California State University, Northridge

Impacts of Agricultural Development on Ephemeral Channel Planform:

Using GIS to Evaluate Change of the Cuyama River, CA - 1938-2011

A thesis submitted in partial fulfillment of the requirements

For the degree of Master of Arts in Geography

By

Joshua Andreas

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The thesis of Joshua Andreas is approved:

Dr. Helen Cox	Date
Dr. Mario Giraldo	Date
Dr. Amalie Orme, Chair	Date

California State University, Northridge

Dedication

I am very grateful for the support and encouragement of so many family members, friends, instructors, advisors, and peers. Many of them will never read this thesis, but it is written for them, and I truly appreciate their positive influences in my life. I would like to explicitly thank a few people. First and foremost: words cannot express how happy I am that Dorothy is not only a loving and supportive wife, but also a scholar and academic writer who can provide sound advice and alternative perspectives. I am very thankful for her patience with me in this process and her willingness to put aside her own writing at times in order to take care of our family while I was living in the library. I am also thankful for my mother, Lydia, and my mother-in-law, Karen, who gave up a great deal of time to help care for our boys, Sam and Ben, following the birth of the latter. I would not have had much time to finalize this thesis without their help.

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ABSTRACT

Impacts of Agricultural Development on Ephemeral Channel Planform:

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Humans have impacted river systems for millennia in order to support agricultural activities. Deliberate modifications are made to river systems to provide irrigation or flood control, and include activities such as damming river courses and channelization or diversion of flow. Additionally, river systems are also impacted by many non-deliberate effects of agricultural land use, especially since the implementation of modern, collectivized, and industrial-scale farming in the 20th century.

The purpose of this study is to investigate the effects of agricultural land use growth on the channel planform of the Cuyama River in California. GIS was used to register aerial photographs, digitize channel boundaries, and then measure various characteristics of river channel form from 1938 to 2011. Channel planform characteristics measured in this study are: channel width, lateral meander migration, and sinuosity. Subsequent measurements to meander wavelength and amplitude were taken for a portion of the study reach in order to gain additional understanding of the initial three

characteristics. The results of this study show that during this period, the river experienced significant geomorphologic activity, which was exacerbated by the growth of agriculture in the surrounding valley. Specifically, a deliberate channelization and straightening of the river caused lasting effects downstream. The discussion that follows examines the numerous challenges which make it difficult to link non-deliberate effects of agriculture to change in river form; however, there is evidence that there are more influences affecting channel pattern than changes in climate and discharge. This study shows the effectiveness of GIS to measure changes to river form over time, and offers a unique case study examining the effects of agriculture on a dryland river.

Chapter I - Introduction

Humans have impacted river environments in a variety of ways for millennia. Intentional modification of rivers occurs when humans deliberately alter the course of the river to suit their purposes, such as damming for flood control or channelization for irrigation. There are also many unintended ways which humans indirectly affect both the geomorphology and habitats of river systems (Goudie, 2005). Land use and land cover modification represents one way in which humans' activities near a river system can cause non-deliberate changes to the river's characteristics. Arguably, the use of land near rivers for agriculture has had the most pronounced effects on river systems throughout history because agricultural land use is often a catalyst for both deliberate and non-deliberate modification of a river.

The primary objective of this study is to investigate how the growth of modern, irrigated agriculture has modified the channel form of an ephemeral/intermittent river. The site for this study is the Cuyama River in the Sierra Madre Mountains of Santa Barbara County, California (Figure 1). Following an initial examination of available data and a thorough literature review, two

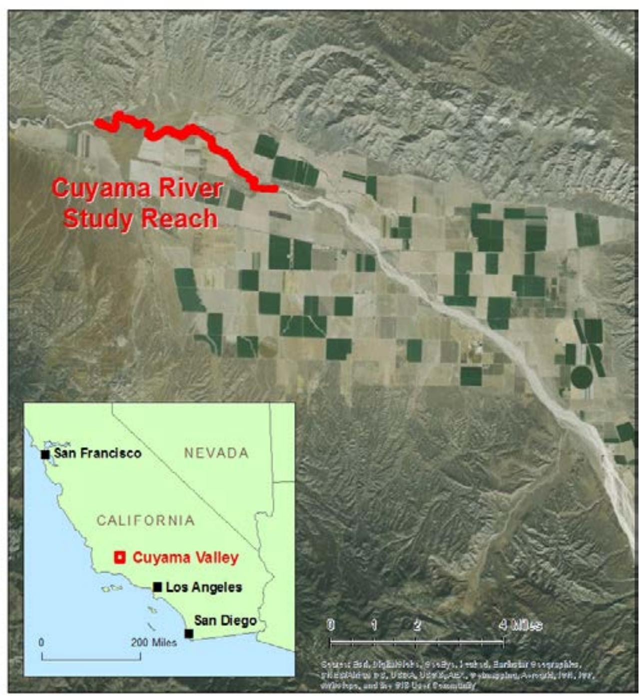

Figure 1: Location of Study Site

research questions emerged which are addressed in this study:

1) How has the channel form changed in the past 80 years as modern agricultural practices have become the dominant land use along the reaches of the Cuyama River?
2) Can changes in channel form be attributed to the growth of agriculture in the region?

These research questions will be abbreviated as RQ1 and RQ2 in this thesis. The goals of this study are to contribute to knowledge regarding present day geomorphologic behavior of the Cuyama River (RQ1), to provide a case study which uses GIS methods to investigate geomorphologic change (RQ1), and to discern the magnitude of anthropogenically-influenced shifts in channel behavior (RQ2).

RQ1 is a descriptive question which seeks to add to the body of knowledge on the Cuyama River by examining modern channel form change. Two studies by DeLong et al. (2011; 2008), provide exceptional insight into the geomorphologic Quaternary history of the Cuyama River; however, these studies do not examine changes which may be due to human activity. A recent study broadly examines land use and ecological impact throughout the entire valley and includes a historical examination of changes in riparian vegetation, but it does not assess channel form beyond an examination of channel width (Andersen et al., 2009). By answering RQ1, this study provides a unique, quantitative description of modern channel planform change for the study reach of the Cuyama River. Additionally, in order to answer RQ1, this study uses GIS to register aerial photographs, digitize aerial photographs, and measure channel width, lateral migration, and sinuosity. Compared to traditional field methods, GIS is used sparsely for studies in topics related to fluvial geomorphology; therefore, this study contributes to the body of literature regarding the emerging use of GIS in fluvial geomorphology.

RQ2 addresses the main theme of this research: the capability of humans to alter the channel form of a river both deliberately and non-deliberately with modern agricultural practices. The aerial photographs used to answer RQ1 are also used to map the growth of agriculture near the study reach. The literature review in Section 3.5 shows that prior research has been able to link agricultural practices to changes in the nature of channel behavior. This study shows how deliberate modifications to support agricultural activities have affected channel planform. The non-deliberate impacts of the growth of agricultural land use are also examined. Discussion of these impacts will reveal the challenges of making direct correlations, but also present opportunity for future research in this area. Ultimately, this study effectively measures channel form changes in the Cuyama River and presents a robust discussion of the impact of agriculture.

Chapter II – Study Site: Cuyama River

2.1 - Physical Description & Geomorphologic Characteristics

The Cuyama River flows through the Sierra Madre in Santa Barbara County and the Caliente Range in San Luis Obispo County. The river exhibits both ephemeral and intermittent behavior, with upper reaches only flowing immediately after rain events, and lower reaches flowing for longer durations in the wet season. Draining more than 2100 km^2, the river has three distinct channel characteristics: braided as it flows NNW from its headwaters to the agricultural areas around New Cuyama; an entrenched, meandering arroyo as it continues westwards; and a sinuous, narrow bedrock channel as it moves southwestwards and ultimately drains into the Santa Maria River (Delong et al., 2011).

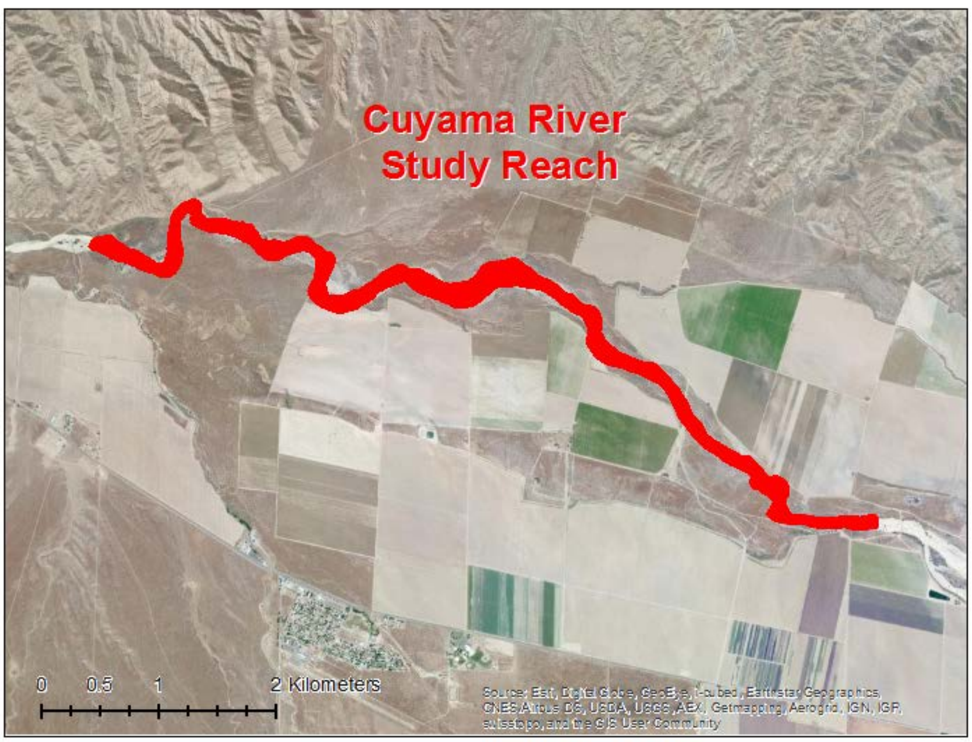

Figure 2: Detail Image of Study Reach

This study will focus on the first ~9 km of the entrenched, meandering arroyo which begins in the heart of the agricultural area of the Cuyama Valley (Figure 2).

Delong et al. (2011, 2008) note that the processes of incision and sedimentation which occurred in the late Holocene resemble the patterns seen in dryland rivers of the Basin and Range despite the semi-arid Mediterranean climate pattern of cool, moist winters and hot, dry summers experienced in the region today. The area is also noteworthy for its tectonic complexity, as the surrounding mountains are experiencing ongoing uplift and deformation associated with the "Big Bend" portion of the San Andreas Fault.

2.2 – Land & Water Use

The Cuyama Valley sits at the junction of four counties in California, with the Cuyama River representing a major portion of the boundary between Santa Barbara and San Luis Obispo counties; Kern County and Ventura counties bound the eastern stretches of the valley. The valley is sparsely populated with just 568 people residing in the two census-designated places of Cuyama and New Cuyama (U.S. Census Bureau, 2010).

The valley was originally settled in the mid 1800's by Spanish colonists. Ranching was the dominant land use until 1938 when pumping systems were implemented to use groundwater to irrigate crops (Andersen et al., 2009). Plowed agriculture quickly became the dominant land use in the valley. The valley experienced an economic boom in the 1950's after oil was discovered in 1948 (Lantis et al., 1973). However, according to the California Department of Conservation (2010) less than 2% of original oil reserves remain in the field. Therefore, agriculture has once again become the dominant economic force in the valley. This also may prove unsustainable as groundwater levels have been steadily declining. As of 2010, 99% of water withdrawn from the Cuyama groundwater basin is used for agriculture, and withdrawals of 38,133 acre-feet per year vastly surpass the recharge rate of 6,944 acre-feet per year (Almy and Schaefer, 2012). As groundwater levels continue to decline, pumping costs increase and irrigated farming may prove to be too costly.

Chapter III – Theoretical and Methodological Background

The two research questions investigated in this study rely upon concepts from a broad spectrum of geography: geomorphology, human-environment interaction, and GIS. In order to bring diverse topics together, the review of literature in this chapter is organized to begin by addressing the main theme of this study and then subsequently discuss specific concepts and methods.

The first three sections of this chapter review the theoretical concepts that support RQ2, which addresses the main theme of this study. Section 1 broadly discusses the human impact on fluvial geomorphic processes. This leads into a detailed examination in section 2 of the many ways that agriculture has been shown to affect river behavior in a variety of landscapes. Section 3 of this chapter examines the unique characteristics of dryland rivers in order to pinpoint specific concepts which apply to this case study.

From this theoretical foundation, Section 4 examines the methods which have been used in previous studies, namely the measurement of short-term changes in the form and pattern of river channels. This will provide background on the methods which are used to answer RQ1.

The chapter concludes in section 5 by reviewing current research that attempt to attribute changes in channel form to agricultural land use. The literature cited in this section use the GIS methods described in section 4 to address the problem of agricultural effects on geomorphology, presented in the prior sections. This section provides the methodological background from which RQ2 will be answered.

3.1 - Introduction to Anthropogenic Fluvial Geomorphology

Humans have modified natural landscapes for millennia since the agricultural revolution allowed humans to transition from nomadic, hunter-gatherer societies to settled civilizations. The implementation and acceleration of technology applied to all aspects of agriculture and industry has led to the use of the term "Anthropocene" to refer to a new geological epoch in which humans are the dominant force of geological and ecological change (Steffen et al., 2007). Estimates of the amount of total earth moved by human activities have been used to quantify the geomorphologic impact of humans on the landscape (Rozsa, 2007). Thus, the emerging discipline of anthropogenic geomorphology focuses on this impact (Szabo, 2010).

Within the broad context of anthropogenic geomorphology, the impacts of humans on fluvial systems are among the earliest and most significant forms of human-induced change in the environment. The manipulation of river systems for irrigation played a critical role in the development of early agricultural civilizations (Nials et al., 2011). In the American Southwest, for example, native societies built check dams and irrigation canals to support crops; critical to their ability to eschew a nomadic lifestyle (Hundley, 2001). With the growth of 19th and 20th century industry, expanding urban areas had major effects on fluvial systems (Gregory, 2006). In California, hydraulic mining and groundwater pumping led to massive alterations of waterways in the 1800s, to include the disappearance of Tulare Lake in the San Joaquin Valley, which, at one time, covered an area four times larger than Lake Tahoe (Hundley, 2001). Mount (1995) contends that over the past 150 years, "the rules by which the rivers of California operate have been fundamentally changed".

Two major types of human change on fluvial systems exist: deliberate and non-deliberate changes (Goudie, 2005). Deliberate changes directly affect the system itself, by design. Two of the most common forms of intentional modification are damming and water withdrawals (Harden, 2006). Direct transformation of channels, such as straightening and the development of artificial embankments, continue to impact the nature of discharge, channel erosion, and sediment transport (Hooke, 2006). Indeed in this study, channel straightening has occurred in order to divert water to expand agricultural fields closer to the channel. Understanding how direct modifications such as this have an effect on river channel form and pattern is relatively straightforward: the channel itself was altered deliberately making it quite clear that human activity impacted the landscape.

On the other hand, non-deliberate changes occur when human activities which are not intended to modify a river system consequently become a catalyst for change in the river system (Goudie, 2005). Non-deliberate effects should not be mistaken to imply that the activities themselves are not deliberate actions taken by humans to modify their environment; but rather that the action was not intended to affect the river system. For example, deforestation is a conscious decision to alter the environment; however, the impact of deforestation on a downstream river system is an unintended effect. Most examples of non-deliberate change can be seen in the broad category of land use change; where effects from urbanization, deforestation, or agricultural land use alter hydrologic characteristics which ultimately affect the shape of the river channel. The effects of non-deliberate changes on rivers require consideration of many more factors than deliberate change.

