Damming Ephemeral Streams: Understanding Biogeomorphic Shifts and Implications to Traversed Streams due to the Central Arizona Project (CAP) Canal, Arizona

by

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ABSTRACT

Ephemeral streams in Arizona that are perpendicularly intersected by the Central Arizona Project (CAP) canal have been altered due to partial or complete damming of the stream channel. The dammed upstream channels have experienced decades long cycles of sediment deposition and waterlogging during storm events causing the development of "green-up" zones. This dissertation examines the biogeomorphological effects of damming ephemeral streams caused by the CAP canal by investigating: (1) changes in the preexisting spatial cover of riparian vegetation and how these changes are affected by stream geometry; (2) green-up initiation and evolution; and (3) changes in plant species and community level changes. To the author's knowledge, this is the only study that undertakes an interdisciplinary approach to understanding the environmental responses to anthropogenically-altered ephemeral stream channels.

The results presented herein show that vegetation along the upstream section increased by an average of 200,872 m^2 per kilometer of the CAP canal over a 28 year period. Vegetation growth was compared to channel widths which share a quasi-linear relationship. Remote sensing analysis of Landsat TM images using an object-oriented approach shows that riparian vegetation cover gradually increased over 28 years. Field studies reveal that the increases in vegetation are attributed to the artificial rise in local base-level upstream created by the canal, which causes water to spill laterally onto the desert floor. Vegetation within the green-up zone varies considerably in comparison to pre-canal construction. Changes are most notable in vegetation community shifts and abundance. The wettest section of the green-up zone contains the greatest density of woody plant stems, the greatest vegetation volume, and a high percentage of herbaceous cover. Vegetation within wetter zones changed from a tree-shrub to a predominantly tree-herb assemblage, whereas desert shrubs located in zones with intermediate moisture have developed larger stems. Results from this study lend valuable insight to green-up processes associated with damming ephemeral streams, which can be applied to planning future canal or dam projects in drylands. Also, understanding the development of the green-up zones provide awareness to potentially avoiding flood damage to infrastructure that may be unknowingly constructed within the slow-growing green-up zone.

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1. INTRODUCTION

Background and Purpose

Humankind has influenced the transformations of landscapes by altering natural processes throughout time. George Perkins Marsh is one of the first known American scientists to write about human and environment interactions (Marsh 1885; Marsh 1965). In his book, he observes and summarizes the physical changes to “the woods, the waters, vegetable and animal species, and the sand” influenced by human activity (Marsh 1885). During this century, philosophies of human-environment interactions also emerged in other parts of the world. An Italian naturalist and geologist, Antonio Stoppani, considered humans to be a “new physical element” introduced to the geologic time of Earth in which he coined as “the anthropozoic era” in his published work in 1873 (Stoppani and Malladra 1900; Crutzen 2002). Stoppani’s position was based on humans having the ability of changing or influencing their environment. The philosophies of scientists such as Marsh and Stoppani persist in modern-day geographic thought.

In many cases, understanding environmental changes due to human influence is contextualized in assessing the susceptibility or potential hazards to the physical Earth and humans (Turner et al. 2003). Humans may change a system to an extent that is destructive to human populations and biotic systems whether on a global or local scale. Some examples of these dramatic alterations to the Earth and life include mining (Hendryx et al. 2008; Mudder and Botz 2004; Fernandas et al. 2004); nuclear waste sites (Makhijani et al. 2000); nuclear power plants in Fukushima (Buesseler et al. 2012; Buesseler et al. 2011) and Chernobyl (Wynne 1989; Anspaugh et al. 1988; Rahu 2003); overfishing (Jackson et al. 2001; Scheffer et al. 2005); damming rivers (McCully 1996;

Baxter 1977; Lignon et al. 1995). In the latter example, damming rivers can dramatically alter the landscape around it.

In many instances, dams are essential to sustaining human life and used for flood control, hydro-electric power and reservoir retention to meet water demands. As a consequence, the use of dams impacts the multiple aspects of the system including the biota, hydrology and geomorphology. These environmental variables are dependent on one another and adjust based on changes (Thoms and Parsons 2002; Corenblit et al. 2008). The human influence in changing the dynamics of a river system by altering the geomorphology is described in the works of Gregory (2006), Goudie (1993), and Goudie (2013). Dams hinder sediment movement downstream, change the morphology of channel structure and behavior, and alter the aquatic and terrestrial biota with varying degrees. Primarily, perennial and intermittent rivers have been the focal point of river research along dammed and non-dammed rivers. There are two main fundamental concepts that have been developed that deal with the understanding and prediction of environmental attributes displayed based on processes of a given river along a longitudinal gradient (i.e. upslope to downslope). One of the concepts deals with a non-dammed riverine system, while the other describes changes along a dammed perennial river.

