ABSTRACT

GEOMORPHIC RESPONSE TO LAND USE CHANGE,
MIDDLE VERDE RIVER, ARIZONA

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The Verde River, a semi-arid alluvial river, flows through the Verde Valley in central Arizona, which is home to the communities of Clarkdale, Cottonwood, and Camp Verde. From 1968 through 1995 climate variability caused increasing flood magnitudes that affected river morphology. Concurrently, the town of Cottonwood became urbanized while Camp Verde remained largely rural. Using historic aerial photography in a geographical information system (GIS), this study statistically tested the effects of tributary watershed characteristics on the geomorphology of the Verde River. Land use as measured by percent impervious surface area was used to model potential effects of urbanization on morphology of the river, based on two alluvial reaches in the Cottonwood and Middle Verde areas.

Historic aerial photos of the Verde Valley in 1968 and 1995/1997 were used as base imagery in a GIS to map geomorphic features of the Verde River within 26 segments that received input from 26 ephemeral tributary watersheds. USGS topographic maps, ALRIS streams layer and Yavapai County roads, building footprint, floodplain and 2-foot contour layers were used to map watershed characteristics. Sinuosity and area data were calculated in GIS and exported as data tables. An existing surficial geology map was used to classify erodibility of watersheds. Simple linear regression and multiple linear regression analyses were use to analyze relationships between watershed predictor variables and geomorphic response variables.

Young Piedmont alluvium (Yp) was found to have the greatest effect on river morphology. Yp, fluvially active sediment in tributary washes, was positively related to channel width and scoured bare sediment width. Tributary wash toe slope (gradient within 1.3 miles of river) was positively related to river sinuosity. Ranked percent impervious surface area was negatively related to river sinuosity.

These results were interpreted to mean that sediment discharge from tributary washes can increase the local gradient of the river causing widening and straightening of the channel and reduction in sinuosity by meander bend cutoffs. Urbanization along tributary washes with higher than average slope and greater than average occurrence of Yp can cause greater than average changes in river sinuosity, beyond what would have been caused by watershed characteristics and climate variability alone. This is likely due to more rapid runoff, greater stream power in tributary washes, and mobilization of stored sediment in urbanized areas.

Recommendations were made to the Town of Camp Verde based on results of the study. Caution was advised when developing roads and buildings in areas where adjacent tributary washes have slopes greater than 3.2 percent and a dominance of Young Piedmont alluvium, due to the greater probability of mobilizing stored channel sediment following urbanization. A collaborative process was recommended to improve drainage from private properties to the Verde River to protect property and to preserve ecological functions that are associated that are associated with geomorphic processes.

ACKNOWLEDGMENTS

I would like to first acknowledge the instruction and support of my committee. Thank you to Abe Springer, who was open-minded 10 years ago when a pregnant hydrologist came to him with an idea for an Arizona Water Protection Fund grant to study historic riparian changes in the Verde Valley. Three projects later, this thesis has come to fruition and Abe's son Isaac and my son Gabe are entering 4th grade. Dave Ostergren provided wit and wisdom and a keen understanding of the politics of nature. I deeply appreciate Diana Elder Anderson for her roles as mentor, friend and consummate geomorphologist.

Thank you to the many individuals and organizations who provided data layers and insight into the use of GIS. Kevin Blake of Yavapai County Geographic Information Systems and Jeff Low of Yavapai County Flood Control District graciously supplied much needed land use and floodplain layers. I am indebted to Mark Manone, Kirsten Ironside, Michael Peters, Crystal Krause and Paul Heinrich at the Geospatial Research and Information Laboratory (GRAIL) for making the lab's resources and workspace available and for answering my many niggling questions when I got stuck.

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I dedicate this thesis to my children Gabriel and Andrea Lopez to laud their fascination with the natural world and their great good company.

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PREFACE

This thesis was written in journal format with Chapter 2 representing a journal article for publication in the format of *Geomorphology*. Chapter 1 is an introduction to the study area, summary of previous work and a discussion of relevant geomorphic principles. Chapter 3 is a policy paper intended for use by the Town of Camp Verde Town Council and Town Planner.

CHAPTER 1

Introduction

The Verde Valley in north central Arizona is a verdant corridor in an otherwise austere high desert environment. The Verde River flows through the Verde Valley unimpeded by dams in a reach where low flows are regulated by irrigation diversion, but where flood waters surge through the valley unfettered. The name ‘Rio Verde’, Spanish for ‘green river’, reflects the lush and inviting riparian corridor. While the river supplied life-sustaining water for farming by indigenous Sinagua people and later by Europeans who settled there, population growth over the past half century has shifted the character of parts of the valley from rural to urban. From 1960 to 2000 population in the Verde Valley towns of Cottonwood and Camp Verde grew from approximately 2,000 to almost 30,000 persons (U.S. Census Bureau 2008). In some areas agricultural fields and open space were converted to residential housing and commercial development. Construction of roads, parking lots, and buildings increased impervious surfaces in the Verde River’s watershed, potentially causing greater instantaneous peak flows during storm events. Climate variability has affected how floods reshape the river channel bottom. To evaluate impacts on the Verde River from land use change, this study assessed the possible contributions of climate variability, land use change, and riparian tree distribution change to adjustments in river morphology for the period 1968 to 1997. Historic climate records, climate indices, stream flow data, aerial photos, and geologic maps were interpreted and maps of landscape features were generated using Geographical Information Systems (GIS) to model geomorphic response of the Verde River to catchment geology, geomorphology and land use change.

Geomorphologists have extensively studied geomorphic changes in rivers over time scales both long (centennial to millennial) and short (annual to decadal) (Church 2006, Viles and Goudie 2003, Benda and Dunne 1997, Kochel et al. 1997, Richards 1982). Attempts have been made to relate geomorphologic shifts in river systems to anthropogenic changes in watersheds (Brown and Quine 1999). In regulated rivers, dams and channelization are the dominant anthropogenic forces affecting sediment transport, sinuosity, channel width, and channel entrenchment, whereas in unregulated rivers anthropogenic effects on river morphology are more related to changes in the watershed (Richards 1982). While natural fluvial processes governed by geology and climate exert substantial control over river morphology, these forces appear even more dominant in unregulated rivers. Although river regulation by irrigation diversion dams in the Verde Valley could affect the low flow channel geometry, such limited regulation is unlikely to affect bankfull stage, the discharge at which moving sediment forms or removes bars, forms or changes bends and meanders, and generally does the work that results in the morphologic characteristics of channels (Dunne and Leopold 1978). The challenge of this project was to measure on a decadal time scale the small portion of variability in Verde River geomorphological change that was due to human activity in the Verde Valley.

Study Area

The study area is located in central Arizona along the middle Verde River in the Verde Valley (Figure 1). Two 10-mile reaches of the Verde River are evaluated. The upper “Cottonwood Reach” starts at the Verde Ditch irrigation diversion dam and flows through the relatively urban town of Cottonwood. The lower “Middle Verde Reach” starts 52,000 feet upstream of the Beaver Creek confluence and flows through a rural part of the Town of Camp Verde. These reaches were selected because the channel belt, also called common flood channel, is wide and the Verde River has room to meander compared to more confined reaches (YCFCD 2008). As observed on historic aerial photography, the greatest changes in river morphology during the interval 1968 to 1995/97 are apparent in these unconfined reaches. Between the two reaches Oak Creek, a perennial stream, contributes baseflow and peak flow discharges to the Verde River. Numerous dry washes also provide discharge of water and sediment during storm events.

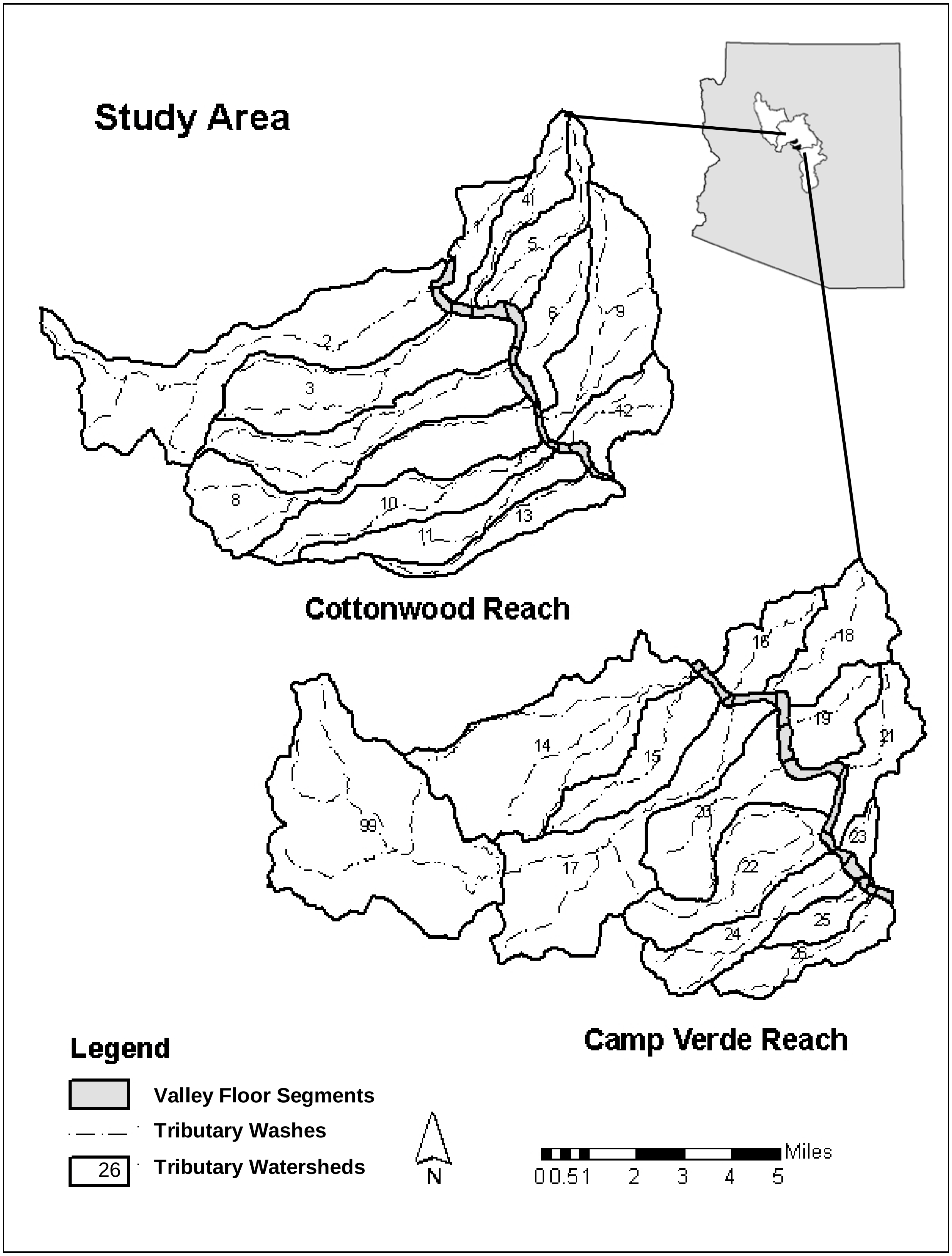

Figure 1. Study Area - Geomorphic response to land use change, middle Verde River, Arizona. Upper, middle, and lower Verde River watersheds are shown in the State of Arizona inset.

Geology and Hydrology

The Verde Valley is situated in Arizona's Transition Zone geological province in Arizona in the Verde Basin, a half-graben structural basin bounded by the Verde Fault and Black Mountains to the southwest and a series of faults extending to the Mogollon Rim on the northeast side of the valley (House and Pearthree 1993, Smith 1984, Blasch et al. 2005, Figure 2). The basin floor is predominantly composed of the Verde Formation which formed during the Tertiary period, 8 to 2 million years ago, when sediments were deposited in a large freshwater lake while the Verde Basin was naturally dammed at the southern end, before the modern Verde River formed (Nations et al. 1981). The Verde Formation is characterized by limestone and fine-grained silt- and clay-rich deposits (Donchin 1983). The Verde Valley started developing in its modern form about 2.5 million years ago when the natural dam at the southern end of the valley breached. Downcutting has continued to the present (Pearthree 1996). The Verde River is incised into the Verde Formation. The limestone beds of the Verde Formation are relatively resistant to erosion, forming cliffs throughout the study area. In the study area, the Verde River's planform may be described as a predominantly single-threaded continuous alluvial channel with a gravel bed and low to moderate sinuosity (Brierley et al. 2002). Changes in river channel position in the past few thousand years have occurred within the limits of the geologic floodplain that is bounded by older resistant beds, alluvial fans and terrace deposits of tributary streams (Pearthree 1996). Large alluvial fans composed of late Pliocene- to late Holocene-aged alluvial deposits extend to the valley floor on both sides of the river (House and Pearthree 1993).

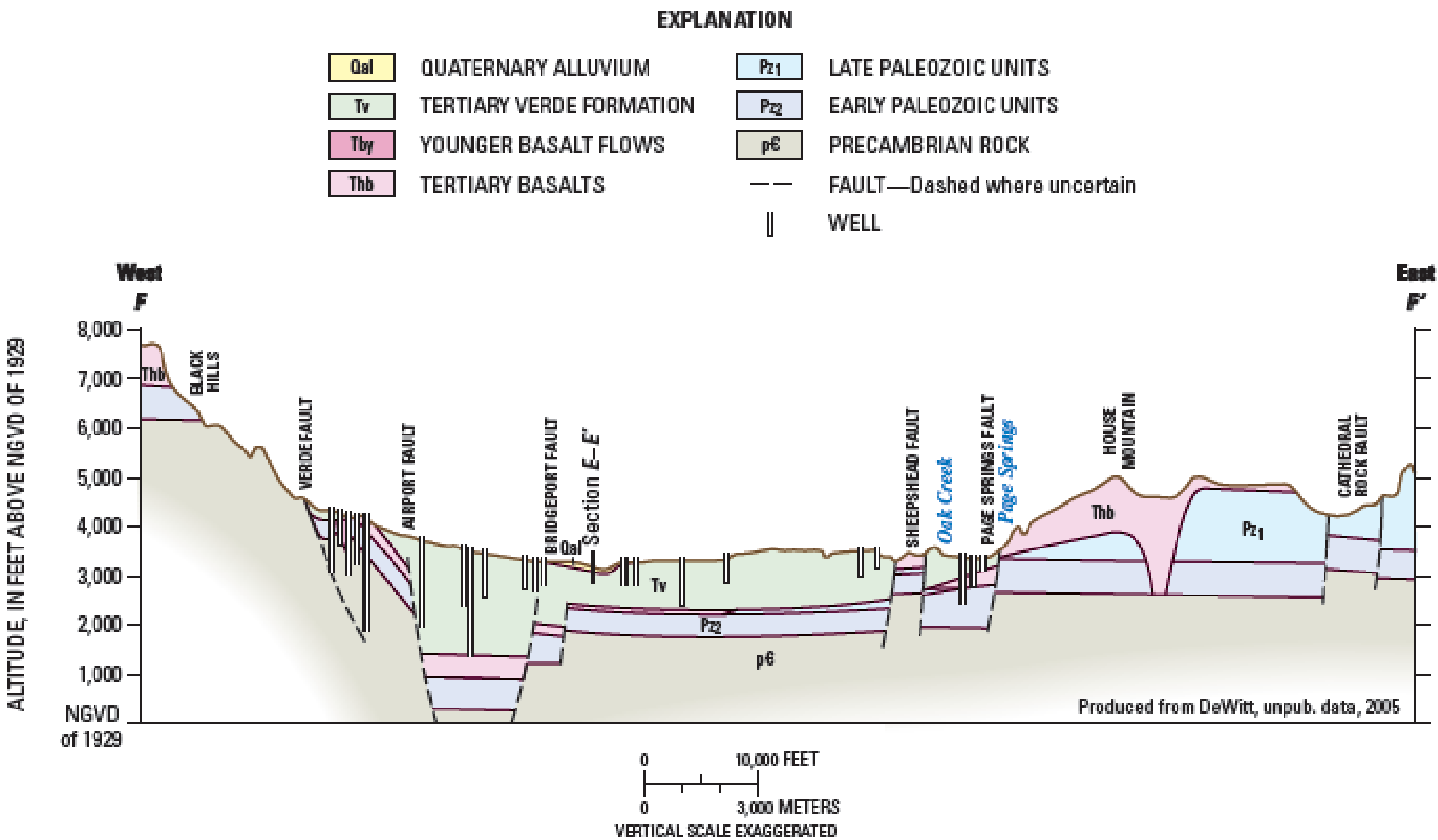

Figure 2. Geologic cross-section of the Verde Valley through Bridgeport at Cottonwood. (Copied from Blasch et al. 2005)

Tributary washes dissecting the large alluvial fans contribute sediment to the river channel in the study area, as do the river's mainstem and larger tributaries that descend from the Black Mountains and Mogollon Rim. Ephemeral tributary washes consist of well-defined sand and gravel bed streams, with slightly incised braided channels, steep slopes, frequent bedrock exposures, high rates of sediment transport, and narrow floodplains (Fuller 2002). At the mouths of the tributary channels the shallow canyons widen into small alluvial fans that extend onto Verde River geologic floodplain. These small fans are characterized by distributary radial drainage patterns and decreased channel capacity, which lead to sediment deposition and sheet flooding. Verde River flood flows can erode the margins of these fans, adding to the flood water sediment load.

Climate and Flooding

The Verde Valley is located in the semi-arid American Southwest. Annual precipitation in the valley is about 12 inches, whereas higher elevation headwater locations can receive 20 to 30 inches of annual precipitation, much of it as snowfall (WRCC 2008). Climate in central Arizona exhibits a bimodal pattern of precipitation (Springer and Haney 2008). Winter snowfall and rain contribute moisture at higher elevations in the headwaters of the Verde River, while winter precipitation in the valley is dominated by rain. Summer monsoon provides storm showers that are spatially heterogeneous. Research since the mid-1990s has shown that hemispheric climate teleconnections exert strong influences on the precipitation regime of the Southwest United States on a decadal time scale (McCabe et al. 2007, Brown and Comrie 2002, Gutzler et al. 2002, McCabe and Dettinger 1999, Cayan et al. 1998). Starting in the mid-1960s the Southwest entered a wet period that corresponded with a positive phase of the

Pacific Decadal Oscillation (PDO). The PDO is a z-score climate index of north Pacific sea surface temperature with a period of 20 to 30 years for each of 2 phases, negative (aka warm) and positive (aka cool) (Mantua 1997). Nested within the PDO are 6- to 7-year cycles of the El Niño-Southern Oscillation (ENSO). During the positive phase PDO, El Niños are more frequent and of greater magnitude, while La Niñas are more prevalent during negative phase PDO (Figure 3). For Arizona, this usually translates into greater winter precipitation during the El Niño-dominated positive phase PDO and drier winters during La Niña-dominated negative phase PDO.