3.2 - Impact of Agriculture on Fluvial Processes

Agriculture is a well-documented catalyst for human-induced change on the landscape. Indeed, attempts to quantify total earth moved by human activities reveal that rural, agricultural land use remains the dominant catalyst of anthropogenic change worldwide (Rosza, 2007). Most impacts of agriculture come in the form of deliberate changes in fluvial systems, including damming, diversions, and channelization (Hooke, 2006). But agricultural land use also non-deliberately impacts channel processes which ultimately determine channel form. These in turn reflect slope, discharge, and sediment load. This section focuses on research which has demonstrated how agricultural practices can affect the latter two of these variables and therefore result in non-deliberate impacts on channel form and pattern.

Abundant research regarding the effects of agricultural land use on river processes comes from Europe, where agricultural practices modernized rapidly following World War II. This modernization caused a shift from small farms with hedgerow borders to large collective fields, resulting in increases to local surface runoff (O'Connell et al., 2007). In the United States as well, widespread mechanization of farming has resulted in what has been called "the homogenization of the landscape" (Mount, 1995; 254). The tilling or plowing of soil significantly alters its hydrologic properties and surface roughness (Mousa et al., 2002). Initially, tilling increases infiltration capacity by loosening the soil; however, porosity, permeability, and roughness degrade over time and produce a surface seal which reduces infiltration, which ultimately results in increased runoff (Mousa et al., 2002). The increase in runoff leads to an increase in erosion, which has been shown in field experiments to move soil amounts that are over an order of magnitude greater than rates of soil loss in similar, but non-tilled environments (Poesen & Hooke, 1997). Increased runoff can also result in gullies at the edges of fields (Valcarcel et al., 2003). These gullies then lead to an increase in the amount of runoff which will ultimately contributes to channel discharge and also reduces the lag time of this runoff following precipitation (O'Connell et al., 2007). By and large, the dominant theme of current research is that intensive agricultural land use tends to increase surface runoff and erosion, which would then ultimately result in increased discharge and sediment load in the affected stream channel.

Another major variable affecting channel morphology is riparian vegetation. Riparian vegetation serves as a moderator between the cropland and the river channel. Hupp and Osterkamp (1996) demonstrate the interrelationship between vegetation and geomorphology. The presence of riparian vegetation greatly affects bank stability and rates of erosion, which in turn affects how much the channel will change. Research reveals contrasting responses to riparian vegetation based on the effects of agriculture. For example, VanLooy and Martin (2005) cite lower groundwater tables due to pumping for irrigation as a cause of a reduction in riparian vegetation. Conversely, Sandercock, et al. (2007) note that in some areas, irrigated cropland can increase discharge due to an increase in runoff from nearby fields. Fernald et al. (2007) discuss how groundwater seepage from irrigated fields can increase riparian vegetation. This leads to a paradox which exemplifies the difficulty in determining causation of channel pattern change: increases in runoff from plowed fields would result in increased discharge and greater bank erosion in the channel; however, if the same increase in runoff results in more riparian vegetation, then bank stability will increase and result in a lessening of lateral migration.

Assessing the effects of agricultural land use on fluvial systems is further complicated by the temporal variability of farming practices. Farmers often change their practices annually or seasonally which alters field drainage (Mousa et al., 2002). Casali, et al. (2008) investigated the inter-annual variability in the effects of agricultural practices and discovered that the cycle of plowing, planting, and harvesting in modern agriculture often results in situations where tilled soils are left exposed to rain/weathering for 30% of the year. When these periods of exposure coincide with intense rainfall, the result is large runoff on exposed soils, leading to increased sediment load (Casali et al., 2008) and river flows (Holman et al., 2003).

Finally, even though increases to runoff and erosion are the most common effect of agricultural practices, different sites and different conditions may yield different results. For example, in ephemeral channels, fields which were frequently plowed were shown to have increased infiltration and therefore less runoff and discharge (Bull et al., 1999). Harden (2006) also notes that tilling can increase infiltration, but increased tractor use can compact the soil and therefore increase runoff. Furthermore, in many locations fields are being parceled, not collectivized, and therefore runoff decreases as parcel boundaries interrupt overland flow (Harden, 2006). In sites where there is extensive groundwater pumping, a lowering of the water table may also reduce discharge in the river (VanLooy and Martin, 2005). While cases such as these are a minority, they show that the dominant effects of agricultural land use on fluvial processes are not universal.

The impact of agricultural land use on fluvial processes will always vary based on site and situation.

3.3 - Unique Characteristics of Dryland Rivers

Studies of fluvial geomorphology in dryland river systems require additional considerations owing to the ephemeral or intermittent nature of flow. Gregory (2006) asserts that arid rivers will often exhibit contrasting responses compared to humid-land (perennial) rivers subject to the same human-induced changes. Since the effects of agricultural land use on fluvial systems are site dependent, and the Cuyama River is a dryland river, it is important to understand the unique characteristics of such rivers and their response to human-influenced change.

Tooth's (2000) review of dryland river research highlights several major differences in the fluvial processes of dryland rivers:

1) Precipitation is highly variable both temporally and spatially;
2) Downstream volume decreases due to transmission losses by infiltration;
3) Hydrographs reveal that discharge increases and decreases rapidly during a flood event;
4) Channel forming flows are larger by comparison due to a high ratio of large to small floods;
5) Dryland rivers are greatly affected by the presence/absence of vegetation.

The variability in precipitation of dryland rivers has an enormous impact on fluvial processes. The temporal variability of precipitation means that most geomorphic work takes place during infrequent flood events, therefore irrigation for farming can complicate these processes during the dry periods (Graf, 1983). Another implication of the interannual variability of precipitation is that the hydrographs of dryland rivers may require a much longer record before a pattern emerges which can be used to predict future behavior (Walker et al., 1995). As a result of the spatial variability of precipitation within a dryland river catchment, different parts of a river will flow at different times or perhaps not at all during the same storm event (Shannon et al., 2002). Therefore, effects of a particular storm can be highly localized, which presents challenges to broad area studies of channel form and pattern over time.

This localization is further exacerbated by the tendency of dryland rivers to lose volume downstream due to transmission loss. Transmission losses occur as water infiltrates into the permeable bed and banks of the river channel (Shannon et al., 2002). Transmission losses in many dryland rivers may result in their termination at tributary junctions or in fan systems (Bull, 1997) instead of joining another river or draining into the ocean. Furthermore, in some situations overland flow may infiltrate further downslope and never contribute directly to the river discharge (Beven, 2002). When coupled with the spatial variability of precipitation, transmission loss results in variable flow along a river. This has a direct effect on its erosional and depositional processes with scour occurring in one reach and fill occurring in another (Tooth, 2000). Therefore it is possible that during the same flood significant geomorphic activity could be taking place in one reach, but reaches further downstream may not experience flow.

The properties of floods in dryland rivers differ greatly from rivers in humid climates. The typical hydrograph of a dryland river will exhibit the pattern of a flashflood: steep rising peak and steep recession (Nanson et al., 2002). While precipitation in arid climates is infrequent, it is often very intense and therefore results in large overland flows (Beven, 2002) which result in the steep peak of the hydrograph. The sharp recession is due to transmission losses and the fact that overland flow is the dominant process contributing to streamflow (Tooth, 2000). This is different from humid rivers which may have a perennial baseflow due to groundwater, and where subsurface flows result in a gradual tapering of the recessional limb of the hydrograph (Mount, 1995). This feature of dryland rivers may enhance the ability to evaluate the effects of agricultural land use change. Since runoff is the dominant contributor to river discharge, changes in runoff due to agriculture may be more pronounced.

Based on many of the factors previously discussed above, floods in dryland rivers tend to be infrequent, yet often much greater in magnitude (Nanson et al., 2002). Dryland channels are highly sensitive to the effects of large floods, so large flooding tends to produce the most geomorphic change (Tooth, 2000). Smaller floods tend to only occupy smaller braided channels within the main channel, where flow velocity is very slow due to the high width/depth ratio; but large events often will fill the entire channel with a high velocity flow which can scour the channel bed and cause mass sediment transport (Shannon et al., 2002). The impact of large flood events on channel geometry is often so drastic that the river never returns to its previous position (Tooth, 2000). These large events may only recur every 10-50 years (Shannon et al., 2002), whereas the normal channel-forming, bankfull discharge in humid rivers typically occurs every 1.5 to 2 years (Mount, 1995). The implication for this study is that large magnitude flood events in drylands may occur so infrequently that it becomes much harder to attribute channel changes to land use change.

Many differences exist in the characteristics of riparian vegetation in ephemeral dryland rivers when contrasted with vegetation at perennial rivers. One major difference is that vegetation can colonize inside the channel bed during periods of no flow and then initiate the formation of depositional features (Nanson et al., 2002). So with dryland rivers, vegetation not only reduces erosion, but also enhances deposition. Additionally, in many arid and semi-arid areas, riparian vegetation tends to rely far more on flow of the river due to lower groundwater tables (Hupp and Osterkamp, 1996). This offers a much greater opportunity for agricultural practices to have an influence in dryland areas if runoff from irrigated fields contributes to an increase in riparian vegetation by providing a consistent source of water (as discussed in section 2.2 of this paper).

The unique characteristics of dryland rivers present both opportunities and challenges for this study. The effects of agriculture on runoff during floods, or on seepage during times of no precipitation may become more evident in a dryland river. On the other hand, the shaping of dryland rivers by large, infrequent flows may mean that it is impossible to determine “normal” rates of geomorphic change, and therefore prevent the determination of whether or not human activity has caused a change.

3.4 – Measurement of Historical Changes in River Channel Form

Successful investigation of the research questions proposed for this study relies on understanding how to measure change in river channel form. Studies which examine the historical change of channel form typically focus on planform – that is, the geometry of the channel – since this feature of river's form is measureable based on aerial photography or historical maps, which are typically far more available than historical information from field surveys (Hooke, 1997). This section reviews methods for collecting, digitizing, and analyzing historical aerial photographs to describe channel planform change.

Aerial photographs are widely used for use in analysis of historical planform change (Gilvear and Bryant, 2003). Studies of this nature begin by collecting aerial photographs of the study site from different years and co-registering them so channel positions can be analyzed in an overlay (Hughes et al., 2006). While this process can be done manually, the use of a GIS to digitize aerial photographs offers many distinct advantages, perhaps the greatest two of these being the ability to quantify linear and aerial changes in planform and the ability to store, retrieve, and manipulate data (Downward et al., 1994).

Several recommendations exist regarding the quality of aerial photography to be used for studies of channel planform change. Scale of the aerial photographs is a major concern with larger scales providing better ability to reduce error in identification and digitization of features, so Downward et al. (1994) recommend that photographs should be close to 1:10,000 scale, and Gilvear and Bryant (2003) recommend photography to be 1:20,000 or better for studies of channels that are between 20-200 m wide. On the other hand, for studies across large areas, use of photographs with larger scale means that many more photographs will be required to cover the entire area (Gilvear and Bryant, 2003). Cost and availability of obtaining aerial photographs of larger scale is often prohibitive; therefore, many studies exist which use photographs with smaller scales for planform change analysis, some as small as 1:60,000+ (e.g. O'Connor et al., 2003; Wellmeyer et al., 2005). The resolution at which the photographs are scanned is also an important factor to consider during the collection of aerial photography (Hughes et al., 2006). While none of the publications in the review of literature gave specific recommendations, the coarsest resolution used in studies was 600 dpi (e.g. Buckingham and Whitney, 2007; Surian et al., 2009). Once obtained in a digital format, the aerial photographs must then be co-registered to a common projection (Downward et al., 1994). While there are several methods to accomplish this, the process known as polynomial georectification is perhaps best suited for application of aerial photos to river change analysis (Hughes et al., 2006).

Measuring channel planform change from aerial photos relies on proper digitization of channel geometry in GIS. Typically, researchers attempt to delineate the bankfull width (e.g. Downward et al., 1994; Wellmeyer et al., 2005) or to define a channel centerline (e.g. Micheli et al., 2004; Urban and Rhodes, 2003) or both methods (e.g. O'Connor et al., 2003). Digitizing channel features introduces error into the study as it is often difficult to define channel banks during times of low flow (Surian et al., 2009) or to define channel centerline during periods of high flow (Micheli et al., 2004). In dry river channels, such as the Cuyama River examined in this study, the active channel can be determined by delineating gravel-dominated areas (Manners et al., 2007). This is the method which will be used for the digitization of channel boundaries in this study.

Following digitization of river channel form, there are several methods used to describe channel changes either qualitatively or quantitatively. Qualitative descriptions are typically made by applying a classification or typology of change (Hooke, 1997). Quantitative measurements are made in a variety of ways, including:

- Channel width (VanLooy and Martin, 2005)
- Area between meander positions (Micheli et al., 2004)
- Lateral migration along predefined transects (O'Conner et al., 2003))
- Sinuosity and/or meander wavelength (Nicoll and Hickin, 2010).

The list above represents many common methods to quantify channel planform change, but this list is not exhaustive. It should also be noted that most of the research reviewed above uses a combination of multiple forms of measurement. When studies rely on just one form of measurement, it is typically channel width, such as in VanLooy and Martin (2005), and in the previous study of the Cuyama River conducted by Andersen et al. (2009).

The ability of GIS to quantitatively measure a variety of characteristics across a broad area enhances the use of statistical testing to help determine significant relationships and/or build predictive models. Julien et al. (2012) use several two variable regression analyses to examine the relationships between several channel planform characteristics and stream power. Similarly, Richards et al. (2005) use measured data from aerial photographs to perform a variety of statistical tests, including Pearson product-moment correlation. In studies such as these, the statistical tests aim to identify significant associations between channel form change and possible influencing factors; however, these tests do not prove causation (Richards et al., 2005).

Tracking the changes in river channel planform using methods reviewed in this section is an important component in overall understanding of river behavior. As rivers migrate they can threaten agriculture and structures so prediction of future migration is needed (Gilvear et al., 2000). Conversely, there is also a need for monitoring responses to river alterations induced by human activity in order to predict the effects of future projects (Hooke, 1997). The research conducted in this study addresses both of these implications for river management, as meandering of the Cuyama River has the potential to affect structures and cropland, but the river itself also has been directly modified by human activity. RQ1 and RQ2 aim to address these issues, respectively, by examining river planform change for the past 80 years and attempting to attribute this change to agricultural land use.

3.5 Linking River Planform Change and the Effects of Agriculture

While there is substantial research regarding the effects of agriculture on many geomorphic and hydrologic processes such as erosion and runoff, far fewer studies attempt to take the next step and directly attribute changes in river channel planform to these effects. Conceptually, it is accepted that changes of stream flow and sediment production due to agricultural land use result in modifications of channel geometry and channel pattern (Hooke, 1997); however, attempts to quantify these changes are sparse. Several studies which attribute changes in channel planform to agriculture are reviewed in this section.

The previous studies which have been conducted on this topic vary greatly in scope and method. Many studies examine the deliberate effects of agricultural land use, such as the work of Urban and Rhoads (2003) who used centerline measurements from aerial photographs to evaluate meander migration changes due to channel straightening in Illinois, and Ollero (2010) who examined how dykes built to protect agricultural lands resulted in the cessation of meander migration. Other studies attempt to examine the indirect effects of land use/cover change from forest cover to agriculture. Micheli et al. (2004) measured meander migration rates along the Sacramento River in California and compared the rates in agricultural areas to forested areas. Their study concluded that river reaches with agricultural land use in their floodplain had significantly higher migration rates than reaches in forested areas. Similarly, Julian et al. (2012) examine land use changes in the floodplain of the Canadian River in Oklahoma and their relationship with channel geometry such as width and sinuosity. Gordon and Meentemeyer (2006) statistically analyzed the relationship between bankfull area and agricultural land use as part of their study of Dry Creek in California.

