharged water into irrigation ditches during the growing season, and into the river the rest of the year. The third wastewater treatment plant in Santa Fe, built on Siler Road in 1941, was a trickling filter plant that discharged into an open ditch in Agua Fria, and only resulted in discharges to the river during the winter months due to the sale of effluent for irrigation purposes (Lang 2006: personal communication). Although the upper and urban reaches carried some wastewater and much stormwater over the years, today it is the lower reach that functions as the main recipient and remover of waste flows from Santa Fe.

Complete lower reach dewatering occurred until the installation of the current WWTP below the sand and gravel mines in 1963. With the addition of about 5.8 mgd of nutrient-rich effluent to the channel, the city's Paseo Real Wastewater Treatment Plant returned additional functionality to the desiccated, incised river (City of Santa Fe 2009a). The Clean Water Act of 1972 required EPA to promulgate federal regulations establishing guidelines for pretreatment programs, effluent limits for discharges to rivers, a permit program for point source emitters, and water quality criteria, among others (Percival *et al*. 2003). The laws outline the specifications for wastewater treatment before discharges to the environment occur. The wastewater processing required by law involves three phases: pretreatment, primary treatment and secondary treatment. The product of these treatment phases is suspended solid-free water that contains elevated levels of nutrients, and with its discharge to the channel, some functionality returned as well. Between 1963 and 1996, the artificial streamflows supported uncontrolled cattle grazing below the plant, and their access to the riparian corridor denuded most of the riparian vegetation (Johnson 2004). Now, due to restoration efforts including corridor fencing, dense streamside vegetation lines the channel banks. These restoration efforts are collaboration by the city, and Forest Guardians, a non-profit organization (Chapter 8, Section 8.1.3.1). Other benefits of effluent discharge include higher water levels in wells surrounding the treatment plant; estimates of up to 330 acre-feet per year are likely returned to the aquifer (Lazarus, Drake, and Shoenfeld 2007). Livestock watering has been restricted to fenced areas, and riparian habitat for amphibians, fish, and birds has returned.

The laws associated with discharged effluent are complex. New Mexico law states that despite the possession of water by the city, it is property to be put to use, and discharging the effluent is not seen as the best way to do so (Lazarus, Drake, and Shoenfeld 2007). Today, the city sells some of this effluent to local businesses for industry and irrigation, and benefits greatly from this huge revenue-generator: water prices have gone from $85 per acre-foot water right in 1967 to $12,000 per acre-foot water right in 2007. Downstream users argue with the city over the sale of effluent, believing they are entitled to its delivery. However, New Mexico has adopted a statute recognizing that water rights for effluent may be created; however, the rights of the first owner (in this case the city) are superior. Thus, downstream farmers may have the right to the effluent in the stream, but they have no recourse if the city decides to stop or redirect the water to other uses (Lazarus, Drake, and Shoenfeld 2007). The restriction of effluent discharges is highly unlikely however, given that the Interstate Stream Compact (i.e. Rio Grande Compact) requires the city to return water to the river, and some of this return flow requirement is met through the effluent discharges (Kleyman 2007).

7.3.3 Uranium mining in La Bajada

The history of mining in La Bajada begins in the early twentieth century. Although water from the river was not known to be directly applied to the uranium mining process, its discussion is relevant here because the adverse effects of local mining operations have the potential to impair river function. Mining began in the canyon in 1928, after the discovery of copper twelve years prior to its extraction. In a single year, the two shafts owned and operated by the La Bajada Copper Mining Company produced 8.8 metric tons of ore, from which 680 gm of silver and 1099 kg of copper were shipped off-site and smelted (Chenoweth 1979). In 1950, miners discovered uranium. Its withdrawal began in 1956. The underground shafts produced the ore for only one year before the underground structure became unsafe, and the removal method changed to open-pit extraction. Pit mining for ten years produced 9,649 tons before all available resources were exhausted. Further investigations in the area were unfruitful (McLemore and North 1984). After mining ceased, the pit filled with water because the elevation of the rim is only slightly above the river (Chenoweth 1979).

Whitworth (1995) used mass balance equations to estimate that between 19,300 and 107,550 tons of mine spoil remained on-site from the ten-year operation. Due to its proximity to the river, the potential for significant amounts of mine spoil to be washed into the river and further into Cochiti Lake is likely during high magnitude flood events. If contamination occurs, it may be possible for the dissolved total radium concentration to exceed regulatory standards (30pCi/l) (Whitworth 1995). Negative environmental effects of the mine spoil in the river include water quality problems, channel sedimentation, and bioaccumulation in bottom-feeding aquatic life. Bioaccumulation could ultimately affect humans via consumption, degrade the Cochiti Pueblo Fishery and reduce revenue, and limit recreation in Cochiti Lake. Acid mine drainage from the small copper operation is not likely to adversely affect the river due to the high alkalinity and acid-buffering ability of river waters. Because of the potential problems posed by the presence of the large volumes of mine spoil, the New Mexico Bureau of Mines and Mineral Resources recommended the area for restoration. Since reclamation and remediation efforts by the USFS in 1996, (including mine spoil and river stabilization) the river continues to meet water quality standards for total ammonia and gross alpha (New Mexico Environment Department 2000).

7.4 CHAPTER CONCLUSIONS

This chapter describes the foundational import of the Santa Fe River to basin residents since settlement in 1610. Chapter 7 offers new findings regarding the role of the river in site selection, settlement, and survival. In the upper watershed, grazing and mining was possible because of the river. Ironically, it was the river that brought attention to degrading landscape conditions in the upper watershed due to these activities, and was the catalyst for use restrictions and watershed closure. From this chapter, we learn of the river's significant function in the maintenance of acequia agriculture. As a contribution to the literature, the acequia network reconstruction technique illustrates the application of GIScience in a novel way. This technique can translate to other arid areas with similar datasets and histories. The physical reconstruction of the ditch system has historical significance: the spatial extent of the network contextualizes the degree of past and present human-induced landscape change on the valley floor, elucidates the morphology of the physical landscape prior to the construction of upstream dams, and enlightens anthropologists, historians, and Santa Fe acequia associations to the legacy of this important network.

The effects of dams on Santa Fe acequias comes to light in, Acequia Agriculture: Water, Irrigation & their Defining Roles in Santa Fe History from *Santa Fe, History of an Ancient City, rev ed.*, (Noble 2008). Much literature on water in the West has focused on the downstream effects of dams on the hydrologic regime, fluvial geomorphology, and ecosystem dynamics. This published chapter highlights the effects of dams on the history of Santa Fe acequias within the context of physical river system and land cover change not seen elsewhere. Beyond the river corridor, this dissertation includes new connections between fluvial geomorphology and the cienega complex, and its connection with the river. This research presents new ideas for its formation, grounded in process-form relationships, highlights its importance in local traditions and settlement survival, and calls for its recognition as a foundational landscape feature for the villa. Throughout its history, Santa Fe River functions extend beyond acequia irrigation and domestic use to include recreation, resource extraction (grazing and mining), hydropower, milling and brewing, and waste disposal.

THE LIVING RIVER

"Reason is the first casualty in a drought" -Marc Reisner, Cadillac Desert

8.0 CHAPTER OVERVIEW

The desire for a living Santa Fe River dominates its history. Irrigators long for river water to fill their acequias and water their fields; water company owners need instream waters to replenish their reservoirs and supply their customers; environmentalists aspire for water in the river to promote their ideals of sustainability, restoration, and land stewardship. The animate connotation *living* reflects on a time when the river was the villa's "lifeblood." Returning water to the river seems the most direct way of reconnecting with the romanticized past identity of Santa Feans as a land-based people, functioning in harmony with the landscape, and achieving a connection to the villa's idealized history when life appeared more slow, and simple, and good. Whatever the outcome of restoration efforts, a living river never will replace these symbols of desire with feelings of content; for river flow, form, and function are in a continuous state of change, whether the change is physical or human-induced. The river's configuration will always fall short of some objective, as it historically has failed to meet the multitudes of expectations placed upon it.

Santa Fe River management passed a turning point in the last decade: community involvement and cooperative effort slowly is replacing mismanagement. From the upper reach through La Bajada, however, the theme of discontinuity dominates these efforts.

The purpose of Section 8.1 is to provide a review of restorative intentions on the upper, urban, and lower reaches of the river. This research critiques these efforts within the context of presented findings, and identifies potential success and shortfalls.

Section 8.1.1 details the landcover management endeavors in the upper watershed and their potential effects on downstream river hydrology and fluvial geomorphology. These critiques include the recent conversion of the dewatered Two-Mile reservoir and its surrounds to a nature preserve, and the upper watershed thinning by the USFS. Section 8.1.2 describes the history of efforts to manage the river in the urban reach as more than a stormwater conduit. This spatial and temporal daisy chain of channel engineering attempts from downtown Santa Fe to beyond the San Ysidro Crossing addresses degraded fluvial geomorphology. Throughout the last three decades, disjointed restoration efforts within disparate political jurisdictions have hampered river continuity and longitudinal functionality. Different associated groups applied dissimilar strategies at different times in discontinuous sections. Mired in a cycle of emergency response to rapidly degrading conditions, the efforts lacked overall coordination, which in fact, diminished project success. The ever-changing physical landscape and the evolving state of knowledge about the river and restoration methodologies leads project managers to reflect on earlier efforts with disdain, and desire for the planning efforts of the past to have involved more thought about the future. In the downtown area of the urban reach, the living river initiative includes the restoration of some streamflow and pits the city's public water supply against political and cultural desires for water in the channel. Within Section 8.1.3 are discussions of lower reach restoration downstream of the WWTP by Forest

Guardians, NHNM, and the USFS, specifically within the context of sediment and pollution mitigation in this 303d-listed reach.

The second purpose of this chapter is to provide management recommendations based on the findings of this research. Human-induced landscape change results in system adjustments that veer from the natural condition. Though efforts to return the river to a more natural state now are hampered by limitations of the altered physical landscape, they also are skewed by the perceptions of the meaning of *living river* defined by the various stakeholders who ultimately will determine its restored condition. Within the context of restoration recommendations, this chapter describes how these perceptions are rooted in political motives and Wilson's (1997) myth of Santa Fe. To identify system limitations and to set the stage for what is possible for the river, the current state of the river and its watershed requires historical study and authentic reference. This research benefits scientists, basin managers, and the resident society by providing an in-depth, scientific basis for future restoration efforts. It emphasizes how selecting a societal idealized river "theme," which is inappropriate for the limits of the current human-altered landscape, likely, will induce more degradative outcomes.

Within Section 8.2, recommendations for Santa Fe River flow (8.2.1), form (8.2.2), and function (8.2.3), include the management of the river's flow regime, channel planform and geometry, and land management, including the acequia system, and the catchment basin, respectively. Stakeholders' current efforts to establish a *living river* includes several different ideas about the ideal outcome. This research makes connections between the various desires of the different decision makers and their physical and legal constraints for implementation within the basin. To bring the river back to life successfully, intricate coordination between various stakeholders requires some semblance of a congruent outcome. A living river is more than a running river. It also involves channel mitigation and landscape management.

The third purpose of this chapter is to reflect on the research objectives, to review the innovative methods and practical applications contributed by this research, and to close the work with a summary of selected findings. Section 8.3 highlights the importance of river restoration based on present landscape limitations, scientific discovery, and historical inquiry on a watershed scale. The conclusion of this research coincides with Santa Fe's Cuarto Centenario. This anniversary provides opportunity for reflection on the past and contemplation about the future to be an important part of the present dialog. As a result, the findings of this research are timed opportunely to reach and appeal to a broad and diverse audience.

8.1 RIVER RESTORATION

Overall, Santa Fe River restoration efforts are ill defined. From an ecological perspective, the act of restoration involves returning the system to a predisturbed (pre-human) state, while focusing on both system forms and processes (NRC 1992). Given the drastic changes in the flow regime, fluvial geomorphology, landcover, and land use, returning the river to a state of predisturbance is not possible. The current focus should instead be termed river rehabilitation, with the end goal being a state of functionality within the confines of the current physical landscape. For restoration efforts to be successful, they must be based on current and predicted future landscape conditions. Therefore, this research recommends that these goals include: (1) reversing the continuous degradation of the channel bed from erosive stormflows by developing a city-wide stormwater management plan that manages the spread of impervious surfaces, (2) returning some continuous (albeit small) flow to the channel bed through the downtown area during the growing season to replenish shallow groundwater and nourish riparian vegetation, (3) inducing the creation of river channel forms and aggrading the riverbed to slow high velocity events and allow instream water to pool and restore subsurface flows, and (4) providing a sediment source for the maintenance of those channel forms. Because the common language in Santa Fe uses restoration as the term to signify river flow and channel engineering modifications, it will be used from this point forward, considering, however, that the outcome of true river restoration is no longer attainable.