Researchers have also found teleconnections between large-scale climate indices and streamflow in the American West (Redmond and Koch 1991, Pagano et al. 2001). Ely (1997) found that decadal scale climate variation strongly paralleled sharp decreases and subsequent increase in the southwestern paleofloods. Streamflow magnitudes in Arizona appear related to Pacific Decadal Oscillation (Thomas 2007). Although gauging data for the Verde River gage near Clarkdale (USGS gage 09504000) is missing data between 1920 and 1966, we know from other historic information that the Verde River flooded less during the negative phase of PDO from 1943 to 1965 (USGS 2008). (In Chapter 2, I will present analyses that demonstrate a statistical correlation between PDO and Verde River flood magnitudes.) Tree ring records and other climate proxies have indicated that the ENSO effects on the Southwest extend back at least 1000 years and that the PDO has existed for at least 400 years (D'Arrigo 1991, Biondi et al. 2001). Because a relationship exists between ENSO and PDO, if climate variability and geomorphic response of the Verde River is significant at the decadal time scale, it may be possible to interpolate this relationship to the centennial time scale.

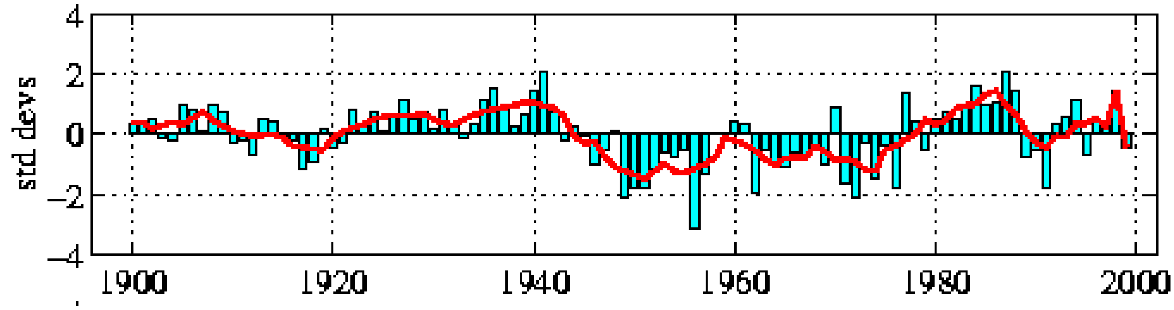

Figure 3. Pacific Decadal Oscillation (PDO) index from 1900 to 2000, based upon projections of observed North Pacific sea surface temperature (sst). Index values are normalized for October to March averages. Solid red lines depict 5-year running average values for each index, respectively (Mantua 1999).

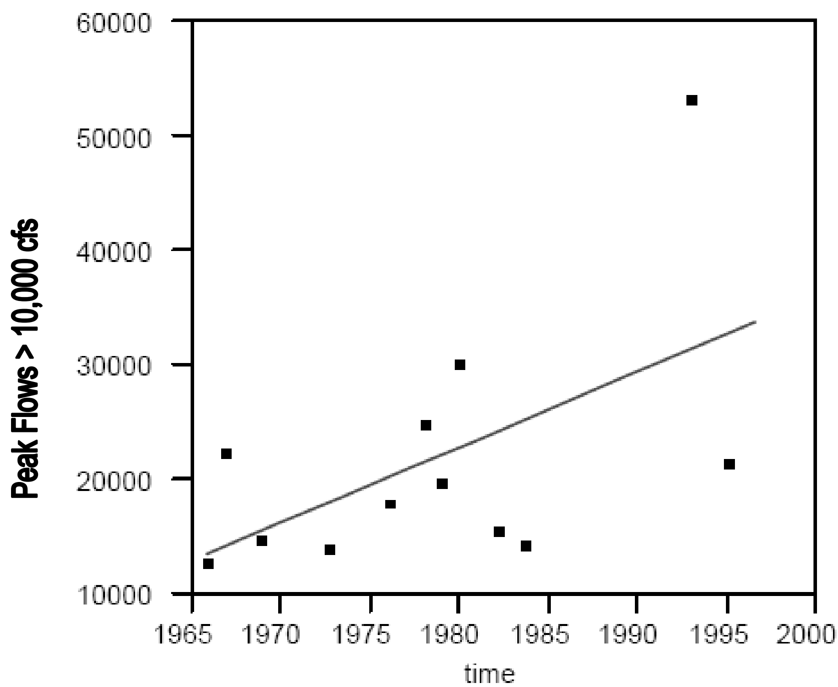

Figure 4. Peak flows greater than 10,000 cfs at USGS "Verde River new Clarkdale" gauge 1965 to 1995. Regression shows increasing flood magnitudes according to the formula: $-1.27 \times 10^6 + 655.34$ time, $p=0.0652$ (USGS gage 09504000).

Climate and precipitation variability can illicit complex geomorphic responses in fluvial systems (Kochel et al. 1997, Schumm 1977). During the dry period of the 1940s through early 1960s, the Verde River channel narrowed and riparian tree cover gradually increased (Masek Lopez and Springer 2002). Verde River streamflow records for 1965 through 1995 show a trend of increasing floods greater than 10,000 cfs (Figure 4). Rivers in semi-arid regions commonly adjust channel and floodplain morphologies to less frequent large floods because these are the only flows competent enough to alter river morphology (Kochel 1988.) From the mid-1960s to the mid-1990s, increased Verde River flood magnitudes coincided with the positive or cool phase of the PDO, and Verde River channel area and riparian tree cover changed in response to floods (Masek Lopez 2003, Masek Lopez and Springer. 2002).

Peak annual discharge data USGS gauges Verde River near Clarkdale (gage 09504000) and Oak Creek near Cornville (gage 09504500) can be found at the National Water Information System (NWIS) website (USGS 2008). Flood flows in the upstream reach in Cottonwood area are reflected by the Verde River near Clarkdale gauge. For the lower reach in Camp Verde, peak annual discharge is generally reflected by the upstream Verde River near Clarkdale gauge plus the Oak Creek near Cornville gauge, not accounting for contributions from ungauged washes. Streamflow data for the Verde River at Camp Verde is not available for the historic period covered by this study.

Fluvial Geomorphology

Precipitation, runoff, vegetation, and sediment availability determine how much sediment is eroded from the landscape and carried through a fluvial system by available water (Dunne and Leopold 1978). When more sediment is delivered to a valley than can be transported effectively, channel aggradation occurs. Aggraded rivers can become more unstable, especially where braided channels are separated by bars of gravel rather than vegetated islands, leading to rapid, unpredictable channel relocation (Dunne and Leopold 1978). Climate variation affects flood flows. When climate conditions generate larger flows, increased stream power is capable of transporting valley alluvium as bedload and suspended sediment (Bull 1991). Streams in semi-arid climates are particularly responsive to climate variations and subsequent flood events (Tooth 2000). In the semi-arid zone, low-intensity precipitation events contribute to the growth of vegetation and reduced sediment discharge in the watershed, leading to stabilization of river channel geomorphology (Dunne and Leopold 1978). Conversely, high-intensity precipitation and flood events can destabilize dryland river channels (Tooth 2000).

In river ecosystems, ecological processes are regulated by five critical components of the flow regime: the magnitude, frequency, duration, timing, and rate of change of hydrological conditions (Poff et al. 1997). Riparian vegetation along the Verde River such as cottonwoods and willows rely on the timing and magnitude of winter floods for recruitment (Stromberg et al. 2007). Moderate winter flood flows can increase cottonwood and willow regeneration by exposing moist, bare sediment. Flood timing is critical to recruitment; floods must be timed such that beneficial seed bed conditions coincide with seed dispersal peaks (Stromberg et al. 1993). Hence, cottonwood/willow stands tend to occur in age cohorts from years when regeneration was possible, so that riparian tree stands often have uneven age distributions. Conversely, high intensity flood flows in semi-arid environments can cause considerable mortality of riparian plants (Friedman 1996, Stromberg 1997, Baker 1990). Moderate magnitude floods in the Verde Valley in 1969, 1973, and 1976 (14,800, 14,000 and 18,000 cfs respectively) created beneficial sedimentation and soil moisture conditions for the regeneration of cottonwoods and willows. Riparian tree cover along the Verde River peaked around 1977 (Figure 5). As riparian cover expanded, river channel width deceased to a minimum in 1977. When floods of increasing magnitude moved through the area in 1978, 1982, and 1995 (25,000, 30,100, 53,200 cfs respectively), riparian vegetation was removed and channel width increased. This Verde River response is consistent with extensive regional flooding that in some cases resulted in widespread loss of riparian habitat in 1941, 1978–1980, and 1993 (Graf et al. 2002). Because discharges as measured at the upstream USGS ‘Verde River Near Clarkdale’ gauge were relatively consistent (71 cfs, 76 cfs, and 82 cfs) on the dates of aerial photography in 1968, 1978, 1983, and 1995 respectively, it is assumed that the river was at baseflow during each photo event. Hence, based on increased channel area as revealed through analysis of aerial photography, the width-to-depth ratio of the river channel must have increased in response to increased flood magnitudes.

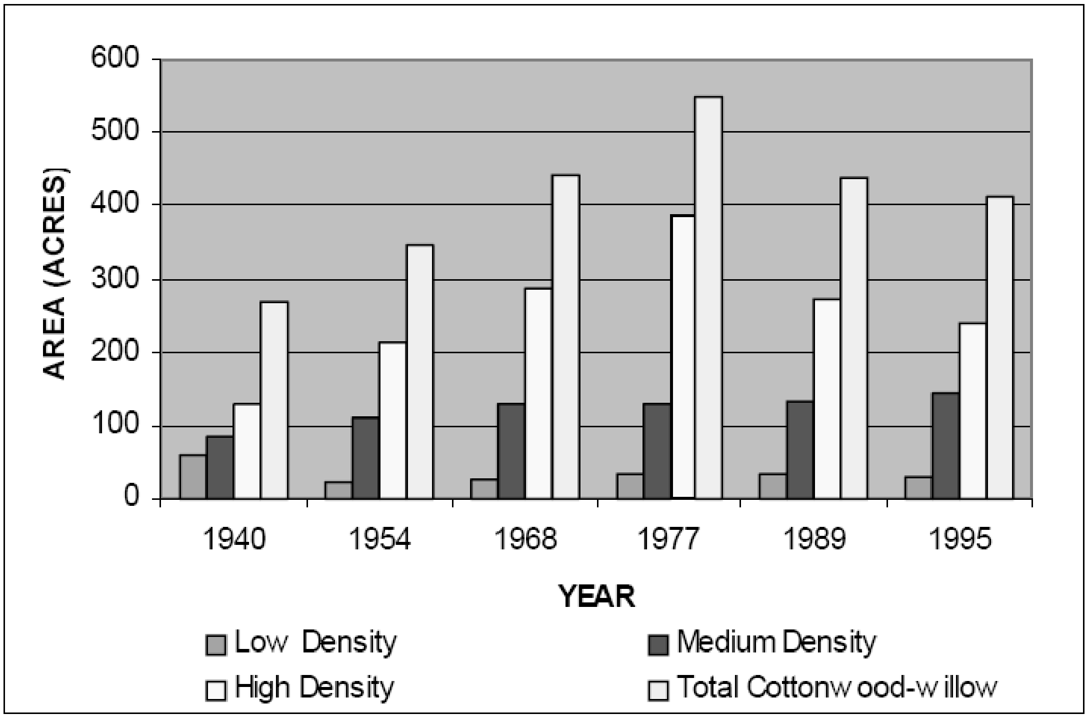

Figure 5. Riparian cover changes along the Verde River near Cottonwood, 1940 to 1995 (Masek Lopez and Springer 2002).

Land Use Change

When an area is developed for housing or other urban purposes, impervious surface increases. The impervious surfaces present in urban environments decrease infiltration and increase the rate and volume of water delivered to channels (Galster et al. 2006). Increased speed of water transmission in channels and conduits leads to at least temporary increase in sediment yields (Dunne and Leopold 1978). Drainage density is reduced with urban development, which leads to greater sediment loads in remaining trunk channels. For small drainages, increased discharge and flow velocity cause channel enlargement by widening, downcutting, or a combination of both, which overcompensates for increases in sediment yield, resulting in more channel erosion than deposition (Dunne and Leopold 1978, Trimble 1997, Park 1997, Booth and Jackson 1997, Brown and Caraco 2001). Galster et al. (2006) concluded that urbanization leads to higher discharges in watercourses, which can increase erosion, degrade aquatic habitats, and significantly alter channel forms. In the case of the Verde Valley, urbanization could lead to increased instantaneous peakflows and stream power in the Verde River as well as mobilization of young piedmont alluvium from tributary washes. Increased discharge and sediment inputs from urbanized areas can cause river channel morphology responses including changes in width, depth, and planform geometry. Following urbanization, sediment inputs over time could decrease while discharges remain high, potentially leading to removal of coarse sediments in the river channel again shifting river morphology (Clark and Wilcock 2000).

Land use change has varied in the Verde Valley. While Cottonwood grew rapidly from the late 1960s through the 1990s, Camp Verde remained a largely rural environment with farms, pastures, gardens and a small higher-density core of businesses and homes (Figures 6 and 7). Starting in the1960s, real estate development, the establishment of a regional hospital, an influx of retirees, and the creation of small businesses in Cottonwood led to urbanization. Cottonwood's population grew from 1,879 persons in 1960 to 19,789 in 2000 (U.S. Census Bureau 2008). Farms and open space converted to residential and commercial land use with concomitant increases in impervious surfaces. Camp Verde census data is not available prior to 1990, but the town's general plan states that Camp Verde population grew from 3,824 residents in 1980 to just below 10,000 residents in 2000 (Camp Verde 2004). For the Middle Verde portion of Camp Verde, where the study reach is located (Block Group 1, Census Tract 16, Yavapai County, Arizona), census data shows that population rose from 2,472 in 1990 to 3,653 in 2000.

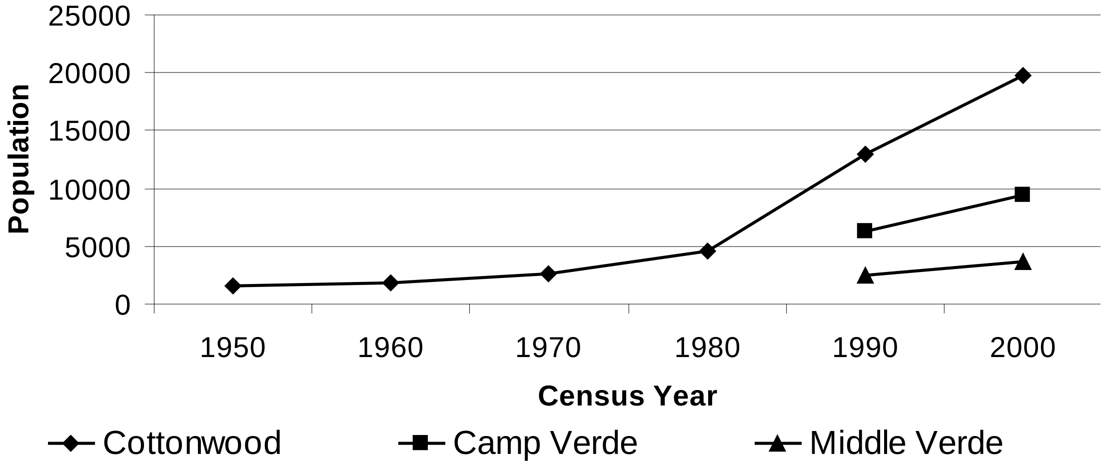

Figure 6. Population growth in the Verde Valley, 1950 to 2000 (U.S. Census Bureau 2008)

The Middle Verde population is classified as 100% rural by the Census Bureau, while the Cottonwood population is classified at 97% urban. Other than the building of Interstate 17 and adjacent commercial properties, Middle Verde land use did not change markedly from the 1960s through the 1990s. Based on characteristic urban vs. rural physiographic differences, I hypothesized that Verde River morphology at Cottonwood would have changed more than at Middle Verde over the period of 1968 to 1995/1997 due to increased flood peaks and sediment discharge from tributary washes as a function increased impervious surface, although some downstream effects of Cottonwood's urbanization may be expressed in the Middle Verde reach.

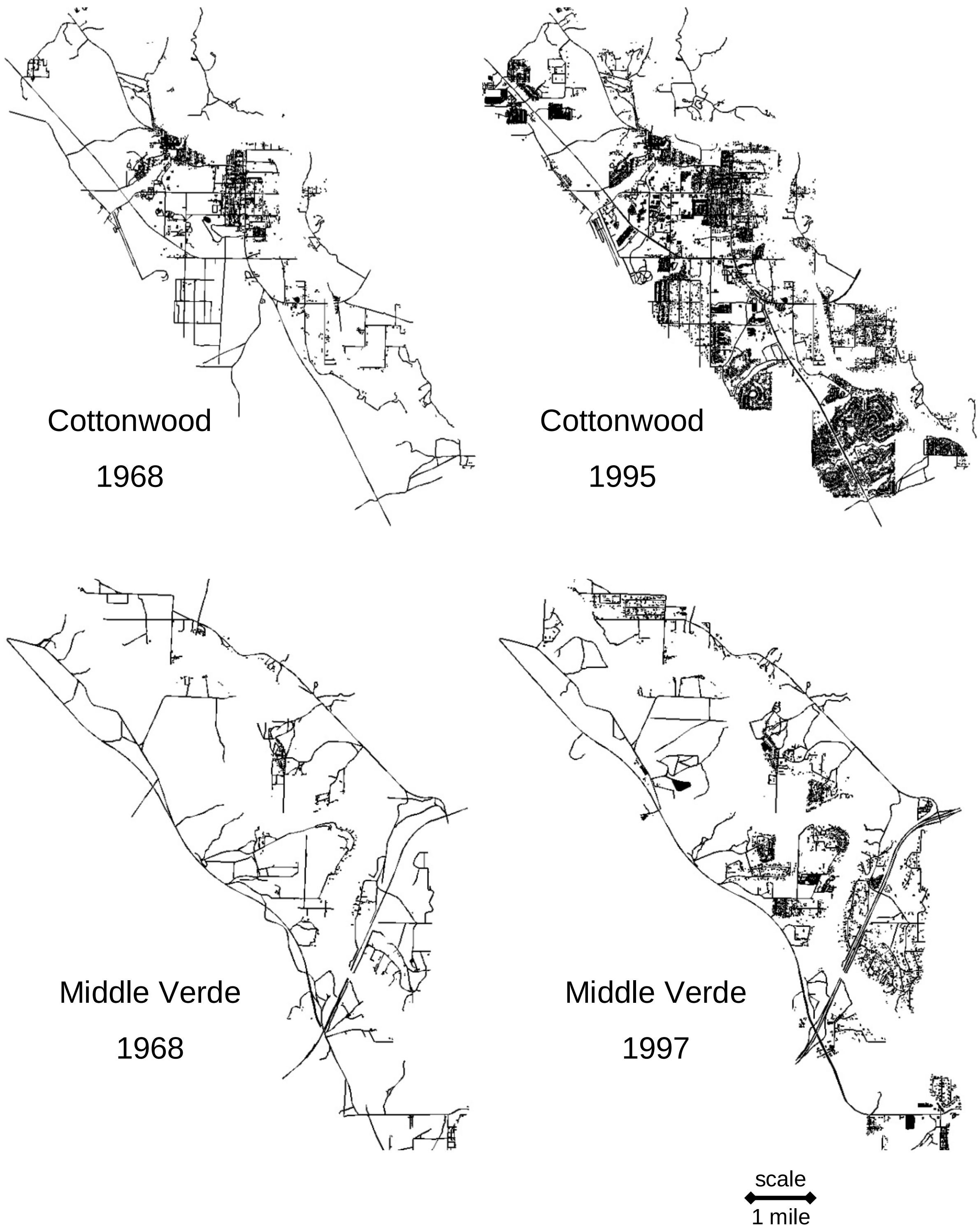

Figure 7. Land use change in the Verde Valley, 1968 to 1995/1997. Roads and building footprints are shown for Cottonwood and Middle Verde in 1968 on the left and in 1995 and 1997 on the right.