The limited number of studies which have attempted to directly attribute channel planform changes to the deliberate or non-deliberate effects of agriculture presents great opportunity for additional research. Additionally, none of the studies listed above (nor any others found in database searches) examine these effects in a dryland river. Manners et al. (2007) measure both channel features and agricultural land use within an arid floodplain in Peru; however, their scope was different and resulted in an alternative, but related claim: that climate driven variables affected the channel planform which then affected the availability of arable land. The study proposed in the Cuyama River thus provides a unique attempt to examine the effects of agricultural land use in a dryland river.

Chapter IV – Data and Methodology

4.1 - Data

To address RQ1 and build the products from which RQ2 can be addressed, this study used historical aerial photographs and modern satellite images to analyze planform changes of the ~9km section of the Cuyama River. Concurrently, the images also were used to map the growth of agricultural land use adjacent to this section of the river.

Aerial photographs were purchased from the collection at University of California, Santa Barbara thus providing coverage for the study reach for 1938, 1954, 1967, 1978, 1989, and 2002. Table 1 provides details regarding the original sources, scale, and resolution of these aerial photographs. Additionally, high-resolution

Year	Original Purchaser:	Flown by:	Flight	Frame	Scale	Resolution	RMSE (m)
1938	Santa Barbara Co.	Fairchild Aerial Surveys	C-4950	6509	1:24,000	600 dpi	3.395
	Santa Barbara Co.	Fairchild Aerial Surveys	C-4950	6416	1:24,000	600 dpi	5.221
1954	USDA	Pacific Air Industries	BTM-1954	7K-106	1:20,000	600 dpi	2.231
	USDA	Pacific Air Industries	BTM-1954	7K-112	1:20,000	600 dpi	4.726
	USDA	Pacific Air Industries	BTM-1954	7K-184	1:20,000	600 dpi	1.287
1967	USDA	Western Aerial Contractors, Inc.	BTM-1967	3HH-162	1:20,000	600 dpi	2.995
	USDA	Western Aerial Contractors, Inc.	BTM-1967	3HH-185	1:20,000	600 dpi	3.905
1978	USDA	Park Aerial Surveys Inc.	USDA-40-06079	278-117	1:40,000	600 dpi	4.681
1989	USGS	USGS	NAPP	1892-61	1:40,000	600 dpi	3.611
2002	USGS	USGS	NAPP-3C	12451-101	1:40,000	600 dpi	3.435

Table 1: Aerial Photograph Metadata & Root Mean Square Error

orthorectified imagery was obtained from the United States Geological Survey. This imagery has 1 foot resolution and was taken on 7/25/2011 and was available free of charge in a GeoTiff format on the USGS EarthExplorer site (http://earthexplorer.usgs.gov/). The aerial photographs and USGS imagery provide six time periods from which to examine changes in river planform.

In addition to the imagery required to directly answer the research questions, climate data were gathered to help explain channel changes. Data were available at no charge from the NOAA Climatic Data Center and cover the period of study. Weather coverage in the Cuyama Valley exists from November 1, 1944 onward, with a change of station in 1974 from Cuyama to New Cuyama. Table 2 below describes the weather stations in greater detail.

NOAA Climatic Data Center Station Metadata:		
Station ID	**Location**	**Period of Record**
GHCND:USC00042236	CUYAMA, CA; 34.93333, -119.61667	Nov 1, 1944 to Dec 31, 1973
GHCND:USC00046154	NEW CUYAMA, CA; 34.9455, -119.6827	Jan 1, 1974 to present

Table 2

4.2 – Image Preparation

Before working with the aerial photographs, it was necessary to process the images to fit them to a common coordinate system. This ensured that measurements of the river will be as accurate as possible between photos. Co-referencing of the historical aerial photographs was conducted using the principles of Hughes et al. (2006).

The high-resolution orthorectified imagery from the USGS was used as the base layer since it has a known geographic position. A mosaic of these orthorectified images was created, and the imagery's native coordinate system was retained: NAD_1983_StatePlane_California_V_FIPS_0405_Feet. Based on the guidance of Hughes et al. (2006), the goal was to establish 30 control points for georectification with each aerial image, and this goal was met in all but one of the images. The third frame from 1954 only held a small portion of the study reach, and therefore much of the photograph did not overlap with other images. "Hard points" such as road intersections and corners of buildings were prioritized; however, “soft points” like trees were necessary on the older images due to the lack of development in the study area in as seen in the earlier images. Additionally, every effort was made to place control points as close to the river as possible based on the recommendations of Hughes, et al. (2006; 4).

Unfortunately, the older images used in this study often lacked hard or soft points which could be identified on the 2011 base layer. Therefore, it was necessary to register some control points with a previously registered image in order to attain the goal of 30 control points. Every effort was made to link as many points as possible with the base layer before resorting to link control points with the previous image. Images were therefore georectified in reverse chronological order, starting by geo-rectifying the 2002 image with the 2011 base layer. Then the 1989 image was rectified with both the 2011 base layer and the 2002 geo-rectified image. This process was continued iteratively until all of the images were rectified. For each image, geo-rectification was accomplished using third-order polynomial method, which consistently had the smallest root-mean-square error (RMSE) compared to the other methods offered by ArcGIS. Warping due to the 3rd order transformation was limited to the areas well outside the study reach. The root-mean square error (RMSE) associated with each image is listed in the last column of Table 1.

4.3 – Digitization and Processing River Channel Geometry in ArcGIS

Once the aerial photographs were registered in ArcGIS, manual digitization of the river channel boundaries defined the position of the river in each photograph. Water is not clearly present in the channel in any of the photographs apart from the 1938 photo;

therefore, it was not possible to use the centerline digitization method. Instead, the banks were digitized based on the presence of gravel dominated areas with little or no vegetation (Manners et al., 2007). Figure 3 provides an example of the differentiation between "gravel dominated" areas and areas which are vegetated and therefore deemed part of the channel.

Figure 3: Example of Channel Bank Digitization

Once polygons were built depicting the channel area for each year, the channel centerlines were automatically calculated and drawn using tools in ArcGIS (Dilts, 2011). Once centerlines had been created for all of the polygons, the centerlines were overlaid in order to identify areas where the river was relatively stable throughout all of the years. Based on the work of Winterbottom (2000), these nodal points of relative stability were

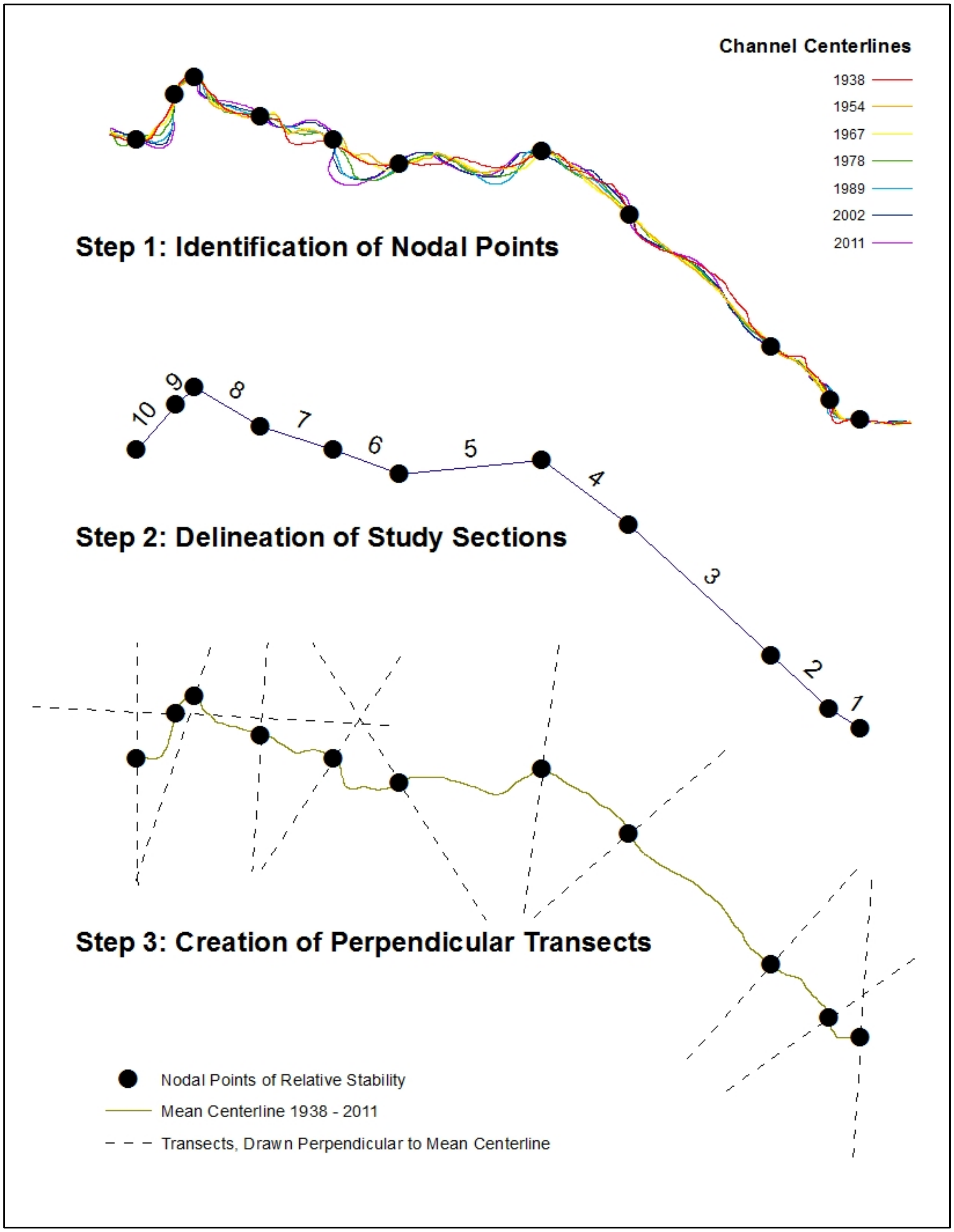

Figure 4: Nodal Points, Study Sections, and Transects

then used to divide the entire study reach into smaller sub-reaches, hereafter referred to as sections. This process resulted in 11 nodal points which divided the study reach into ten sections for further analysis; this process is detailed in Figure 4. Using tools available in ArcGIS, the seven centerlines were distilled into one mean centerline, which described the mean position of the river between 1938 and 2011. Transects were drawn perpendicular to this mean centerline in order to establish boundaries between the ten study sections which were most likely to be relatively perpendicular to the flow direction for a given year.

Lines were then drawn between nodal points, which depict the length of the valley for each section. This was the final preparation of channel geometry necessary to begin measurement of channel change.

4.4 – Measurement and Calculation of Channel Change

Three characteristics of river channel geometry were measured in order to quantify channel change in the study reach: channel width, sinuosity, and lateral migration. Channel width in this study refers to the measured distance between the digitized banks of the river channel. Sinuosity refers to the ratio of the length of the channel centerline and the straight length of the valley. Lateral migration is the term that this study uses to describe the amount of migration in river position perpendicular to the flow direction of the river – such as the migration that would occur when a cutbank erodes to expand a river meander.

Channel width and sinuosity were able to be measured using relatively straightforward techniques. To measure channel width, measurements of the length between the digitized channel banks were taken at each transect. For sinuosity, the length of the river channel centerline for each study section was divided by the straight-line length of the same study section. This resulted in a ratio which describes the sinuosity of each study section.

Lateral migration was calculated based on the “eroded area” polygon technique used by Micheli et al. (2004). With this method, the centerlines from two different channel positions are fused together to create a polygon. The area of this polygon is divided by the measured length of the section in order to get the width of the polygon. This width measure translates into the mean lateral movement of the river between the two channel centerline positions. For this study, this method was adapted to take the area of all of the polygons within each study section and then divide by the length of the study section. In this way, the amount of mean lateral migration for the entire study section could be calculated. Figure 5 shows how this calculation occurred between the centerlines of the river in 2002 and 2011 in Section 4 of the study reach.

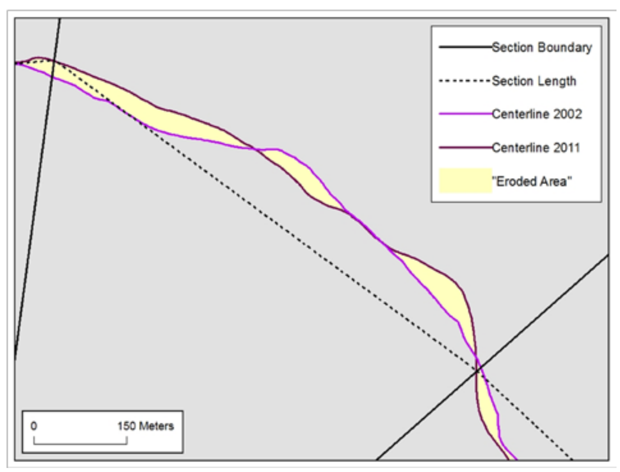

Figure 5: Eroded Area Polygon Example

The aerial photographs were also used to determine changes in agricultural land use between 1938 and 2011. Since effects of agriculture are inherently localized (O’Connell et al., 2007), and runoff and discharge responses of dryland rivers are also subject to high spatial variability, land use was only measured within a buffer of 1 kilometer of the river mean centerline.. Land was defined as “agricultural” not only for parcels with active crops, but also fallow fields. These measurements were made for each aerial photograph in order to document the change in agricultural land use near the river.

4.5 –Analyzing Channel Changes

Once the mapping and measuring of historical channel planform and agricultural land-use changes was completed, data were compiled and analyzed to quantify the effect of agricultural growth on changes to the river planform (RQ2). Statistical correlation tests were run to pair measured channel change data with agricultural growth statistics during each time period. In order to strengthen any conclusions which may be derived from these statistical tests, control data were collected and used to provide alternative explanations for the measured channel changes.

The initial selection for a control variable was stream discharge; however, discharge data is only available for two sites on the Cuyama River that are well outside the study area. As discussed in Chapter 3.3, transmission losses in dryland rivers make data outside the study area less relevant, therefore, it would have been inappropriate to use discharge data from a station far removed from the study area. As an alternative to discharge, precipitation data were chosen based on its availability and direct impact on river discharge. Precipitation data were gathered from the National Climatic Data Center at the National Oceanic and Atmospheric Administration and provide daily precipitation records since 1944.

Data were categorized for each time period between aerial photos as follows:

- Number of days with precipitation between 20mm and 40mm
- Number of days with precipitation between 40mm and 60mm
- Number of 3 day periods with total precipitation between 40mm and 60mm
- Number of 3 day periods with total precipitation above 60mm
- Number of 30 day periods (~1 month) with total precipitation over 100mm.

These categories were designed to capture moderate-to-large rainfall events which would be likely to produce a channel-forming discharge. The following chart (Table 3) shows the number of events which occurred during each time period in this study.

Precipitation Events

	1954 - 1967	**1967 - 1978**	**1978 - 1989**	**1989 - 2002**	**2002 - 2011**
# Days 20 mm to 40 mm	6	13	15	23	15
# Days Greater than 40 mm	4	2	0	6	0
# of 3 Day Periods 40 mm to 60 mm	6	13	2	25	6
# of 3 Day Periods Greater than 60 mm	5	0	0	11	1
# of 30 Day Periods Greater than 100mm	46	20	14	147	19

Table 3: Counts of Total Number of Precipitation Events

Correlation tests were then conducted to link the channel characteristics for each section in each time period with potential forming characteristics. Five variables for channel characteristic were derived from the three characteristics which were measured:

- ChanWidth – The measured channel width (m) at the end of the specified time period

- ChanWidChg – The calculated change in channel width (m) during the specified time period
- Sinuosity – The measured sinuousity at the end of the specified time period
- SinuosChg – The calculated change in sinuosity during the specified time period
- LatMigration – The measured rate of lateral migration (m/yr) during the specified time period.

These five channel characteristics were paired with the following 8 potential channel forming characteristics:

- AgGrowth – The calculated change in agricultural area during the time period in a given section.
- AgTotal – The total amount of agriculture measured in the entire study reach at the end of the specified time period.
- AgTotalChg – The change in agricultural area in the entire study reach during the specified time period.
- Five precipitation variables from the 5 variables listed on the previous page; labeled for testing as: Days20to40, Days40Plus, 3Days40to60, 3Days60Plus, Month100, respectively.