Thus far, sections of restoration occurring as patches along the channel have minimal concerted effort. The sections are disjointed and each task has: (1) a unique definition of the problem, (2) a discrete idea as to what will work in the small sub-reach at hand, and (3) an individualized final objective. "Coordination is woeful. Santa Fe River stakeholders lack understanding of causality, agreement on objectives, commitment to solutions, and a spirit of mutuality" (Heggen 1997: 2). The different levels of involvement create a river that lacks coherence and efforts are less effective, given the need for continuity within functioning stream systems. Descriptions of restoration efforts on the upper, urban, and lower reaches are not all-inclusive, but focus on milestones that will determine future river flow, form, and function within the watershed.

8.1.1 Upper Reach Restoration

8.1.1.1 The Santa Fe Canyon Preserve

Within the upper reach, the focus of restoration is improving landscape condition. Restorative actions, specifically the conversion of the Two-Mile reservoir site to The

Nature Conservancy's Santa Fe Canyon Preserve, indirectly influences river flow, form, and function. In 1978, the State Historic Preservation Office (SHPO) notified the water company (at the time, the Public Service Company of New Mexico, or PNM) of the listing of Two-Mile Dam and reservoir on New Mexico's Register of Cultural Properties (Lewis 1996). Two-Mile dam, inspected repeatedly by the National Dam Safety Program, also made the National Dam Inventory list for high-hazard potential. By 1992, the downstream toe of the dam had deteriorated enough to warrant reservoir draining, and subsequent breaching in 1994: rodent holes, tree-roots, cracks, and material slump combined to create a hazardous condition, and the cost associated with its repair was prohibitive (Lewis 1996). Left in place due to its cultural status, the breached dam still holds 10 acre-feet of water for aesthetics, wildlife habitat, and groundwater recharge. The water company donated the land surrounding the reservoir to The Nature Conservancy in the year 2000. The area now is the Santa Fe Canyon Preserve (Goldman 2003). The trail winding through the preserve gives the visitor a tour of one of the greenest accessible spaces in the Santa Fe watershed.

The former Two-Mile reservoir serves a positive function for the aim of a living river. The water that seeps to groundwater from its remaining storage to the terrace gravels of the Ancha formation replenishes some shallow subsurface flow, which was once a primary source supporting gaining stream conditions and perennial baseflow. This seepage, albeit small, is one genesis of a living river. Results of this process are evident in the presence of wetlands. Siberian elm (*Ulmus pumila)* and Rio Grande Cottonwoods (*Populus wislizeni*) flourish below the dam in an area currently under private ownership. Two-Mile reservoir also influences river form, but only indirectly, because the river now bypasses the reservoir. For a few thousand feet below the structure, as the river meanders through high terraces, the effects of saturated subsurface flow and the presence of dense riparian vegetation stabilize the banks.

8.1.1.2 The Santa Fe Municipal Watershed Project

In the early twentieth century, upper watershed managers did not anticipate that eliminating fire from the watershed eventually would create a massive fire hazard. The dense doghair thickets that now cover the hillsides and the decades of ground fire suppression create a substantial volume of forest fuels and a highly flammable condition (Figure 8.A). This management strategy is misaligned with the landscape's natural fire regime, which includes a history of low intensity ground fires, and very few large stand-replacement fires (the last one having occurred in the spruce forest in 1683) (Margolis and Balmat 2009). A crown fire in the Santa Fe watershed similar to the Cerro Grande fire in Los Alamos in May of 2000 could damage soils, create highly erosive hillslope runoff and gullying, and deliver sediment-laden flows to the river; potentially destroying 40 percent of the city's water supply by flooding the canyon reservoirs with mud. Such an event also could devastate downtown Santa Fe.

Figure 8.A. Excessive forest fuels in the upper watershed
Source: photos by author (2006)

To combat the negative implications of watershed non-management after closure (reduction of water volume in the river, large crown fire hazard, and poor ecosystem health and biodiversity), the USFS initiated a project to thin and burn some of the dense stands. The project intentions were to reduce the volume and break up the continuity of fuels, reintroduce fire as part of the natural landscape cycle, and study the ecosystem effects. The part of the upper watershed that underwent thinning lies within the Española Ranger District of the Santa Fe National Forest. Because the project involved federal lands and funding, it falls under the requirements of the National Environmental Policy Act (NEPA) of 1969.[25] The Act codified federal policy "to use all practicable means and measures… to create and maintain conditions under which man and nature can exist in productive harmony, and fulfill the social, economic and other requirements of present and future generations of Americans" (§ 101a, 42 U.S.C § 4331 (a)).

As a procedural statute, NEPA requires that all federal agency activities include a decision-making process to examine the likely environmental effects, and ensure that proposed federal actions do not degrade the "quality of the human environment." The process begins with the preparation of an Environmental Assessment (EA). The EA contains a brief description of the proposed action, potential alternatives, and likely impacts (including cumulative impacts). After public notification and a period for comment, a determination is made on whether the action constitutes a Finding of No Significant Impact (FONSI) or Environmental Impact Statement (EIS) preparation. For "major federal actions," analysis of the project's effects includes the preparation of a detailed EIS, which outlines the project's environmental impact, unavoidable adverse effects, potential alternatives, relationships between short-term and long-term outcomes, and permanent resource commitments (42 U.S.C § 4332 (C)).

Because the upper watershed thinning was to include "actions with effects that may be major and which are potentially subject to Federal control and responsibility," the project required the preparation of an EIS (40 C.F.R. § 1508.18). The EIS successfully identified various alternatives to the proposed action, including the implications of no action; potential environmental concerns with the process and its outcome; and its effects on vegetation, soils, water, aquatic, riparian, and terrestrial habitats, recreation, heritage resources, and the social environment (Santa Fe National Forest 2001). The chosen alternative included a multi-year timber stand improvement. Up to 7,270 acres (29.4 km^2) (42 percent of the 17,384 acres (70.4 km^2) of permissible land in the watershed area (about 10,000 acres (40.5 km^2) within the Pecos Wilderness are off-limits to thinning) were to be thinned to alleviate overcrowding and reduce the density of trees per acre from 800 to 1,200 to a more natural 100 to 200.

Prior to project action, the Forest Service had to overcome much public resistance (Hurlocker 2006: personal communication). Decades of watershed closure solidified a hands-off approach to management within the public consciousness. Watershed residents perceive this ecosystem as pristine and are highly protective of its resources. Many residents make assumptions about river hydrology and geomorphology from old photographs and local hearsay, despite less than one percent of the population ever having entered the area. After holding several public meetings, circulating informative publications, and receiving public relations assistance from the Santa Fe Watershed Association, the City of Santa Fe and the Mayor, the Forest Service successfully relayed the scientific benefits to watershed residents and resistance waned (Hurlocker 2006: personal communication).

Between 2002 and 2006, hand-thinning and mechanical mastication (called chunking), cleared the small trees (≤ 4” diameter) and created piles of material for future burning via prescribed methods (Santa Fe National Forest 2006). The thinning process felled a few larger trees as well. When laid perpendicularly to the hillslope, these trees effectively combat erosion. In 2005, burning was successful on approximately 200 acres (0.8 km^2), but dry weather conditions since have precluded additional burns. Photographs taken during 2006 field reconnaissance show the dramatic effects of the clearing and burning process (Figure 8.B).

Figure 8.B. Panorama of thinning project results
(left) doghair thicket, (center) fire break, (right) hillside after thinning and prescribed burn
Source: photos by author (2006)

This project has several implications for river flow, form, and function. The thinning project includes a monitoring plan designed to evaluate the long-term effects of the management choices on river flow quality, quantity, and the forest ecosystem (Santa Fe National Forest 2001). Although the focus is water quality after thinning, addressing the hypotheses for the long-term reduction in river water volume is an ancillary part of the continued monitoring plan. Monitoring of streamflow in a paired-basin study intends to address the hypotheses by comparing water output between an untreated basin and a thinned basin. Figure 8.C shows how snows reach and accumulate on the forest floor after thinning. Stream gages installed at the sub-basin outlets will look for relationships between precipitation and streamflow. After several years, scientists will be able to evaluate whether thinning increases the amount of water entering the river via subsurface flow and runoff. Unfortunately, the initial paired basin study is flawed (Hurlocker 2006: personal communication). The two chosen basins for stream-gaging and analysis physically were adjacent to each other but later found to be dissimilar. The higher elevation of the control basin holds snow longer, and causes for differences in the outflows (Hurlocker 2009: personal communication). After accounting for the differences via statistical methods, an increased flow appears to be a result of thinning; however, determining if the increase is statistically significant will require ongoing study.

Figure 8.C. Example of snowfall reaching floor of a cleared stand
Source: Falk (2007)

Regaining approximately 20 percent of the average annual flow currently lost to the dense stand condition would add a measurable amount of water to the river each year. The project successfully thinned 27 percent of the entire upper watershed catchment (comprised of 17,327 acres (70.1 km^2) of city, National Forest, and private land, and 10,000 acres (40.5 km^2) of Pecos Wilderness). By multiplying the average total volume generated within the catchment by the area thinned, the river would receive approximately 260 additional acre-feet each year. This volume equates to the daily needs of 2,100 watershed residents, respectively (assuming the same 110 gallon-per-day usage rate as the city uses in its long-range water supply plan (City of Santa Fe 2008)). If research shows that flows increase in total annual volume after thinning, a byproduct of reducing wildfire threat is an improvement in river's function as a city water supply source. However, because the city's water division legally can only store 5,040 acre-feet of water in their reservoirs, any additional waters generated because of thinning are destined for acequias and the river. Increases in river flow in the downstream urban reach are considerably important to river rehabilitation and the living river initiative because of the additional benefits to river form and function from the presence of water in the channel. These benefits include the induction of bedforms and meanders, groundwater recharge, bank stabilization via the support of riparian vegetation, and improvements in ecosystem diversity.

8.1.2 Urban Reach Restoration

8.1.2.1 Rio de Santa Fe Report and Recommendations

In 1985, the Santa Fe River Committee penned the first report to include recommendations for the river's physical rehabilitation in the downtown area, calling attention to its degraded condition, and offering a myriad of suggestions for use, economic development, transportation, flood protection, aesthetics, safety, and maintenance changes in downtown Santa Fe. In the report, the committee emphasized how "the Santa Fe River does, in fact, provide one of the last, large, physical and psychological linkages between Santa Fe's built environment and the unique landscape which in so many ways has shaped our City" (Santa Fe River Committee 1985: 20).

Although never implemented, the plan and its suggestions were a starting point. Given current knowledge about hydrology and fluvial geomorphology, it is thankful that many of the suggestions remained on paper. Some were inappropriate for the physical landscape conditions; others misguided in their hypotheses. For example, the statement that mentions how "low stone walls, though not continuous, give definition to the river bed" shows how those making the inference were unaware that such "definition" actually funnels the channel flow in a highly unnatural way, focuses the energy of the river into its bed, and contributes to downcutting (Santa Fe River Committee 1985: 13). The suggestion to revitalize the acequia system is an excellent way to encourage groundwater infiltration and revitalize Santa Fe's acequia institutions and customs, but gets off-track when the ditches are hoped to be used for stormwater management. Damage occurs quickly to unlined ditches conveying storm flows, either by downcutting or by sedimentation. Purposefully directing storm flows through acequias also violates acequia laws that protect the rights of residents of upper valleys of stream systems (Section 72-5-29, NMSA 1978; New Mexico Acequia Association 2005).

Lastly, some of the statements within the *Rio de Santa Fe Report* failed to recognize the river's truly unnatural state: "on the west side of the Palace Avenue bridge, the Santa Fe River takes on a very natural, non-urban appearance, *despite intermittent stone and rip-rap retaining walls and occasional picnic tables, benches, and trash receptacles*" (emphasis added, Santa Fe River Committee 1985: 13). This statement is laughable, given how it first mentions how the river is “very natural,” then immediately cites features of an engineered, urban environment. Unfortunately, the “public desires a ‘natural’ waterway while hydrology and geomorphology ceased to be ‘natural’ decades ago. Constituent politics has led to channel satisfying neither conveyance or beauty” (Heggen 1997: 28). Not all of the suggestions were out of line. Some recommendations are the same as those currently being pursued (encouraging water ponding for infiltration to groundwater, and reducing the abrupt discontinuity between the level of the riverbed and the street elevation) or implemented (stabilizing downstream banks, removing invasive species and planting native riparian vegetation, and frequently removing litter).

8.1.2.2 The Santa Fe River Corridor Master Plan

In the fall of 1995, a second attempt at river planning moved slightly closer to action. The Santa Fe River Task Force, a collection of city staff, private engineers, and planners authored the Santa Fe River Corridor Master Plan. The plan included recommendations for riparian corridor improvement, channel stabilization and erosion reduction, public uses (including trails), and a stormwater management plan (which thankfully included no mention of acequias) (The Santa Fe River Task Force 1995). The document also presented design guidelines for future river projects and emphasized the importance of using natural materials and minimizing the use of rigid, impervious materials like concrete. Also in 1995, the city finally succeeded in purchasing the private water utility, making the Sangre de Cristo Water Division publicly owned (Goldman 2003). As a result, improved coordination now was possible between the city’s land, water, and planning offices. For the first time, downstream water releases could potentially be coordinated with the city’s land and water management goals instead of being driven by the priorities of a private company primarily concerned with reservoir management.