Previous Contributing Investigations

Verde River hydrogeology, geomorphology, and flood history are described in a progression of reports (Twenter and Metzger 1963, Smith 1981, Owen-Joyce and Bell 1983, House and Pearthree 1993, Pearthree 1993, House 1994, House et al. 1995, Pearthree 1996, House and Hirschboeck 1997, Beyer 1997, Fuller 2002, Blasch et al. 2005). Ecology of the Verde River basin and its vital riparian areas are elaborated in Thornburg et al. 1991, Sullivan and Richardson 1993, and Haney et al. 2008.

This study makes use of GIS image and data layers, as well as analysis results, from two previous studies completed by the author. Summary data for these two studies can be found in Appendix A (Tables 6, 7, and 8, Figures 21 and 22). In 2002, Northern Arizona University completed a historical analysis of Verde River change in the Verde Valley. The Upper Verde Valley Riparian Area Historical Analysis (UVVRAHA) was supported by a grant from the Arizona Water Protection Fund. The study culminated in the report Assessment of Human Influence on Riparian Change in the Verde Valley, Arizona (Masek Lopez and Springer 2002). On contract with the Town of Camp Verde (Camp Verde) the author mapped and analyzed changes in riparian vegetation over a 60 year period. This work culminated in the report Camp Verde Riparian Area Historical Analysis (Masek Lopez 2001).

Several parallels became apparent between the two riparian area historical analyses in the vicinities of Clarkdale/Cottonwood and Camp Verde. In both studies there was an overall increase in both cottonwood-willow (*Populus fremontii, Salix gooddingii*) and mesquite (*Prosopis velutina*) riparian vegetation between 1940 and 1968. After 1968, both studies showed a general increase in density of mesquite, which seems to be related to increased precipitation. Both studies showed a decrease in cottonwood-willow between 1968 and 1995. However, because the UVVRAHA study also included data from 1977 and 1989, we know that at Cottonwood the maximum extent of cottonwood-willow occurred in the late 1970s. Based on examination of available historic aerial images (Fuller 2002), the historical maximum extent of cottonwood-willow in Camp Verde also likely occurred in the late 1970s.

Previous investigations have quantified changes in Verde River morphology and riparian tree distribution in the study area over time. However, previous work did not link geomorphic changes to watershed characteristics that may have determined them. My research hypothesis was that Verde River geomorphology responds strongly to tributary watershed characteristics including basin area, relief, and surficial geology, while land use change, as measured by change in impervious surface, may have some limited effect on the sediment transport from tributary washes and hence the extent of geomorphic response in the river channel. Based on previous study results, riparian tree stand area was expected to be inversely covariant with changes in channel width and channel scour area.

CHAPTER 2

Geomorphic Response to Land Use Change, Middle Verde River, Arizona

INTRODUCTION

Alluvial rivers respond to climate variability, watershed attributes, and urbanization with adjustments in channel geometry, including channel width and sinuosity and scour and fill of fluvial sediment (Dunne and Leopold 1978, Richards 1982, Reid and Frostick 1989, Thomas 1997). Channel form is controlled by discharge, sediment load, bed and bank material composition, and valley slope (Park 1997). Geomorphic responses may be associated with extrinsic or intrinsic geomorphic thresholds, complex response, or episodic erosion (Schumm 1977, Bull 1991, Ritter et al. 2002). In this study, I modeled geomorphic response of the Verde River, Arizona to watershed geology and urbanization in 1968 and 1995/97, at the beginning and end of a wet period associated with a positive phase of the Pacific Decadal Oscillation. Model results were used to interpret how urbanization of the Verde Valley might impact morphology of the Verde River.

Decadal Scale Climate Variability and Geomorphology

Stronger and more frequent El Niños occurred in the 1980s and early 1990s associated with positive (cool) phase Pacific Decadal Oscillation (PDO) (Viles and Goudie 2003). In Arizona, these strong El Niños increased winter precipitation and rain-on-snow events leading to increased flood magnitudes (Ely 1997). The magnitude of flood events has an important bearing on how channels evolve and function (Ritter et al. 2002). Verde River flood magnitudes from 1965 to 1995 were significantly related to the PDO (Masek Lopez 2003.) Therefore, the years 1968 and 1995, which bracket a positive phase PDO and increased flood magnitudes, were selected to compare river morphology under dry and moist conditions. This time frame also captured a period of urbanization in the Town of Cottonwood, while the Town of Camp Verde remained largely rural, allowing for an assessment of urbanization contributions during this geomorphically active period.

Urbanization

Urbanization increases impervious surfaces resulting in reduced infiltration, reduced depression storage, faster overland flow velocities on smooth surfaces, and increased rate and volume of discharge delivered to channels (Richards 1982, Galster et al. 2006). Increased stream power of urban runoff can cause channel erosion that is a major source of sediment yield, which can then degrade aquatic habitat and significantly alter channel forms of receiving rivers as channel form adjusts to maintain sediment transport (Richards 1982, Booth 1990, Trimble 1997, Osterkamp and Toy 1997, Galster et al. 2006). Urbanization can thereby impact fluvial geomorphology by means of increased discharge and sediment yield.

In King County, Washington, urbanization was found to increase channel widths and depths, and heterogeneous channel morphology became more simplified and uniform (Booth and Jackson 1997). In Puerto Rico, urbanization increased the size, abundance, and stratigraphic elevation of in-channel gravel bar deposits, decreased channel depth, and increased the frequency of overbank flooding downstream (Clark and Wilcock 2000). In urbanizing watersheds, increases of about 10% effective impervious surface area can cause aquatic habitat degradation (Booth and Jackson 1997, Schiff and Benoit 2007). In this study percent impervious surface was measured and used to model the effects of urbanization on the morphology of the middle Verde River.

STUDY AREA

The middle Verde River is a perennial river located in semi-arid central Arizona. The middle Verde River flows through the Verde Valley, which is situated in a half-graben basin of the Central Transition Zone, with the Black Hills rising abruptly on the southwest side of the Verde Fault. Extensive alluvial fans descend from the Black Hills and are drained by elongated watersheds to the right bank of the river. Slopes on the northeast side of the river are less steep. Surficial geology on the left bank is dominated by lacustrine deposits of the Verde Formation that formed in a large freshwater lake that breached 2.5 Ma. For this study, two geomorphically similar alluvial river reaches were evaluated, an 8.4 mile reach that urbanized (Cottonwood) and a 9.5 mile reach that remained largely rural (Camp Verde) during the period 1968 to 1995/1997 (Figure 1). Thirteen tributary washes empty into the river in each reach. These are dry washes that flow only during storm events. The river's common floodway (a.k.a. 100-year floodplain) was divided into 26 segments extending from the upstream bound of tributary wash influence (determined by alluvial fan width at the mouths of tributaries) to the next wash confluence.

Tributary wash watersheds were paired with the river segments into which each wash drained to evaluate geomorphic response of river morphology geometry to watershed characteristics. Sinuosity, channel width and scoured bare sediment width were the response variables. Watershed area, gradient, erodibility, and percent impervious surface were the predictor variables. A conceptual model of how predictor variables relate to response variables is shown in Figure 8, with measured variables listed in italics.

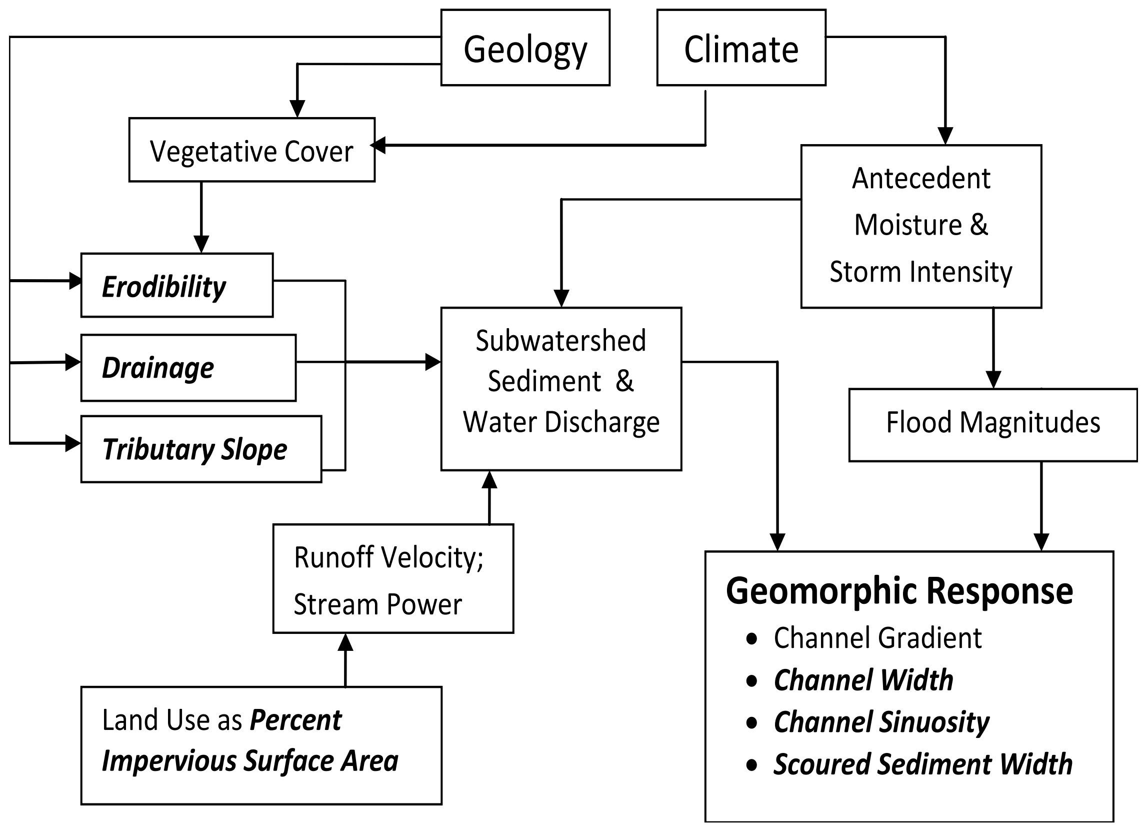

Figure 8. Conceptual model of how geology, climate and land use interact to affect river morphology. Measured variables are shown in italics. Geomorphic response to land use change, middle Verde River, Arizona.

METHODS

This research assessed river morphology response in urbanizing and non-urbanizing reaches of a semi-arid alluvial river valley. Historic aerial photos of the Verde Valley from 1968 and 1995/1997 (Table 1) were scanned and georeferenced using ERDAS Imagine (ERDAS 2000) for use as base layers along with USGS 7.5 minute topographic maps in a GIS. Discharges at the nearest upstream USGS gauge 09504000 (Verde River near Clarkdale) on the four photo dates in May 1968, June 1995, and June 1997 were 71, 82, and 72 cfs respectively. Long term gauging shows that baseflow at gauge 09504000 is 79 cfs (Haney et al. 2008), so the river was considered at baseflow on each of the photos dates. Using the base imagery to digitize layers, data were generated in GIS and exported for statistical analysis.

Table 1. Historic aerial photography used for interpretation of land use and river morphology.

Photo Year	Date flown	Agency	Scale	Color	Source
Cottonwood					
1968	5/25/1968	Forest Service	1:15,840	black & white	USDA
1995	6/20/1995	Yavapai County	1:15,841	color	Rupp Aerial Photography
Camp Verde					
1968	5/25/1968	Forest Service	1:20,000	black & white	USDA
1997	6/1/1997	Forest Service	1:12,500	color	USDA

Mapping predictor and response variables

In ArcGIS 9.2 (ESRI 2006), existing shapefiles were modified and new shapefiles were generated by onscreen digitizing from georectified aerial images and topographic maps (Figure 9). Shapefiles were created for watershed boundaries, river channel area and scoured bare sediment area for 1968 and 1995/1997. Line shapefiles of the river

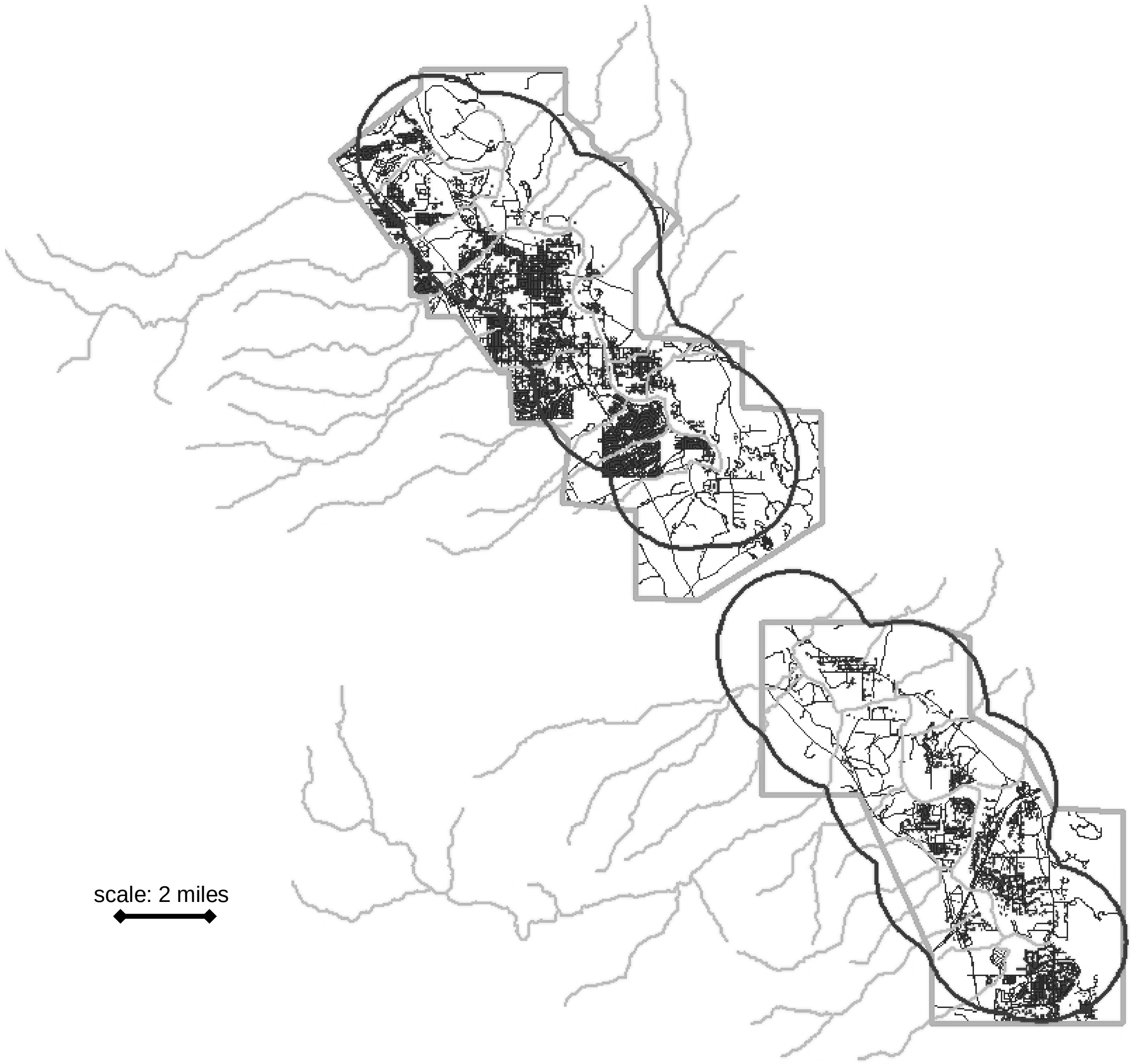

Figure 9. Examples of some of the shapefiles modified or created for this study. Medium grey lines are streams. Angular polygons with wide grey boundary lines are the extent of aerial photography. Wide black lines are a 1.3-mile buffer around the two river reaches. Fine black lines are roads. Small black polygons are building footprints. North is to the top of the page. The northern half is the Cottonwood Reach. The southern half is the Camp Verde Reach, which is located upstream of the Beaver Creek confluence.

location were also digitized for each photo date. Yavapai County GIS provided polygon shapefiles of floodplains and building footprints and polyline shapefiles of roads and 2-foot contours, dated 2004 (YAVGIS 2004). The road and building footprint layers were modified to create shapefiles of land use in 1968 and 1995/1997 within a 1.3 mile buffer around the river, which encompassed most development that occurred during the historic period. A 15 foot buffer was set around roads to create a polygon shapefile.   Road and building footprint layers were clipped to the watershed boundaries, areas were calculated and data tables were exported for analysis outside GIS. Watershed "toe slope", which is the gradient of the tributary watershed within 1.3 miles of the river, was estimated from topographic maps using the 1.3-mile buffer area.

A 100-year floodplain polygon was cut into segments with lines perpendicular to the 1968 channel at tributary confluences. These valley floor segments were then used to clip channel area, bare sediment area and river location polygons. For each segment, river channel area and scoured bare sediment area were calculated using Arc Toolbox in ArcGIS 9.2 and river sinuosity was calculated using Hawth's Tools (Beyer 2004). Data tables were then exported for analysis outside GIS.   Channel area and bare sediment area values were divided by averaged 1968 and 1995/1997 river lengths for each segment to yield a standardized width measurement to compare between unequal-sized segments.

I attempted to measure river gradient, but the lack of precision in the elevation data nearest 1968 (1972 20-foot contours) and the elapsed time of the 2-foot contour data (9 and 7 years after 1995/1997 photo dates) made it impossible to accurately estimate gradients. Regression analysis proved the inaccuracy of the gradient data that were produced, and so the data were discarded from further analysis.

Erodibility Index

An erodibility index (E) was devised based on surficial geology that had been previously mapped (House and Pearthree 1993, House 1994). Most of the study area is covered by piedmont alluvial deposits ranging in age from modern to 500,000 years, with some older alluvial and bedrock units ranging in age from 0.8 to 8.5 million years. Erodibility of surficial geology was ranked based on age of deposits, texture, and soil development on a scale of 1 to 4 with 4 being the most erodible. Geologic units that were older, coarser, and had greater soil development were considered less erodible, while younger, finer grained units with poor soil development were considered more erodible (Table 2). On 1:24,000 hard copy maps, watershed boundaries were delineated and 1-inch square equivalents of geologic units were counted. Weight was given to fluvially active Young Piedmont Alluvium (Yp) that occurs in wash bottoms by counting each 1-inch segment of the narrow deposits rather than square inches. Counts were then used to rank the occurrence of geologic units and the occurrence ranks were multiplied by the erodibility rank. These products were then summed for each watershed to produce an erodibility index (Table 3).