Each section during each time period was treated as an individual record. This resulted in 50 available records for use in testing. The data from the time period between 1938 and 1954 were not used for testing for two reasons: 1) weather data were unavailable prior to 1944, therefore it would have been impossible to accurately count all of the weather events during this time period; and 2) the poor quality of the 1938 photograph may have resulted in inaccuracies while digitizing; this is discussed further in section 6.4. Two different correlation tests were conducted using SPSS software: Pearson's Correlation and Kendall's Tau-b. Pearson's Correlation was chosen primarily as a baseline test due to its widespread use. Kendall's Tau-b was chosen due to its ability to work well with data that is tied – that is, where the data is identical across several records. Since the precipitation data is the same for all 10 sections in a given time period, there are multiple cases of tied data for this test sample.

Qualitatively, map products were produced which highlighted changes and offered insights for explanation. The map products are both a vector compilation of the historic positions of the river for the dates of each aerial photo and also mosaics of the aerial photographs which show specific areas of interest.

Chapter V – Results

5.1 – Changes in Cuyama River Channel Form since 1938

Using the GIS methods described in the previous section, this study documented changes to river channel planform in the Cuyama River since the first available aerial photographs were taken over the area in 1938. The record of change comes both from quantitative data from GIS measurements, and qualitative descriptions of broad changes which could not be captured simply through measurements alone. These measurements and descriptions combine to answer the first research question (RQ1) of this thesis: how has the channel form changed in the past 80 years as modern agricultural practices have become the dominant land use along the reaches of this study area?

The measurements in ArcGIS provide quantitative data which can help describe the changes to river form. The “eroded area polygon” technique produced data for Total Lateral Migration (in meters) for each section during the time periods between photographs in the time series. These results are displayed in Table 4.

Total Lateral Migration (m)

	1938 - 1954*	1954 - 1967	1967 - 1978	1978 - 1989	1989 - 2002	2002 - 2011
Section 1	26.15	9.97	12.18	18.28	22.09	12.15
Section 2	28.55	15.74	7.27	7.5	9.38	4.82
Section 3	40.37	6.15	10.88	2.17	15.43	11.85
Section 4	34.03	13.5	30.78	7.46	34.51	22.52
Section 5	31.17	16.03	27.22	21.88	41.68	11.24
Section 6	32.57	32.04	85.13	37.35	28.61	46.67
Section 7	55	7.66	24.18	13.21	34.65	16.59
Section 8	17.75	9.4	14.63	18.63	16.5	18.59
Section 9	18.13	18.56	10.75	6.41	5.59	3.25
Section 10	6.65	13.48	23.72	32.34	12.13	20.77
Mean	29.04	14.25	24.67	16.52	22.06	16.84

Table 4: Total Lateral Migration

From these measurements, it is possible to then divide the Total Lateral Migration by the number of years between each photograph to yield data which describe the Annual Lateral migration (m/yr) for each section. These data are displayed in Table 5.

Annual Lateral Migration (m/yr)

	1938 - 1954*	1954 - 1967	1967 - 1978	1978 - 1989	1989 - 2002	2002 - 2011
Section 1	1.63	0.77	1.11	1.66	1.7	1.35
Section 2	1.78	1.21	0.66	0.68	0.72	0.54
Section 3	2.52	0.47	0.99	0.2	1.19	1.32
Section 4	2.13	1.04	2.8	0.68	2.65	2.5
Section 5	1.95	1.23	2.47	1.99	3.21	1.25
Section 6	2.04	2.46	7.74	3.4	2.2	5.19
Section 7	3.44	0.59	2.2	1.2	2.67	1.84
Section 8	1.11	0.72	1.33	1.69	1.27	2.07
Section 9	1.13	1.43	0.98	0.58	0.43	0.36
Section 10	0.42	1.04	2.16	2.94	0.93	2.31
Mean	1.81	1.1	2.24	1.5	1.7	1.87

Table 5: Annual Lateral Migration

Additionally, the measurements for channel width were recorded for each photograph, and then the change between years was calculated. These data are presented in Table 6 and Table 7, respectively.

Channel Widths (m)

	1938*	1954	1967	1978	1989	2002	2011
Section 1	34.85	23.44	22.99	54.36	35.65	44.94	65.99
Section 2	38.13	36.24	46.35	56.39	48.33	82.11	85.14
Section 3	131.5	39.67	47.57	58.98	56.86	73.75	65.16
Section 4	158.6	43.25	45.58	128.1	120.7	101.4	73.16
Section 5	124	44.87	45.59	122.6	104.7	141.4	138.3
Section 6	127.2	38.3	127.8	194	160.8	160.7	129
Section 7	128.9	36.4	40.96	148.5	122.6	106.8	73.41
Section 8	36.98	30.08	35.81	87.35	58.37	93.64	67.29
Section 9	44.86	17.96	27.46	47.53	26.36	52.44	36.79
Section 10	48.83	45.93	24.14	68.48	44.75	94.82	81.77
Mean	87.39	35.61	46.42	96.63	77.91	95.2	81.6

Table 6: Channel Width

Channel Width Change

	1938 - 1954*	1954 - 1967	1967 - 1978	1978 - 1989	1989 - 2002	2002 - 2011
Section 1	-11.41	-0.45	31.37	-18.71	9.29	21.05
Section 2	-1.89	10.11	10.04	-8.06	33.78	3.03
Section 3	-91.8	7.9	11.41	-2.12	16.89	-8.59
Section 4	-115.4	2.33	82.52	-7.39	-19.33	-28.22
Section 5	-79.17	0.72	77.01	-17.88	36.68	-3.15
Section 6	-88.91	89.49	66.23	-33.2	-0.12	-31.71
Section 7	-92.53	4.56	107.5	-25.92	-15.75	-33.42
Section 8	-6.9	5.73	51.54	-28.98	35.27	-26.35
Section 9	-26.9	9.5	20.07	-21.17	26.08	-15.65
Section 10	-2.9	-21.79	44.34	-23.73	50.07	-13.05

Table 7: Channel Width Change

The measurements for sinuosity were also calculated using ArcGIS. The length of the channel centerline for each section was divided by the straight length of the section in order to yield sinuosity. The composite sinuosity was calculated by simply adding the raw figures for each section and computing the sinuosity. This was intended to help describe the overall trend amongst all the sections. An additional calculation was made to describe total sinuosity for the entire study reach by using the straight-line distance between the beginning and end of the entire study reach. The data for sinuosity is presented in Table 8.

Sinuosity	1938	1954	1967	1976	1989	2002	2011
Section 1	1.48	1.16	1.14	1.20	1.36	1.17	1.22
Section 2	1.10	1.02	1.04	1.03	1.08	1.09	1.10
Section 3	1.05	1.01	1.02	1.02	1.01	1.04	1.05
Section 4	1.08	1.02	1.03	1.06	1.04	1.04	1.06
Section 5	1.05	1.09	1.09	1.12	1.19	1.14	1.12
Section 6	1.06	1.14	1.11	1.34	1.38	1.39	1.70
Section 7	1.15	1.16	1.17	1.04	1.03	1.14	1.12
Section 8	1.08	1.13	1.11	1.09	1.07	1.07	1.11
Section 9	1.19	1.07	1.20	1.12	1.06	1.09	1.11
Section 10	1.09	1.09	1.08	1.14	1.27	1.34	1.44
Composite	1.10	1.07	1.08	1.09	1.12	1.13	1.17
Total Study Reach	1.23	1.20	1.21	1.23	1.26	1.26	1.31

Table 8: Sinuosity

In addition to the data which was measured in ArcGIS, by overlaying aerial photographs in ArcGIS, this study allowed for a qualitative examination of the changes in the Cuyama River. Several notable characteristics of change can be seen and described through a visual examination of the photographs in sequence.

Figure 6: Channelization and Straightening of Sections 2-4 in 1954 Image

The most significant discovery which came from visual examination of the photographs was that of a significant channelization of a portion of the study reach which presents itself in the 1954 photograph. This channelization occurs in Sections 2-4 of the study reach and can be seen clearly as two straight sections in Figure 6 on the previous page. The sides of the channelization are clearly present as lightly colored, disturbed earth. An investigation into this channelization yielded no information from local sources or government records, so the exact date it was implemented is unknown.

Following the discovery of the channel straightening, post hoc measurements of meander amplitude and wavelength were taken for study sections 5-10 for years 1954-2011 in order to further investigate the downstream effects of the river straightening. Meander wavelength was defined as the straight line distance between two consecutive meander apexes on the southern banks of the river. Meander amplitude was defined as the distance from the outer bank of each southern meander apex to the outer bank of the corresponding northern meander, measured perpendicular to the line created to measure meander wavelength. These measurements yielded the following results:

Meander Amplitude(m) and Wavelength(m) Study Sections 5-10
(Downstream from Channel Straightening)

Mean Value - Sections 6-10:		Individual Meander Measurements:							
Amplitude 1954:	116.2	138.3	102.1	32.1	83.6	96.7	87.8	152.0	236.9
Amplitude 1967:	155.7	74.8	218.0	112.9	90.1	140.3	297.8		
Amplitude 1978:	293.4	285.6	290.5	195.5	401.9				
Amplitude 1989:	252.8	318.7	276.6	132.5	283.5				
Amplitude 2002:	250.2	326.4	340.6	138.4	195.3				
Amplitude 2011:	248.7	309.7	350.1	157.3	177.7				
Wavelength 1954:	442.5	626.3	439.1	365.3	297.9	207.1	326.4	695.9	582.0
Wavelength 1967:	524.3	242.2	832.8	523.1	303.4	645.2	599.2		
Wavelength 1978:	721.5	1199.5	599.2	600.9	486.3				
Wavelength 1989:	735.6	1181.9	677.6	606.2	476.7				
Wavelength 2002:	757.1	1277.5	593.8	693.2	463.9				
Wavelength 2011:	734.6	1174.5	607.4	700.8	455.7				

Table 9: Meander Amplitude and Wavelength in Sections 5-10

Visually, the photographs and the river channel polygons created in ArcGIS show the creation of large meanders from 1938 onward. This progression can be seen best in Figure 7 below which shows the position of the channel boundaries in each photograph.

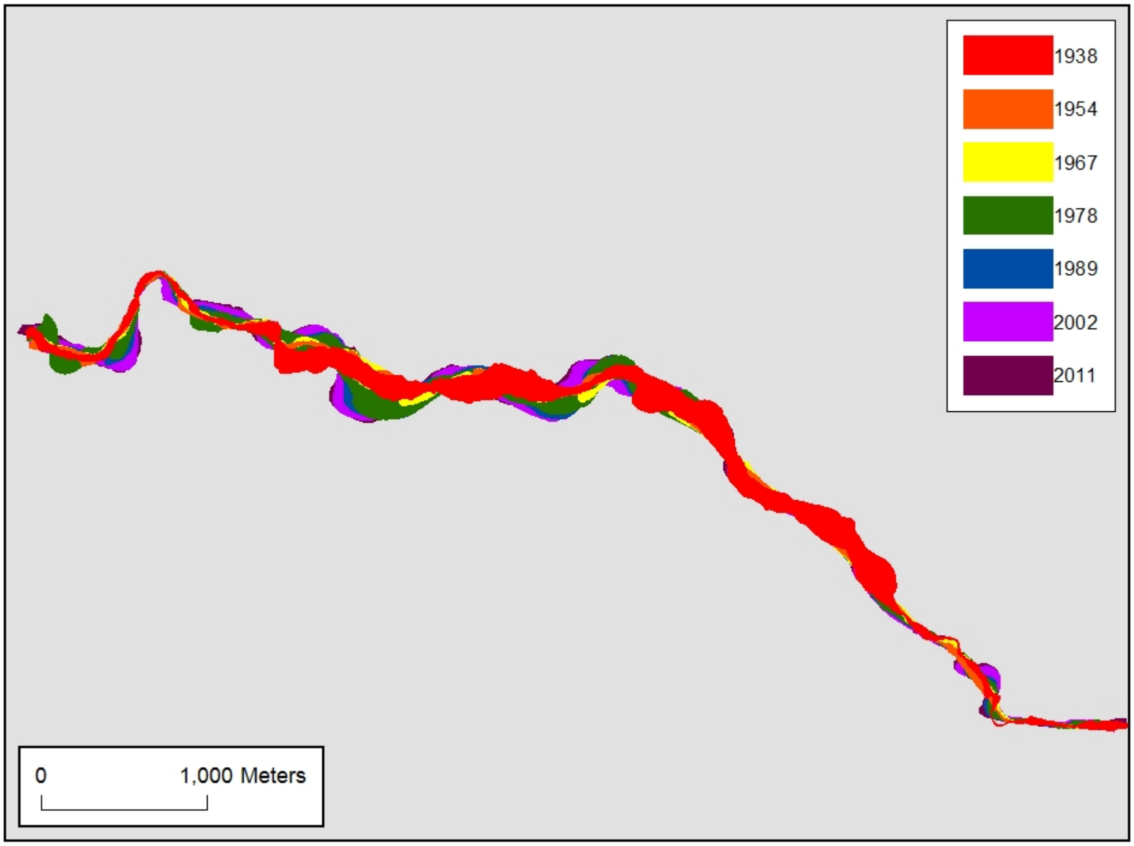

Figure 7: Composite Array of Channel Positions from 1938 to 2011

Finally, it is also clear from visual examination of the photographs that the landscape surrounding the river has experienced significant change from 1938 to 2011 as modern agriculture dominated the landscape. This presents itself in two distinctive ways:

1) A smoothing and flattening of topography in order to accommodate large fields. An example of this change is clearly seen in Figure 8, which depicts the same geographic area during 4 years of the study period. The wide east-west

arroyo running through the middle of the images has been greatly diminished, and smaller arroyos have been smoothed completely to accommodate the growth of fields.

2) A reduction in natural vegetation, not only due to clearing of land for planting crops (also seen in Figure 8), but there is also a reduction in vegetation in nearby areas which can be seen in Figure 9.