8.1.2.3 The Santa Fe River Channel, Trail and Greenway Improvements

By 1996, the city's Public Works Department began to move forward on the first river stabilization project since the ACOE had reengineered the Arroyo Mascaras' confluence with the river. The long-term multi-million dollar project, called the Santa Fe River channel, trail and greenway improvements, will remediate the urban reach between Patrick Smith Park and Frenchy's Park, a distance of about 2 river miles (City of Santa Fe 2005a). This project began with Phase I and II, and focused on the reach between St. Francis Drive and Camino Alire (0.8 river miles). The project engineer Souder Miller & Associates worked closely with the city's Public Works Department (Clemens and Associates *et al.* 1998). These and future phases include bank stabilization with stacked boulders, removal of invasive species and planting native plants like willow bundles, and installing a pedestrian and bike path. In the summer of 1997, two open house meetings gave the public the opportunity to comment on the project goals and design, to voice their concerns, and to ask questions.

Ten years after the restoration of this section, many of the design pieces are working. Bed aggradation is occurring downstream from the Arroyo Mascaras confluence and particle sizes are more variable than upstream. In some areas, riparian vegetation is dense, precluding river access, but successfully stopping erosion along the banks (Figure 8.D). Some design elements, however, are failing. River migration cut banks not reinforced with boulders or vegetation (Figure 8.E). Stacked and grouted boulders line the banks and create a chute reminiscent of the downtown reach, but on a larger scale (Figure 8.F). Here, vegetation is high above the water table, and the river is not able to meander and create bed and bank forms. These failures are discouraging, considering that during the project design phase, it was considered acceptable that the constructed works would not withstand either a 50 or 100-year flood (The Santa Fe River Task Force 1995). Between the time of construction and field reconnaissance, the forces of a large flow event had not tested the river redesign.

8.1.2.4 Santa Fe River Watershed Restoration Action Strategy

In September 1998, the New Mexico Unified Watershed Assessment (UWA) identified the Rio Grande-Santa Fe basin as a Category I: "watersheds do not now meet, or face imminent threat of not meeting, clean water and other natural resource goals" (New Mexico Environment Department 1998: 15). In reaction to this status listing, funding provided through Section 319 of the Clean Water Act supported the authoring of the Santa Fe Watershed Restoration Action Strategy (WRAS) by non-profit group Santa Fe Watershed Association and assembled members of the community (33 U.S.C. § 1329 (2006); Grant 2002). The 2002 WRAS became an important document by identifying stakeholders, evaluating basin conditions, identifying water quality problems, creating water quality goals, and recommending future actions.

The document also provided a list of restoration activities on the river or within the watershed between 1995 and beyond. This list shows the escalating rate at which restoration efforts began to affect the river, but also highlights the disconnected nature of these efforts. In longitudinal order from the upper reach to the Rio Grande confluence, the different entities conducting projects are: USFS – City of Santa Fe – Audubon New Mexico and The Nature Conservancy – U.S. Fish & Wildlife Service – City of Santa Fe

Public Utility Department – City of Santa Fe Public Works Department – Acequia Madre Association – private landowners – City of Santa Fe Public Works Department – Santa Fe County Public Works Department – Santa Fe County Operations Division – Santa Fe Watershed Association – County Public Works Department – State Land Office – Forest Guardians – Santa Fe Botanical Garden – USFS – The Conservation Fund – and the BLM.

Figure 8.D. Riparian vegetation effectively stabilizes banks
Photo facing upstream
Source: photo by author (2005)

Figure 8.E. Channel reminiscent of upstream conditions, but on a larger scale
Photo facing upstream
Source: photo by author (2005)

Figure 8.F. Undercut banks where design lacked reinforcement
Photo facing downstream
Source: photo by author (2005)

8.1.2.5 State Land Office Nonpoint Source Pollution Prevention Project

Prior to the publication of the WRAS, the State Land Office (SLO) began restoring some of the riparian bosque on a one-mile reach upstream from the Route 599 crossing. The goal of the project was to reduce nonpoint source pollution by stabilizing the channel and reducing bank erosion (New Mexico State Land Office 1999). The New Mexico Environment Department aided in channel design and incorporated a meander pattern that coincided with the flow regime and sediment load. Rosgen (1994) methodologies were followed to "narrow active channel width and recreate a more natural meandering stream channel through use of riparian plantings, boulder, fabric and log structures, and weir devices" (New Mexico State Land Office 1999: 6). In addition, grade control structures and barriers to prevent access by all-terrain vehicles replaced poorly designed river crossings. Bioengineering techniques, combined with strategic boulder placement, modified the overly straight channel. Lastly, willows (*Salix exigua)*, Rio Grande Cottonwoods (*Populus wislizeni*), riparian grasses, and shrubs, planted in areas where evidence of shallow groundwater would likely sustain the riparian vegetation, took the place of invasive Russian-olives (*Elaeagnus angustifolia)*, Tamarix (*Tamarix chinensis*), and naturalized Siberian elms (*Ulmus pumila*).

Within two years of the completed work, investigations within the restored reach found that "the new channel dimensions constricted the river too much. In response to summer storm events, bio-engineering treatments at the upstream and downstream ends of the constructed meander had begun to fail. New channels were being cut by the force of storm flows in various locations throughout the floodplain" (New Mexico State Land Office 1999: 8). This project made a classic mistake of river restoration by selecting a pre-defined channel from a set of choices based on what humans wanted the river to look like, instead of following the process-form relationships and hydrologic regime conditions dictated by the landscape. Further study by the SLO and consultants found that

> the existing ephemeral system, with alluvial bed material, is a classic braided pattern rather than a defined channel type and the project had attempted to create a typical meander, with static channel dimensions. The braided system requires a much more dynamic channel… by constructing the new channel, we had created an extended reach of narrow channel, when it appears as if the system relies upon an alternating pattern of narrow reaches connected by large wide braided reaches in order to adequately dissipate flow energy and disperse sediment load (New Mexico State Land Office 1999: 8-9).

Project modification in the third year allowed for adaptive management. A quick response to the design errors mainly included repositioning vegetation plantings to match the appropriate channel configuration. The outcome now is more successful in slowing the erosive stormflows. Field reconnaissance in 2005 and 2006 found that much of the planted vegetation was surviving, stabilizing banks, and effectively trapping fine sediments previously transported downstream.

8.1.2.5 San Ysidro River Park and Santa Fe River Channel Restoration

Thus far, the most transformative channel restoration effort occurs at the County of Santa Fe's San Ysidro River Park. During field an investigation in 2005, the deeply incised 1.2 km (0.8-mi) reach between San Ysidro Crossing near Agua Fria Village to Caja del Oro Grant Road had failing banks reaching over 9.1 m (30 ft) high. Simply planting streamside vegetation could not mitigate this section's degradation. Instead, massive regrading work and channel engineering: (1) redistributed sediment from the steep, raw banks to the channel bottom using a maximum side slope of 3:1, (2) raised the bed, (3) stopped the cycle of incision, and (4) allowed the river to interact with its floodplain (Figure 8.G). To complete the work, the County of Santa Fe acquired its first conservation easement along the channel in May of 2001, and its second in November of 2003 (Baker 2009: personal communication). For the protection of watersheds, water quality, and access to water for wildlife, a Wetlands Protection Development Grant (a program under Clean Water Act §104 (b) (3)[26]), funded the beginning of channel design in October of 2003, and construction in March of 2006 (33 U.S.C. § 1254; Baker 2009: personal communication). The park opened to the public in May of 2007. For efforts to be successful, the County of Santa Fe addressed the downstream activities of the sand and gravel mines. Without an end to these aggregate removals, headward erosion would continue to threaten the restoration work. The county eventually settled with one of the mines to close operations, and changed the other downstream permits to limit mining to the surrounding landscape. All instream aggregate removals since have stopped. The county also secured the services of a fluvial geomorphologist, who worked closely with the engineering team to design a channel form that would be stable within the understood limits of the physical system.

Downstream from the San Ysidro crossing, the vertical banks were backfilled, smoothed, and reinforced with boulders. Engineers constructed meanders to slow floodwaters and positioned the thalweg away from the most disturbed banks (Figure 8.H). The geomorphologist incorporated some innovative techniques for bank stabilization within the design. Slowly decaying juniper (*Juniperus sp.)* poles, driven into the bed at a slight angle, act as post veins to collect sediment and induce bank accretion (Zedike 2008: personal communication). The exposed bank in Figure 8.H shows how posts driven into the sands of the Tesuque aquifer are successful in capturing debris and collecting sediment.

By overlaying the engineering drawings with the previously digitized 1951 channel in a GIS, spatial relationships show that the newly constructed channel bed is twice as narrow as its pre-incised braided predecessor of 60 years ago. With the new channel design, sinuosity of this sub-reach has increased from 1.03 in 1951 (which clearly fits within Rosgen (1994) braided category) to 1.14 in 2008. The new channel misses Rosgen's (1994) meandering category by 0.06 only because the first 274.3 m (900 ft) maintains its original straight planform pattern through a section of steep banks. Large boulders, positioned in an upstream facing V, act as grade control structures and mitigate the downcutting that is common in the overly steepened gradient of this straight section. Undercutting of hard concrete grade controls and their subsequent failures upstream have taught engineers that in fluvial environments dominated by unconsolidated sediments such as the Santa Fe River, it is more successful, whenever possible, to use in their designs materials that are more malleable. After exiting the straight section, the river flows through a semi-circular amphitheater; a design element intended to distribute flows evenly within the wider channel. As the river flows downstream, it encounters eyebrows of boulders positioned to induce meandering in a specified configuration. The meander wavelength and radius of curvature of the first large meander are less than successive meanders downstream (Figure 8.I). The intent of this large bend is to slow stormflows and direct the flows away from one of the most damaged banks. The design also included riparian plantings, such as Rio Grande Cottonwood (*Populus wislizeni*). By the fall of 2008, over 80 percent of the cottonwoods were surviving (Zedike 2008: personal communication). These trees, planted directly into the aquifer unit, are watered periodically via vertical PVC pipes to encourage survival (Figure 8.J).

Over time, it will be interesting to observe how the designed channel geometry and planform respond to the system processes, and how effective these design elements are at stabilizing the banks, slowing erosive stormflows, aggrading the bed, and encouraging floodplain interaction. This channel engineering project is only 4.0 km (2.5 mi) upstream from the State Land Office project site, where restorers found out the hard way that system processes and landscape conditions warranted a braided channel pattern, and that attempting to force the river into a misplaced meandering morphology led to design failures. I hope that better data and knowledge about process-form relationships were the basis of this channel design. However, given the abundance of unconsolidated sediments, the condition of the upstream reach (relatively straight and incised), the stormflow-dominated flow regime, and the continuously urbanizing watershed, I am not

Figure 8.G. Paired photography of the pre- and post- restored channel
Photos facing upstream
Source: photos by author, top (2005); bottom (2007)

Figure 8.H. Juniper post veins encourage accretion along the channel banks
Photo facing downstream
Source: photo by author (2008)

Figure 8.I. Aerial photography overlaid with channel engineering design
Source: Resource Technology, Inc. (2005)

convinced that the river will maintain these engineered meanders, regardless of the planted vegetation and strategically placed boulder-lined bank reinforcements. "Planting trees or shaping land forms sometimes are used to jumpstart recovery but the ultimate goal is to allow process restoration to naturally drive ecosystem recovery" (Stromberg 2001: 19). As an alternative, stormflows also could be dissipated by increasing the channel's width-to-depth ratio, which may be more appropriate for this river section than the meander planform. With future money and support from adjacent landowners, county restoration efforts will continue downstream. This research recommends detailed observation of the current project and implementation of an adaptive management strategy within future planning and design.

Figure 8.J. Cottonwood planting within the Tesuque unit, with PVC watering pipe
Source: photo by author (2008)

8.1.2.6 The Living River

The most contemporary landmark for urban reach restoration concerns the effort to introduce consistent flows to the channel bed. As it stands today, the river flows only after the reservoirs and acequias receive their legal allocations. As a result, the presence of water in the channel is seasonal and large flows are rare. These releases of water to the river count toward meeting New Mexico's legal obligation to deliver water to Texas via the Rio Grande (Harwood 2006: personal communication). The Rio Grande Compact of 1939 ensures that Rio Grande water apportioned between Colorado, New Mexico, and Texas occurs equitably, and that upstream users do not overstep their rights by withholding (and using) too much[4] (Harry S. Truman Library and Museum 1938). In 2004 and 2005, Santa Fe River reservoirs released an average of 933 acre-feet downstream to maintain Compact compliance. The State Engineer can refuse the Compact's call for water releases under the futile call doctrine,[27] because it is unlikely that the flows will ever reach the Rio Grande, and the water becomes unusable for public supply by its release (although there are a multitude of other benefits for instream waters). Through a basin accounting process, the city can designate instead flow discharges from the WWTP toward meeting the annual Compact requirements, and reserve upstream waters for public water supply distribution.