Table 2. Erodibility ranks for surficial geology. Surficial geology symbol, name, period, age, texture and soil development are taken from previous work (House and Pearthree 1993, House 1994).

Rank	Symbol	Name	Period	Age	Texture	Soil Development
4	Yp	Young Piedmont Alluvium	Holocene	< 5 ka	extremely coarse near Black Hills; silt, sand, gravel elsewhere	none; currently active fluvial processes
3	S1, S2	Sheepshead	late Pleistocene to Holocene	0 to 500 ka	fine grained clay, silt, sand minor gravel	very calcareous; derived from Verde Formation
3	C2	ChuckwallaGroup - younger	latest Pleistocene to early Holocene	5 to 20 ka	finer grained nearer Verde River	light clay, moderately calcic
3	Tvl	Verde Formation - lucustrine facies	late Miocene to Pliocene	2.5 to 8 Ma	freshwater limestone, sandstone, silstone and marl; cliff-forming unit in some places, but clay rich layers are characterized by soft-looking slopes	
3	Tvu	Verde Formation - undifferentiated	late Miocene to Pliocene	2.5 to 8 Ma	interbedded or indistiguishable lacustrine and gravel facies	
2	M	Montezuma Alluvial Fan Complex	Pliestocene	500 ka	coarse gravel	fairly strong clay texture; moderate calcic development
2	C1	ChuckwallaGroup - older	middle to late Pleistocene	50 to 250 ka	coarse; resistent to stream erosion	strong argillic horizons with light clay; moderate calcic development
1	O	Oxbow Group	early Pleistocene to latest Pliocene	0.8 to 2.5 Ma	very poorly sorted coarse gravel	well developed calcic horizons
1	Tvg	Verde Formation - gravel facies	late Miocene to Pliocene	2.5 to 8 Ma	forms rounded high-standing hillocks; concentrated on the eastern flank of the Black Hills	

Table 3. Example of surficial geology erodibility index (E) calculation, Watershed 14 - No Name Wash at Verde Estates 2.

Within 1.3 miles of river							
Unit	Count	Occurrence		Erodibility		Value	E Index
Yp	2	1	x	4	=	4	
S, C2, Tvl	3	3	x	3	=	9	
M,C	4	4	x	2	=	8	
O, Tvg	3	2	x	1	=	2	
						∑ =	**23**
Upper Watershed							
Unit	Count	Occurrence		Erodibility		Value	E Index
Yp	0	0	x	4	=	0	
S, C2, Tvl	0	0	x	3	=	0	
M,C	9	4+3+2	x	2	=	18	
O, Tvg	2	1	x	1	=	1	
						∑ =	**19**

Young Piedmont Alluvium

In the process of generating the erodibility index values, I became aware that larger alluvial fans occurred at the mouths of washes with larger surface area of fluvially active Young Piedmont Alluvium (Yp). This pattern was especially noticeable in watershed 14, Hayfield Draw (Figure 10). Sand and gravel mining has operated at the mouth of Hayfield Draw for decades attesting to the copious supply of sediment that flows down the wash. Realizing that greater Yp in the watershed probably means greater sediment discharge to the river, which could then affect river morphology, I decided to use the Yp counts as a predictor variable.

Commercial sand and gravel extraction can cause channel adjustments (Park 1997). Three historic aggregate mining operations were identified on historic aerial photographs, although there may have been sand and gravel mines that were not apparent. Mined aggregate was apparently Young river alluvium (Yr) and in some cases

Young Piedmont alluvium (Yp) at the mouths of tributaries. Each of the two evaluated reaches included one gravel extraction area comprised of linear pits separated by stringers of trees. These moderately-sized operations showed surprisingly high geomorphic stability. In contrast, one large gravel mine parallel to old town Cottonwood was devoid of vegetation during the 1980s and experienced significant channel relocation and scour during the 1993 flood. Although gravel mining clearly had some impact on geomorphic change in the Verde River between 1968 and 1997, the discontinuous occurrence of gravel mining areas made it difficult to model their effects as part of this study. Therefore, geomorphic variability due to gravel mining operations was not quantified.

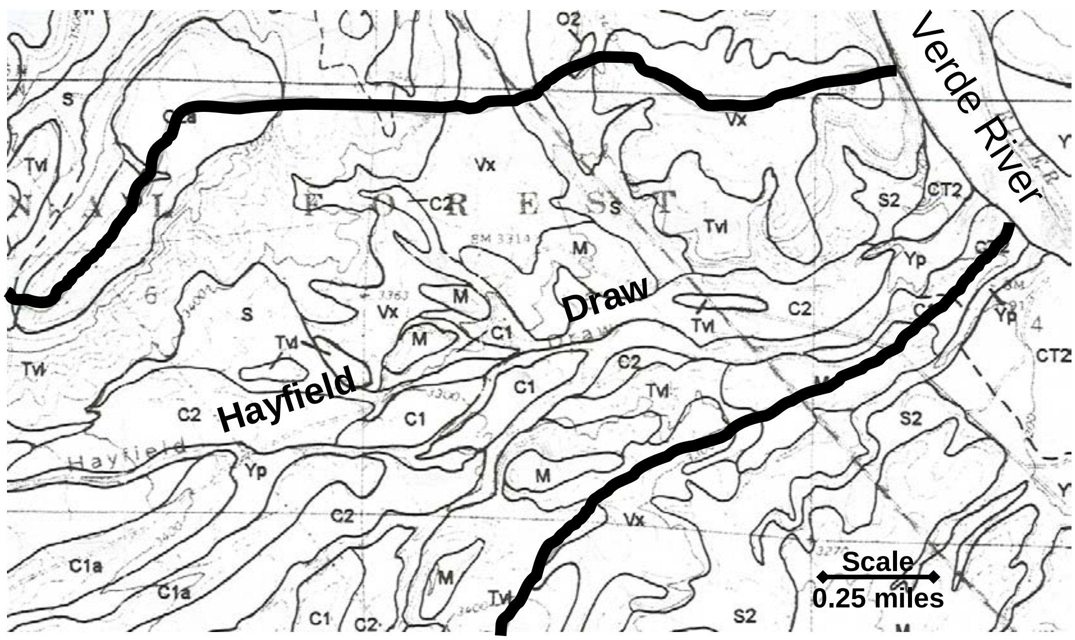

Figure 10. Surficial geology in the Hayfield Draw watershed (House and Pearthree 1993). Geologic units are described in Table 2. Vx is used in areas where weathered bedrock, alluvium and eolian materials are essentially indistinguishable.

Statistical Analysis

Exported predictor and response variable data were modeled using linear regression analysis in JMP 7.0 software (SAS 2007). Because sample size was small (26 for individual observation years, 52 when years were combined), only first order linear regression was used. Interpretations of simple linear regression were used to identify significant relationships between single predictor variables and response variables and also among response variables. Most predictor variables were not highly correlated, making them meaningful to use together in models. [An exception was "bank". Due to very distinct geologic and geomorphic characteristics of the right bank and left bank, the parameter "bank" was highly correlated with most predictor variables, and hence to be eliminated from modeling.] Multiple linear regression analysis was conducted to generate models that were then compared using p values and adjusted R^2 values. Models were selected that offered the best explanations of relationships between watershed characteristics and river morphology geometry.

Percent impervious surface proved challenging to use in the regression analyses. Without transformation there were no significant relationships. Because previous researchers have classified or categorized impervious surface according to empirical data that indicate threshold responses in aquatic systems (Booth and Jackson 1997, Kang and Marston 2006), I first tried transforming the data by breaking it into 5 categories: 0 to 5, 5 to 10, 10 to 20, 20 to 40, and > 40 percent impervious surface. Categorizing the percent impervious surface data did not help. Because the assumption of normality may not be valid and knowing that the nonparametric technique of ranking data can fix problems of data normality (Rock 1988), I ranked the percent impervious surface data and used the rank values in regression analysis. This procedure was analogous to the Wilcoxon rank-sum test or the Mann –Whitney U-test. Ranking of percent impervious surface worked well.

RESULTS

Significant relationships among response variables appeared to reflect the highly covariant nature of river morphology parameters. Figure 11 is a conceptual representation of the covariant nature of the response variables. As channel gradient increases, channel width and scoured bare sediment width increases, while sinuosity decreases.

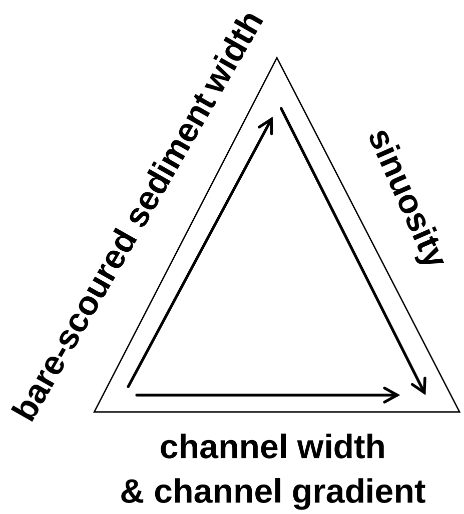

Figure 11. Conceptual diagram of covariant relationships among geomorphic response variables.

There were some significant results from the simple linear regression analysis and some results which were not significant. Data generated by this study, which were used for regression analyses, are found in Appendix B (Tables 9 and 10). Simple and multiple linear regression analyses were used to statistically analyze relevant data generated in GIS. Several statistically significant relationships were found between watershed predictor variables and river morphology response variables. Table 4 shows relationships that were found using simple linear regression. Based on the results of simple linear regression, several multiple linear regression models were tried to relate combinations of predictor variables to response variables. Some of these models were found significant. Significant simple linear regression models (Table 4) included:

a. 1995 channel width as response to tributary watershed area,
b. 1995 bare sediment as a response to toe slope,
c. sinuosity as a response to toe slope,
d. channel width as a response to right bank erodibility,
e. channel width as a response to Young Piedmont alluvium (Yp), and
f. sinuosity as a response to ranked percent impervious surface area.

Significant multiple linear regression models (Table 5) included:

a. channel width as a response to Yp occurrence and watershed area,
b. channel width as a response to Yp and ranked percent impervious surface area,
c. channel width as a response to Yp, watershed area and ranked percent impervious surface area,
d. 1995 bared-scoured sediment width as a response to toe slope and ranked percent impervious surface area,
e. 1995 bared-scoured sediment width as a response to toe slope and Yp occurrence,
f. 1995 bared-scoured sediment width as a response to toe slope, Yp occurrence, and ranked percent impervious surface area, and
g. sinuosity as a response to toe slope and ranked percent impervious surface area.

Table 4. Results of simple linear regression analysis. The p values in **bold** are for significant positive relationships. The p values in ***bold italics*** are for significant negative relationships. α = 0.10

	RESPONSE VARIABLES								
	channel width			**bare-scoured sediment width**			**sinuosity**		
PREDICTOR VARIABLES	1968	1995	change	1968	1995	change	1968	1995	change
Watershed Metrics									
area (acres)	0.28	**0.03**	0.138	0.5	0.5	0.91	0.15	0.2	0.35
gradient (%)	0.43	0.4	0.85	0.86	0.81	0.93	0.49	0.42	0.82
toe slope (%)	0.21	0.32	0.89	0.76	**0.022**	**0.017**	**0.046**	**0.094**	0.16
Erodibility (E)									
E upper watershed	0.33	0.21	0.62	0.22	0.37	0.74	0.29	0.54	0.28
right bank	**0.0003**	**0.013**	0.79	0.31	0.88	0.31	0.23	0.18	0.83
left bank	NA	NA	NA	NA	NA	NA	NA	NA	NA
E watershed toe	0.65	0.90	0.54	0.85	0.51	0.44	0.55	0.54	0.74
right bank	***0.0423***	***0.0308***	0.35	0.42	0.11	**0.0127**	0.14	0.14	0.75
left bank	0.68	0.36	0.76	0.90	0.24	0.33	0.98	0.97	0.94
E watershed ave.	0.35	0.38	0.90	0.74	0.79	0.99	0.26	0.39	0.36
right bank	**0.0074**	0.1029	0.90	0.55	0.45	0.20	0.77	0.74	0.98
left bank	NA	NA	NA	NA	NA	NA	NA	NA	NA
Yp watershed	**0.0011**	**0.0019**	0.74	0.20	0.68	0.17	0.25	0.40	0.32
Yp watershed toe	**0.0338**	0.1989	0.54	0.76	0.88	0.70	0.66	0.81	0.64
Percent Impervious surface									
1995	NA	0.28	0.1001	NA	0.24	0.57	NA	***0.0106***	0.49
1995 categorized	NA	0.21	0.20	NA	0.37	0.88	NA	***0.0546***	0.34
1995 ranked	NA	0.34	0.58	NA	0.40	0.59	NA	***0.0853***	0.51
1968 ranked	0.6	NA	NA	0.98	NA	NA	***0.0137***	NA	NA

Tables 5. Results of multiple linear regression modeling. Significant p values are in **bold**. Selected best models are marked with *.

Model	parameter 1	parameter 2	parameter 3	response	p value	Adjusted R2
C1	Yp watershed			channel width 1995	**0.0019**	0.3079
C2	Yp watershed			channel width 1968	**0.0011**	0.3379
C3*	Yp watershed			channel width all	**<0.0001**	0.3106
C4	Yp watershed	impervious surface 1995		channel width 1995	**0.0056**	0.3073
C5	Yp watershed	impervious surface 1968		channel width 1968	**0.0046**	0.3120
C6*	Yp watershed	impervious surface all		channel width all	**<0.0001**	0.2985
C7	Yp watershed	Watershed acres		channel width 1995	**0.0076**	0.2891
C8	Yp watershed	Watershed acres		channel width 1968	**0.0033**	0.3379
C9	Yp watershed	Watershed acres		channel width all	**<0.0001**	0.2970
C10	Yp watershed	Watershed acres	impervious surface 1995	channel width 1995	**0.0197**	0.2676
C11	Yp watershed	Watershed acres	impervious surface 1968	channel width 1968	**0.0084**	0.3254
C12	Yp watershed	Watershed acres	impervious surface all	channel width all	**0.0003**	0.2840
BS1	toe slope			sediment width 1995	**0.0228**	0.1645
BS2	toe slope			sediment width 1968	0.7664	-0.3776
BS4	toe slope	impervious surface 1995		sediment width 1995	**0.0592**	0.1499
BS5	toe slope	impervious surface 1968		sediment width 1968	0.9539	-0.0825
BS6	toe slope	Yp watershed		sediment width 1995	**0.0561**	0.1538
BS7	toe slope	Yp watershed	impervious surface 1995	sediment width 1995	**0.0157**	0.2834
BS8	toe slope	Yp watershed	impervious surface 1968	sediment width 1968	0.6499	-0.0563
S1	toe slope			sinuosity 1995	**0.0939**	0.0755
S2	toe slope			sinuosity 1968	**0.0455**	0.1213
S3	toe slope			sinuosity all	**0.0082**	0.1144
S4	toe slope	impervious surface 1995		sinuosity 1995	**0.0756**	0.1316
S5	toe slope	impervious surface 1968		sinuosity 1968	**0.0119**	0.2607
S6*	toe slope	impervious surface all		sinuosity all	**0.0002**	0.2693

CONCLUSIONS

Two models were selected as the most explanatory of dynamic processes between tributary watersheds and Verde River morphology in the Verde Valley and ways in which land use contributes to those processes. One model demonstrates that as the amount of Young Piedmont Alluvium in a tributary watershed increases the channel width of the receiving segment of the Verde River increases (Figure 12), according to the formula:

Channel Width (feet) = 56.56 + 1.152Yp total.

The second model shows that Verde River sinuosity in the Verde Valley is related to two variables within a 1.3 mile buffer of the river, the tributary wash slope (a.k.a. toe slope) and the ranked percent impervious surface area, according to the formula:

Sinuosity = 1.113 + 0.04256 toe slope – 0.00802 impervious surface

with p = 0.0002 and adjusted R^2 = 0.2693.

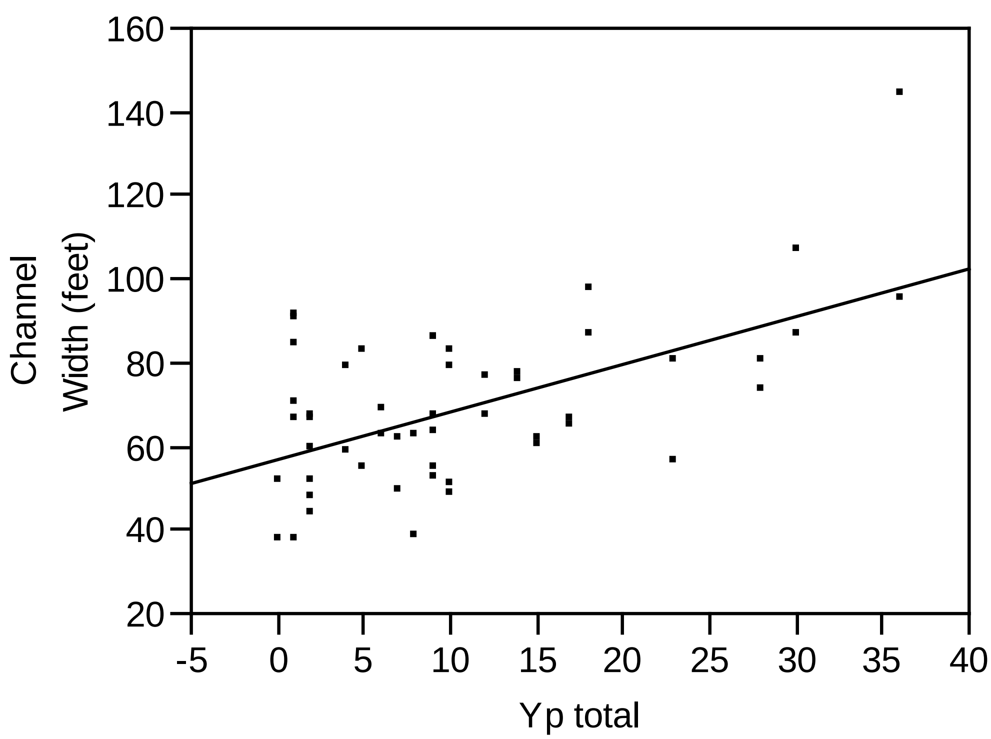

Figure 12. Young Piedmont Alluvium (Yp) effect on Verde River Channel Width in 1968 and 1995/97. Channel Width (feet) = 56.56 + 1.152Yp total, p <0.0001, adjusted R^2 = 0.310591.