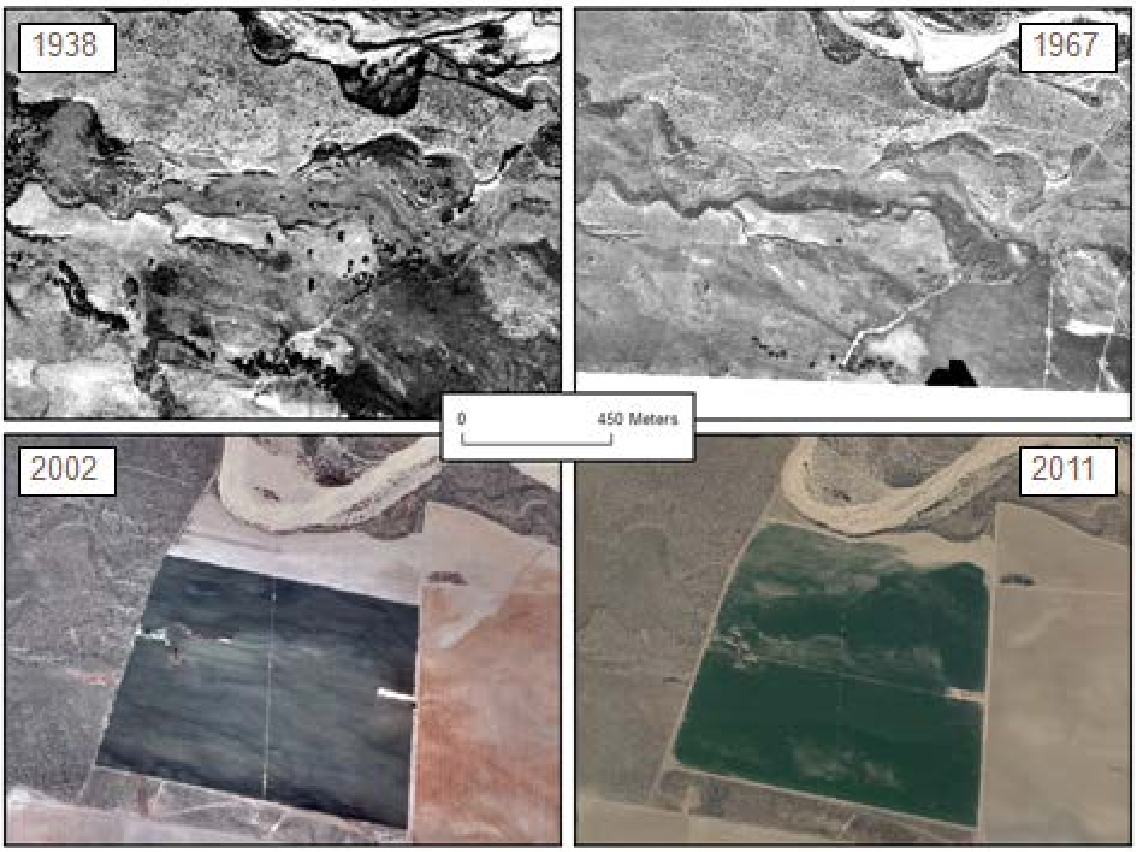

Figure 8: Homogenization of the Landscape: Visible Smoothing and Flattening of Topography to Accommodate Agricultural Use

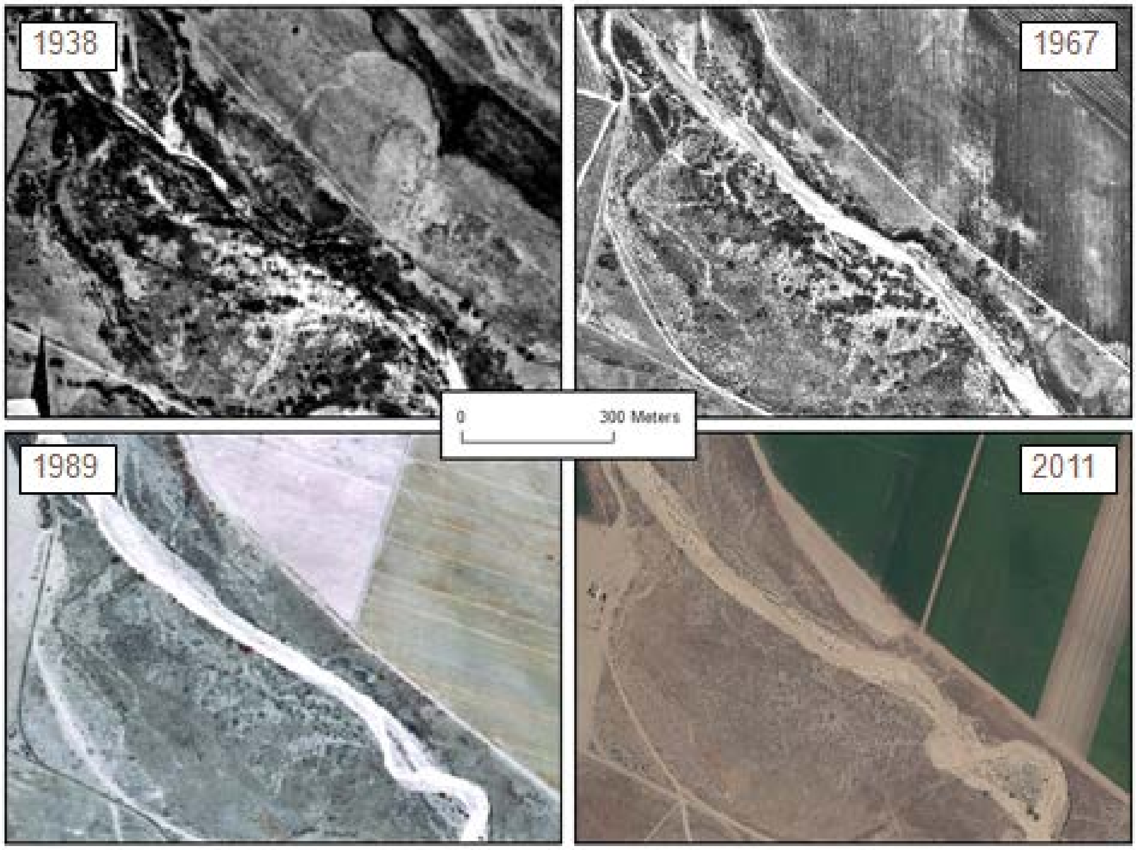

Figure 9: Loss of Natural Vegetation

5.2 – Quantitative Statistical Analysis

The second research question seeks to determine if any of the changes in channel planform can be attributed to deliberate or non-deliberate effects of increased agricultural land use. In this section, the results of two quantitative correlation tests are presented. These results will be interpreted in section 6.3, along with further qualitative discussion which addresses RQ2.

Prior to running the correlation tests, it was necessary to map the growth of agricultural land use in the Cuyama Valley using the methods discussed previously in section 4.4. The mapping of farmed and fallow fields for each photograph documents the rapid growth of agricultural land use in the study area. The land was mapped and measured within each study section's buffer, and the resulting measurements are found in Table 10 below:

Agricultural Area, in acres

	1938	1954	1967	1978	1989	2002	2011
Section 1	0.16	38.47	39.2	37.52	659.7	720.45	708.4
Section 2	8.62	118.26	119.13	122.12	676.68	776.85	765.59
Section 3	190.07	449.09	443.97	442.93	979.39	1089	1110.2
Section 4	184.04	593.82	581.34	575.03	753.22	750.24	837.4
Section 5	130.44	521.51	506.11	494.85	520.95	597.77	718.95
Section 6	0	175.16	169.82	163.65	128.76	456.57	552.39
Section 7	0	53.18	48.53	43.5	16.29	323.27	340.95
Section 8	0	0.31	0.17	0	0	250.48	249.48
Section 9	0	0	0	0	0	93.75	93.35
Section 10	0	7.93	7.7	8.18	7.89	49.88	50.45
Entire Reach	190.07	728.43	713.27	704.82	1493.8	1933.5	2040.2

Table 10: Agricultural Area in Each Section's Buffer

The correlation tests only used data from 1954 onward. The 1938 data was discarded due to reliability concerns with the digitization of the river channel; these concerns which are discussed in section 6.4. In both the Pearson and Kendall Tau-b tests, only six pairs of variables yielded statistically significant results ($p<0.05$):

- Channel Width vs. # Days with 20 to 40 mm precipitation
- Channel Width vs. # of 3 day periods with 40 to 60 mm precipitation
- Channel Width Change vs. Total Agriculture
- Channel Width Change vs. Total Agriculture Change
- Channel Width Change vs. # of Single Days with 40 mm or More Precipitation
- Channel Width Change vs. # of 3 Day Periods with 40-60mm of precipitation.

These significant results are highlighted green in Tables 11 and 12 below. A sinuosity test which was significant at a p<0.10 level is shown in yellow and will also be discussed.

Pearson Correlations									
		AgGrowth	AgTotal	AgTotalChg	Days20to40	3Days40Plus	3Days40to60	Days60plus	Month100
ChanWidth	Pearson Correlation	-.013	.172	.096	.353*	.004	.284*	.011	.121
	Sig. (2-tailed)	.931	.233	.507	.012	.980	.045	.940	.403
	N	50	50	50	50	50	50	50	50
ChanWidChg	Pearson Correlation	-.166	-.440**	-.407**	-.161	.389**	.431**	.091	.141
	Sig. (2-tailed)	.248	.001	.003	.264	.005	.002	.528	.329
	N	50	50	50	50	50	50	50	50
Sinuosity	Pearson Correlation	.103	.246	.075	.218	-.135	.000	-.023	.000
	Sig. (2-tailed)	.478	.086	.602	.128	.352	.999	.873	.998
	N	50	50	50	50	50	50	50	50
SinuosChg	Pearson Correlation	.178	.100	.026	.077	-.226	-.142	-.168	-.162
	Sig. (2-tailed)	.217	.491	.859	.595	.115	.324	.244	.262
	N	50	50	50	50	50	50	50	50
LatMigration	Pearson Correlation	-.111	.034	-.055	.164	-.062	.130	-.093	-.030
	Sig. (2-tailed)	.444	.817	.702	.256	.669	.368	.523	.837
	N	50	50	50	50	50	50	50	50

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Table 11: Pearson's Correlation Results

Kendall's Tau-b Correlations									
		AgGrowth	AgTotal	AgTotalChg	Days20to40	3Days40Plus	3Days40to60	Days60plus	Month100
ChanWidth	Correlation Coefficient	.014	.087	.213*	.300**	-.030	.278**	-.046	-.014
	Sig. (2-tailed)	.887	.412	.044	.005	.779	.008	.673	.891
	N	50	50	50	50	50	50	50	50
ChanWidChg	Correlation Coefficient	-.088	-.387**	-.289**	-.119	.375**	.390**	.110	.195
	Sig. (2-tailed)	.371	.000	.006	.259	.001	.000	.308	.065
	N	50	50	50	50	50	50	50	50
Sinuosity	Correlation Coefficient	.053	.150	.060	.132	-.025	.078	.048	.042
	Sig. (2-tailed)	.587	.156	.572	.212	.819	.462	.661	.694
	N	50	50	50	50	50	50	50	50
SinuosChg	Correlation Coefficient	.034	.108	.090	.090	-.122	.011	-.078	-.083
	Sig. (2-tailed)	.732	.305	.392	.392	.261	.918	.471	.431
	N	50	50	50	50	50	50	50	50
LatMigration	Correlation Coefficient	-.068	.047	.065	.123	-.030	.145	-.048	-.025
	Sig. (2-tailed)	.487	.656	.538	.245	.779	.171	.661	.811
	N	50	50	50	50	50	50	50	50

Table 12: Kendall's Tau-b Correlation Results

Chapter VI – Discussion

The results presented in the previous chapter reveal that the Cuyama River has most certainly changed since the first available aerial photograph in 1938. There has been marked development of meanders in the study reach, which in turn resulted in an increase in the meander belt width. It is also quite clear that deliberate modification of the Cuyama River to support agricultural activities occurred at some point between 1938 and 1954. It is far less certain that the growth of agriculture caused non-deliberate modification of the river.

The sections in this chapter discuss the significance of the results yielded from this study. First, Section 6.1 answers RQ1 by detailing the changes which occurred in the Cuyama River since the first aerial photograph in 1938. The chapter will examine the effects which agricultural growth in the region had on the Cuyama River in the next two sections. Section 6.2 will present the impacts of the straightening of the river as a deliberate modification related to agricultural development. Section 6.3 will discuss some potential non-deliberate effects of agricultural land use which may be present in Cuyama. These potential effects are less clear, due to many constraints on the efficacy of this study, which are discussed in Section 6.4. Related to the conceptual limitations of the study, this chapter will conclude by briefly presenting other possible explanations for the changes in channel form.

6.1 – Channel Planform Changes since 1938

The reach of the Cuyama River examined in this study most certainly experienced change in channel planform since 1938. Three noteworthy changes have occurred since

1938: 1) The deliberate straightening of Sections 2-4 of the river; 2) growth of meanders, especially those downstream from the straightened section; and 3) progressively increasing sinuosity. The latter of the two changes are likely interrelated. These two changes will be the focus of this section; the straightening and its effects will be discussed further in the next section (6.2).

Extensive growth of the meanders occurred in the Cuyama River between 1938 and 2011. This growth was often very rapid, such as in Section 6 of the study, which experienced an average of 85.13 meters of lateral migration between 1967 and 1978. At

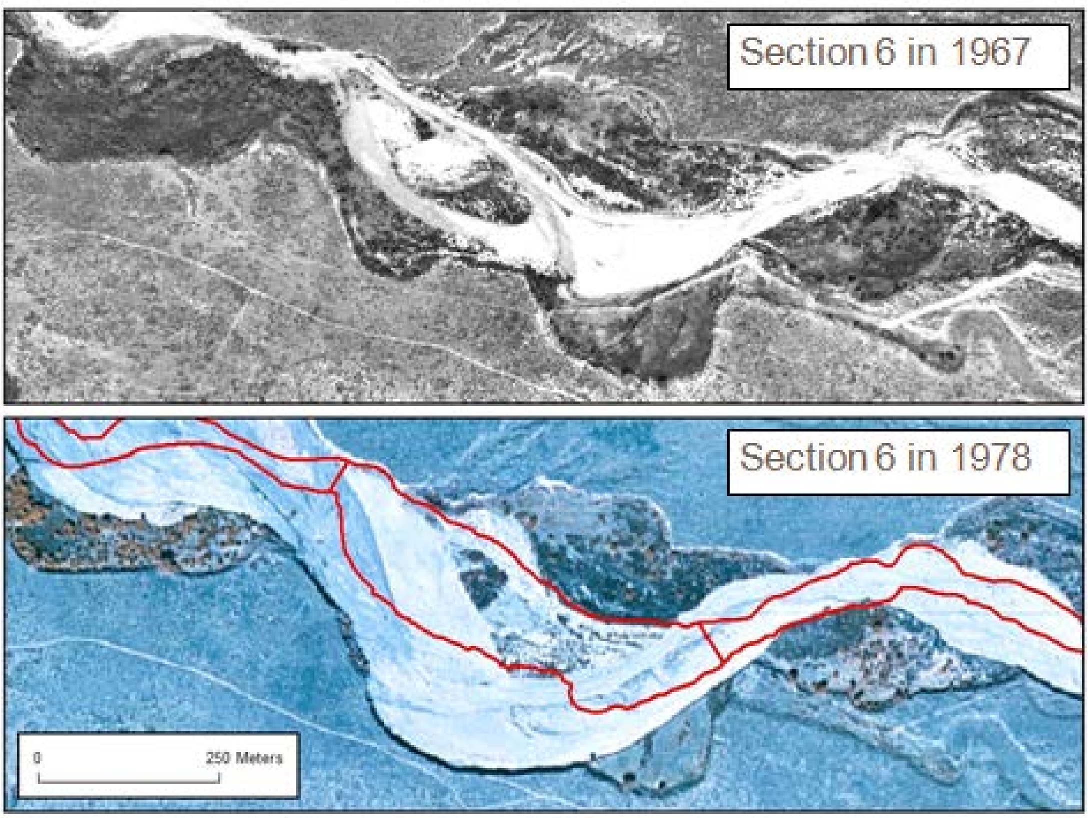

Figure 10: Vast Shift in Lateral Meander Migration; 1967 channel boundary depicted in red in 1978.

the apex of the meander, 155 meters of lateral migration occurred during this time period. This migration can be seen in Figure 10, where the boundaries of the 1967 channel banks are depicted in red on the 1978 image. While this section illustrates the largest migration which occurred in a given time period between aerial photographs, it is noteworthy that the meandering has continued growing. Since the straightening of the upstream sections 2-4, the apex of the meander in Section 6 shifted laterally by 236 meters from 1954 to 2011. This progression can be seen in Figure 11 below.