Ultimately, there are no water rights for the river itself. The idea of a living river includes having a continuous, albeit very small flow. A year-round, or even dedicated seasonal, flow would recharge groundwater; supply native streamside vegetation and create a migratory route and habitat for amphibians, fish, and songbirds within the corridor. Benefits to river water are not just environmental. Visitors and residents of Santa Fe flock to the river when it is wet, and partake in recreational opportunities such as bird watching, fishing, and, in the heaviest flows, kayaking. Utility bills now provide the option to city residents to donate money towards purchasing a water right for the river. The city matches each private contribution, and once it has enough funding, will be responsible for purchasing the water right.

In its 2008 long-range water supply plan, the city outlined the release of 1,000 acre-feet per year to the river (City of Santa Fe 2008). Except under extreme conditions (such as upper watershed fire) or drought, this water will recharge groundwater, and increase recreation, aesthetics, riparian and aquatic habitat, and biodiversity. Between 2008 and 2011, the Sangre de Cristo Water Division is defining river releases: the incremental springtime release now underway is part of this effort (City of Santa Fe 2008). Typically, the springtime water releases from the reservoirs average between 0.566 and 0.850 cms (20 and 30 cfs). For a few weeks, the public enjoys recreational opportunities such as fishing (after stocking) and sometimes kayaking. With the onset of summer, the river is "turned-off," and downstream flows remain in the reservoir.

Recent findings indicate that water released to the riverbed at a consistent rate would benefit the city in the long-term: aquifer recharge could be a viable way for the city to store water in times of plenty. The current springtime release strategy is less effective at recharging the aquifer than a low, steady release. Grant and Williams (2009) found that an incremental release averaging a flow rate of 0.070 cms (2.47 cfs) would contribute 489 acre-feet of "evaporation-proof" groundwater each year, and the recharge would be noticeable in city well levels within a few years. Currently, city wells and others are pumping water out of the aquifer faster than it is being replaced, and well levels have dropped over 61 m (200 ft) since their installation in the late 1940s and 1950s (refer to Figure 4.B; Grant and Williams 2009). Unfortunately, 0.070 cms (2.47 cfs or 1,788 acre-feet per year) exceeds the 1,000 acre-feet proposed for release each year by the city. By combining these releases with the Rio Grande Compact releases, however, wells would begin to recover. This management strategy increases the likelihood of water sustainability for Santa Fe. This research recommends that the Sangre de Cristo Water Division implement this approach in average and high flow volume years.

8.1.3 Lower Reach Restoration

8.1.3.1 The Santa Fe River Preserve

In 2000, with City of Santa Fe approval, Forest Guardians, a non-profit group, initiated restoration measures on the river below the WWTP. In this 2.5 km (1.6 mi) reach named the Santa Fe River Preserve, their goals were to improve water quality and enhance riparian habitat by excluding livestock and planting over 5,000 cottonwoods (*Populus fremontii*) and 15,000 willows (*Salix exigua*) (Forest Guardians 2004). From the perspective of geomorphic and ecologic structure and function, there are both positive and negative elements associated with the Forest Guardians' restoration efforts in this location. Benefits include the exclusion of grazing from the channel (which promotes ecosystem and geomorphic diversity), the removal of invasive species, reducing water temperature via streamside shade, and the uptake of excessive nutrients by the thousands of plantings.

However, several components of their project deviate markedly from both the natural condition of this river reach and the optimal geomorphic and ecologic structure and function possible for the current conditions in this setting. Section 6.3.2 of Chapter 6 mentions the effects of these restoration efforts on channel form. Perhaps unknowingly, the restoration efforts of Forest Guardians have created conditions that are far different from their pre-disturbed state. In their final report, the group proudly stated how "[o]verall, Forest Guardians believes the implementation of our project has significantly improved the ecological health and enhanced the water quality of this portion of the Santa Fe River. Streambanks have been stabilized, and the stream has narrowed and is beginning to deepen" (Forest Guardians 2004: 3). From a geomorphic perspective, the keywords "narrow" and "deepen" typically carry negative connotations. The dense plantings lock the river in place and there is little lateral movement. In addition, the WWTP delivers a mono-flow regime, rarely inundated with enough large velocity flows to break up the dense plantings and initiate geomorphic and ecologic structure, thus limiting function. As seen in the NHNM species study, and other scientific literature (Friedman *et al*. 1998; Bendix and Hupp 2000; Anderson, Nilsson, and Johansson 2000; Church 1995; Bednarek 2001), a varied flow regime and dynamic channel cross-sectional geometry will introduce gradations in plant communities with distance from the channel. Unfortunately, Forest Guardians missed an opportunity to produce a riparian ecosystem truly representative of native conditions when they planted so closely to the channel in such a dense and unvarying approach.

8.1.3.4 Large-Scale Impacts of Humans within the Watershed

Quantifiable changes in urban expansion and pressure on water resources aid effective restoration strategy design, and more specifically, water and sediment budget development. In 1990, the average daily water use per person in Santa Fe was 117 gallons per day (BASIN 2004). Use climbed to a high of 168 gpd by 1995. As water rates increased and new construction implemented low-flow fixtures, use had dropped to 142 gpd by 1998. By 2007, conservation measures had successfully reduced average usage to a low of 110 gallons per capita daily (City of Santa Fe 2009b).

In arid regions, urban expansion results in substantial changes to watershed hydrology. Regardless of conservation, increases in population correlate with reductions in pervious surfaces, and the concurrent increases in runoff result in more floods and less groundwater recharge. Inferences about future water resources need to include land cover change information, as land management dictates future water availability. To make predictions concerning future water needs and urban expansion in the Santa Fe River watershed, unsupervised classification, a remote sensing technique, quantifies past spatial changes in urban land cover.[28]

Urban land cover increased by 68 percent between 1989 and 1999 in the watershed (Table 8.1). Concurrent decreases in forest vegetation (5 percent) and grassland (56 percent) have made way for urban infrastructure. Increases in bare soil cover (52 percent) and disturbed areas (55 percent) indicate large human influences throughout the watershed. Implications of such disturbance on water resources include an increase in impervious surfaces and surface runoff. Instead of slow percolation and groundwater recharge, concentrated, erosive storm flows enter channels and are "routinely one or two orders of magnitude greater than mean flow rates" (Grant 2002: 8). These flood waves are not conducive to floodplain storage and cause riparian habitat dessication and streambank destabilization. "The absence of riparian vegetation along most drainage ways including the Santa Fe River is a loss in terms of its contribution to channel stabilization, flood flow attenuation, wildlife habitat and recreational and aesthetic values" (Grant 2002: 16). Channel scouring and aggradation likely follow. Grassland cover reductions and increases in bare and disturbed areas also cause the watershed's erosive soils to enter the hydrosystem as nonpoint-source pollution (Grant 2002).

Table 8.1. Land Cover Areas and Percent Change, Santa Fe River Watershed
*Areas in square kilometers

	Urban	**Forest Vegetation**	**Manicured Vegetation**	**Grassland**	**Bare Soil**	**Disturbed**
1989 Image	17.07	206.03	2.48	351.17	59.36	28.54
1999 Image	53.00	196.76	2.63	225.75	123.32	63.28
% Change	67.78	-4.71	5.43	-55.56	51.86	54.91

Planning for future urban expansion requires informed, accurate assessments of water needs in the region. Results indicate that urban expansion will continue at a staggering rate unless controlled by planning measures, and water availability will continue to decline due to poor land conservation measures. Watershed restoration efforts should include ways to reduce overland flow and to attenuate storm flows for groundwater recharge. If urban land cover continues to increase in concert with population and water use, future water availability and the overall health of the watershed are in jeopardy.

8.2 RECOMMENDATIONS

In Santa Fe, there is nostalgia for a past that is purely an invention of the modern landscape's current expression. The present manicured, closely monitored architectural style of adobe that appears in harmony with its surroundings seems reflective of a past landscape where the actions of land-based people were in tune with the cycles of nature. This past perception of harmonious sustenance simply was not the perfect balance that modern visionaries desperately want to emulate. "Historical amnesia… interfere[s] with the public understanding of the origins of contemporary social, economic, and political structures" (Wilson 1997: 313). This mythmaking also frames the desires for the river to be made into what it cannot be, and sets lofty restoration ideals up for eminent failure. To restore system functionality to the river, managers must set aside their historical amnesia to acknowledge that it never will be what it once was, and that it never was what it is envisioned to have been.

The present scene idealizes a romantic vision of the historical Santa Fe; yet struggle, not harmony, dominates the reality of its past. The Santa Fe of centuries past is not a place to be emulated or envied: nor a vision to return to. The streets and homes were made of mud, the people were largely illiterate, and farmers desperate to survive were held captive each year by the whims of climate. In the driest years, the people resorted to eating roasted cowhides, and when the river lacked water for agriculture and they fought viciously with their neighbors over every drop. After seasonal flooding, they repeatedly had to labor to repair damage to acequias, *presas*, homes, and bridges caused by the torrents of mud and debris that time after time roared down the mountain. Numerous statements litter the historical record referencing the pitiful state of the villa. Fray Francisco Atanasio Domínguez comments in 1776 about the place, and how:

> the location, or site, of this villa is as good as I pictured it in the beginning, but its appearance, design, arrangement and plan do not correspond to its status as a villa nor to the very beautiful plain on which it lies, for it is like a rough stone set in fine metal… for in the final analysis it lacks everything. Its appearance is mournful… (Adams and Chávez 1956: 39).

In 1849, a letter from an American traveler mentions that he:

> can hardly imagine how [Santa Fe] is supported. The country around it is barren. At the North stands a snow-capped mountain while the valley in which the town is situated is drab and sandy. The streets are narrow... A Mexican will walk about town all day to sell a bundle of grass worth about a dime. They are the poorest looking people I ever saw. They subsist principally on mutton, onions and red pepper (Anonymous 1849).

These statements are spurned for the more perfect, romanticized Santa Fe; but unlike a city setting that can be redesigned (or revitalized) to reflect any desired look and feel, the river is bound by the constraints of the physical system, and cannot successfully be reengineered to fit an idealized form without the supporting processes. The desired river is not the unpredictable, high debris-yielding locomotive of the pre-dam canyon, but an acquiescent stream that flows continuously, and is reflective of an environmental utopia:

> our river *lives* as crystalline water with meadows along its banks and natural springs sustaining the jarral reeds and willows… Many *perceive* the river as the

> 'lifeblood of the community coming down from the mountains, connecting neighborhoods, and feeding the acequias. Farmers and fishers provided for their families from the river while their children splashed along the banks in the shade of ancient cottonwoods.' These are both the memories and the dreams for the Rio de Santa Fe (emphasis added, The Santa Fe River Task Force 1995: 5).

These perceptions are not unfounded, as the river did provide these functions; however, the vision is glorified and fails to acknowledge the authentic reality of its setting. The river was the villa's lifeblood, for without its water the city's initial placement, plan, and current condition would be markedly different. So too, however, was the cienega complex. Despite its complete dewatering, no one calls for its restoration because it is completely lost to the public conscience beneath a vast expanse of pavement. Despite its various historic roles in the villa's placement and survival (water supply for the Rio Chiquito, convent garden's pond, and Palace ditch among others, and exemplary example of community land stewardship), this vital source of water is neither symbolic of strife nor romantic in expression. The cienega lacks the visibility of the river. As a result, there is minimal hope for recognition of its importance and its connection to the river, or for its restoration.