Model Interpretation

These models can be interpreted to reveal processes that tie tributary watersheds to the river morphology. First, Young Piedmont Alluvium (Yp) has a large bearing on the morphology of the Verde River in the Verde Valley by providing fluvially active sediment to the river. Where greater amounts of sediment are input, the river gradient likely increases and the response is a widening of the river channel. Second, the slope of the washes just before they enter the river affects the river sinuosity, probably by affecting the velocity of water entering the river. These findings are consistent with Booth (1990) who found that geologic material and channel slope are particularly critical for predicting channel erosion response due to urbanization. Third, increased impervious surface causes a greater loss of sinuosity than would have otherwise occurred naturally, probably by changing the storm hydrograph so that runoff is flashier with a higher peak and shorter duration. Stormwater pulses that pass through urbanized areas can mobilize sediment stored in the lower reaches of tributary washes and deposit sediment on the valley floor, thereby adding to flood-related gradient shifts that episodically change river sinuosity by cutting off meander bends (Hooke 2002, Tooth 2000, Heede et al. 1988, Schumm 1977). In the Verde Valley, within 1.3 miles of the river impervious surface $\geq$ 15 percent was associated with below average channel sinuosity, even though the upper portions of most watersheds were largely undeveloped.

DISCUSSION

Tributary watershed effects on river morphology

Verde River channel width and sinuosity have been shown to be affected by the amount of fluvially active sediment in tributary washes and by tributary wash watershed toe slope and percent impervious surface area. Occurrence of Young Piedmont Alluvium, the fluvially active sediment in tributary wash channels, was the best predictor of channel morphology. Channel width was the best response variable, demonstrating significant relationships with several predictor variables. Sinuosity was the best response variable to show effects of the predictor variable percent impervious surface area.

Demonstrating significant relationships between watershed characteristics and the amount of scoured bare sediment in the active channel area was difficult. This may be because scoured bare sediment was mapped in a more interpretive way than the other predictor variables that had more precise boundaries. Only bright white bare areas were mapped, which produced some good relationships between watershed characteristics and scoured bare sediment in 1995/1997 but not in 1968. Perhaps due to the length of time since disturbance, some of the vegetated portions of the 1968 bar areas could be included and give a better result. Or perhaps measuring scoured bar sediment is only relevant after disturbance events.

Some response variables were significantly related to predictor variables for 1995/1997 data but not for 1968 data (Figure 13). This may be indicative of the relative contributions of the tributary watersheds during wet and dry cycles. Because climate in the decades leading up to 1968 was relatively dry, less water and sediment were likely mobilized during smaller storm events and so the impact on the river morphology was less. During the wet phase that corresponded with the positive phase of the PDO between 1968 and 1995/1997, greater storm events probably caused greater runoff and

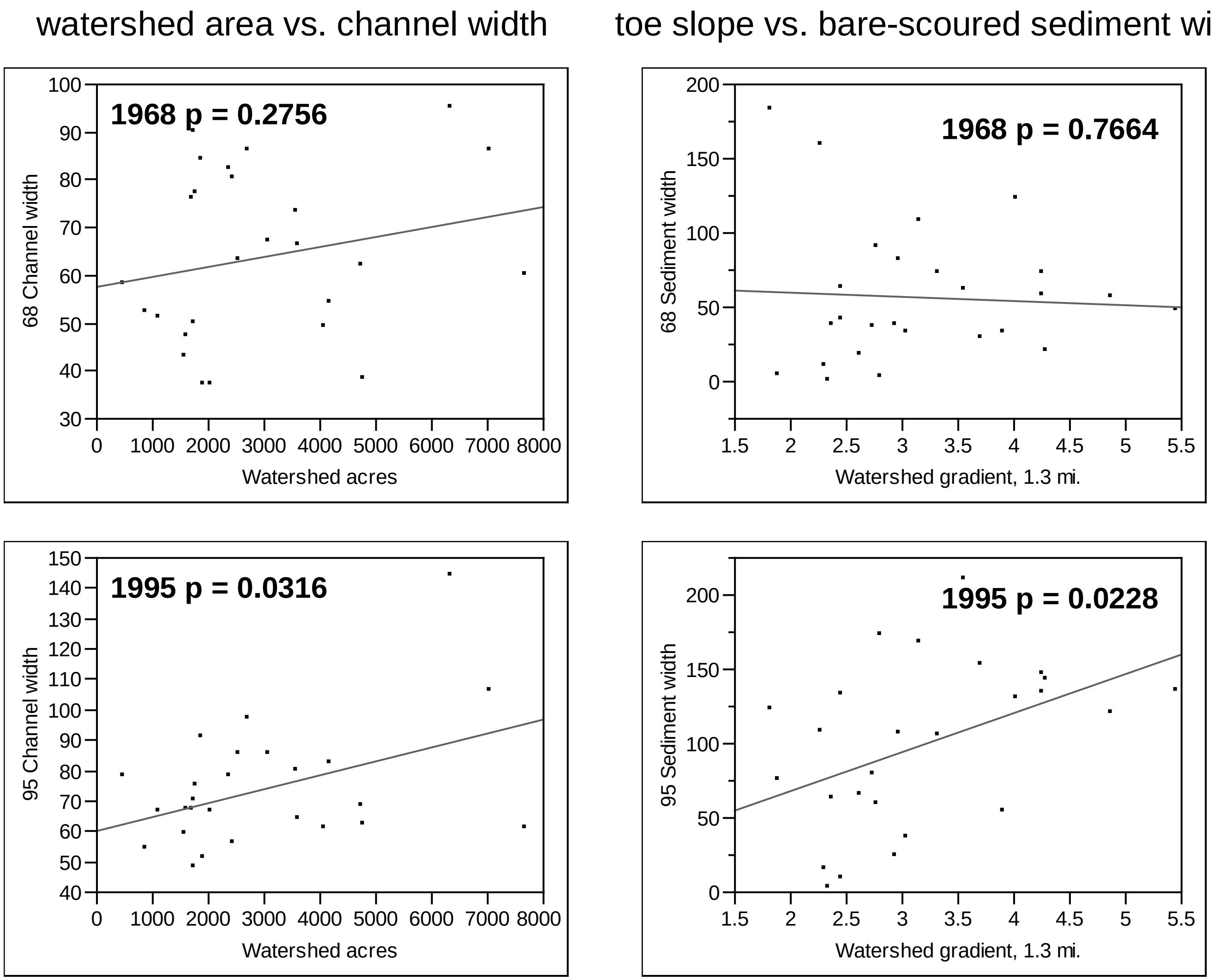

Figure 13. Differences in geomorphic response between 1968 and 1995/1997. The plots on the left show that channel width was significant related to watershed area in 1995/1997 but not in 1968. The plots on the right show that bare-scoured sediment width was significantly related to toe slope (tributary wash gradient within 1.3 miles of river) in 1995/1997 but not in 1968.

mobilization of tributary wash sediment to the river, which in turn affected the morphology of the river.

The surficial geology erodibility index (E) was not able to produce consistent results. However there was a strong relationship between E of the heterogeneous right bank watersheds and the morphology of the receiving river segments (Figure 14). Therefore, there may be some potential for applying this methodology to other river systems that have heterogeneous geology on both sides of the river, or perhaps there is a way to correct for the homogeneous watersheds that would otherwise distort the regression.

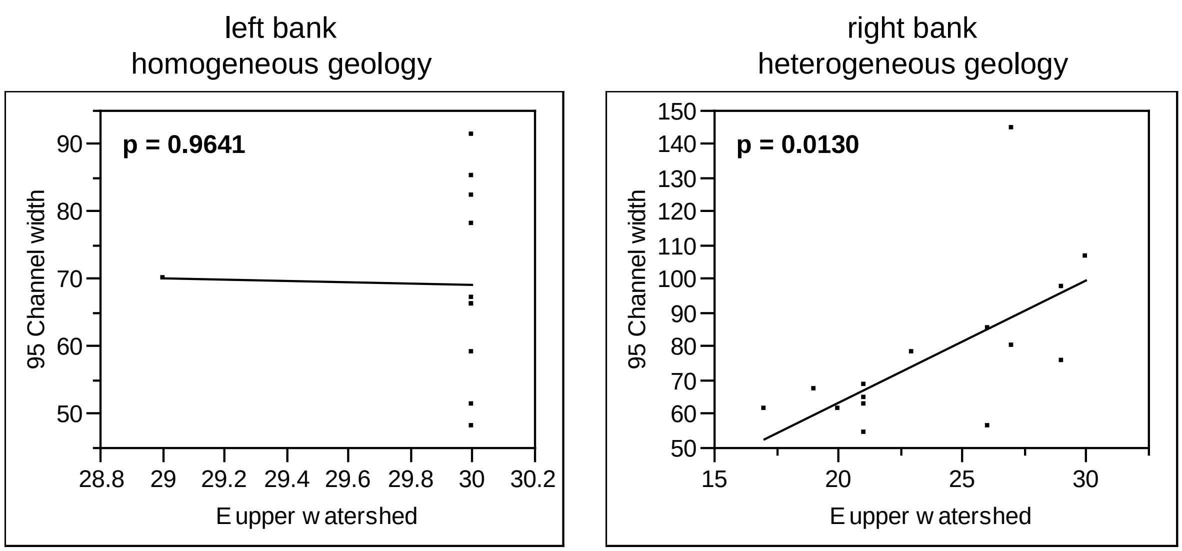

Figure 14. Left bank and right bank differences in channel width response to watershed erodibility. The upper portions (greater than 1.3 miles from Verde River) of the left bank tributary watersheds were homogenous lacustrine deposits of the Verde Formation, while surficial geology the right bank upper watersheds was heterogeneous with several ages of deposits and varying texture and soil development. 1995 channel width was significantly related to erodibility (E) of the right bank watersheds but not the left bank watersheds.

Urbanization effects on river morphology

In looking for effects of urbanization, percent impervious surface area worked well as a predictor variable, with a few caveats. First, the data had to be transformed by ranking to solve a normality problem. Nonparametric statistics may be more applicable for such data sets. Second, ranked impervious surface could be combined with other variables to generate statistically significant relationships, but for most of the models the variable was only tolerated, meaning it did not improve a simpler model, but it did not ruin it either. In only one case, where sinuosity was modeled as a function of toe slope and ranked impervious surface, was the model improved by the addition of impervious surface. Hence, there is potential for further exploration of the relationship between impervious surface and sinuosity of river in the semi-arid Southwest. Such research, if combined with ecological investigations, could provide valuable guidance for protecting Arizona rivers.

Further research

There is some evidence that effects of urbanization in the Verde Valley have relatively diminished over time. Simple linear regression analysis of ranked impervious surface vs. sinuosity decreased in significance from 1968 to 1995/97 ($p= 0.0137$ and $p=0.0853$ respectively). This might be due to the implementation of stormwater management practices subsequent to passage of the Clean Water Act. A more rigorous investigation could perhaps detect the stormwater management practices that have been effective in mitigating impacts on river morphology.

Because Young Piedmont Alluvium (Yp) appears to be a driving factor in Verde River morphology, texture analysis of Yp and river alluvium combined with geomorphic cross-sections could provide further insight into how the delivery of different grain sizes affects sediment transport and consequent morphologic adjustments. Such relationships could be used in tandom with study of aquatic habitat requirements to refine management strategies for watersheds with large amounts of Yp. This is important because at the reach scale, dominant fluvial and ecological processes appear congruent – involving both the dynamic changes of meandering or braiding channel patterns and the patch dynamics of ecosystem turnover and maintenance (Richards et al. 2002).

A final recommendation for further research is to use the existing data sets to evaluate braiding of the Verde River channel. Along with channel widening and decreased sinuosity, there is evidence from aerial photo interpretation that braiding of the river channel increased. In 1968 the river was predominantly single thread, while in 1995/97 channel branching was evident (Figure 15). This apparent braiding may be due to coarse sediment that was stored in tributary channels and delivered to the river during larger magnitude flood events in the 1980s and 1990s. Clark and Wilcock (2000) have asserted that when increased sediment load includes a substantial portion of coarse bed material, the time required to evacuate sediment will be longer and sedimentation will focus on bed aggradation and storage in channel bars. An assessment of the relationship between watershed characteristics and channel braiding along with the other morphologic responses could provide a more complete picture of the evolution of Verde River morphology. A complete discussion of whether the river is at equilibrium is beyond the scope of this paper. However, my observation is that on a decadal scale the river appeared in equilibrium during the dry phase of the 1940s through the 1960s, then shifted out of equilibrium during the wet period of the 1970s through the mid-1990s. It is not possible using these methodologies to determine whether Verde River morphology has been in equilibrium on larger time scales of centuries or millennia.

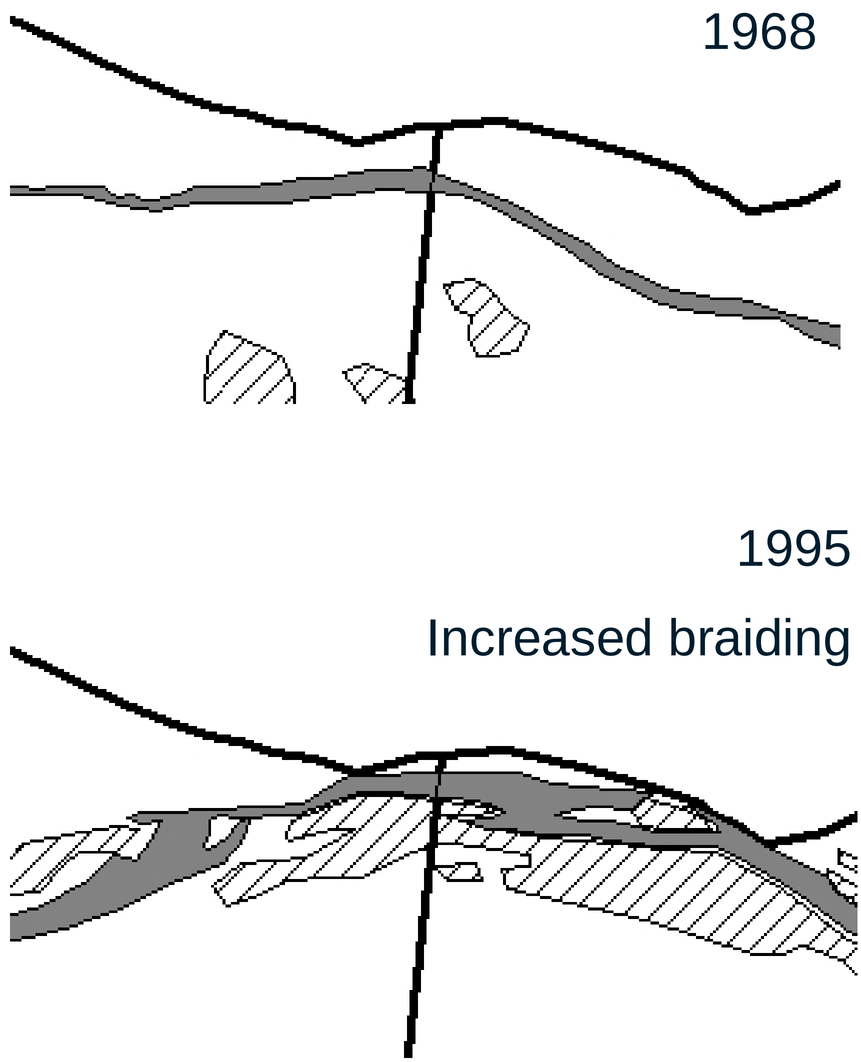

Figure 15. Increased Verde River braiding is apparent at segment adjacent to Deadhorse Ranch State Park. The river channel is shown in grey. Hashed polygons are bare-scoured sediment. Black lines are valley segment boundaries.

CHAPTER 3

Geomorphic Considerations for Camp Verde Land Use Planning Policy

Introduction

Statistical modeling was used to correlate changes in land use in the Verde Valley, Arizona with geomorphic response of the Verde River in the vicinity of Cottonwood and Camp Verde for the period 1968 to 1995. A proposed mechanism for the observed geomorphic changes is that increased impervious surface in urbanized areas has apparently led to more rapid runoff that has mobilized sediment in tributary washes of the Verde River. Increased stream power and sediment inputs have affected Verde River channel sinuosity beyond changes that would have occurred due to natural processes associated with climate variability and flood discharge. Based on these findings, local government policy development should consider potential impact of continuing urbanization on the morphology and stability of Verde River. Policies should be developed through public participation and in concert with existing environmental protection and natural resource management authorities to provide cost effective and practical solutions for stormwater management. Well-conceived and implemented policies can help protect property from loss or damage due erosion, sedimentation and flooding, while preserving the ecological integrity of the river system.

Other than Town of Camp Verde Storm Water Management Plan (SWMP), the Town of Camp Verde has no comprehensive policies for addressing problems related to sediment-laden stormwater runoff that impacts property and river system health. The SWMP lacks specific implementation goals. Although Arizona State Statutes and Town of Camp Verde ordinances require compliance measures for new subdivisions and land development (Arizona 2008, Camp Verde 2007), these regulations may not be suited to the specific geomorphic processes that exist in the lower Verde Valley and may not adequately protect against erosion and sedimentation. Furthermore, existing residential developments are currently experiencing erosion, sedimentation, and flooding problems associated with a lack of defined flowpaths and dedicated drainage easements (Fuller 2002). Engaging public support and securing funding to address these environmental challenges requires foresight. In this paper, options for policy development will be discussed and policy recommendations will be provided.

Middle Verde locality

The area in this study identified as "Middle Verde" lies within the corporate boundaries of the Town of Camp Verde. Middle Verde is comprised of land on each side of the Verde River and is bounded by Interstate 17 to the east, State Highway 260 on the south, and the Camp Verde town boundary on the west and north (Figure 16). A significant number of lot splits and subdivisions on the north side of the river at Middle Verde occurred prior to the current floodplain management regulations, which were first instituted in December, 1981. Subsequently, residential areas typically do not have adequate drainage easements or flood control structures to convey the runoff generated from offsite watersheds to the Verde River (Fuller 2002). The Town of Camp Verde General Plan designates that the "260 Corridor" west of the Interstate 17 and Highway 260 interchange to the Town's north border is suitable for future development (Camp Verde 2004). Commercial properties and high-density housing are planned for the 260 Corridor as population grows. The 260 Corridor growth area coincides with the Middle Verde reach that was evaluated in this research project. Recommendations for Camp

Verde's urban growth area arise from the research results. Because Middle Verde has begun to urbanize but is still largely rural, recommendations are made here to help ensure proper management of surface water runoff on both sides of the Verde River at Middle Verde as the area develops.