One of the first influential longitudinal concepts constructed to explain biological elements and processes along a river channel is known as The River Continuum Concept (RCC). The RCC was developed to be used for smaller perennial rivers and falls short in predicting ecosystem function to larger rivers such as the Amazon (Sedell et al. 1989). Shortly after the RCC, a new broad concept of explaining how a barrier (i.e. dam) would affect processes and biological components along a longitudinal gradient emerged known as The Serial Discontinuity Concept of Lotic Ecosystems (SDCLE) (Ward and Stanford 1983).

The SDCLE was developed because the reality was that several rivers were longitudinally disconnected (i.e. dams) where the RCC could not be applied as a predictor. Processes are affected by the position of a barrier along a river gradient; for example, dams placed closest to the headwaters would have the greatest decline in the ratio of coarse particulate to fine particulate organic matter just below the dam (Ward and Stanford, 1983). The SDCLE, as its name indicates, is a broad theoretical concept applied to perennial-type rivers. Both the SDCLE and the RCC cannot be applied to predicting processes and biotic changes of longitudinally connected or disconnected ephemeral channels as processes and biological make up vary from perennial to ephemeral channels. There are several studies detailing the significance of understanding ecologic and geomorphic changes on anthropogincally-obstructed perennial channels. Overwhelmingly, studies focus on perennial rivers where little attention is given to ephemeral channels. To date, there are no studies or conceptualization models of geomorphic and riparian changes to ephemeral channels due to longitudinal barriers, which is the centrality of this dissertation.

In this dissertation, the Central Arizona Project (CAP) canal is the subject of damming ephemeral streams in the Sonoran Desert, Arizona. The main purpose of this dissertation is to establish a fundamental understanding of the human-environment interaction between the human-created barrier, the CAP canal, and its related environmental response. This dissertation lays the theoretical groundwork for both conceptualizing and quantifying biogeomorphic responses to partial and/or completely damming ephemeral streams.

The CAP canal transects hundreds of ephemeral channels throughout its 336 mile-long path. It begins in Lake Havasu City and ends in Tucson extracting 1.5 maf per year from the Colorado River delivering water to major urban and agricultural areas. Canal construction was initiated in 1973 and was completed twenty years later. The CAP canal is one of the largest and most expensive canal projects in the US. In the canal's design, culverts and/or overchutes were built into the canal for larger streams to flow downstream, but may still experience waterlogging upstream during large storm events. Whereas, smaller streams are in most cases completely dammed without an outlet causing stormwater runoff to pool upslope behind the canal wall/berm. An ephemeral stream that traverses the CAP canal falls under one of the three categories: completely dammed, partially dammed or non-dammed.

Semi-arid regions have sensitive thresholds where a small change in water supplies can produce substantial changes to vegetation. Some changes in vegetation are so extreme that xeric regions have become drier leading to desertification while other areas alter into more mesic environments called "green-up zones." Green-up zones occur on both, completely dammed and partially dammed ephemeral streams along the upslope end near the canal's boundary. Understanding green-up zone development, spatial behavior, and plant community adjustments due to changes in geomorphic form or hydrology will aid in the greater theoretical perspective of the outcomes expected from barriers placed across desert landscapes. This will aid in predicting these outcomes to be implemented in future desert projects.

Significance

As far back as 1864, Perkins Marsh understood the importance of human caused changes to Earth. The changes affect the ecosystem, human sustainability and potential hazards to human populations caused from altering these fragile systems. In relation to ecosystems, ephemeral streams in drylands are susceptible to significant changes. Intermittent and ephemeral streams lend valuable ecosystem services and biodiversity (Acuna et al. 2014). There is strong support to protect temporary waterways including ephemeral streams (Acuna et al. 2014). Less than 1% of lands in the western US consists of riparian vegetation zones supported along stream channels (Knopf et al. 1988). These dryland riparian zones are essential in supporting wildlife habitats and vegetation that merit further studies in ephemeral research (Zimmerman et al. 1999); it is important to understand the impacts and influences humans cause by constructing barriers across desert landscapes. In order to understand changes to these small but important zones, the geomorphology and hydrology need examining as well. A bio-geomorphic understanding of the changes to dammed ephemeral streams along the CAP canal will provide valuable insight to future canal projects or dammed ephemeral streams in other parts of the world.