The selection of a predetermined ideal for river restoration is a common mistake; one that is seen in the Santa Fe River Committee's suggestion of restoration to a "mountain stream *theme*," for example (emphasis added, Santa Fe River Committee 1985). Although the idea of water majestically tumbling over boulders through the urban reach may be an appealing vision that fits within the downtown historical mythos, this mountain stream theme is not fitting for the current limitations of the physical system. Water must be present in the channel for such a stream to be visually alluring, but its continued presence may not be realistic given the current and expected future climatic variability, the water supply needs of the growing resident population, and the tourist economy. This theme also fails to address many of the present biologic and morphologic issues within the system, like the need to slow erosive stormflows by inducing meanders, pool water to encourage infiltration to shallow groundwater, and support streamside vegetation. Boulder-bed streams designed to match the desired mountain theme are similar to the river high in the upper watershed, which fails to mitigate these concerns due to its small riparian corridor and moisture storage capacity within the banks (Chapter 6, Section 6.1.3). In-situ geologic conditions fail to support this design strategy. The unconsolidated bed and banks in this section mobilize easily, and recreating a boulder-bed type channel would be extremely expensive given the need to purchase, transport, and deposit such materials to the reach. Recommendations for Santa Fe River flow, form, and function draw from this dissertation research and attempt to strike a balance between the limits of the physical system and the desires of watershed residents and basin managers. The findings of this dissertation fill voids within the present state of knowledge about system structure and function. Ultimately, the overall theme of these recommendations is that current and predicted future landscape conditions must be the basis for all river restoration initiatives. The recommendations are:

Recommendations for River Flow (8.2.1)

1. *Institute a seasonal minimum instream flow requirement*
2. *Manage dam releases more effectively for environmental benefit and groundwater recharge*
3. *Move beyond the minimum Storm Water Management Plan (SWMP)goals*

Recommendations for River Form (8.2.2)

1. *Develop a sediment budget for the watershed*
2. *Include adaptive management in project planning and design*

Recommendations for River Function (8.2.3)

1. *Revive acequia agriculture*

2. *Move toward watershed-scale land and water management*

8.2.1 Recommendations for River Flow

1. *Institute a seasonal minimum instream flow requirement*

As part of the adopted long-range water supply plan, the City of Santa Fe intends to release 1,000 acre-feet of water to the river each year beginning in 2011 (City of Santa Fe 2008). There are several caveats to the plan, including Rio Grande Compact implications, legal restrictions, drought, emergency conditions like upper watershed fire, a functioning Buckman Direct Water Diversion, among others. Despite the overwhelming evidence that downstream releases have positive effects and numerous benefits, the city has no legal requirement to follow the intent of their plan. Given the history of the water company's dealings with acequia associations, and despite the stated intentions, as population grows and the unknowns of global climate change affects winter snowpack, it is likely that good-faith releases to the river will be limited. This research supports the pursuit of legal avenues to secure water rights for the river, which includes purchasing a water right for the river through the Santa Fe River Fund (utility check-off program). This research supports seeking a minimum instream flow requirement, but because the dams no longer generate hydropower, there is no legal avenue such as the Federal Energy Regulatory Commission relicensing procedure to force such a proviso. The city is not bound to any license requirements, as there is no license, but only limits of their New Mexico storage and diversion permits.

Water released to the river has the potential to recharge local groundwater and to act as a storage option for recovery via wells during times of drought. Recent studies of water infiltration indicate that a consistent flow through the channel is more effective than the springtime releases and summer stormflows that are typically the only instream waters (Grant and Williams 2009). It is time for the city to shift its thinking from times past when released water was thought to be "wasted down the Santa Fe river bed" (*The Santa Fe New Mexican* July 9, 1946), and instead acknowledge that consistent releases are an innovative way of storing water during times of plenty. This water is neither wasted nor lost. Since the city passed an ordinance restricting the drilling of new wells on property with available waterline access, this governmental entity and its water customers are the primary beneficiaries of this strategy (Grant and Williams 2009). New Mexico passed a Groundwater Storage and Recovery Act in 1999, which makes such a project possible via permit, but legal problems restrain the city from its implementation (19.25.8 NMAC). Because the city is only entitled to 5,040 acre-feet of *river* water each year, any reservoir water released to the river for the stated purpose of recovering it later as groundwater violates their storage and diversion permits. According to the Interstate Stream Commission, any water that the city chooses to release for this stated purpose will count against their annual San Juan-Chama water allocation (the San Juan-Chama Diversion brings water from the San Juan River in the Colorado basin to be distributed to users in the Rio Grande basin) (Grant and Williams 2009). Perhaps a viable solution is to *state explicitly* that the intent of water releases is to improve the environment: the benefits of a consistent instream flow go beyond groundwater recharge. Instream flows increase osmotic pressure within unconsolidated bank sediments like the Ancha terrace alluvium and increase stability. Steady flow supports riparian vegetation, which in turn increases bank stability, mitigates stormflows, shades the channel, keeps water temperatures low, provides wildlife habitat, recreation, and aesthetics. Groundwater recharge would be an implied benefit of water releases from which both private landowners with wells, and the city, would benefit.

This research considers that a consistent, seasonal release strategy may be more fitting than a consistent year-round release. Seasonality dominates the river's historical hydrologic regime. Because the delivery of winter moisture determines river flows and reservoir storage, it may be wise to wait until moisture delivery is ensured each year, and to restrict flows to the growing season. Flow regime naturalization, which includes a seasonal component, is a common restoration strategy throughout the Southwest (Poff *et al.* 1997; Mahoney and Rood 1998). Restoring a flow regime in the Santa Fe basin should reflect the ability for local the climate to support it. Withholding flows for the growing season will allow more volume to fill the channel during time when riparian vegetation would be apt to use it: dividing the same volume over an eight-month period instead of all twelve months. Not only does this release regime more closely mimic nature, it considers reservoir management for drought as a defining factor in city planning. With a seasonal release strategy, the city can assess the previous winter's moisture delivery to determine a custom release schedule prior to the beginning of each growing season. However, a seasonal release does not mean a high velocity pulse of low frequency and duration. In this context, a seasonal release strategy includes a conservative flow rate sustainable throughout growing season each year. The consistent release volume will depend upon the moisture conditions in the previous winter. Recommending a seasonal release strategy however does not condone the city's hydrologic regime management strategy that has historically released larger-than-effective flows to the river during the springtime only. These flows, although similar to the pre-dam hydrologic regime in their timing (and sometimes velocity), no longer are fitting for geomorphic and biologic conditions in the urban reach (Section 8.2.2).

2. *Manage dam releases more effectively for environmental benefit and groundwater recharge*

In 2009, for the first time since the installation of upstream dams, the release of excess water to the river is being managed carefully to last as long as possible. In the past, water releases occurred in a pulse reminiscent of pre-dam springtime flows. From the perspective of restoration, recreating a flow pattern reminiscent of the natural hydrologic regime often is one of the main goals of such initiatives; however, when the geomorphic and ecosystem structure and function no longer represent natural conditions, the "natural" flow regime may no longer be fitting for the setting, and may cause additional system degradation. For example, released springtime pulses were high in both velocity and scour potential, given their sediment-free nature. Kayakers would take advantage of high water in the river, and cutthroat trout (*Oncorhynchus clarkii*) would be stocked for the annual fishing derby, but by June or July, the water would be "turned off," leaving the dry, evaporate-covered cobbles of the channel bed to be wetted only by storm runoff. The brevity of the releases, although "natural" in their timing, had limited usefulness in recreating geomorphic and ecosystem structure or function.

Resolution 2009-47, passed on April 29, 2009, authorized the city to "support a living Santa Fe River by allowing water to pass through McClure and Nichols Reservoirs in 2009" (City of Santa Fe 2009c). The resolution cites several reasons for these releases, including social and environmental benefits, and specifically mentions the opportunity for the collection of "necessary physical, biological, chemical, and ecological data" to promote river system understanding. These releases will provide important information necessary to develop a management strategy as part of the stated intent of the long-range water supply plan. Because the Santa SRS stream gaging station sits below the reservoirs, publically available streamflow data can assesses this process. The city also intends to make reservoir release information available via their website as it becomes available.

As part of the city resolution, a proposed release schedule postulates that between May 1 and May 31, approximately 268 acre-feet of water would be released in weekly increments, flowing at a rate of 0.085 cms (3 cfs), increasing to 0.198 cms (7 cfs), then decreasing to 0.113 cms (4 cfs); thus, producing the natural peak historically seen in spring flows (Chapter 5, Section 5.4.4). Daily streamflow data from the SRS station indicate that, thus far, the city has released more than triple the anticipated amount: deviating from anticipated releases makes studies dependent on cause and effect hypotheses difficult to replicate. Determining an effective release rate, volume, and duration requires connecting specific conditions to observed results. This research recommends scientific study of surfacewater-groundwater interactions within shallow wells along the river for a period of three to five years while using identified flow rates, durations, and timings before determining a best management strategy for the hydrologic regime. This period should provide adequate time to observe the effects of a continuously (or growing-season) wetted channel on various hydrologic, geomorphic, and ecologic indicators, as water released to the Acequia Madre in 1992 as part of the court ordered allocation were observed in nearby monitoring wells within three years (Shomaker 1998).

3. *Move beyond the minimum Storm Water Management Plan (SWMP)goals*

Watershed urbanization creates problems that are specific to the conversion of natural to impervious surfaces. As the surface areas of impervious pavements, streets, sidewalks, rooftops, and other infrastructure expand, groundwater recharge decreases while flooding increases: water volumes increase due to the lack of infiltration. Runoff generated by these surfaces during precipitation events has no chance at infiltration, and flows rapidly to curb inlets, storm drains, and surface waters. Flooding becomes flashy because of the rapid runoff rate and water delivery to streams; the rising limb of the hydrograph is steeper in slope. Sediment, oils, and other pollutants from roads, parking lots, and other various surfaces reduce water quality due to their direct delivery, without any filtration, to storm drains.

In 1999, EPA promulgated the Clean Water Act's Stormwater Phase II Rule of the National Pollutant Discharge Elimination System (NPDES) (64 FR 68722 (Dec. 8, 1999)). Currently, the permitting authority for NPDES permits in New Mexico is the Region VI office of the Environmental Protection Agency (EPA). Under the Clean Water Act of 1972, the Phase II Rule classifies the urbanized area of Santa Fe, based on 2000 census population densities, as a small municipal separate storm sewer system (MS4). A MS4 is a "conveyance or system of conveyances (including roads with drainage systems, municipal streets, catch basins, curbs, gutters, ditches, man-made channels, or storm drains)" that collects and conveys untreated stormwater into waters of the United States (40 CFR 122.26 (b)(8)(2005)). As a small MS4, the city's Storm Water Management Division received a NPDES permit (No. NMR040000), and is charged with permit compliance, and the development and implementation of a Storm Water Management Plan (SWMP).

The EPA identified six minimum control measures within Santa Fe's SWMP plan, including measurable goals and improvements necessary to maintain compliance (City of Santa Fe 2009d). These minimum control measures are: (1) public education and outreach on storm water impacts, (2) public participation and involvement, (3) illicit discharge detection and elimination, (4) construction site storm water runoff control, (5) post-construction storm water management in new development/redevelopment, and (6) pollution prevention/good housekeeping (City of Santa Fe 2009d: 4). In the summer of 2008, the city began seeking comments on a draft SWMP. The city's proposed measurable goals include, but are not limited to, mapping the stormwater outfalls; documenting the number of citizen complaints; counting the number of pamphlets distributed to individuals during meetings; enumerating the number of individuals trained on the negative effects of stormwater; documenting the number of "clean up after your pets" signs posted; and educating a percentage of elementary school age children each school year. Santa Fe's stormwater management plan mainly includes talking about stormwater management. Few proposed actions manage the actual water. There are no concrete plans to measure the present or future volume of stormwater entering the river: actions that would establish baseline conditions and enumerate future changes in volume. A sampling plan would also indicate if their actions were making a difference in improving water quality. If a living river is truly a goal of the city, than managing the runoff generated by impervious surfaces must involve more than talking about managing it.

The most threatening problem to Santa Fe River restoration is not the lack of water, but the uncontrolled presence of it: polluted water generated by storm events enters the river via outfalls, curb inlets, and drains. Stormwater directed to the river, especially large volume flows, degrade other restoration efforts and reduce their effectiveness (Figure 8.K). This research recommends a series of action items and structural best management practices that move beyond the minimum goals of the draft SWMP, and actively manage the storm-generated water. These include:

1. (1) establishing a stormwater sampling plan that measures the *volume* of flow generated by storm events of quantified magnitude and duration, and the quality of flows within the river at incremental locations along its course,
2. (2) mandating the development of a series of stormwater retention basins (less than 10 acre-feet) at strategic locations throughout the basin for directing stormwater and allowing for infiltration,
3. (3) passing ordinances to require low-impact development (LID) methods for all future construction within the basin,
4. (4) mandating water harvesting measures and conversion of impervious surfaces (where appropriate) for all public buildings,
5. (5) providing the general public with water harvesting tools like rain barrels, funding small projects for homeowners to convert impervious surfaces to pervious covers, and rewarding efforts through monetary incentives and awards.

The successes seen in the reduction of daily water use between 1995 and 2008 can serve as a model for reducing stormwater.

A variety of measures, specifically LID, can mitigate the effects of urbanization on watersheds. LID includes practices that reduce stormwater runoff from impervious surfaces and mitigate pollution delivered to waters during storm events. Some examples include permeable pavement, vegetated rooftops, grass swales, and bioretention basins. Homeowners can harvest draingutter water in barrels for irrigation. Strategies for new development includes minimizing impervious surfaces as much as possible, including reducing street widths if allowable, creating central cobbled areas with xeric vegetation in cul-de-sacs and parking lots, and replacing concrete sidewalks with paving stones. LID

Figure 8.K. River in flood at River Road, July 14, 2008
Source: photo by Lars Anderson (2008)

measures are more cost effective during construction, but may require some additional maintenance: permeable pavement needs frequent vacuuming to remove accumulated sediment, vegetated rooftops and swales need pruning and mowing, and bioretention basins require sediment excavation every few years to maintain their filtering capabilities.