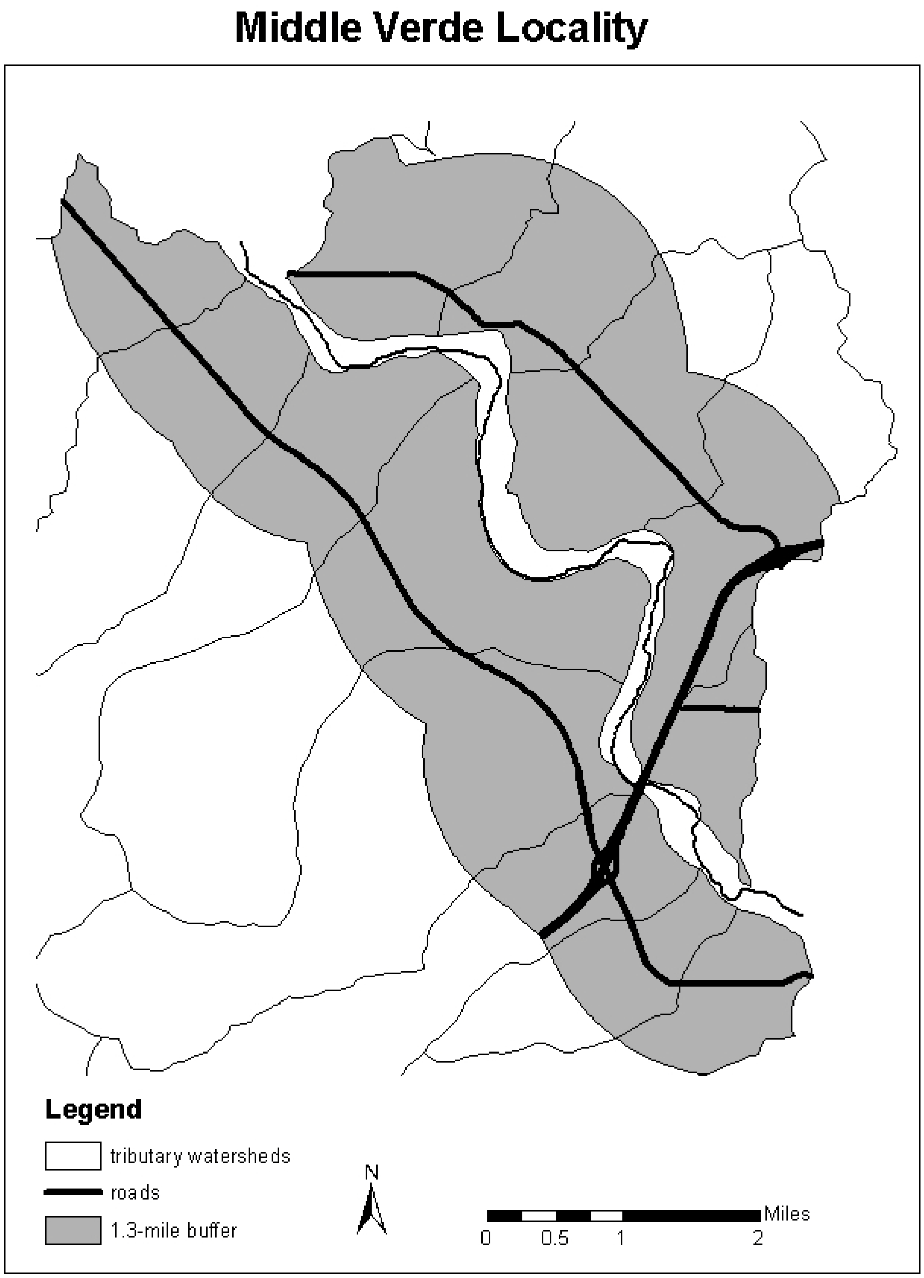

Figure 16. Middle Verde locality within the Town of Camp Verde, which was evaluated as part of study. Policy recommendations are made based on characteristics of this reach of the Verde River and its tributary watersheds.

Regulatory framework

The Clean Water Act (CWA) is the federal law that governs water quality protection in the United States. According to CWA § 101(a), the Clean Water Acts's purpose is to "restore and maintain the physical, chemical and biological integrity of the nation's waters". Sections of the CWA that pertain to protection of water quality due to land use management and geomorphic processes are numerous and interrelated. CWA Section 401 requires state certification for federally licensed activities that cause a discharge into navigable waters. In Arizona, CWA § 401 is administered by the Arizona Department of Environmental Quality, except on tribal lands.

Several sections of the Clean Water Act pertain to this study and water management in the Verde Valley. CWA § 402, the National Pollution Discharge Elimination System (NPDES) is administered by the US Environmental Protection Agency (EPA). The NPDES program permits discharge to surface water, including MS4 Phase II Stormwater Permits for cities with population less than 50,000. The NPDES Phase II Storm Water Permit Program requires most local governments to take action to improve water quality in rivers and streams in their areas. Communities are required to reduce the pollution load coming from their storm sewers and drainage ditches. Sediment is considered a pollutant under NPDES. Best Management Practices (BMPs) to reduce pollution from stormwater runoff and measurable goals for BMPs are required of local governments to comply with NPDES. As part of the NPDES program, local governments may require stormwater pollution prevention plan (SWPPP) for development and construction activities. A SWPPP is a written document that describes a construction operator's activities to comply with the requirements in the construction general permit (CGP). The SWPPP is intended to facilitate a process whereby the operator evaluates potential pollutant sources at the site and selects and implements appropriate measures designed to prevent or control the discharge of pollutants in stormwater runoff.

CWA § 319, the Nonpoint Source Management Program, provides funds and technical assistance for efforts to reduce water pollution from dispersed (nonpoint) sources, which includes sediment due to erosion. In the state of Arizona, CWA Section 319 programs are administered by the EPA through cooperation and Indian Tribes on Indian trust lands and the Arizona Department of Environmental Quality (ADEQ) on non-tribal lands. CWA § 404 regulates discharge of fill or dredged material into the Waters of the U.S. In Arizona, Section 404 Permits are administered by the U.S. Army of Corps of Engineers for tribal lands and by ADEQ for non-tribal lands.

Policy development in the Verde Valley is complicated by several federal, state and county laws that work in conjunction with the Clean Water Act. For instance, the Town of Camp Verde is surrounded by Prescott National Forest. The USDA Forest Service must comply with by the National Environmental Policy Act (NEPA) that requires Environmental Assessment (EA) or an Environmental Impact Statement (EIS) be completed prior to management actions, including watershed management.

The Federal Emergency Management Agency (FEMA) administers regulations promulgated by the Robert T. Stafford Disaster Relief and Emergency Assistance Act, PL 100-707. FEMA oversees floodplain protection by designating Special Flood Hazard Areas (SFHA) that requires flood insurance according to Flood Insurance Rate Maps (FIRM) that show the limits and types of flood hazards. FEMA also requires

Single Jurisdiction Local Mitigation Plans for Camp Verde, Cottonwood and Yavapai County.

The Yavapai County Flood Control District (YCFCD) was created in 1981 by the YCFCD Board of Directors after the Arizona State Legislature delegated authority to county flood control districts to adopt regulations designed to promote the public health, safety, and general welfare of its citizenry (YCFCD 2008). Regulations and requirements include a Flood Damage Prevention Ordinance (1981), intended to minimize public and private losses due to flood conditions, and the Yavapai County Drainage Criteria Manual (1998), used for preparing hydrologic, hydraulic and drainage related reports required by Yavapai County. The purpose and goals of the YCFCD are many, including: 1) regulation of floodplains and watershed development, 2) regulation of development in and along watercourses with drainage areas greater than 80 acres, 3) identification of flood hazards and associated problems, 4) construction of flood control structures and drainage related facilities, 5) maintenance and operation of completed structures and facilities, 6) operation of a network of streamflow and rainfall gauges, 7) county watercourse and drainage master planning, 8) education for flood prevention and safety, and 9) administering a Stormwater Management Program for pollutant discharge elimination.

The Town of Camp Verde has jurisdiction over 42.6 square miles within its corporate boundaries that were established in 1986. The Verde River flows 18 miles within the Town limits and is cherished by town residents for its beauty and natural wonder. Town of Camp Verde General Plan, approved by voters and adopted by Camp Verde Town Council in 2004, is the primary tool and blueprint for guiding the Town's future growth and development (Camp Verde 2004). The General Plan elements were mandated by legislation passed by the State Legislature in 1998 and 2000 titled the Growing Smarter Legislation and Growing Smarter Plus.

Many community values expressed in the General Plan are consistent with environmental protection that would take into account the interaction of land use planning and geomorphic processes and their effects on the Verde River. These values include maintaining the town's rural atmosphere and scenic beauty, conserving the natural environment, protecting natural resources, preserving open space, and maintaining a high value of environmental quality especially water quality. Specifically, the General Plan lays out an implementation strategy that calls for coordination with the Regional Planning Group to minimize contaminated runoff into the Verde River and ditches. The Camp Verde Storm Water Management Plan provides the foundation for developing a stormwater management program in compliance with the National Pollution Discharge Elimination System (CWA § 402). More work is needed to define the scope of the town's stormwater management program (Debo and Reese 2003). Community members have an opportunity participate in a public collaborative process to address stormwater and sediment discharge problems that affect safety, property, and health of the Verde River.

In 2006 Arizona voters passed Proposition 207 (Prop 207), which entitles owners to compensation for any reduction in their existing right to use, divide, sell or possess their property caused by any land-use law enacted after the passage of the proposition. Prop 207 complicates the ability of the Town of Camp Verde to create land use regulations or use eminent domain for the purposes of stormwater management, flood control and protection of the natural environment. Anticipating litigation by property owners claiming loss of property value due to newly enacted land use regulations, small governments in Arizona may find it impossible or prohibitively expensive to control "wildcat" development, protect washes, and improve water management in rural areas (Arizona Republic 2006). The League of Arizona Cities and Towns has recommended that local governments request a waiver of a property owner's Prop 207 claim if the owner applies for a re-zoning or other legislative land use actions within a municipality's jurisdiction (LACT 2007). *Legislative* land use decisions establish local zoning and/or development standards that apply throughout a municipal jurisdiction or district. In contrast, *administrative* land use decisions determine whether and how a specific development will be permitted on particular site; they usually are made based on specific criteria already established in preceding legislative decisions, provide fewer opportunities for public input, and result in a narrower range of outcomes (UrbanFauna 2008).

Geomorphic change and stormwater management

Stream channel erosion can be the major source of sediment in urbanizing watersheds (Trimble 1997). In urbanizing watersheds, channel enlargement will occur in the absence of stormwater controls (Brown and Caraco 2001). Enlarged channels convey greater volumes of water with more power and erosive force. Because channel enlargement can have significant economic and ecologic implications, from impacts to infrastructure such as culverts, sewers, bridges or pipelines to impacts on water quality and biology, stormwater engineers and managers need to develop and assess stormwater design criteria that directly address the channel enlargement problem (Brown and Caraco 2001). Trimble (1997) found that channel erosion accounted for about two-thirds of the measured sediment yield from San Diego Creek in Southern California. His assessment is consistent with other findings that urbanization increases stormwater discharge and erodes stored sediment in trunk channels (Dunne and Leopold, 1978, Galster et al. 2006, Clark and Wilcock 2000.) Erosional processes can be problematic because channel enlargement is often lateral, thus removing substantial areas of valuable urban land, damaging parkland, bridges, and other infrastructure, and making channels unsightly (Trimble 1997).

Impervious surface area increases during urbanization through the construction of paved road ways, parking lot pavement and building roofs. When infiltration capacity is reduced due to impervious surfaces, an urbanizing area develops a higher runoff coefficient, which is the percentage of rainfall that runs off an area (Dunne and Leopold 1978). Storm events produce more rapid runoff that can cause soil erosion and channel erosion. Changes in discharge, and thus stream power, associated with increased impervious area are highly variable and dependent upon watershed-specific conditions (Bledsoe and Watson 2001). While impervious area alone is a flawed surrogate of river health, it can be used in conjunction with other basin characteristics such as channel slope and geologic material to identify susceptible terrain in need of management measures (Booth et al. 2004, Booth 1990).

This research project analyzed the effect of increased impervious surface on geomorphic response of the Verde River. Geomorphic change during the period 1968 to 1997 was analyzed using historic aerial photographs and a Geographical Information System (GIS). The selected time period corresponded with urban development of the town of Cottonwood, while the Town of Camp Verde remained relatively rural. From

1968 to 1997 the Verde River channel narrowed and then widened again, with a net increase in channel width from 1968 to 1997. Meanwhile scoured bare sediment on bars increased and sinuosity decreased. These changes occurred during a wet period in the Verde Valley during the late 20th Century when flood magnitudes of the Verde River increased, apparently in correspondence with a positive phase of Pacific Decadal Oscillation climate index and the increased incidence and intensity of El Niño storm events (Masek Lopez 2003). Changes in Verde River channel area, sinuosity and area of scoured bare sediment were modeled as responses to tributary channel gradient, tributary watershed surficial geology and changes in impervious surface.

Results showed significant relationships between various predictor and response variables. The strongest relationships were the following:

1. Channel widths of the Verde River in 1968 and 1995 were positively related to the amount of Young Piedmont Alluvium (fluvially active sediment) in tributary washes (Figure 17),
2. Scoured-bare sediment on river bars in 1995 (following large floods) was positively related to tributary wash "toe slope" within 1.3 miles of the river (Figure 18),
3. Verde River sinuosity in 1968 and 1998 was positively related to tributary washes toe slope (Figure 19), and
4. Verde River sinuosity in 1968 and 1995 was negatively related to percent impervious surface (Figure 20).

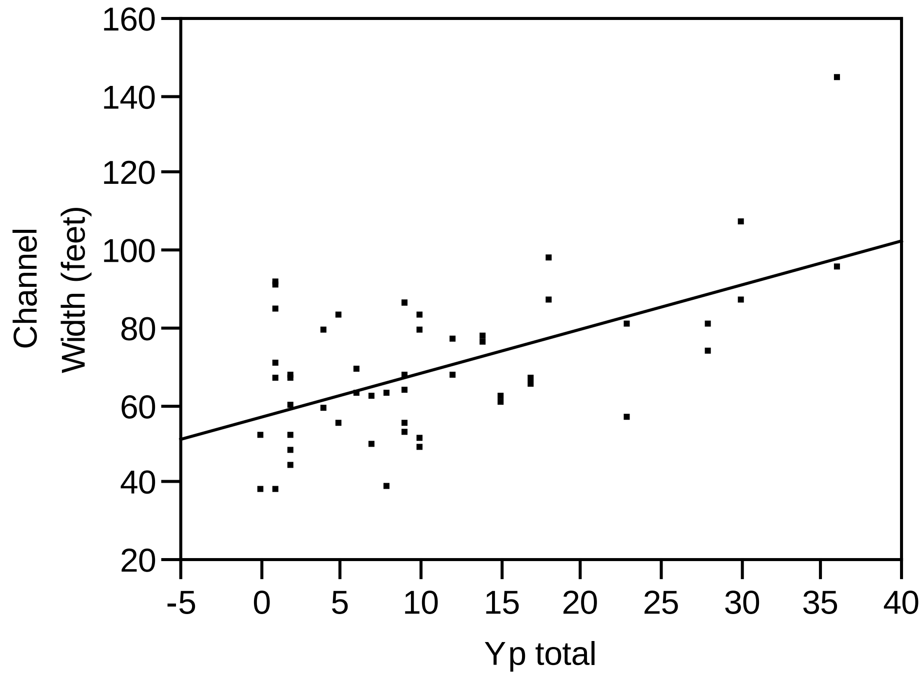

Figure 17. Verde River channel width response to Young Piedmont alluvium (Yp) in tributary washes of the Verde Valley, per simple linear regression analysis. Channel Width (feet) = 56.56 + 1.151*Yp total, $p < .0001$, Adjusted $R^2 = 0.3105$

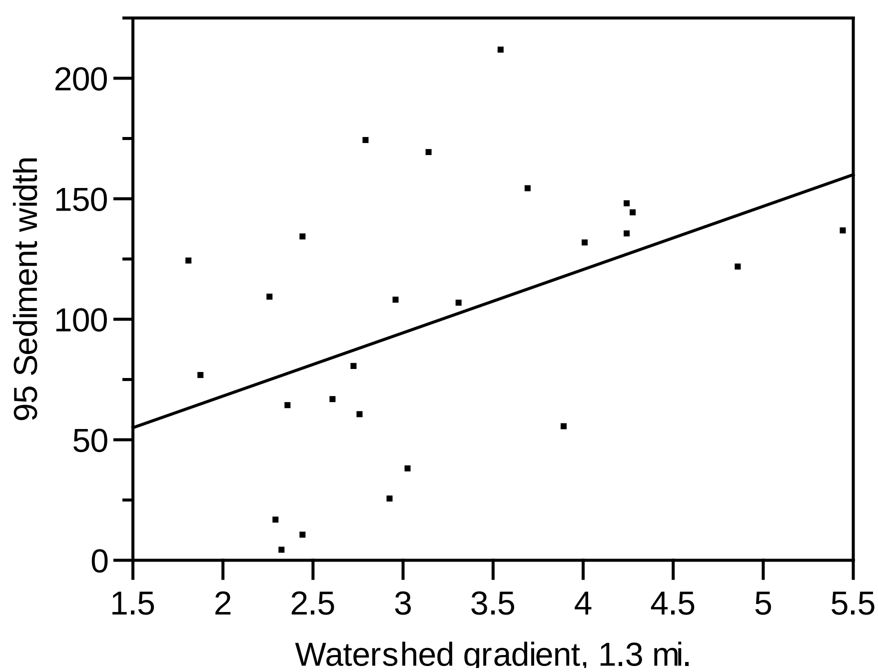

Figure 18. Scoured bare sediment width as a function of tributary watershed toe slope (gradient within 1.3 miles of the Middle Verde River. 95 Sediment width = 15.17 + 26.32*Watershed gradient, 1.3 mi., $p = 0.0228$, Adjusted $R^2 = 0.1645$

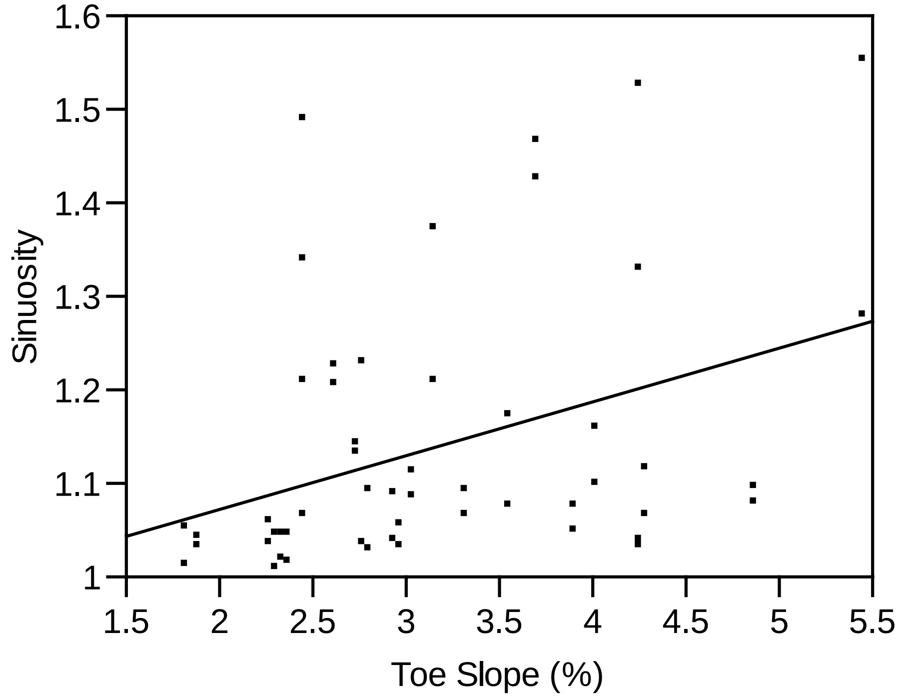

Figure 19. Verde River sinuosity as a function of tributary watershed toe slope (gradient within 1.3 miles of the river) in the Verde Valley. Sinuosity = 0.9596 + 0.05687*Toe Slope (%), $p = 0.0082$, Adjusted $R^2 = 0.1143$