As desert populations increase and as societies globally transition from agrarian to urban, greater demands will arise to use more of Earth’s resources including the most fundamental element: water. This resource is key in sustaining societies and providing habitable environments especially in desert environments. In dryland regions, canals are constructed to connect river(s) to urban and agricultural areas to meet societies’ water demands. Jordan, Israel and the Palestinian Territories are in a current state of water shortage owing to a heavily populated desert region with limited water supply. A canal has been proposed to transport water from the Red Sea to the Dead Sea in order to sustain the inhabitants of this region (Beyth 2007). Several of the research studies regarding the potential environmental effects are regarding the Dead Sea's water chemistry, flora and fauna (Asmar and Ergenzinger 2002; Asmar and Ergenzinger 2002). These studies do not consider the potential changes of ephemeral streams that the canal will intersect in its proposed path. The biogeomorphic analyses in this dissertation can be used to project future outcomes of ephemeral streams along the Red-Dead Canal and can be used to implement better or different planning strategies with scientifically informed decisions.

Ephemeral rivers/streams that flood during large storm events are responsible for damage to infrastructure and, in extreme cases, even death. In the Mediterranean, flash flooding of ephemeral streams have claimed the lives of hundreds (Hooke and Mant 2002). The extreme flooding of ephemeral streams (i.e. wadis, washes, ramblas) in neighborhoods and streets due to torrential surface runoff during heavy rainfalls are characteristic to semi-arid regions (Lopez-Bermudez and Alonso-Sarria 2002; Greenbaum and Bergman 2006; Camarasa-Belmonte and Soriano-Garcia 2012). In Egypt, researchers propose several dams to be placed along mapped sections of ephemeral streams in response to a large flood event that damaged sections of a major highway (Youssef et al. 2011). It is important to understand the effects of damming ephemeral streams to make informed decisions. This dissertation research will lend insight to these planned projects in semi-arid regions.

Dissertation Structure

In order to understand the bio-geomorphic responses and adjustments to ephemeral streams influenced by the CAP canal, I examine the streams on multiple scale levels that are partially or completely dammed by the CAP canal. In each case, I focus on the bio-geomorphic or bio-hydrogeomorphic connection to changes in the landscape influenced by the CAP canal over time in four studies/chapters.

I begin with an initial study of a small ephemeral stream that is completely impounded by the CAP canal to understand the bio-geo interdependencies of the dammed ephemeral system. Secondly, a large scale study to gain a broader understanding of vegetation green-up over time in relation to stream morphology was conducted using satellite imagery. In general, a time series of vegetation green-up along partially and wholly dammed stream channels was quantified. Thirdly, understanding the evolution of green-up zones on a smaller field-scale level was conducted. Finally, I examined the processes occurring within the green-up zone between specific vegetation species and the changed hydrogeomorphic dynamic of the partially dammed system. Below, is a general outline of the studies discussed above.

In my second chapter, I examine the bio-geomorpholigical changes along a completely dammed ephemeral stream. This chapter serves as the initial analysis to understanding spatial relationships of riparian vegetation distribution to hydrogeomorphic changes as well as quantifying changes in vegetation green-up.

In my third chapter, I quantify the increase in vegetation cover over time within these green zones and their relation to channel geometry. The main question in this chapter is: How has the spatial cover of riparian vegetation along ephemeral channels within the Arizona desert changed by altering processes due to partial and complete damming created by the CAP canal?

In my fourth chapter, I compare/contrast two ephemeral streams. One stream has developed a green-up zone while the other stream has maintained a “characteristic” riparian zone. I examine the initial conditions necessary to set the stage for green-up development on the upslope end of the CAP canal and potential hazards associated with green-up zone inundation. The main purpose of this study is to understand the geomorphic processes that lead to the development and growth of green-up zones over time.

In my fifth chapter, I examine compositional shifts in vegetation, changes in vegetation structure and density to understand the effects of altering water availability due to the CAP canal. The main focus in this chapter is: What vegetational shifts and spatial adjustments have occurred to xeroriparian plant communities over the course of 35 years in response to the construction of the CAP canal? In my concluding chapter (chapter 6), I have summarized my findings of biogeomorphic responses to barriers in the desert. The concept is based on my findings in Chapter 2, 3, 4 and 5.