The benefits of stormwater management outweigh the costs. As the city and public invest millions of dollars to add water to the river, it seems counterintuitive to allow stormwater management to continue without more proactive strategies. Stormwater is a serious challenge for Santa Fe: as land values increase and the city center completely fills with development, the incentive to set land aside for detention basins becomes more difficult, yet increasingly important.

8.2.2 Recommendations for River Form

1. *Develop a sediment budget for the watershed*

This research illustrates the continuously escalating disequilibrium between flow and sediment since the arrival of humans to the watershed. Human-induced changes affecting the river's sediment load include extensive grazing in the sierra, the construction of reservoirs, landcover conversions of agriculture to impervious surface and rangeland to bare soil, and aggregate mining from the channel. These human-induced changes to the flow and sediment delivery process at the atmospheric-lithospheric boundary induce form adjustments, including localized changes to cross-sectional geometry (including bed aggradation and degradation), and reach-scale planform (Chapter 6). Anthropogenic watershed changes increase complexity in sediment budget development, and alter the transfer and storage of sediment to downstream reaches (Knighton 1998). In Santa Fe, the reservoirs act as a sediment sink by actively filtering downstream-migrating sediment from the upper watershed, while past sand and gravel mining within the channel removed a great deal of sediment and activated headward erosion. The current conditions of the urban and lower reaches are starkly different from undisturbed sediment regimes of compound and braided rivers. Future initiatives for river management and restoration, which include consistent, sediment-free water releases, channel reengineering, and the exclusion of aggregate mining from the channel, necessitate additional understanding of the landscape processes at work within the basin, specifically the effects of rapidly urbanizing, uncontrolled sprawl at the city fringes. Managing the sediment-free flows introduced to the channel via reservoir releases and other future river initiatives requires watershed-scale sediment budget development.

An effective sediment budget will foster understanding of watershed responses to both natural and anthropogenic influences; budget information is essential for successful channel form redesign to fit within present and future processes at work at the basin scale. Currently, the watershed's sediment regime links closely to the stormflow management goals discussed above. Specifically, the sediment budget should include: (1) identifying sediment sources; (2) quantifying bedload and suspended sediment load concentrations and volumes; (3) estimating erosion rates, instream sediment storage volumes, transport rates, and residence times; and (4) evaluating sediment production by land use and land cover type. Methods for budget development need to employ fieldwork and GIScience techniques. Sediment source identification and channel change affecting sediment redistribution are quantifiable using LiDAR, orthophotographic rectification of historical imagery, and road bridge surveys. Translating sediment production by specific land cover types to the basin scale is possible with landcover classification via remote sensing. Instream sediment sampling within flows will quantify the fraction of bedload and suspended load within discharges of different magnitudes. Characteristics of sediment loads inform geomorphologists reengineering channel planform and cross-sectional geometry of potential river forms fitting for the anthropogenic landscape.

2. Include adaptive management in project planning and design

The NRC (1992) stated that it is not enough to restore a specific river reach to a state of pre-disturbance, but that the effort must include restoring system functionality. Thus, the key to effective restoration is to identify and subsequently halt the processes impairing the system in the first place. However, in complex urban watersheds, identifying the processes impairing the system may be possible, but subsequently halting them is unlikely: here, for example, upstream dams and impervious surfaces are permanent features. In Santa Fe, the effective restoration of river flow, form, and function will consider and work within the limits of existing and future natural and anthropogenic landscape processes. Adaptive management improves river restoration outcomes over the long-term by allowing for mid-process investigation, continued learning, and adjustment to unforeseen conditions or misinterpreted relationships. The process of adaptive management necessitates extensive study of reach forms and processes prior to design, monitoring project design after initial efforts, and subsequently adjusting engineering and prescribed regimes after observation. Therefore, monitoring, adaptive management, and evaluation lean heavily on the original project goals and baseline data. Monitoring involves collecting data parameters similar to those gathered during the baseline investigation and comparing pre- and post- restoration indices. Monitoring allows for flexibility during the restoration process, so to adjust the direction of restoration upon encountering unforeseen conditions or obtaining new information. Lastly, evaluating restoration efforts at completion is an important part of the process, as it determines whether the initial goals established during project planning are met effectively.

Effective adaptive management reflects on failures to understand why a particular design was ineffective. Was there a misinterpretation of system processes and forms? Did the channel form design include human desires where the existing structure and landscape conditions could not support such a function? Such examples already exist in the watershed, as described in Section 8.1. To move beyond past mistakes that cost both time and money, this research suggests incorporating adaptive management strategies in all future ‘Request for Proposal’ requirements for awarded contracts at the city and county level, educating the public about the benefits of adaptive management, and encouraging all private landowners, non-profit, and public entities involved in restoration to proceed with adaptive management in future endeavors.

8.2.3 Recommendations for River Function

1. Revive acequia agriculture

This research clearly elucidates the contributions of irrigated agriculture and the leakiness of the unlined acequia network to the river via subsurface flow. From settlement until the early 1900s, acequia farmers spread trillions of gallons of water across the valley floor each year. Ultimately, these actions led to a saturated Santa Fe, and a likely perennial river for most of its course. Although most of the acequia network is now defunct, with subdivisions and impervious surfaces now covering many of the fields, the possibility of agricultural renewal may present a unique opportunity perhaps only befitting a "city different." This research recommends acequia agricultural revival on undeveloped lands once irrigated by the ditch network, near or within the Village of Agua Fria or La Cienega.

In 1981, Scanlon & Associates, Inc., presented a series of wastewater reuse options to the City of Santa Fe, one of which was irrigated agriculture. They recommended land application of treated water to fields of alfalfa hay as a means of phosphorous and nitrogen control, but cautioned that the appeal of such cropping operations were declining as land values were escalating. Despite high land prices, the county successfully converted river margins to conservation easement for the San Ysidro restoration, and set a precedent for preserving land for the public good. The San Ysidro restoration illustrates the possibility for cooperation between various groups (Trust for

Public Land, Santa Fe County Open Space and Trails, El Camino Real River Connection, City of Santa Fe, Agua Fria Village, Santa Fe Watershed Association, and Santa Fe Conservation Trust), and private landowners.

The revival of several small, but contiguous plots of irrigated agriculture close to the river would provide a multitude of benefits for the watershed and people of Santa Fe. From an environmental perspective, water applied to fields would readily infiltrate the subsurface, recharge the local aquifer, and return baseflow to the river, just as in the past. Non-potable filtered/disinfected waters from the treatment plant could be pumped a short distance and discharged to an acequia. The leakiness of the ditch would also aid groundwater recharge. Recreational parks, sport fields, and golf courses already receive city wastewater; some infrastructure exists currently for such a process to proceed. Agua Fria or La Cienega are in close proximity to the WWTP, further reducing infrastructure construction costs. The acequia network reconstruction completed in this research could aid in site selection and assist in ditch identification, as many are now filled with silt and perhaps lost to the naked eye. Water from the acequia spread via traditional methods to grow crops, such as beans and alfalfa, would convert nitrogen from the nutrient-rich water, and would reduce the possibility of groundwater contamination.

From a social standpoint, the crops could be sold at the city farmer’s market frequented by local residents and tourists. Purchasing locally grown products is becoming increasingly popular, and it is likely that purchases from a Santa Fe acequia revival farm would bring pride to the community. Although revenue from the crops could not realistically sustain the farm, marketing a traditional farm experience as ecotourism might attract the tourism industry (which is the largest moneymaker in Santa

Fe). Archambault and Ulibarri (2007: 491) found that market analysis "indicated that there are cultural and environmental attributes of acequia agriculture landscapes that are not captured in the market-assigned value of acequias," and that the nonmarket value could improve through initiatives like "supporting education and research of the cultural and environmental contributions of acequias; and promoting the interests in tourism in acequia communities." By inviting members of the four remaining acequia associations to participate, oral traditions of water application and spreading pass to visitors, interested residents, and youth of Santa Fe, thus reviving traditional ties to land, water, and community. School groups could participate in farming, and in the process learn about Santa Fe history, and local traditions. Local universities could use the farm as a source for the study of Hispano ethnography and traditional agricultural techniques. The ditch would require initial and subsequent cleanings and provide opportunities for public participation. The annual ditch cleaning of the Acequia Madre has become so popular that hundreds of local community members (not on the acequia) have volunteered to participate (Bové 2008: personal communication).

This idea is not without problems: mostly of the legal and monetary sort. To avoid legal issues associated with water rights, prior appropriation, and adjudication, this proposal does not include recreating an acequia community, or attempting to validate the water right of the land plots adjacent to the ditch. The proposed project would involve purchasing water from the city, which owns the wastewater and can sell or allocate it as they decide. The ditch simply is the method of traditional conveyance and groundwater recharge, which requires collaboration and consultation with the New Mexico Acequia Association and the State Engineer. The creation of a non-profit group likely would be the best option for running the operation. Land purchases may be coordinated through the Trust for Public Lands (State Land Office) as a conservation easement, like in the San Ysidro restoration project (Section 8.1.2.5). This project will require grant money, coordination, and concerted effort, and is not without many obstacles. The city prides itself on its agricultural roots; perhaps such an endeavor would create a multitude of environmental and social benefits for residents and visitors alike.

2. Move toward watershed-scale land and water management

Understandably, the move toward watershed-scale land and water management is difficult; however, this research recommends beginning with cooperative data collection initiatives at the watershed scale. Data acquisition efforts for this project illustrated repeatedly how the politically divided nature of this system introduces an additional layer of disconnectedness to the already physically divided river. Spatial datasets generated by different political jurisdictions typically stop at their borders, adding increased difficulty to this research, and decreasing the effectiveness of the results. For example, the city collects high-resolution imagery and LiDAR, which is invaluable for modeling land cover change, flood inundation, and sediment migration through the system. However, its value is reduced when the data stop at their boundary while the processes continue downstream. Geologic quadrangles were important for explaining process-form relationships, landscape scale dynamics, and groundwater-surfacewater interactions, but were available at different scales within the eastern, central, and western portions of the watershed, thus making spatial comparisons difficult. In order to restore system continuity, datasets used to model landscape processes need to cover the entire landscape.

Fragmented data only prolong the problem of river fragmentation and encourage disjointed, incomplete solutions.

8.3 REVIEW OF OBJECTIVES, CONTRIBUTIONS, AND CONCLUSIONS

8.3.1 A Reflection on Research Objectives: The Effects of Humans on the Santa Fe River and its Watershed

Geographic study helps unravel the complex and intricate connections between system variables to explain the interconnectivity between humans and the environment (National Research Council 1997). As a geography dissertation, this research sought: (1) to describe the past and present condition of the Santa Fe River and its watershed from a physical perspective, including the effects of human actions on hydrology (flow) and fluvial geomorphology (form), and (2) to document Santa Fe River function throughout the last four centuries of its history, while emphasizing the role of water in the region's initial survival, subsequent growth, current prosperity, and future challenges. This research met these objectives by employing a web of geographic methods and historical descriptions. The amalgamation of diverse datasets presents a perspective on the basin that provides advanced comprehension of system evolution. "The highest degree of confidence is achieved by combining multiple, independent data sources and historical methods" (Swetnam, Allen, and Betancourt 1999: 1201). Through the innovative use of spatial technologies, this research illustrates the diversity of geography, and its place at the forefront of scientific discovery. GIScience translates a fabric of geographic tenets into a tangible scene, where historical data layer to render intricacies once elucidated through the written word. Inferred relationships become spatial realities, features with correct space and scale materialize as a visual of historical landscape evolution, and the basin's environmental history emerges from the geography of river flows, the changing river forms, and the functioning acequia institution.

Though standing upon the current historical narrative of Santa Fe, this research moves beyond descriptive history-telling to expand the anthropologic record and literature via a process-form perspective of environmental conditions and human interactions. This dissertation presents a unique historical perspective of Santa Fe that is bound to water, stresses the importance of acequia agriculture in river hydrology and fluvial geomorphology, and is the first known document to present the history of a Rio Grande subbasin. Explanations for specific physical landscape and river form responses to human modification tie directly to reach-specific conditions that occur on a longitudinal continuum. Physical landscape factors like geology, climate, and landcover adjust in the downstream direction, and set the stage for upper, urban, and lower reach responses to human modification.

8.3.2 A Review of Research Contributions and Conclusions: Innovative Methods and Practical Applications

This dissertation is both timely and significant for several reasons. Scientists within several research fields will benefit from the innovative method that establishes a connection between tree-ring predicted streamflows and annual river carrying capacity for irrigated agriculture. This technique, not encountered elsewhere in the literature, adds an element of quantification to historic happenings in Santa Fe, while an innovative method combining field reconnaissance and GIScience techniques digitally reconstructs the acequia network. The information presented through the river carrying capacity method, combined with the acequia network reconstruction, enlightens scholars to the degree of human-induced landscape change in Santa Fe. These techniques add to the current body of literature that estimates the historic impact of irrigated agriculture on landscapes, and illustrates that despite rudimentary technologies, human actions are transformative to process-form relationships in arid watersheds. Both the irrigation carrying capacity and acequia network reconstruction techniques can translate to other places where such data and landscape history are present to further local discovery.