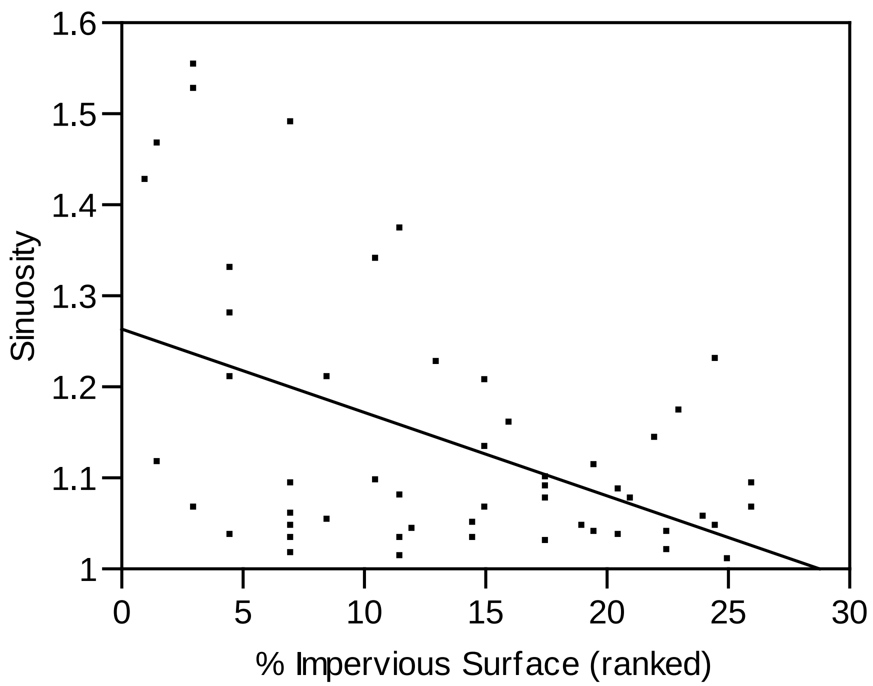

Figure 20. Verde River Sinuosity negatively affected by increasing impervious surface in the Verde Valley. Sinuosity = 1.263 - 0.009158*Percent Impervious Surface (ranked), $p = 0.0003$, Adjusted $R^2 = 0.2122$

Geomorphic response of the river to conditions in the tributary drainages was attributed to greater availability of sediment from some watersheds and to urbanization that caused more rapid and voluminous inputs of sediment from tributary washes to the Verde River during flood events. In general, where greater volumes of sediment were input to the river, channel width increased, scoured bare sediment increased and sinuosity decreased. At four locations sinuosity dropped dramatically as the river channel cut across meander bends, likely causing a decrease in pools and increase in riffles.

Changes in river morphology can affect the ecology of species inhabiting the river corridor. Channel widening and scouring of bars during flood events of the 1980s and 1990s coincided with loss of cottonwood/willow riparian vegetation along the Verde River. When a river channel widens and becomes shallower and adjacent tree cover is lost, stream temperatures can increase and less leaf litter is contributed to the stream. These changes can affect benthic invertebrate communities through nutrient deprivation, which can have a cascading effect for some trophic pathways, leading to a loss of aquatic faunal diversity (Booth et al. 2004). While some fluctuation in channel morphology is natural, geomorphic effects of urbanization should be evaluated in light of habitat needs for species such as native fish. Geomorphic shifts in the pool-to-riffle ratios may benefit non-native fish over native fish (Rinne and Miller 2006). Homogenization of habitat is less supportive to species with specific habitat needs, such as native spikedace, while favoring generalists such as non-native carp, bass, and green sunfish (Pam Sponholtz personal communication, Haney et al. 2008).

Fluvial hydrology and geomorphology play an important role in understanding the dynamics of river ecosystems. Flood-driven fluvial processes maintain high species diversity, bioproductivity, and habitat complexity in riparian ecosystems (Graf et al. 2002). As the field of geomorphology advances, geomorphologists will increasingly assist planners and engineers in river management including risk assessment, floodplain planning, determination of instream and environmental flow needs, environmental impact assessment, river restoration and design of ecologically acceptable channels and structures (Gilvear 1999).

Policy approaches

The Town of Camp Verde General Plan calls for an implementation strategy that utilizes conservation easements, acquisition of development rights, grants and other funding sources to acquire property for preservation of the natural environment. The implementation strategy also includes the development and implementation of natural drainage protection guidelines. In developing land use policies for drainage protection, the Town has two basic options, an administrative approach or a collaborative approach.

An administrative approach could be taken by the town planning department and Town Council to develop programmatic alternatives based on geology and engineering principals. Some public input could be incorporated into the decision-making, but ultimately the town administrators would set land use policy through amendments to the Town of Camp Verde General Plan. Broward County, Florida provides an example of drainage protection planning through policies regarding stormwater management minimum design criteria and construction standards during land development and capital improvement plans for drainage improvements (Broward County 2002). The benefit of this administrative approach to developing land use policies for drainage protection is that a comprehensive policy could be adopted that uses sound land use planning and stormwater management principals. Ideally the policy would be fair and equitable across land ownerships.

One example of a possible administrative land use planning decision would be the establishment of a stormwater utility. The Town is required to have a NPDES Phase II MS4 stormwater permit. A stormwater management plan has been completed (Camp Verde 2003). The Town could choose to take the next step and establish a stormwater utility and use utility revenues to fund drainage protection projects, such as the City of Flagstaff has done since 2003 (Flagstaff 2008). The cost of Phase II is widely variable. EPA established a stormwater utility cost estimate as $1,525 + $3.50 per person with an expected range of $3.75 to $6.00 (2003 dollars) per citizen per year when the program is fully formed (Debo and Reese 2003). Due to low population density and unequal distribution of stormwater management problems, this may not be a cost effective or equitable solution. Cost of stormwater utility administration might infringe on funds available for on-the-ground improvements. In that case, additional funding would be needed for project implementation.

A collaborative approach would rely heavily on stakeholder involvement, participation of landowners and commitment to workable solutions (UrbanFauna 2008). Achieving environmental improvements depends on the actions of people, communities, industries, nonprofit organizations, landowners and other working together, often voluntarily to protect the environmental while achieving other economic and social objectives (Randolph 2004). Some collaborative efforts work better than others, so evaluating successful collaborative models is well advised (Wondolleck and Yaffee 2000). In the Town of Camp Verde, collaborative land use planning could be done on a watershed-by-watershed basis. A citizens and technical advisory group could develop alternatives for stormwater routing. The Town could negotiate drainage easements with private and public landowners and other stakeholders for the installation of drainage ditches, detention basins, erosion-control structures and improved road crossings (Yavapai County 2005). These measures would reduce the incidence of erosion, sediment deposition and flooding due to poorly-routed stormwater flow.

To implement drainage protection strategies, the town could establish improvement districts for drainage management. An example of the successful creation of improvement districts that alleviated drainage problems while using an open public involvement process is the Kiowa-Comanche County Improvement District in the community of Mountainaire, Arizona (Coconino County 2008). Landowners within improvement districts would be assessed for drainage improvements and could be required to sign Prop 207 claim waivers (LACT 2007). One benefit of this collaborative approach could be a high level of citizen participation and support. Another benefit may be a more equitable distribution of improvement projects. One drawback is the time commitment to complete the process. Another drawback is that, after considerable effort, the Town could end up with a set of band-aid solutions and no comprehensive plan to address watershed problems.

A hybrid of the administrative and collaborative approaches might be to establish drainage districts throughout the entire town and develop a comprehensive drainage management plan through a process with a high level of public involvement and collaboration. The plan would include guidelines for drainage management, goals for each drainage district, estimated budgets for implementing goals, a rate schedule for assessing districts, priorities for project implementation and timelines for achieving goals. Like the Town of Camp Verde General Plan, a Drainage Management Plan could be put to a vote by the citizens and adopted by town council. Districts could agree to proceed with specific planning and implementation of projects as they are ready and according to the priority list. Additional funding could be sought from various sources. Legal considerations might fall more in the realm of laws governing special districts (ARS Title 48 – Special Taxing Districts), rather than land use planning law (ARS Title 9, Article 6 – Municipal Planning), perhaps affording some protection from Prop 207 liability. However, a complete legal review would be needed before pursuing this policy approach. Because landowners in a given district would all be assessed for drainage improvements, and these improvements are important to protect landowners from drainage-related property damage, there could be considerable within-district social pressure for land owners to agree to prompt drainage improvements.

Recommendations

The following are policy recommendations to the Town of Camp Verde based on results of modeling geomorphic response of the Verde River to land use change within 1.3 miles of the river for the period 1968 to 1997.

1. Prioritize careful land use development planning in tributary watersheds where Young Piedmont Alluvium (Yp) is abundant (Figure 21). The following list ranks watersheds, which have greater than average abundance of young piedmont alluvium, from highest to lowest priority for careful planning:

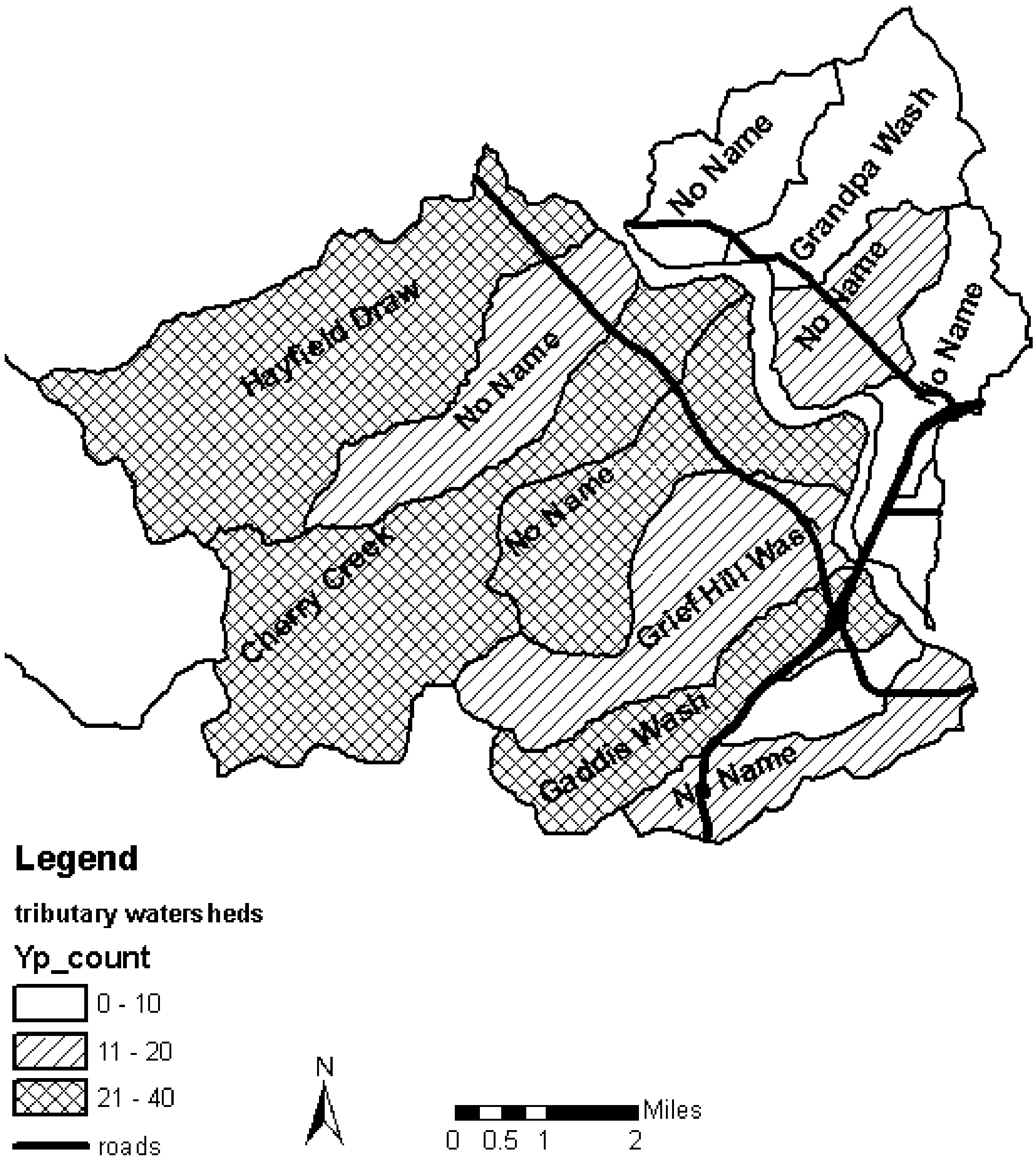

Figure 21. Abundance of fluvially active Young Piedmont Alluvium (Yp) in tributary watersheds. Yp was counted as 1-inch segments of the narrow channel deposits as viewed on a 1:24,000 scale map (House and Pearthree 1993). Abundance is shown as low (white), medium (hashed) and high (cross-hashed). Low is below average, medium is average to one standard deviation, and high is greater than one standard deviation, based on evaluation of 26 tributary watersheds in the Verde Valley.

a) Cherry Creek

b) Hayfield Draw

c) No name (descends from Hull Hill)

d) Gaddis Wash

e) No name (down valley from Hayfield Draw

f) Grief Hill Wash

g) No name (at the end of the study area, southwest of the river)

h) No name (at Middle Verde)

In general, the watersheds up-valley from Interstate 17 on the southwest side of the Verde River should be considered a special development planning area to protect against mobilization of stored channel alluvium, which could cause undesirable geomorphic changes to the Verde River.

2. Require more comprehensive stormwater management in places that are in or adjacent to areas with a dominance of Yp and youngest Chuckwalla Group (C2) alluvial units. Surficial geology maps (House 1994) should be referred to in making such determinations. Places requiring comprehensive stormwater management due to surficial geology would include building sites that fall within the watersheds listed above, with particular attention to Hayfield Draw and Gaddis Wash. The goal of stormwater management in these areas would be to maintain pre-development storm hydrographs by slowing runoff from developed areas. Hence, evaluation of predevelopment runoff conditions is critical.

3. Require more comprehensive stormwater management in places that are adjacent to tributary channel slopes greater than 3.2 percent, which is the average toe slope, to

guard against above average increases in scoured sediment and decreases in sinuosity of the Verde River. Priority watersheds include Grief Hill Wash and especially watersheds northeast of the Verde River. Stormwater planning is particularly important in the “no name wash at Middle Verde” watershed, because much greater than average toe slope of washes is combined with greater than average abundance of Young Piedmont Alluvium. A drainage evaluation has been completed for the Middle Verde area with recommendations that should be followed to address existing and potential erosion in this particular watershed (Fuller 2002).

5. Establish drainage easements at the time of subdivision.
6. Negotiate with existing owners of already-subdivided lands to designate drainage easements. Acquire drainage easements through agreement, purchase, or condemnation. Use historic aerial photography to prioritize locations for drainage easements and provide justification for eminent domain if needed. Require landowners to sign a waiver of Proposition 207 claims before drainage easements are established and improved on their properties.
7. When creating drainage easements, allow adequate time in the planning process for completion of Section 402, Section 404, Section 401 permits as needed, as well as environmental assessments on national forest lands.
8. Establish watershed-based special districts within the town limits for drainage management. By using a hybrid administrative/collaborative approach, developing area-specific plans, engendering resident support, and requiring property owners to waive Prop 207 claims, the Town may develop policies that can be implemented with a minimum of impediments (Singleton 2002).

9. Improve riparian habitat as a defense against river channel relocation that can damage or destroy property, with the understanding that even exemplary restoration projects can not guard against "acts of God". Base riparian restoration projects on the best available science and knowledge gained through other successful efforts. Plan ahead to assure that plant materials are available from local genetic stock adapted to site conditions.
10. Negotiate the use of State of Arizona instream flow rights for irrigating riparian trees during their establishment. Adequate water availability is critical for the survival of young phreatophytes. Be prepared to pump from the river or deliver water through irrigation ditches to ensure the survival and establishment of planted cottonwood, willows, and other native vegetation.
11. The Yavapai Apache Nation is a significant land owner and stakeholder. Tribes can receive Clean Water Act Section 319 competitive grants to address nonpoint source pollution through the improvement of riparian areas. Therefore, the Town and local environmental groups should work collaboratively with Yavapai Apache Nation to restore riparian vegetation in the degraded reach of the Verde River that passes through the reservation. Encourage other land owners and organizations to also apply for CWA§319 funds from the Arizona Department of Environmental Quality and Arizona Water Protection Fund grants from the Arizona Department of Water Resources to expand the scope of restoration projects along the river.
12. Based on goals and objectives, secure funding for drainage improvements, erosion control and riparian restoration from diverse sources such as
    (a) drainage improvement special district assessments,

(b) stormwater utility fees,

(c) land use development impact fees,

(d) Small MS4 Phase II funding assistance from ADEQ,

(e) Arizona Water Protection Fund, and

(e) CWA Section 319 funding through ADEQ or from EPA to the Yavapai Apache Nation.

13. Work closely with and draw on the expertise of the Yavapai County Flood Control District in developing policy and implementing projects.

14. Take full advantage of scientific research available through the Arizona Water Institute. Request that scientific studies be conducted to suit the Town's needs for land use planning and natural resource protection. Effective policy and managements plan can best developed through cooperation and communication between researchers and decision makers (Letey 1999).

15. Conduct public outreach to watershed stakeholders including private land owners, Yavapai Apache Nation, Prescott National Forest, Verde River Greenway, the Verde Watershed Advisory Committee, The Nature Conservancy, Audubon Society, and citizen groups so that drainage improvements in Camp Verde complement overall Verde Watershed protection. Local efforts to rehabilitate rivers and reverse the debilitating effects of land use change ultimately will not be effective unless restoration is approached at the watershed scale.

Conclusion

The Town of Camp Verde has many options for improving surface water drainage to reduce erosion and safeguard the Verde River environment and private property from loss or damage due to sediment-laden discharge from tributary washes. By working collaboratively, using the best available science, the town can institute policies that will protect the Verde River in ways that are consistent with local values.