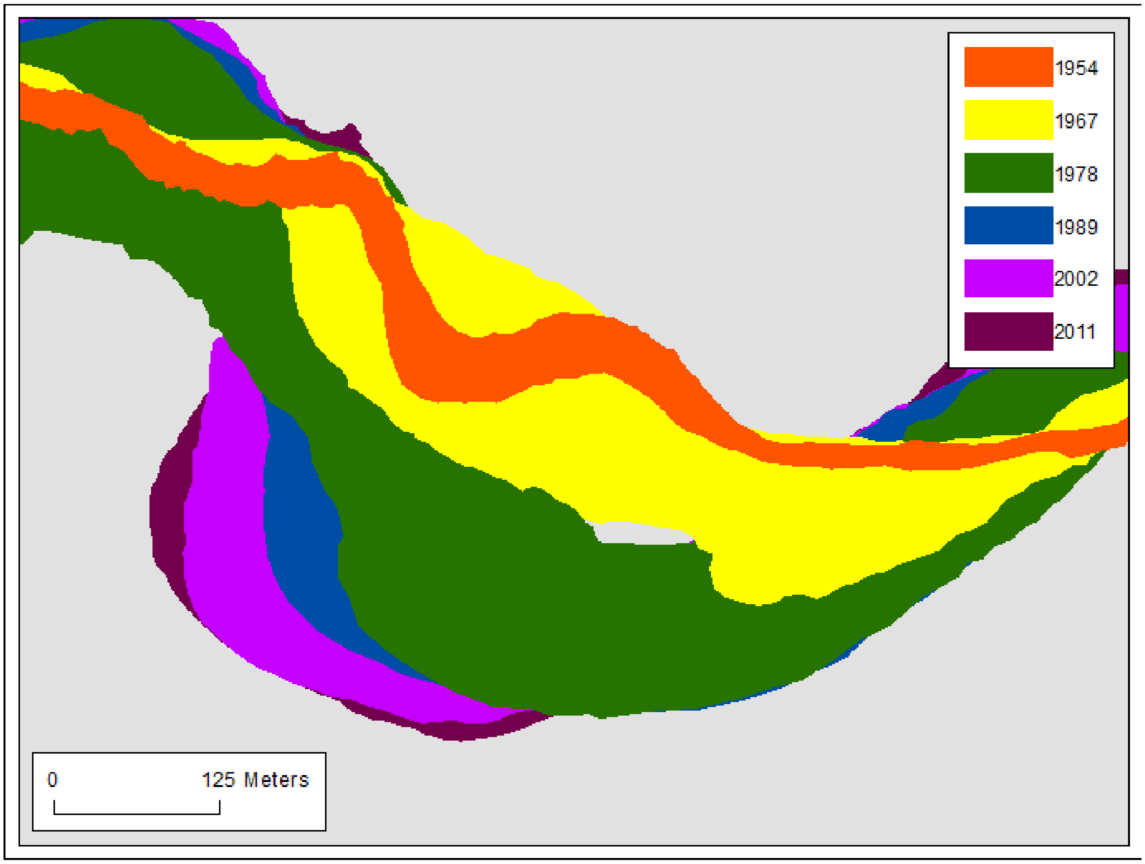

Figure 11: Progression of the Section 6 Meander - 1954 to 2011

While Section 6 experienced the most change of all of the study sections, it is not unique in the fact that the meander has continued to grow throughout the period of record of this study. While the measurements taken for lateral migration clearly show that migration has occurred, they lack directionality – it would be possible for the migration to occur to the left for a period of time and then back to the right for another period, and both would indicate that migration occurred. However, the composite array of channel banks provides strong visual evidence of the progression of the meanders across the entire study reach.

The measurements for sinuosity help confirm this visual observation of meander growth. The measurements for sinuosity consistently increase throughout the study from 1954 to 2011. Not surprisingly, significant losses in overall sinuosity took place from 1938 to 1954 due to the deliberate straightening of sections 2-4. It could be conjectured that much of the growth of sinuosity after 1954 may be due to the straightened section rebounding to a natural, meandering state. While the sections 2-4 most certainly have begun meandering again, it is noteworthy that the other sections increased in sinuosity even more than the straightened section during the same time period. Figure 12 illustrates the change in sinuosity between the straightened and non-straightened reaches during the study period.

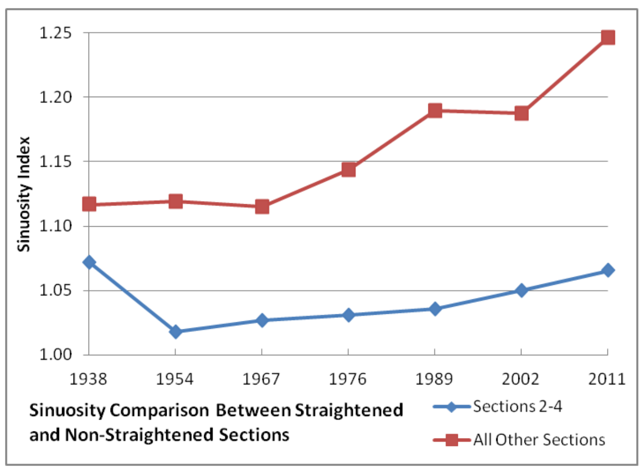

Figure 12: Sinuosity Comparison Chart

Both the increased growth of meandering and the increase in sinuosity indicates that this particular reach of the Cuyama River is in a state of adjustment. The meandering is not remaining within the confines of the floodplain, or in this case, the arroyo walls. In fact, the meanders are causing significant erosion of the arroyo, which can be seen once again in Section 6 (Figure 13). While it is common for arroyos to expand laterally and widen to eventually form a new floodplain, what is most noteworthy from the sinuosity data is the acceleration of the rate of growth in sinuosity during the time period of this study, particularly in the study sections downstream from the channel straightening. This will be examined further in the next section (6.2). In addition to highlighting the

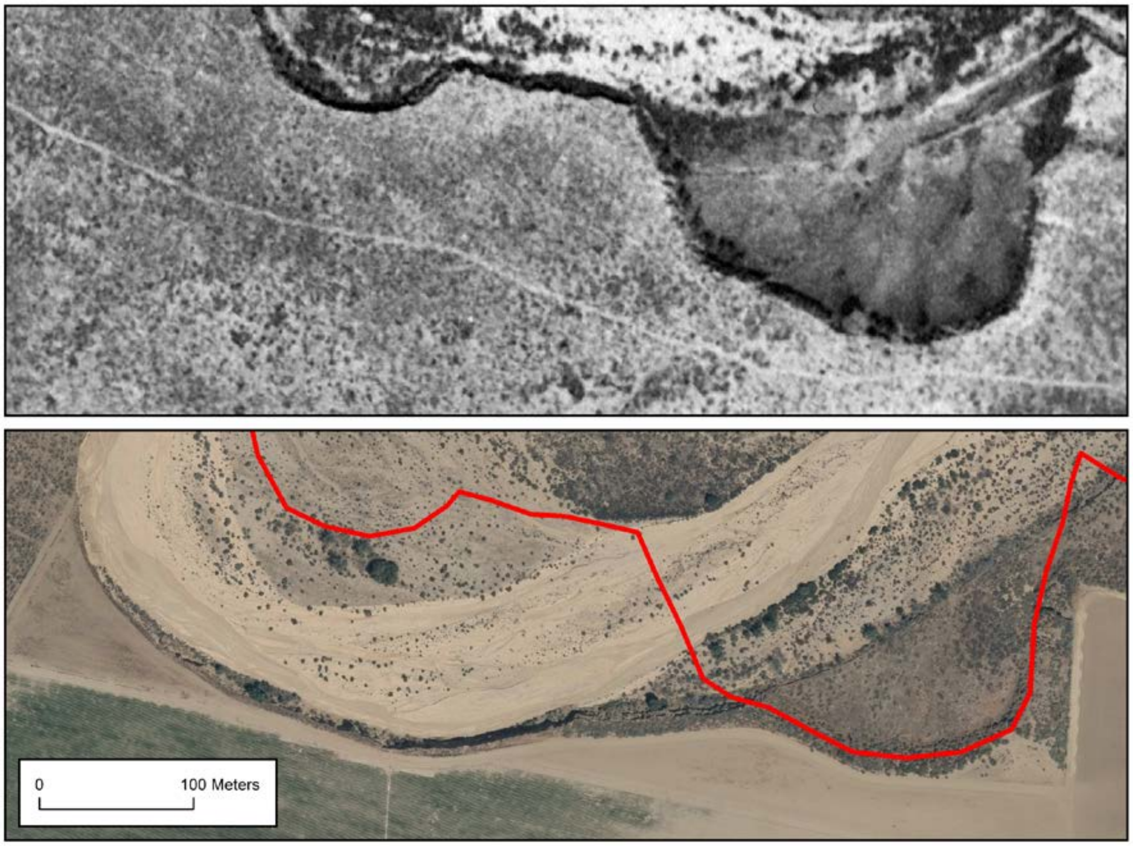

Figure 13: Shift in Arroyo Position from 1954 (top) to 2011 (bottom, with 1954 position denoted in red)

extensive expansion of the arroyo, Figure 13 reveals the presence of an older meander which predates this study and also expanded the arroyo in the eastern, upstream portion of this study section. Based on its distance from the main channel in both 1954 and 2011, it is clear that large meandering has occurred in the recent past, before 1938. It is worth mentioning that the arroyo position in 1954 is the same as it was in 1938, but the 1954 photograph is being used for this visual comparison due to its clarity. It is likely that the two meander positions are related – with the current, growing meander being the next iteration of the old meander position. This shift in arroyo position indicates that the apparent quasi-equilibrium in this section, seen by the downstream translation of meanders, operates over a time scale greater than the 74 year period recorded in this study.

6.2 – Deliberate Straightening of the Cuyama River

The most intriguing discovery made with this study was the presence of channel straightening in the 1954 photograph. Unfortunately, it was not possible to gain any information regarding this straightening from textual resources or from local water resource experts; therefore, all evidence comes from this image itself. The straightening occurs in two different segments which span study sections 1-4. The first segment is 450 meters long, begins at the end of section 1 after the river bends to the NW, and ends in the middle of section 2. The second straightened segment is much larger, and at 2130 meters it nearly spans the entire length of sections 3 and 4. The two straightened segments are connected by a small curved stretch of the river which also appears to have been channelized, but not straightened. This is evident by the presence of a very clear meander scar which is not present in the 1938 photograph (Figure 14, next page). This meander scar also indicates that the river had some time to meander from its 1938 position, so the channelization likely occurred closer to 1954.

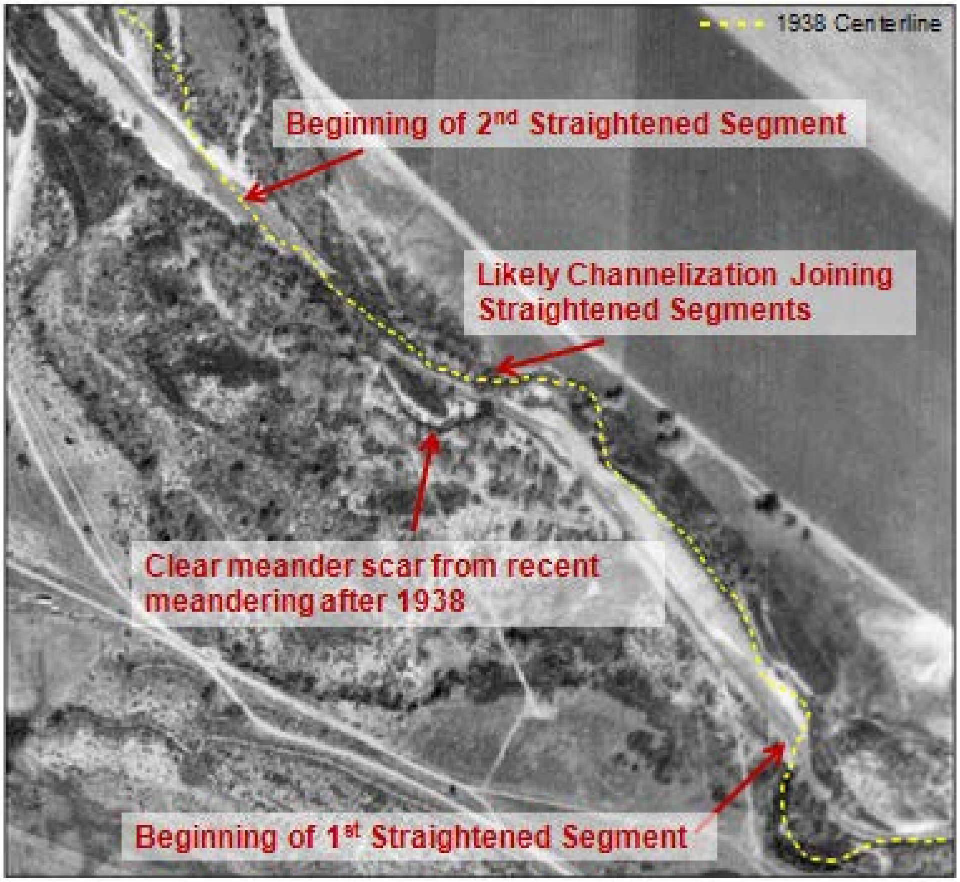

Figure 14: Channelization Between 1st and 2nd Straightened Segments; 1938 channel position indicated with yellow dashes. Meander scar between the two segments was not evident in 1938.

Presumably, the channelization occurred in order to stabilize the banks for expansion of farmland. The first expansion of farmland occurred between 1938 and 1954. The existing farm expanded not only on the south side of the river, but also expanded across the river, as shown in Figure 15. From the image, it is possible to discern that the boundaries of the fields are adjacent to the arroyo wall in many places on both sides of the river. It is logical to presume that the channelization and straightening was conducted in an effort to stabilize the banks of the arroyo to prevent losses to crops.

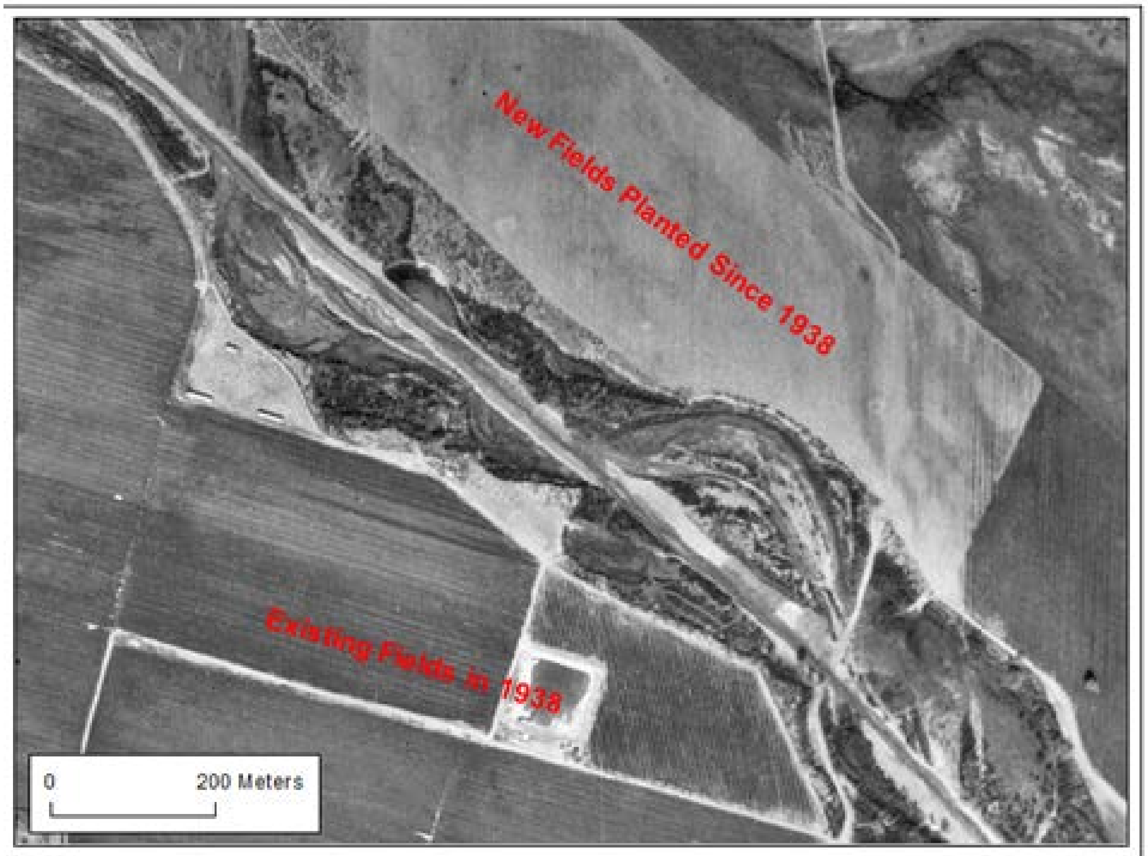

Figure 15: Agricultural Growth on Opposite Bank; note close proximity of fields to meander scars and the arroyo wall

Furthermore, while it is obvious that this deliberate modification had unintended consequences downstream from the straightening in the years to come. The study sections downstream from the straightened sections experienced increased sinuosity at a higher rate. The largest lateral migrations occurred in sections 5 and 6, which are directly downstream from the straightened sections. Figure 16 below shows the progression of these sections following the straightening, in the years from 1954 to 1978.