This dissertation is also practical because it translates science to the field for direct application in future restoration efforts. Process-form relationships and landscape dynamics elucidated through this scientific research will help replace the predetermined restoration designs (as in the State Land Office reach), and limited approaches (such as the Forest Guardians riparian work) with concrete data and appropriate conclusions necessary for the sustainable restoration of river flow, form, and function. This research also exposes how past environmental responses to human landscape modification and the tightly controlled architectural style currently influence perceptions about appropriate river restoration. The following synthesis of selected findings from this research brings awareness to the effects of humans on the environment in Santa Fe and calls attention to how contemporary mythmaking and the desires to recreate "natural" conditions outside the recommendations of science factor into the complexity of river restoration.

FLOW

- Prior to dams, climate fluctuations and water availability for annual irrigation limited the extent of arable land, while the vast application and spreading of water in the porous alluvium transformed the river via subsurface flow. Centuries of human-landscape modification from open space to irrigated agricultural fields and acequias transformed the physical environment, and perennially wet the river. Now, as human-landscape modification shifts from agriculture to urban development and expansive impervious surfaces, there are misunderstandings about the river's flow regime, and what may be reasonably attained via flow restoration efforts. Irrigated agriculture created a flow condition that was not "natural," but that nevertheless came to be considered so in the minds of watershed residents and managers. Given the modern land cover conversion, however, expectations for the restoration of river flows are elevated beyond possibilities of the current reality, having roots in an irreparably lost landscape condition.

FORM

- Alluvial terrace topography at the mountain front dictated acequia placement, size, and gradient; in turn, the road network and city layout still represent the pattern. Now, despite the loss of functioning acequias and their purposes (which are truly historic), Santa Fe's landscape of historical fantasy preserves the acequia-influenced pattern in perpetuity. The irony of the current initiative is that the aim is more to preserve and restore the fabricated scene than the features influential to city development and sustainment.
- After humans built dams, the downstream river adjusted its planform and cross-sectional geometry by narrowing and deepening in response to the modified hydrologic regime and sediment conditions. The present channel constructions through downtown have been in place for eighty years; the pre-dam configuration is lost to the present psyche, and historicity lures the present to impose a restored form not fitting current and future landscape conditions. Restoration to a theme similar to the upper watershed "mountain stream" (that most have never seen yet matches an ideal fitting the fabricated landscape), will likely neither stabilize the river nor meet the multitude of expectations of the living river initiative.

FUNCTION

- Landscape degradation in the upper watershed because of grazing and logging induced sediment mobilization that filled dams. The societal reaction determined that watershed closure was the best response, which ultimately led to increased threat of catastrophic fire. The upper watershed has been closed to public entry for more than a generation. Because a hands-off approach is the only way most have ever known, the idea of entering and disturbing the landscape brought anxiety and public resistance. However, moving from an ideology of non-management to an adaptive management strategy with such a successful outcome illustrates how the careful application of science befitting the landscape conditions is as important for the transformation of the physical environment as it is for molding the ideals of watershed residents and managers.

- Some landscape features were more pivotal to human survival in the watershed than others. This research illustrates the formation of the cienega complex from a geomorphic perspective and highlights the importance of this landscape feature's elements in Santa Fe physicality and history. This research credits the cienega complex with a dominant role in site selection (perhaps even more so than the river), and illustrates its interconnectivity with the river, source of the Rio Chiquito and convent pond. In times of drought, the cienega complex afforded survival, and was an exemplary example of traditional Spanish communal land stewardship. Yet, despite its transformative nature, there is no call for its restoration or recognition of its role because it lies beneath a sea of pavement. The cienega's downplay as a foundational feature is indicative of the selective nature of Santa Fe history.

For the next year, the City of Santa Fe commemorates its Cuarto Centenario and celebrates its unique place in U.S. history. This opportunely timed research elucidates four-hundred years of water resource use at the foot of the Sangre de Cristo Mountains in northern New Mexico. This year, deliberate contemplation of history is part of the present philosophy as the city postulates future conditions for its land, water, and people. This work links the Santa Fe River to the city's history, and provides a perspective on river restoration not swayed by the current aesthetic scene of modern adobe appearing in harmony with the surrounding landscape. The watershed's authentic past reveals highly complex interactions between the physical landscape and the resident society. The framework of Santa Fe River flow, form, and function presents an authentic history of the river, and illustrates how romantic ideas attached to the past Santa Fe originate with the present scene. The translation of these ideas onto a management design strategy, rooted in an unrealistic utopia, will set river restoration efforts up for failure. It is the present physical landscape and the future limitations induced by an ever-expanding urban surface and increasing population, coupled with the inevitable water scarcity induced by global climate change that need dictate the vision for a living river.

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APPENDIX A – THE SUMMARY OF HYDROLOGIC PARAMETERS USED IN THE IHA, AND THEIR CHARACTERISTICS

General Group	Regime Parameter	Stream-flow Parameters Used in the IHA	Examples of Ecosystem Influences
1. Magnitude of Monthly Discharge Conditions	Magnitude Timing	1. Mean discharge for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
2. Magnitude and Duration of Annual Extreme Discharge Conditions	Magnitude Duration	1. Annual maxima one-day means 2. Annual minima one-day means 3. Annual minima 3-day means 4. Annual maxima 3-day means 5. Annual minima 7-day means 6. Annual maxima 7-day means 7. Annual minima 30-day means 8. Annual maxima 30-day means 9. Annual minima 90-day means 10. Annual maxima 90-day means 11. Number of zero-flow days 12. 7-day minimum flow divided by mean flow for year	• Balance of competitive, ruderal, and stress-tolerant organisms • Creation of sites for plant colonization • Structuring of aquatic ecosystems by abiotic vs. biotic factors • Structuring of river channel morphology and physical habitat conditions • Soil moisture stress in plants • Dehydration in animals • Anaerobic stress in plants • Volume of nutrient exchanges between rivers and floodplains • Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments • Distribution of plant communities in lakes, ponds, floodplains • Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
3. Timing of Annual Extreme Discharge Conditions	Timing	1. Julian date of each annual one-day maximum discharge 2. Julian date of each annual one-day minimum discharge	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms • Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish • Evolution of life history strategies, behavioral mechanisms

4. Frequency and Duration of High/Low Flow Pulses	Magnitude Frequency Duration	1. Number of high pulses each year 2. Number of low pulses each year 3. Mean duration of high pulses within each year 4. Mean duration of low pulses within each year	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants • Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain • Soil mineral availability • Access for water birds to feeding, resting, reproduction sites • Influences bedload transport, channel sediment textures, and duration of substrate disturbance
5. Rate/ Frequency of Hydrograph Changes	Frequency Rate of Change	1. Means of all positive differences between consecutive daily values 2. Means of all negative differences between consecutive daily values 3. Number of flow reversals	• Drought stress on plants (falling levels) • Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility stream edge (varial zone) organisms

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[1] This is not an exhaustive list of the groundwater studies available from the New Mexico Office of the State Engineer Library. Aquifer hydrology reports by independent consultants accompany each subdivision construction. For a list of all available technical and hydrology reports, visit the New Mexico Office of the State Engineer Library via the World Wide Web.

[2] Cienega, the Spanish word for wetland, marsh, or swamp, is oftentimes written within historical literature as *ciénaga*. Both are equally correct.

[3] The vector geology layers include: units (as polygons), attributed with their names and ages; structures such as faults and contacts (as lines); geologic and human features like strike and dip markers, springs, windmills, wells, reservoirs (as points).

[4] The Rio Grande Compact is an agreement between the states of Colorado, New Mexico, and Texas, which equitably apportions Rio Grande waters above Fort Quitman to each stakeholder. The Compact became effective on May 31, 1939 by consent of the U.S. Congress. Each state is entitled to the development of their water resources as seen fit; however, each must deliver water to downstream stakeholders on a schedule determined by compact commissioners (consisting of the Colorado and New Mexico state engineers, an appointed commissioner by the Governor of Texas, and a U.S. representative). Based on engineer recommendations to the commissioners, water resource development in Santa Fe takes place under the caveat that a certain volume of water must be released to the Rio Grande each year (under the direction of the NM Office of the State Engineer) to meet the requirements of New Mexico to deliver a volume of water downstream to Texas (State Engineer's Office 2009). The original Rio Grande Compact document is located in Box 40 of the William A. Brophy and Sophie Aberle Brophy Papers (1923-1973), housed at the Harry S Truman Library in Museum in Independence, Missouri. The Rio Grande Compact is available via the World Wide Web at the New Mexico Water Resources Research Institute.

[5] In 1889, the USGS established the first stream-gaging station on the Rio Grande River to measure daily stream discharge (Wahl, Thomas, and Hirsch 1995). The program blossomed into a network throughout the United States, which in 1994 included 7,292 stations, with over 146 million 'at-a-station' daily discharge values recorded since the program's inception (Wahl, Thomas and Hirsch 1995). Due to the massive volume of data over an extended period, this resource is valuable in completing change detection in the hydrologic regimes of rivers. Today, the main purpose of the current stream-gaging network is "to

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provide information on or to develop estimates of flow characteristics at any point on any stream" in the Nation (Wahl, Thomas, and Hirsch 1995: 4). The number of stream-gaging stations has fluctuated throughout the last century, depending on the water needs of the Nation, or budgetary conditions. In New Mexico, there are currently 104 stations in operation recording either daily stage or other daily stream flow characteristics. These values are available via the World Wide Web at the USGS National Water Information System: Web Interface.

[6] Converting the Arroyo Hondo tree-ring chronology to a digital format was necessary to recreate Santa Fe River flow prior to stream gaging. The correlation coefficient from the reconstructed annual precipitation record gave a better result (r = 0.71) than the reconstructed spring precipitation record (r = 0.58), and is the dataset used in this analysis. The arrangement of these data is such that each year's value combines precipitation from the previous August through the current July. Daily streamflows from the Santa Fe River near Santa Fe station are summed by month in cfs, and are organized by water years 1913 through 1925 (water years are calculated from the previous October through the current September). Making these datasets match properly involved rearranging the flow data so that the two annual totals reflect the same monthly ranges. This analysis applies linear regression to these two variables to calibrate the model. Annual streamflow (in cfs) is the dependent variable (X) and the annual tree-ring generated precipitation (in inches) is the independent variable (Y). The resulting equation predicts an annual streamflow value for each annual predicted precipitation value: the output is predicted streamflow from 985 A.D. through 1970 A.D. An R^2 of 0.51indicates a positive relationship between the two variables, and shows that there are other factors contributing to streamflow output.

$$Y = 671.89(X) - 4703.8 \qquad r = 0.71 \qquad R^2 = 0.51$$

[7] After scanning, twenty-two maps were rectified in a GIS using a first-order polynomial. Rectification was accepted if the root-mean squared error was less than 2.0. An average of twenty registration points were used to spatially translate, rotate and scale the maps at the accepted level of accuracy. After rectification, the digitization of acequias occurred. The ditches were attributed with their name and number (if known), their date of predication, and whether they were a main ditch or a lateral. Gates, or *presas*, digitized as points, were snapped to the acequia ends at the point where the ditches joined the river.

[8] LiDAR, or light detecting and ranging, is a method of remote sensing that collects highly accurate elevations of the earth's surface in a dense coverage of points. The hydrologic modeling process steps include: (1) digital elevation model (DEM) generation from LiDAR points using inverse distance weighted modeling, (2) filling sinks to remove internal drainage, (3) calculating a flow direction grid, and (4) calculating a flow accumulation grid. A cell size of 1 foot captures a majority of the microtopography and acequias, as a majority of the ditches are over two feet wide (Snow 1988).

[9] "Land-use/land-cover classification based on statistical pattern recognition techniques applied to multispectral remote sensor data is one of the most often used methods of information extraction" (Jensen 2004: 337). Unsupervised classification uses a clustering algorithm to group spatial land cover with similar spectral signatures into categories. The Iterative Self-Organizing Data Analysis Technique (ISODATA), a method of unsupervised classification, is used in this analysis. The specifics of the ISODATA method are detailed by Jensen (2004). This unsupervised classification technique was applied to each image using ERDAS Imagine v 9.3. Analysis of the 1936 image involved 10 iterations and 15 class designations, while the 1951 image involved 10 iterations with 10 class designations: the two images had different histograms and therefore required different treatments to yield the best results. The resulting rasters were then classified into Boolean layers of saturated pixels (1) and unsaturated pixels (0). The existing vector network was overlain onto the Boolean layers, and the saturated pixels were used to visually identify sections that could be snapped together.

[10] The precipitation anomaly value is derived by calculating a precipitation mean (μp) and standard deviation (sp) for a thirty-year range of data: 1978 to 2008. For each year from 1849 to 2008 (j), the thirty-year precipitation mean (μp) is subtracted from each total monthly precipitation value (Σp), then divided by the thirty-year standard deviation (sp) to yield a precipitation anomaly value for each month and year (Apj):

$$Apj = (\mu p - \Sigma p_{,j}) / sp$$

Apj values graphed by month reveal to reveal any significant trends over time.