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APPENDIX A

Data from previous studies used to support

Geomorphic response to land use change, middle Verde River Arizona

Table 6. Historic land use and river morphology changes in three reaches of the Middle Verde River above, at and below the Town of Cottonwood, Assessment of Human Influence on Riparian Change in the Verde Valley, Arizona (Masek Lopez and Springer 2002)

	LAND USE									RIVER MORPHOLOGY				
	Low Density Residential		High Density Residential		Commercial /Industrial		Agriculture		Total Land Use	Channel		Sediment		Total
	acres	% of total	acres	% of total	acres	% of total	acres	% of total	acres	acres	% of total	acres	% of total	acres
NORTH FRINGE														
1940	nd		nd		nd		nd		nd	nd		nd		nd
1954	nd		nd		nd		nd		nd	nd		nd		nd
1968	0.00		0.00		0.00		0.00		0.00	23.80	*54.3*	20.00	*45.7*	43.80
1977	0.00		0.00		0.00		0.00		0.00	32.47	*64.3*	18.00	*35.7*	50.47
1989	0.00		0.00		0.00		0.00		0.00	29.58	*52.2*	27.12	*47.8*	56.70
1995	0.00		0.00		0.00		0.00		0.00	nd		nd		Nd
CORE AREA														
1940	162.96	*7.9*	116.94	*5.7*	510.66	*24.8*	1270.30	*61.6*	2060.86	201.71	*26.1*	569.97	*73.9*	771.68
1954	267.89	*10.4*	84.03	*3.3*	597.03	*23.2*	1619.78	*63.0*	2569.41	138.99	*21.8*	499.73	*78.2*	638.72
1968	279.45	*12.1*	180.30	*7.8*	621.61	*27.0*	1222.73	*53.1*	2304.66	126.32	*21.2*	468.39	*78.8*	594.71
1977	684.28	*23.8*	423.73	*14.7*	744.31	*25.8*	1028.20	*35.7*	2880.52	128.76	*23.4*	420.63	*76.6*	549.39
1989	851.24	*24.8*	787.21	*22.9*	842.57	*24.5*	955.73	*27.8*	3436.75	149.22	*26.8*	408.05	*73.2*	557.27
1995	1125.35	*28.4*	1066.89	*26.9*	1116.24	*28.2*	656.05	*16.5*	3964.53	217.46	*39.4*	334.91	*60.6*	552.37
SOUTH FRINGE														
1940	nd		nd		nd		nd			nd		nd		nd
1954	1.33	*1.9*	0.00	*0.0*	0.00	*0.0*	69.36	*98.1*	70.69	56.26	*28.9*	138.50	*71.1*	194.76
1968	4.00	*9.1*	0.00	*0.0*	0.00	*0.0*	39.79	*90.9*	43.79	49.15	*31.0*	109.37	*69.0*	158.52
1977	7.56	*16.6*	0.22	*0.5*	0.00	*0.0*	37.79	*82.9*	45.57	52.48	*35.1*	97.14	*64.9*	149.62
1989	25.57	*35.7*	26.90	*37.6*	0.89	*1.2*	18.23	*25.5*	71.59	69.80	*37.6*	116.01	*62.4*	185.81
1995	54.91	*81.5*	12.45	*18.5*	0.00	*0.0*	0.00	*0.0*	67.36	97.18	*37.6*	161.23	*62.4*	258.41

Table 7. Historic riparian vegetation densities along the Verde River above, at and below the Town of Cottonwood, Assessment of Human Influence on Riparian Change in the Verde Valley, Arizona (Masek Lopez and Springer 2002)

RIPARIAN VEGETATION															
	Mesquite							**Cottonwood/Willow**							
	Low Density		Medium Density		High Density		Total	Low Density		Medium Density		High Density		Total
	acres	% of total	acres	% of total	acres	% of total	acres	acres	% of total	acres	% of total	acres	% of total	acres
NORTH FRINGE															
1940	nd		nd		nd		nd	nd		nd		nd		
1954	nd		nd		nd		nd	nd		nd		nd		
1968	28.68	*37.1*	27.12	*35.1*	21.56	*27.9*	77.36	0.89	*33.5*	1.33	*50.0*	0.44	*16.5*	2.66
1977	16.67	*24.3*	28.90	*42.2*	22.90	*33.4*	68.47	1.11	*83.5*	0.22	*16.5*	0.00	*0.0*	1.33
1989	3.78	*9.9*	18.67	*48.8*	15.78	*41.3*	38.23	1.11	*100.0*	0.00	*0.0*	0.00	*0.0*	1.11
1995	8.00	*12.8*	27.57	*44.0*	27.12	*43.3*	62.69	0.67	*30.0*	0.67	*30.0*	0.89	*39.9*	2.23
CORE AREA															
1940	340.36	*31.3*	564.01	*51.9*	181.63	*16.7*	1086.00	57.80	*21.4*	84.26	*31.2*	127.83	*47.4*	269.89
1954	361.48	*35.7*	487.31	*48.1*	163.62	*16.2*	1012.41	22.45	*6.5*	111.38	*32.2*	211.87	*61.3*	345.70
1968	422.55	*41.8*	378.38	*37.5*	208.98	*20.7*	1009.87	24.90	*5.6*	130.50	*29.5*	286.34	*64.8*	441.74
1977	264.55	*30.6*	390.38	*45.2*	208.98	*24.2*	863.91	32.68	*5.9*	129.61	*23.6*	387.94	*70.5*	550.23
1989	317.91	*31.9*	391.27	*39.2*	288.79	*28.9*	997.97	33.57	*7.7*	131.61	*30.2*	271.22	*62.1*	436.40
1995	274.34	*25.8*	397.72	*37.4*	391.05	*36.8*	1063.11	28.46	*6.9*	145.39	*35.3*	238.54	*57.8*	412.39
SOUTH FRINGE															
1940	nd		nd		nd		nd	nd		nd		nd		
1954	63.80	*26.8*	125.39	*52.7*	48.91	*20.5*	238.10	17.79	*33.6*	22.01	*41.6*	13.12	*24.8*	52.92
1968	50.69	*31.7*	74.70	*46.7*	34.46	*21.6*	159.85	6.45	*19.5*	16.23	*49.0*	10.45	*31.5*	33.13
1977	42.68	*21.9*	93.37	*47.9*	58.69	*30.1*	194.74	12.89	*22.0*	26.90	*45.8*	18.90	*32.2*	58.69
1989	47.58	*22.5*	92.26	*43.6*	71.81	*33.9*	211.65	16.23	*30.4*	16.45	*30.8*	20.68	*38.8*	53.36
1995	75.81	*32.7*	85.81	*37.0*	70.25	*30.3*	231.87	13.56	*25.3*	13.12	*24.5*	26.90	*50.2*	53.58

Table 8. Historic riparian vegetation densities along Verde River at Camp Verde (Masek Lopez 2001). Index = *100%-vegetation-cover-equivalencies* per mile of stream (acres/mile).

YEAR	**REACH**											
	Middle Verde		**Interstate-17**		**Old Town**		**Beasley**		**Beaver Creek**		**West Clear Creek**	
Vegetation	7.84 river miles		2.55 river miles		8.00 river miles		3.19 river miles		3.22 stream miles		2.31 stream miles	
Type and	(5051.94 acres)		(2734.70 acres)		(4640.84 acres)		(1747.81 acres)		(918.56 acres)		(1271.11 acres)	
Density	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**
1934												
mesquite		na		na		52.68		31.07		13.53		na
low	na		na		299.72		101.14		44.54		na	
medium	na		na		357.42		74.48		35.17		na	
high	na		na		81.34		16.63		5.59		na	
total	na		na		738.48		192.25		85.3		na	
cottonwood-willow		na		30.23		12.68		9.97		6.18		na
low	na		38.09		54.51		9.95		9.42		na	
medium	na		23.04		40.57		17.77		18.06		na	
high	na		49.54		56.72		16.37		4.42		na	
total	na		110.67		151.8		44.09		31.9		na	
1968												
mesquite		37.02		44.01		48.81		48.46		28.36		28.47
low	248.55		61.4		195.73		124.98		36.35		26.78	
medium	207.55		92.69		272.55		112.77		57.48		42.03	
high	70.35		28.93		141.01		38.14		40.18		28.31	
total	526.45		183.02		609.29		275.89		134.01		97.12	
cottonwood-willow		14.02		49.51		20.1		8.65		9.71		26.23
low	25.68		11.58		14.63		6.09		7.1		12.31	
medium	71.85		63.25		101.89		22.95		24.57		42.79	
high	51.95		78.5		85.11		9.7		11.94		26.94	
total	149.48		153.33		201.63		38.74		43.61		82.04	

Table 8. (continued)

YEAR	REACH											
	Middle Verde		**Interstate-17**		**Old Town**		**Beasley**		**Beaver Creek**		**West Clear Creek**	
Vegetation	7.84 river miles		2.55 river miles		8.00 river miles		3.19 river miles		3.22 stream miles		2.31 stream miles	
Type and	(5051.94 acres)		(2734.70 acres)		(4640.84 acres)		(1747.81 acres)		(918.56 acres)		(1271.11 acres)	
Density	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**	**acres**	**index**
1997												
mesquite		58.5		53.4		51.16		72.96		23.55		53.15
low	328.29		97.68		188.28		105.2		39.93		43.82	
medium	323.71		85.95		264.95		126.86		61.44		71.23	
high	133.53		46.69		167.32		112.37		20.85		59.78	
total	785.53		230.32		620.55		344.43		122.22		174.83	
cottonwood-willow		8.58		43.18		17.68		10.97		10.97		39.6
low	16.22		19.57		22.64		6.91		6.83		7.39	
medium	36.33		62.3		75.28		19.46		23.24		42.9	
high	36.95		60.64		81.99		19.3		17		59.24	
total	89.5		142.51		179.91		45.67		47.07		109.53	

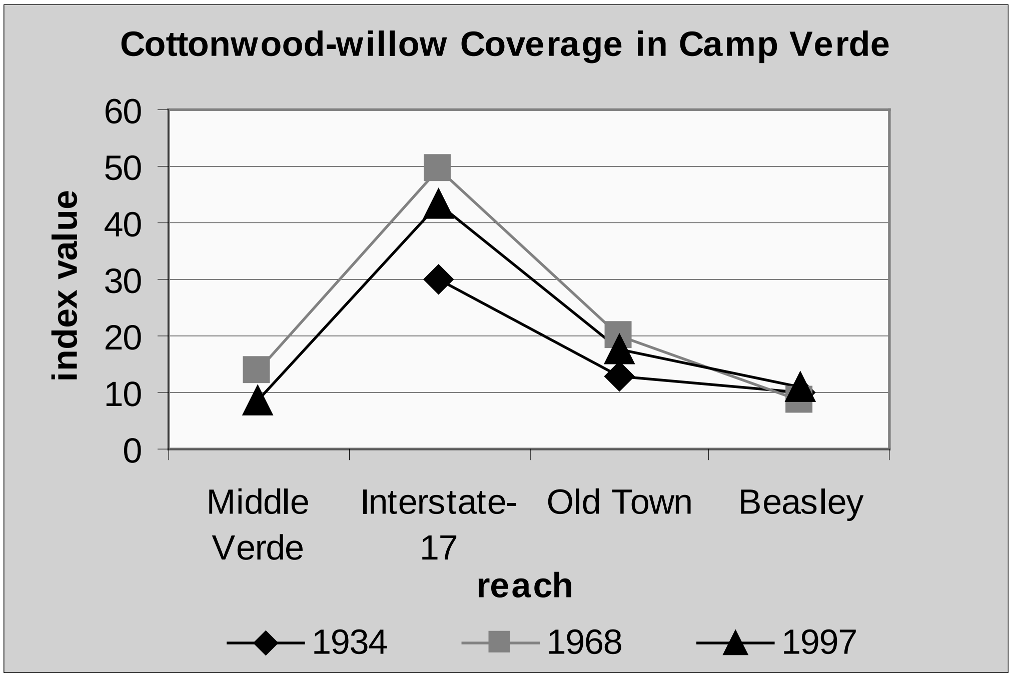

Figure 22. Historic cottonwood-willow coverage along the Verde River in Camp Verde. Index value = 100%-cover-equivalencies per river mile (acres/mile). Camp Verde Riparian Area Historical Analysis, 2001

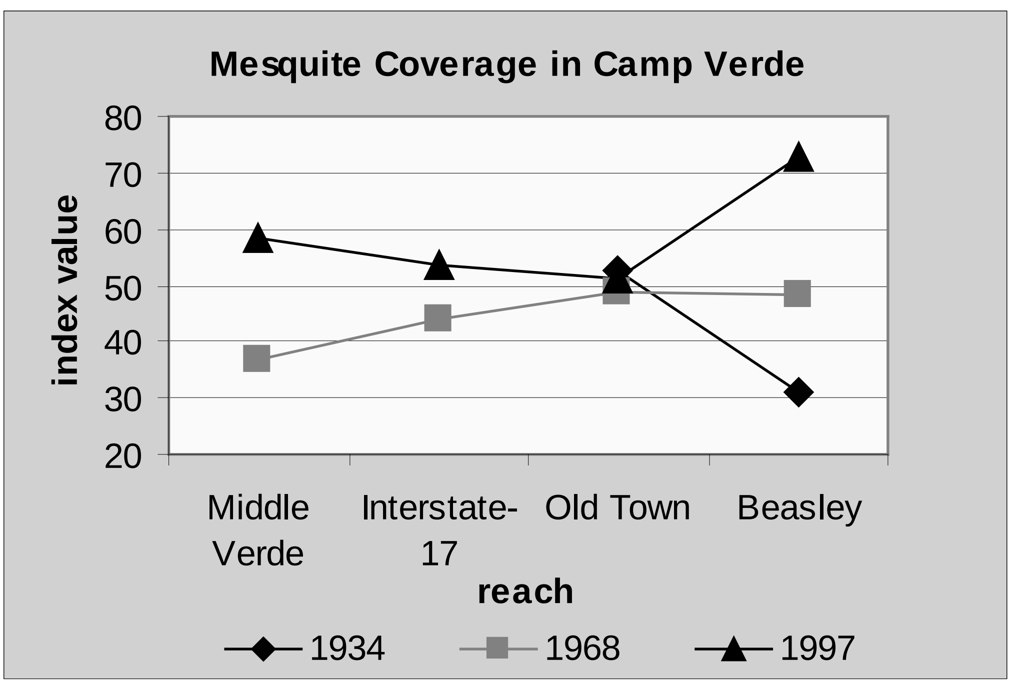

Figure 23. Historic mesquite coverage along the Verde River in Camp Verde. Index value = 100%-cover-equivalencies per river mile (acres/mile).

Appendix B

Data used for regression analyses

Table 9. Data used for regression analysis, Geomorphic Response to Land Use Change, Middle Verde River, Arizona. Young Piedmont alluvium (Yp) is fluvially active sediment in tributary wash that was counted as 1 inch segments at scale 1:24,000.

				1968				1995			
Segment number	**Yp count**	**Watershed area (acres)**	**Toe slope (%)**	**Percent impervious surface (ranked)**	**Channel width (feet)**	**Bare-scoured sediment width (feet)**	**Sinuosity**	**Percent impervious surface (ranked)**	**Channel width (feet)**	**Bare-scoured sediment width (feet)**	**Sinuosity**
1	2	1092	4.25	3	51	57	1.523	4.5	66	134	1.326
2	15	7675	3.55	21	60	61	1.075	23	61	210	1.171
3	8	4762	3.32	26	38	73	1.065	26	62	105	1.091
4	2	1560	4.28	3	43	20	1.063	1.5	59	143	1.114
5	1	2040	3.7	1	37	29	1.422	1.5	66	152	1.462
6	0	1894	3.9	17.5	37	32	1.073	14.5	51	54	1.046
7	7	4059	3.04	19.5	49	33	1.109	20.5	61	36	1.082
8	6	4722	2.3	24.5	62	10	1.045	25	68	15	1.008
9	5	4175	1.89	7	54	4	1.03	12	82	75	1.04
10	9	3081	2.8	7	67	3	1.091	17.5	85	172	1.026
11	10	2371	2.97	11.5	82	81	1.031	24	78	106	1.053
12	10	1729	2.45	7	50	63	1.486	10.5	48	133	1.338
13	2	1586	2.74	15	47	36	1.131	22	67	79	1.14
14	30	7046	1.81	11.5	86	183	1.01	8.5	106	123	1.051
15	18	2709	2.26	7	86	159	1.056	4.5	97	108	1.033
16	1	1746	2.77	24.5	90	90	1.227	20.5	70	59	1.033
17	36	6326	2.36	7	95	37	1.014	7	144	63	1.043
18	9	2525	5.45	3	63	47	1.55	4.5	85	135	1.277
19	12	1702	4.25	19.5	76	73	1.038	14.5	67	146	1.029
20	28	3580	2.62	15	73	17	1.204	13	80	65	1.224
21	1	1870	4.87	11.5	84	56	1.077	10.5	91	120	1.092
22	17	3612	3.15	11.5	66	108	1.37	8.5	64	167	1.206
23	4	468	4.02	17.5	58	123	1.098	16	78	130	1.156
24	23	2421	2.94	22.5	80	37	1.037	17.5	56	24	1.088
25	9	882	2.45	15	52	41	1.063	4.5	54	9	1.205
26	14	1783	2.33	22.5	77	0	1.016	19	75	3	1.042

Table 10. Data eliminated from further analysis due to initial simple linear regression analysis. E = Erodibility Index. 1 = right bank. 0 = left bank.

Seg. no.	Segment name	bank	relief (ft)	1.3 mile buffer E	upper watershed E	average E	tributary fan radius	1968 impervious surface (ft^2)	1995 impervious surface (ft^2)
1	No Name at Tavasci	0	702	31	30	31	370	330522	516370
2	Mescal Gulch	1	4544	26	20	23	270	2120965	5584802
3	Blowout Creek	1	3628	27	21	24	0	6792895	10719977
4	No Name at Deadhorse 1	0	1104	31	30	31	310	163774	329478
5	No Name at Deadhorse 2	0	1114	31	30	31	340	134947	233388
6	No Name at Mingus Ave.	0	568	30	30	30	340	781360	1182709
7	Silver Spring Gulch	1	4564	31	17	24	90	2331619	6199671
8	Oak Wash	1	4573	29	21	25	300	1396181	5067990
9	No Name at Bridgeport 1	0	940	31	30	31	140	447292	1146533
10	Christina Draw	1	3342	29	26	28	80	151179	1091049
11	No Name at Verde Estates 1	1	2704	29	23	26	140	277370	4145174
12	No Name, at Bridgeport 2	0	418	31	30	31	330	651542	1300502
13	No Name at Verde Estates 2	1	1058	23	19	21	460	732277	4412910
14	Hayfield Draw	1	3094	31	30	31	500	217058	284520
15	No Name below Hayfield	1	1145	31	29	30	200	485160	660263
16	No Name opposite Cherry	0	548	29	29	29	300	889451	1250405
17	Cherry Creek	1	552	30	27	29	150	770871	1076255
18	Grandpa Wash	0	564	31	30	31	170	334917	497916
19	No Name at Middle Verde	0	562	36	30	33	170	1806138	2546435
20	No Name from Hull Hill	1	1580	34	27	31	300	1974519	4039934
21	No Name from I-17	0	644	27	30	29	260	1402530	2542158
22	Grief Hill Wash	1	2226	35	21	28	570	1056742	1261843
23	No Name, CV end Left	0	276	30	30	30	0	1137618	1883505
24	Gaddis Wash	1	292	27	26	27	0	1179362	1501751
25	No Name, State Land Tank	1	528	36	21	29	0	337749	179197
26	No Name, CV end Right	1	1500	36	29	33	0	1393611	2000804