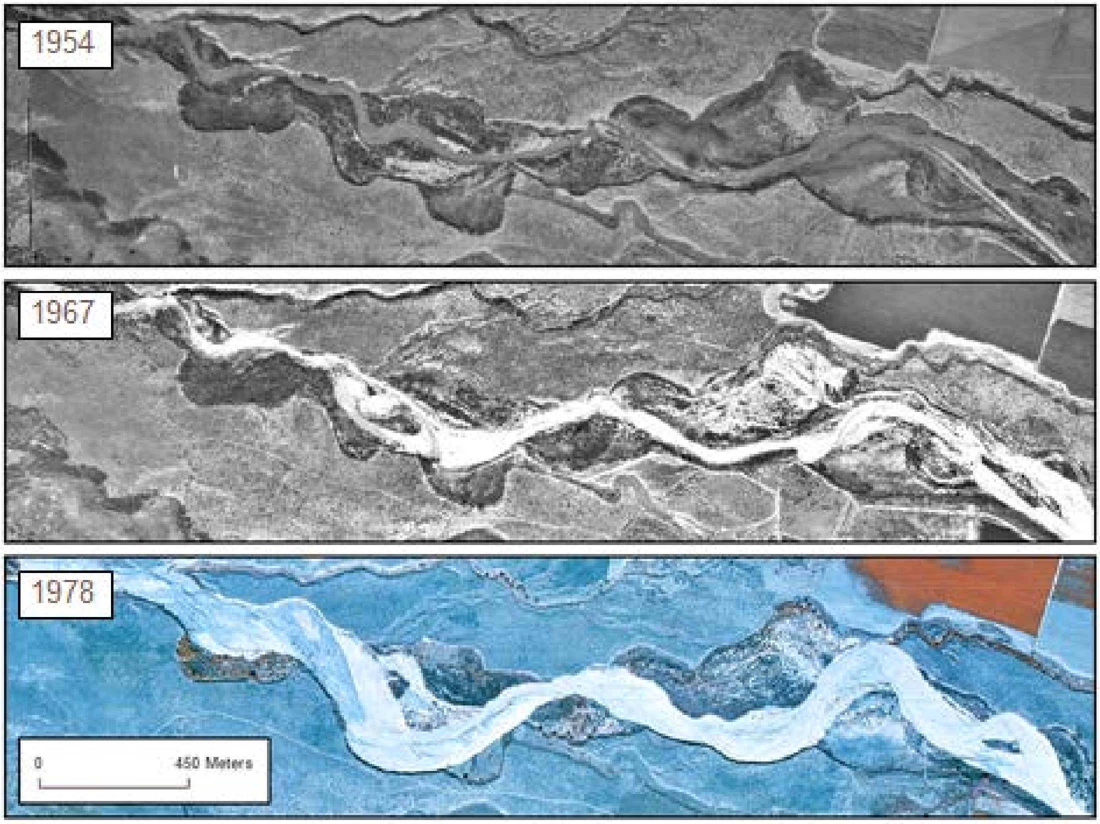

Figure 16: Large Shifts in Meander Amplitude and Wavelength Downstream from Straightening

In order to investigate the effects of the straightening in greater detail, additional measurements were taken for sections 5-10: meander wavelength and amplitude. While the sinuosity measurements show a long term trend of continual growth, the measurements for wavelength and amplitude follow a different pattern. From 1954 to 1978 there is a sharp increase in both wavelength and amplitude, especially during the period from 1967 to 1978. This would indicate a shift from a pattern of small, but frequent meanders to larger, less frequent meanders. Indeed, the number of total meanders in these sections shrinks from 7 meanders in 1954 to 4 meanders in 1978. After 1978, the total number of meanders remains static at 4. Correspondingly, wavelength measurements nearly plateau with slight increase from 1978 to 2002 and a slight decrease to 2011. Amplitude measurements decline slightly from 1978 to 1989 and then very nearly remain the same to 2011. These trends in wavelength and amplitude are markedly different than the measures for sinuosity, which exhibit the highest rates of growth from 1989 to 2011. To summarize, sinuosity increased from 1954 to 1978, while both wavelength and amplitude increased; however, sinuosity increased even more after 1978 as wavelength and amplitude remained relatively static. This is a peculiar shift, and the most logical explanation is that sinuosity is able to increase, despite static wavelength and amplitude, due to an increasing radius of curvature. In different terms, this would mean that the apexes of the meanders are becoming less sharp and more broadly curved. Visually, this appears to be a possibility, which unfortunately cannot be confirmed without more extensive measuring.

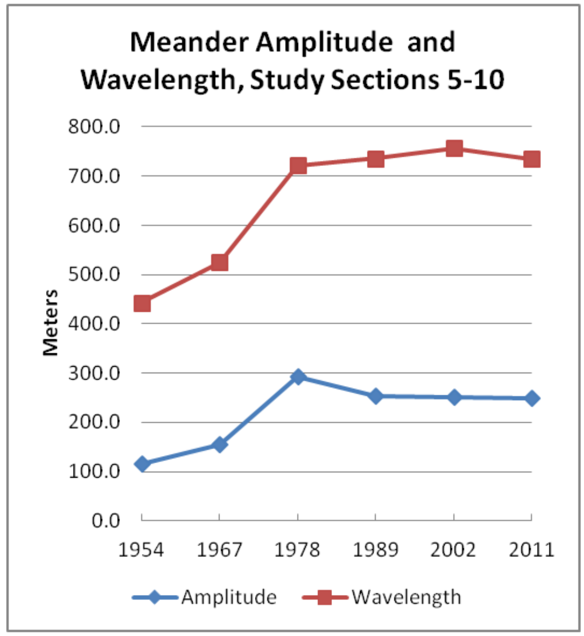

Figure 17: Meander Amplitude and Wavelength Chart

The high growth of both amplitude and wavelength, coupled with the lack of relationship with sinuosity provides evidence that the period of drastic change may have been an effect of the channel straightening. While there were major flood events in the period from 1967 to 1978, there is very little change visually in the reach of the river just upstream from the straightening, compared to the drastic changes which occurred downstream. This would indicate that the channel straightening exacerbated the effects of high discharge events. The sinuosity measurements for sections 2-4 (straightened sections) indicate that in 2011 they still have not yet fully returned to their 1938 level of sinuosity. However, visually the straightening can still clearly be seen in 1967, but by 1978, one would be unable to notice that a straightening had occurred without prior knowledge of its existence. Therefore, it is possible that at some point between 1967 and 1978, the river regained the hydrologic efficiency it lost with the straightening, and therefore subsequent years exhibited little change in wavelength and amplitude. This conjecture could be confirmed in a subsequent study; however, such a detailed examination was outside the initial scope of this study.

Clearly, the river straightening and channelization had both immediate and lasting effects on the river. The shift from smaller, more frequent meanders to large, less frequent meanders provides evidence of the downstream effects of the channel modification. Since the most likely explanation for the straightening and channelization of the river prior to 1954 is to support agricultural growth, this presents a clear example of a deliberate modification of the river to support agricultural activities in the area.

6.3 – Non-Deliberate Effects of Agriculture

Deliberate modifications such as straightening and channelization are relatively straightforward to identify and relate to human activities. It is much harder to attribute non-deliberate changes to anthropogenic activities such as the land use change which took place in the Cuyama Valley as a transition from natural/grazing land to modern, irrigated agriculture took place throughout the time period of this study. Section 6.4

discusses these inherent conceptual challenges further. This section aims to offer possible interpretations of the available data which may lead to a reasonable conclusion that agricultural growth did indeed lead to non-deliberate modification to the form of the river. The statistical evidence is meager, but reveals trends across time which may be related to the growth of agriculture. More compelling evidence is presented from a qualitative visual examination and interpretation of the aerial photographs.

The three statistical measures of channel planform change reveal two trends which may help in attributing the changes to growth of agriculture. First, changes in channel width negatively correlated with changes in total agriculture across the entire study reach. The limitations of using this variable will be discussed in the next section; however, for the purposes of this study, this correlation was statistically significant, and therefore could be meaningful for explaining the processes involved as agriculture grew in the area. A negative correlation indicates that as agriculture grew throughout the study reach, channel widths decreased. This could possibly indicate that increased runoff did indeed occur, as prior literature would suggest. Increased discharge volume and velocity may lead to more degrading erosion during periods of flow, which would lead to a narrower, deeper channel. While this is a possibility, GIS measurements alone cannot measure vertical erosion or deposition processes – only lateral processes visible from the air. Additionally, this explanation would likely result in geomorphologic processes opposite from the ones observed in this study; a narrower, deeper channel would be more likely to have decreased lateral migration and sinuosity. Therefore, an alternative explanation is that river discharge actually decreased due to ground water pumping – also an explanation supported by previous research (VanLooy and Martin, 2005). Field methods would need to be used in order to help confirm the processes involved. It is also worth noting that overall channel width values are higher in 2011 than they were in 1954; which over the long term would mean that the trend is opposite of the correlation with channel width change. The negative correlation may be due to the fact that the most growth occurred from 1967 to 1978, when agricultural land use declined slightly.

The next trend was discussed at length in section 6.1: increasing sinuosity and continual meander growth. While these trends may simply be a natural transformation of the river as the arroyo widens, the fact remains that sinuosity is increasing and agricultural growth is also increasing during the time period of this study. The correlation between sinuosity and total agriculture in the area was nearly statistically significant ($P = 0.086$). Based on the limitations of this study, it would be presumptuous to attribute this increased sinuosity to the growth of agriculture, but it is a trend worth considering for future research. This trend is accentuated when the control data are examined. The correlation measures were unable to find any statistical relationship between precipitation events and increases in sinuosity or lateral migration. The period between 1989 and 2002 was the wettest period of time in this study; however, the sinuosity remained relatively static during the same time period. Similarly, the time period only coincided with the largest periods of annual lateral migration in 4 of the 10 sections. The lack of correlation with the control variables and sinuosity lends credibility to the claim of Hooke (1997) that it is often not possible to attribute changes in geomorphology to any external condition, including climate. Given the lack of explanation from the control variable, one could then conclude that perhaps it is not mere coincidence that sinuosity and agricultural growth both increase in this time period. On the other hand, it is most certainly possible that the increased sinuosity is a result of additional factors occurring in the Cuyama Valley, which are discussed in Section 6.5.

While the quantitative measurements fail to conclusively present compelling data to confirm that agricultural growth in the region has unintended effects on river channel form, a qualitative approach offers additional evidence to support the claim that agricultural land use has affected river form. Figures 8 and 9, presented in the previous chapter, show that the surrounding landscape has most certainly experienced change during the change in land use. These changes are a classic example of what Jeffrey Mount calls the “homogenization of the landscape” (Mount, 1995; 254). Visual examination of the aerial photographs reveals that many of the topographic features have smoothed due to plowing, and much of the natural vegetation has diminished. While this may not yet be directly contributing to change in river form, Mount asserts that such changes will ultimately create a state of non-equilibrium. This qualitative examination lends credibility to the sinuosity data mentioned in the previous section. If the sinuosity is increasingly growing, it would appear as though the river is not in a state of equilibrium. While rivers often naturally progress from one state to another (Rosgen, 1994), the coincidence of this increased sinuosity with an increased “homogenization” of the landscape may indicate that agricultural land use is indeed playing a part in the transformation of river channel form.

While the results of this study do not provide robust evidence to support the concept of non-deliberate change due to agriculture, the trends in the data and qualitative observations retain the possibility that this is indeed occurring. This topic merits further investigation in the Cuyama Valley due to the unique circumstance of having significant agricultural growth occur after the first documented aerial photograph.

6.4 – Limitations and Constraints

Several factors contribute to the challenges faced to attribute channel planform change to the non-deliberate effects of agricultural land use growth. First, there are a multitude of conceptual questions for research which try to link form to processes of any kind. Second, there are inherent errors with a GIS study of this kind which can skew the data. Finally, there are limitations on available data which inhibited a more robust study using sound methods.

Conceptually, challenges exist for researchers seeking to examine and evaluate the impact of agricultural activities in a fluvial system. In their review of the impact of humans in fluvial systems, James and Marcus (2006) stress the importance of an interdisciplinary approach to avoid a "hydraulic myopia that fails to explain how rivers respond as complex non-linear systems interacting with human activities." They also call for theoretical work within the emerging field of "anthropogeomorphology" to help explain change and ultimately provide predictive capabilities. A challenge facing the development of theories is the complexity of geomorphic systems and local variability. In her review of these impacts in the Mediterranean region, Hooke (2006) also notes that the "very high spatial and temporal variability of fluvial processes… creates problems for measurement and monitoring and for assessment of effects." As discussed in the review of literature, this variability is exacerbated in dryland rivers. It takes a much longer record of hydrologic data to demonstrate typical behavior – and even a 50 year record may not demonstrate the flow regime (Walker et al., 1995). For this study, only 74 years of aerial photograph records are available, so it is difficult to assess whether or not changes in channel form are due to cyclical hydrologic processes, or if they are being altered by human activity. As discussed in section 6.1, the presence of large meander scars outside of the channel positions occupied from 1938 to 2011 indicates that the cycle of downstream meander translation is larger than the period of record of this study.

Adding to the conceptual challenge of answering RQ2 is the fact that most studies examining the effects of agriculture on river channel planforms are in areas where the previous land cover was forest. In the Cuyama Valley, land cover is naturally sparse so runoff and erosion may be more similar to that of cropland. Also, the prior land use in the area was grazing, so natural vegetation was often denuded; therefore the soil may have already been degraded. If this is the case, it is possible that there has been little change in runoff or erosion due to the transition to irrigated farming.

Considering these conceptual constraints, the greatest challenge this study faced is that it simply may not be possible to attribute channel form changes to non-deliberate effects of agricultural growth for the limited time period of this study. In fact, the changes may not be attributable to any external conditions (Hooke, 1997). Even with optimal data and the best methods, this study may have not been able to fully answer RQ2.

However, the data and methods for this study were not optimal. The availability of resources is a significant limitation in this study. A limited budget for the purchase of aerial photographs was a major challenge this study faced. More aerial photographs would have vastly increased spatial and temporal coverage and allowed for a more robust project. First, the entire Cuyama Valley could have been mapped in order to accurately capture all upstream change in agriculture, not just the change within the 1 kilometer buffer, which was chosen primarily because it was the only distance which would have coverage in all of the aerial photographs. Second, the entire reach of the Cuyama River which flows through the agricultural heartland of the valley could have been mapped in order to have additional data points. Aerial photographs from years between the chosen time periods were available, and they would have added to the temporal data points, which could have strengthened the statistical testing. Finally, the initial plan for this study called for a control area to be mapped further downstream where the land use was still relatively natural and river conditions were similar. This comparison could have helped identify whether or not changes were due to natural fluctuations. Budget constraints limited the amount of photographs which were purchased to a very small fraction of the photographs which were available. Additionally, the lack of discharge data at or near the study site inhibited the ability to examine whether natural response to precipitation events has changed. This would have been very beneficial for discovering the extent to which agriculture affected runoff.