[11] The first step includes converting a vector line layer of the Santa Fe River to a ten-meter raster layer, with all cell values equal to one. The second step requires multiplying a ten-meter mosaic of DEMs for the watershed by the raster-river, which yields a raster-river grid, in which each cell value is equal to its elevation (in feet). Within the raster-river attribute table, each cell has an automatically generated unique ID number that begins with zero at the outlet, and continues sequentially to the first headwater cell. After importing the attribute table into a spreadsheet program, each unique ID number is multiplied by its cell width (10 meters) to yield a distance value from the outlet cell. After converting the distance units to feet, the distances and elevations, plotted in a scatterplot in reverse order, yield a complete longitudinal profile for the Santa Fe River.

[12] A TIN, or triangulated irregular network, is a digital vector-based surface generated in a GIS by connecting point-level elevation data into a network of facets (i.e. triangles). Unlike a digital elevation model (DEM), a TIN does not represent an evenly spaced distribution of values, but places points most appropriate to capture terrain breaks. TINs are most effective at modeling 3-D terrain and are often used to drape other layers for visualization.

[13] Public and private meetings attended include the Santa Fe Watershed Association, El Camino Real de Tierra Adentro, New Mexico Acequia Association, and the City of Santa Fe Sangre de Cristo Water Division.

[14] A pivotal event in Spanish colonial history, the Pueblo Revolt of 1680 marked the culmination of Indian resentment and the rebellion against colonialism (Sanchez 1989). Pueblos united against the Spanish to drive them out of northern New Mexico. On August 10th the massacre began: Indians slaughtered Spanish residents from every settlement between Santa Fe and Taos. The survivors hurriedly regrouped within the *casas reales* in Santa Fe, and for nine days, were able to withhold their attackers. The Indians, however, severed the acequia serving the stronghold. Without water, the Spaniards were forced to retreat to El Paso. Spaniards abandoned New Mexico for twelve years before the Reconquest in 1692.

[15] Kolmogorov-Smirnoff Test Results:

Variable 1 = SRS: 1913-1925	Variable 2 = SRM: 1998-2008
Sample Size (n) = 4625	Sample Size (n) = 3801
Sample Mean = .427	Sample Mean = .649
Sample SD = .687	Sample SD = 1.063
D-Statistic = .129	D-Critical = 0.030

D-Critical for large samples at α=0.05 $1.36\sqrt{\frac{n_{SRS}+n_{SRM}}{n_{SRS}n_{SRM}}}$

[16] To find the autocorrelation coefficient (r_h) at lag $_h$, calculate:

$$r_h = c_h / c_0$$

by finding the autovariance function, C_h

$$c_h = \frac{1}{N}\sum_{t=1}^{N-h}\left(Y_t - \bar{Y}\right)\left(Y_{t+h} - \bar{Y}\right)$$

and dividing by the variance function, C_0

$$c_0 = \frac{1}{N}\sum_{t=1}^{N}\left(Y_t - \bar{Y}\right)^2$$

Calculate and plot r_h for each time lag $_h$ (r_h is between -1 and 1).

To test for significance, confidence bands are constructed for an alpha of 0.05 using the following:

$$\pm \frac{z_{(1-\alpha/2)}}{\sqrt{N}}$$

[17] IHA discerns the differences in flow parameters at two different stations at two different periods, instead of the pre- and post- dam changes at a single station; an application more typical of this program. To run application in this manner, daily streamflow means (in cfs) at the SFS and SFM stations were normalized by their respective watershed areas, and then multiplied by 100 so that the data were more meaningful. The multiplication does not affect the results because the analysis is examining change in variability and magnitude, and is not interested in the actual volumes of flows. These normalized daily means were inserted into one column in a single input file, with the nodata values between the periods changed to -1 (to indicate missing values). IHA was run using a non-parametric analysis, given the brevity in total years in each period.

[18] The IHA Scorecard for a two-period run contains nine columns. Column 1 describes the parameter under investigation. Columns 2 and 3 display the median streamflow, in cfs (or 50th percentile) for both pre- and post-impact periods. In columns 4 and 5 are the coefficient of dispersion (C.D.) values for both pre- and post-impact periods. The Indicators of Hydrologic Alteration Users Manual (Smythe Scientific Software 2001) defines the coefficient of dispersion as:

C.D. = (75th percentile – 25th percentile) / 50th percentile

Columns 6 and 7 describe the amount of deviation of the post-impact period that each parameter has experienced as compared to the pre-impact period. The Indicators of Hydrologic Alteration Users Manual (2001) defines the amount of deviation by:

[(Post-impact value) – (Pre-impact value)] / (Pre-impact value)

The deviation factor is calculated for both the median and coefficient of dispersion values for each parameter. Columns 8 and 9 display the calculations of a "significance count" for each of the deviation values presented in columns 6 and 7. This parameter is calculated by the random shuffle of all input data and the fictitious recalculation of the pre- and post-impact medians and C.D.s 1000 times. The values reported in columns 8 and 9 are the fraction of trials in which the fictitious values were less than the true values calculated in columns 6 and 7 (Smythe Scientific Software 2001).

[19] In Santa Fe, the growing season is 154 days long, and falls between the date of the last possible killing frost in spring (May 1) and the first possible killing frost in fall (October 1) (Pratt and Snow 1988).

[20] The Urrutia Map is rectified using a first-order polynomial to fit the modern landscape, and the farm fields digitized. The Gilmer Map's rectification required a second-order polynomial due to the distortion of features by the cartographer. A Root Mean Squared Error (RMSE) of less than 2.0 was deemed an acceptable level of accuracy for these rectifications.

[21] Hack (1957) illustrated the theme of area-length relationships in basins with an empirical relationship, where A_d is the drainage basin area, and L is the mainstream length:

$$L = 1.4A_d^{0.6}$$

Using an exponent of 0.6 instead of 0.5 indicates that networks tend to elongate with increasing size. The pronounced elongation of the Santa Fe basin is confirmed when after rearranging the equation to solve for the value of the exponent, it must be increased to 0.65 to hold the drainage area - mainstream length relationship true.

$$46 = 1.4(257)^{0.65}$$

[22] Unsaturated overland flow occurs when precipitation is intense and the land surface simply cannot absorb it as fast as it is falling. It is the type of runoff that occurs in disturbed landscapes, on impervious

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surfaces, or in areas with low surface permeability that experience intense rainfall events. Respective examples of these areas include heavily grazed and logged areas like the upper watershed, parking lots, and semi-arid landscapes such as modern Santa Fe: intense precipitation from orographic thunderstorms during the summer months contributes large quantities of stormflow to the Santa Fe River. Unsaturated overland flow, which has high erosion-generating capacity, moves quickly across the land surface.

[23] The Moore *et al.* (1960) equation for trap efficiency calculates the percent of sediment trapped:

$$T_e = 100\ [1 - (1/(1 + K\ C/A_d))]$$

“where T_e = trap efficiency, C = capacity of the reservoir in ac ft, and A_d = drainage area in mi2, and K is an empirical constant equal to 0.1” (Graf 2002: 269).

[24] A plat of the pond, surveyed in 1948 prior to the school’s construction was scanned from Snow (1988), and rectified in a GIS using digital parcel data from the City of Santa Fe. Because the plat had been shrunken to fit within the pages of a book, the map’s scale of 1-inch equals 30 feet was no longer correct. Creating an additional challenge was the fact that the plat indicated that the lengths of the northern and southern boundaries were 250 feet, which was problematic considering they are different lengths. To solve the spatial positioning problem, the plat was rotated so that north was oriented correctly, and the two known property corners were used to properly scale the drawing. The correct absolute scale was found by measuring the length of the easternmost side in a GIS and creating a ratio using the measured distance and the plat distance. From this ratio, the correct lengths of the other three property boundaries were calculated, and corner points created to complete the affine transformation.

[25] **42 U.S.C. §4332. Cooperation of agencies; reports; availability of information; recommendations; international and national coordination efforts**

[NEPA §102] from Revesz (2005)

The Congress authorizes and directs that, to the fullest extent possible: (1) the policies, regulations, and public laws of the United States shall be interpreted and administered in accordance with the policies set forth in this chapter, and (2) all agencies of the Federal Government shall-

(A) utilize a systematic, interdisciplinary approach which will insure the integrated use of the natural and social sciences and the environmental design arts in planning and in decisionmaking which may have an impact on man’s environment;

(B) identify and develop methods and procedures, in consultation with the Council on Environmental Quality established by subchapter II of this chapter, which will insure that presently unquantified environmental amenities and values may be given appropriate consideration in decisionmaking along with economic and technical considerations;

(C) include in every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on-

  (i) the environmental impact of the proposed action,

  (ii) any adverse environmental effects which cannot be avoided should the proposal be implemented,

  (iii) alternatives to the proposed action,

  (iv) the relationship between local short-term uses of man’s environment and the maintenance and enhancement of long-term productivity, and

  (v) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

Prior to making any detailed statement, the responsible Federal official shall consult with and obtain the comments of any Federal agency, which has jurisdictional by law or special expertise with respect to any environmental impact involved. Copies of such statement and the comments and views of

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the appropriate Federal, State, and local agencies, which are authorized to develop and enforce environmental standards, shall be made available to the President, the Council on Environmental Quality and to the public as provided by section 552 of Title 5, and shall accompany the proposal through the existing agency review process.

[26] **33 U.S.C. §1254. Research, investigations, training, and information**
[FWPCA §104] from Revesz (2005)

(a) Establishment of national programs; cooperation; investigations; water quality surveillance system; reports

The Administrator shall establish national programs for the prevention, reduction, and elimination of pollution and as part of such programs shall-

(1) In cooperation with other Federal, State, and local agencies, conduct and promote the coordination and acceleration of, research, investigations, experiments, training, demonstrations, surveys, and studies relating to the causes, effects, extent, prevention, reduction, and elimination of pollution;

(b) Authorized activities of Administrator

In carrying out the provisions of subsection (a) of this section the Administrator is authorized to-

(2) Make grants to State water pollution control agencies, interstate agencies, other public or nonprofit private agencies, institutions, organizations, and individuals for purposes stated in paragraph (1) subsection (a) of this section;

[27] Establishing priorities for streamflow distributions is a main responsibility of the state engineer. Within the context of the Rio Grande Compact, New Mexico has an obligation to deliver an established water volume downstream to Texas, as determined on an annual basis. If New Mexico fails to meet its required distribution, Texas can issue a priority call, or river call, which informs the New Mexico state engineer's office that it must act to meet the appropriation. The state engineer then orders upstream junior appropriators (like the City of Santa Fe Sangre de Cristo Water Division) to distribute waters downstream. An important exception to this rule is the futile call doctrine. "If the state engineer determines that the increased water flows generated by issuing closure orders to upstream junior appropriators will not reach the downstream senior appropriator making the priority call in usable quantities and in a timely fashion, the state engineer can refuse to issue closing orders… despite a downstream river call" (Stewart and Howell 2003: 947).

[28] The ISODATA method was chosen for four reasons: (1) the method is commonly used and accepted by the scientific community, (2) the area is large in spatial extent, (3) ground reference data are collected on different years than the study imagery, and (4) the aridity of the watershed lends sharp contrast between land cover types and supports the use of an automated technique. To perform an unsupervised classification on the Santa Fe watershed, several data sets were obtained. Two images were downloaded from the University of Maryland Global Land Cover Facility: 1989-05-19 Landsat TM GeoTIFF, and 1999-10-14 Landsat ETM+ GeoTIFF (GLCF 1999). Clipping these images to the watershed boundary in a GIS reduced their large size. Fifty-two digital orthophoto quarter-quads (DOQQs), flown between 1996 and 1998 at 1 X 1 meter resolution, were obtained via the World Wide Web from the New Mexico Resource Geographic Information System Program to serve as ground reference data (RGIS 2004). These images were mosaiced and clipped to the watershed boundary coverage to serve as ancillary data for the confirmation of land cover classes identified via the unsupervised classification. Also obtained via the U. S. Geological Survey (USGS) for ground references purposes was a 15 X 15 meter Landsat 7 composite image of the Rio Grande rift region (USGS 2004). An unsupervised classification of the two Landsat images described above (using ERDAS Imagine v 9.3) involved 10 iterations and 25 class designations for each image. Performing the analysis with fewer classes did not adequately differentiate the urban land cover class from areas of bare soil. After processing, each class was compared visually with the DOQQs, and USGS Landsat image to determine the land cover class identified. The classes are urban, forest vegetation, manicured vegetation, grassland, bare soil, and disturbed. The disturbed class highlights areas where humans have removed the vegetative cover for infrastructure development, such as roadbed preparation, utilities, gravel mining, and current construction. Water is not a spatial feature due to the arid

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nature of the area, and does not warrant a class of its own. Multiplying the number of pixels in each class by the squared pixel size yields the spatial extent of each land cover class.