Methodologically, the mapping of historical land use change and changes in channel planform require a great deal of interpretation in the digitization and classification of imagery – which presents many opportunities for error. This is exacerbated by the fact that ephemeral dryland rivers are often characterized by a lack of distinction between the channel and the surrounding floodplain, making the mapping of channel banks an even more difficult task. Additionally, the aforementioned budget constraints dictated that the aerial photographs purchased for this study were 600dpi resolution. As discussed previously, some studies have used 600dpi, but 1200 is far more common and provides better detail which enhances the ability to distinguish control points while co-registering and to make a better determination of channel bank locations.

Registration of the images by the georectification process described previously yielded relatively low measured error. The mean root-mean square error (RMSE) for all images was 3.55m, with the largest error being 5.22m. While this RMSE compares favorably with similar studies (e.g. Nicoll and Hickin, 2010; Winterbottom, 2000), it is well documented that RMSE does not fully quantify the error which may be present (Hughes et al., 2006; Mount and Louis, 2005); therefore this study accepts that error in both digitization and measurement exist, and cannot be fully quantified. The assumption is that the large magnitudes involved in many of the measured changes – such as those of study section 6 – vastly outweigh potential errors. It remains prudent however to note that smaller measured changes (<20m) may exist nearly entirely due to error in georectification and digitization. This holds true for all studies of this nature.

For the most part, identification of the river channel was relatively straightforward. However, the 1938 photograph presented significant challenges in digitization of the river banks. The poor quality of the original photograph meant it was often very difficult to distinguish the main channel from vegetation. Consider Figure 18, on the following page, which compares the 1938 image with the 1954 image. It is extremely difficult to follow the path of the river through the vegetated area in the 1938 image, whereas in the 1954 image, the river channel is clearly distinguishable from the vegetation at the bottom of the arroyo. Initial interpretation and digitization of the 1938 image was made independently, without consulting the position of the river in subsequent years. This led to the conclusion that dark areas were braided channels, due to their

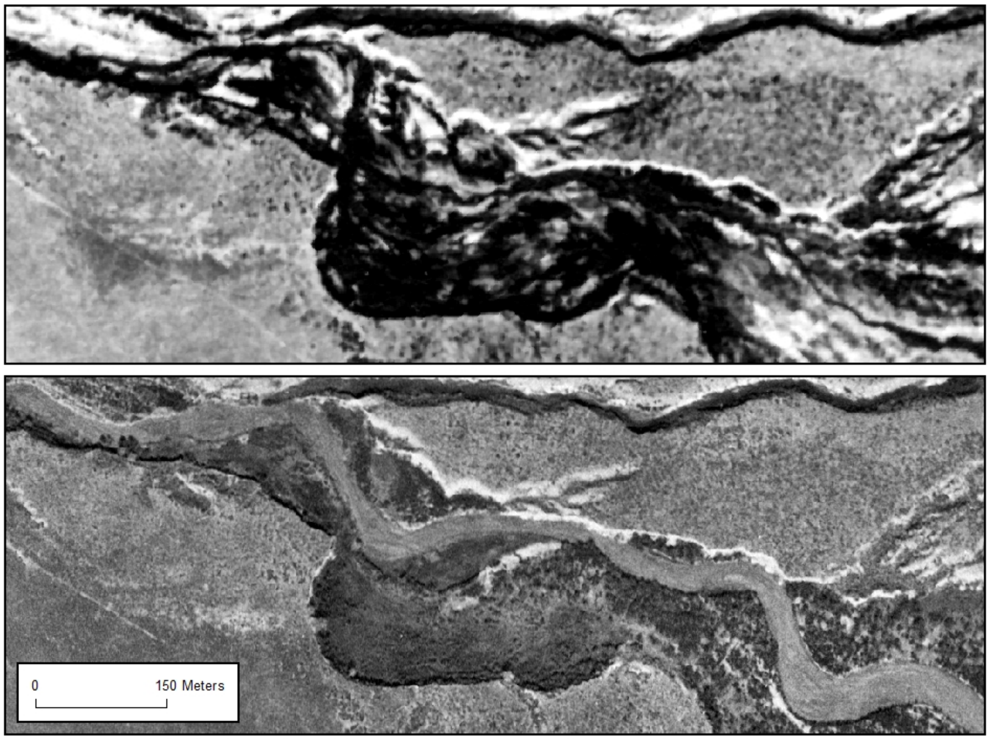

Figure 18: Comparison of Image Quality, 1938 (top) and 1954 (bottom); discerning river bank positions was relatively straightforward in 1954 and beyond, but the 1938 image presented many challenges due to poor image quality and the possible presence of standing water throughout the arroyo floor.

density and different appearance from vegetation outside the arroyo. Following digitization, however, comparisons such as the one in the figure above reveal that areas which may have been digitized as part of a braided system may have likely been vegetation, not the river channel.Based on the challenges of digitizing the 1938 channel positions, the river channel measurements were taken and recorded, but not used for analysis.

Furthermore, the overall effectiveness of the study was constrained by the design choice to use statistical correlation testing to analyze the relationship between agricultural growth and the measured changes to river channel planform. As mentioned previously, the inability to fund the purchase of additional aerial photographs inhibited the ability of this study to conduct this analysis along different reaches of the river, thus providing more unique data points for the statistical testing. Instead, the study area was segmented into sub-sections in order to boost the number of records; which relies on the assumption that each section would draw its greatest response from the amount of agriculture in its buffer, and this may not be the case. Hydrologic modeling would be necessary to estimate the area which would affect each section, and this was outside the scope of this study. The choice to break the study area into sections resulted in the adaptation of the method for determining lateral migration, which took the direction of migration out of the equation by aggregating all of the polygons within each section. This makes the lateral migration measurements no less accurate, but less meaningful on their own. However, when coupled with a visual examination, it is possible to ascertain that the lateral migration of meanders across the study reach throughout the period from 1938 to 2011 was one of cut-bank erosion and expansion of the meander. Therefore, the mean lateral migration measurements made for each section represent how much that section expanded laterally. Future studies attempting to attribute changes in channel form to an upstream factor such as agriculture would likely have better results using the alternative method for measuring lateral migration, using predefined transects (O’Conner et al., 2003), instead of the eroded area polygon method. This would only then provide lateral migration at specific sites in the river; however, this would also be beneficial for providing singe point locations from which to model upstream areas contributing to run off. The correlation test could then pair the lateral migration and channel width at a given site against the agricultural area of the entire contributing area above each point. This would likely lead to a much more valid test.

While this study is limited by many factors, most of the limitations only apply to the portion of the study which sought to attribute changes in river form to non-deliberate effects of agricultural land use growth. The first research question is only partially limited; measurements of channel planform change were effectively made for the period between 1954 and 2011, not 1938 to 2011 as originally planned. Qualitative analysis such as the discovery of the straightened section in the 1954 image retain their effectiveness because they relied on visual analysis and interpretation of the images instead of relying on the accuracy of measurements.

6.5 Other Explanations for Channel Planform Changes

Further exacerbating the difficulties of linking agricultural land use growth with channel planform change is the multitude of other factors which are at work in the Cuyama Valley which could result in a pattern of increasing sinuosity from 1938 to 2011. Ultimately, linking these channel form changes to a singular process would be highly challenging, if not impossible. Therefore, it is prudent to also discuss other possibilities which may be driving the shift in increasing sinuosity and rapid lateral meander migration. Two of the possible catalysts are also human activities: the construction of Twitchell Dam downstream from the study area, and the growth of gravel mining upstream from the study area. Finally, the changes in the Cuyama River could simply be result of general environmental trends such as climatic variation and regional tectonic activity.

The first possible factor which could explain the channel changes is that the time period of this study – especially from the more accurate 1954 image onwards – coincides with the addition of the impoundment of the Cuyama River by damming in 1958. The Twitchell Dam lies 70 kilometers downstream from the study area just upstream from the confluence of the Cuyama and Santa Maria rivers. Even though the study site lies a sizeable distance upstream from the dam, it is possible that the dam could still have played a role in the changing geomorphologic conditions. Damming causes “backwater effects” (Evans et al., 2007,) which raise the base level of a river, thereby causing patterns of aggradation upstream from the river. It is widely accepted that this occurs near the mouth of the reservoir. Evans et al. (2007) used remote sensing and GIS to assess the upstream effects of a dam and found notable changes in aggradation across their entire 4.1km study reach. While studies of effects further upstream remain sparse, the researchers above note that the processes of aggradation upstream from a dam would be very similar to those documented in studies of the upstream effects of climate-driven sea-level change, where effects can be very extensive upstream. In their study of the Three Gorges Dam along the Yangtze River in China, Wang and Hu (2004) demonstrate through scale-model experimentation that the upstream effects of damming on 80 years of depositional processes may result in channel alterations as far as 610 kilometers upstream.

It is therefore possible that the Twitchell Dam has caused conditions resulting in backwater effects extending upstream for 70 kilometers to the study area. Evans et al. (2007) noted that the compounded backwater effects led to increased sinuosity in their case study, so this would be a possible explanation for the increases in sinuosity measured in the Cuyama River. While this stands as a possible cause, given the highly variable rates of flow of the Cuyama River, this would likely be very difficult to investigate further without extensive field work or available discharge data.

While agricultural activities are the dominant land-use in the Cuyama Valley, it is certainly not the only anthropogenic activity which has caused change in the river. As a dryland river, the Cuyama is well-suited for gravel mining. Currently in the Cuyama River, there are four active gravel mines upstream from the study area and one downstream (Andersen et al., 2009). While a full investigation into gravel mining in the Cuyama River is beyond the scope of this study, it is worth noting that the extraction of gravel and sand comes directly from the river bed, often in large quantities. One current operator in the region is approved to extract 500,000 tons annually (Mondaq Business Briefing, 2013) directly from the riverbed. The primary effects of in-stream gravel mining are upstream incision and channel instability (Kondolf, 1997). Downstream effects are less apparent, but tend to present similarly bed erosion and channel instability due to increased discharge velocity due to less surface roughness and/or decreased deposition due to less sediment load (Wishart et al., 2008; Rinaldi et al., 2005; Kondolf 1997). Alternatively, in some cases, aggradation may occur when the upstream incision causes an increase in sediment load that overcomes the sediment loss due to mining (Kondolf, 1997). Extensive field work would be required to investigate these effects in the Cuyama River; however, it is notable that the changes in the Cuyama study site resemble the effects of gravel mining. The channel width change and increased sinuosity described in the earlier sections of this chapter could have occurred due to incision and channel instability resulting from gravel extraction.

Finally, the explanation for the modern trend of increasing sinuosity and lateral migration may simply be the result of environmental processes such as climate variation and tectonic activity. Delong et al. (2008; 2011) offer detailed geomorphologic explanations of these factors in the Cuyama Valley. Tectonic uplift due to the nearby San Andreas Fault results in incision of the Cuyama into both alluvium and bedrock. Climatic fluctuations result in increased sedimentation during periods of increased precipitation. These researchers note that during the late-Holocene, a transition has occurred and the Cuyama is becoming a "more dynamic, narrow, higher energy fluvial system" (Delong et al., 2011). They suggest that incision has been occurring over the past few decades. Their study also notes that the cycles of incision and deposition in the Cuyama River occur at similar times to other dryland rivers in the Southwest, despite little landscape similarity, which suggests that regional climate patterns are the dominant factor.

While the climatic variables measured in this study failed to correlate significantly with the channel changes, it is noteworthy that the number of precipitation events has generally trended upward. The period of record for precipitation in Cuyama is small; therefore, it is difficult to determine whether climate factors are driving the change. Nevertheless, it is probable that the shift in sinuosity could be attributed more to climatic change (either natural or anthropogenic).

The possible causes presented in this section are not intended to deny the impact that agricultural land use had on the Cuyama River. Changes such as the river straightening and the homogenization of the landscape are certainly attributable to growth of agriculture in the region. These alternatives are presented in order to more fully describe the overall factors which could have also contributed to change. None of these factors operate independently; it is certainly possible that these factors work in conjunction with land use change to result in the measured changes in sinuosity and lateral meander growth.

Chapter VII - Conclusion

This study began with a broad desire to examine human impact on the environment. The Cuyama River presents a fascinating opportunity for the case study of rapid growth of modern agriculture. Major agricultural areas throughout the United States tended to be developed earlier than the mid-twentieth century; with the Cuyama, this late growth offers the opportunity to use historical aerial photographs to document the effects.

Methodologically, this study provides another case study on the use of GIS to record and measure certain aspects of channel change. The measurements recorded for the study reach of the Cuyama River provide a clear example of the magnitude of lateral erosion that can occur in a dryland arroyo system. Research question #1 was effectively answered: large changes in the lateral migration of meanders have resulted in a steady pattern of increasing sinuosity throughout the period of study from 1938 to 2011. Furthermore, the identification of a large channelization effort was identified in the 1954 aerial photograph. The record of geomorphic activity documented in this study can contribute to overall understanding of the Cuyama River and, more broadly, dryland fluvial geomorphology.

Conceptually linking the measured channel changes to agricultural land use, in order to answer RQ2, proved to be challenging. This was especially true for the attribution of non-deliberate effects of agriculture due to the limitations of the study and the alternative factors discussed in the previous chapter. The inconclusiveness of the attribution of channel changes to non-deliberate effects of agricultural land use should not be interpreted as a lack of evidence. Indeed, the overall trend of increasing sinuosity – trending upward despite fluctuations in climate – indicates that non-natural factors may be at work. On the other hand, the deliberate modification of the channel, clearance of natural vegetation, and plowing of landscape features are all most certainly linked to agriculture growth. The rapid growth of meander amplitude and wavelength from 1954 to 1978 indicates that the channel straightening had notable effects on downstream river behavior.

Future research should reexamine this issue more thoroughly. Given the availability of aerial photographs which were not used by this study for budgetary reasons, it would be possible to examine the entire valley; or at the very least, choose different study reaches which have been affected by differing levels of agricultural growth. This study attempted to measure the effects of differing levels of agriculture by using different buffer zones for each section; however, it is likely that all of the sections in this study reach were subject to nearly the same conditions, regardless of the amount of agriculture in each buffer. An examination of a much broader area would result in measurements of channel change occurring in areas which were clearly subject to differing amounts of upstream agricultural use.

Furthermore, additional studies should couple the methods used here with field methods, hydrologic modeling, and the use of additional mapping and remote sensing evidence. Field studies can provide insight into vertical changes in channel form, and can also identify gullies forming at the edges of fields – which was a prominent theme in previous research. Hydrologic modeling could ascertain how much of the upstream area contributes to river flow, which could then be used to determine how much agricultural growth has occurred on land which contributes to flow at a particular section. Additionally, the historical channel measurements could be extended further into the past if older topographic maps were used. This would allow a larger sample of natural fluctuation of the river form which could then be contrasted with modern changes since the growth of agriculture. Finally, very recent channel changes could be examined specifically using satellite images. The smaller temporal scale of satellites could help determine the magnitude of change from single precipitation events. Additionally, future studies could specifically focus on the effects of the river straightening, and examine in detail the shift in the relationship between sinuosity and wavelength and amplitude which occurred after the 1978 measurements. Given the other factors which are also present in the Cuyama River system, discussed previously in Section 6.5, a variety of additional studies could also be conducted to examine the upstream effect of damming, or the downstream effect of gravel extraction.

The magnitude of changes measured in this study indicates that the Cuyama is very active geomorphologically. Despite the capability of rapid, vast change to channel form, agricultural growth over just the past decade continues to encroach closer to the banks of the arroyo, ironically coinciding with a time when it is increasingly recognized that rivers should have more space to freely meander. It is inevitable that there will be loss of available cropland at some point in the near future as the arroyo continues to widen. The changes presented in this study have implications on the economic feasibility of continued encroachment toward the arroyo. Unlike floodplain agriculture which can simply replant after a flood, the fields on top of an arroyo will be lost to degradation and downcutting, until the point when the arroyo is wide enough for a foolhardy farmer to plant in the new floodplain.

Therefore, the relationship between agricultural land use and channel change in the Cuyama Valley is two-way. Deliberate and non-deliberate effects of agriculture modify the river form, but the river form will ultimately dictate where agriculture is permitted.

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