2. BIOGEOMORPHOLOGICAL EFFECTS OF THE CENTRAL ARIZONA PROJECT (CAP) CANAL ON A SMALL EPHEMERAL WASH NEAR APACHE JUNCTION, ARIZONA

ABSTRACT

The Central Arizona Project (CAP) canal is approximately 541 km long and traverses the state of Arizona from Lake Havasu City to Tucson. The canal truncates several smaller desert washes, hampering the natural flow of sediment and water downslope and causing water impoundment and sediment accumulation behind the canal. This research investigated how the canal effects biogeomorphological changes on the desert washes it blocks. The section of the canal traversing the study area was constructed between 1986 and 1987; aerial photographs and GIS were used to quantify landscape changes. The results show that, over a 36-year period, vegetation increased by 477% upslope from the canal. Sediment accumulation depths in the channel ranged from 0 to 5.7 cm, increasing in depth near the canal boundary. A kriged map of sediment depths shows that no apparent relationship exists between both sediment accumulation depths and the spatial distribution of vegetation and between sediment accumulation depths and the density of vegetation. Comparison of the interpolated map to visually estimated flow patterns from 1973 shows that channel flow direction did not change. The present-day channel is approximately 13.7 m shorter downslope from its original length observed in 1973.

INTRODUCTION

Throughout history, humans have devised many ways to locate, harness, and collect water for survival. Several different waterway systems used by ancient civilizations have been discovered by archeologists; one elaborate system revealed on the hillslopes in the Negev Desert dated back nearly 3,000 years (Shanon et al. 1969). The ancient city of Petra in Jordan was made possible through a monumental effort at redirecting water in an arid environment (Paradise 2005). The human impact of altering river systems through the construction of dams, canals, and channelization has been documented as early as the late 19th century (Marsh 1864). Anthropogenically altered river systems can have negative effects on the surrounding environment, for example, through erosion of aquatic breeding habitats and by hampering vegetation growth and establishment.

This paper explores how the Central Arizona Project (CAP) canal effects biogeomorphological changes in smaller desert washes that are truncated by the canal. The main purpose of this study is to analyze the human impact on desert washes due to the CAP canal by answering the following questions: (1) How much sediment has been trapped upslope from the canal over time? (2) Are sediment deposition patterns related to changes in the spatial distribution of woody vegetation canopy cover? (3) What are the effects on channel geometry, changes to vegetation spatial distribution, and changes to total amount of vegetation over time due to the presence of the canal, which causes water retention upslope? One ephemeral wash that is truncated by the CAP canal was examined to answer these questions. This analysis provides a basic understanding of the types of processes and changes that a concrete barrier constructed across a vast desert could display over time. This research also adds to the understanding of fluvial geomorphic landscapes in drylands and the interaction between riparian vegetation and hydrogeomorphic processes.

Visual comparisons to other washes cut off by the canal show that the ephemeral wash selected for study displays similar attributes, in having a green-up zone upslope from the canal and a barren zone downslope. The increased moisture upslope from impounded stormwater runoff has created a more mesic environment upslope. This paper reports riparian vegetation changes over time through change detection techniques. Vegetation changes are critical in understanding processes involved in dryland fluvial systems, and alterations of river systems inevitably affect the sensitive interdependent relationships that exist between dryland rivers and vegetation. Understanding system disturbance caused by humans is essential to better planning and management in future construction projects so that we may build infrastructure with the least amount of negative human impact on Earth.

Humans have been altering Earth's systems throughout time and with increasing technological advancements and population growth it is expected that more change will occur. As such, it is critical to understand the impacts of changing these systems. Better understanding of changes resulting from systems built to fulfill human needs will aid in more informed decisions and practices in maintaining a balance between human need and a healthy, self-sustained environmental system in future planning projects. Deserts comprise approximately one-third of the land mass on Earth and are home to about 15% of Earth's human population (Parsons and Abrahams 2009). Several canals have been constructed in desert regions to meet water demands without an understanding of the resulting effects on the landscape. A newly proposed project of constructing a canal in the semi-arid region of Jordan may be implemented as a solution to supplying the neighboring countries' water needs. The canal is proposed to extend from the Red Sea to the Dead Sea, so that waters from the Red Sea will be used to replenish the Dead Sea. Understanding the responses and processes involved in the surrounding desert environment to canal barriers is essential to sustainable living for both humans and the environment. This research was undertaken to better understand environmental responses to canal barriers in desert regions.

In this study, I hypothesized that areas upslope from the canal, where water pools after storm events, would begin to show a significant increase in vegetative cover over time. Furthermore, I hypothesized that flow direction would remain relatively constant, but channel length would shorten down-channel in the wash, as water ponds and sediment is deposited above the canal. Most of the deposited sediment was expected to be closest to the canal boundary, decreasing up-channel. Sediment deposition patterns and vegetation distribution may be less related to one another than is water availability to increases in vegetation cover.

Historical Background and Overview of CAP

The CAP canal is over 540 km long. It begins at Lake Havasu City, Lake Havasu City near the western Arizona–California border and extends eastward into south- eastern Arizona near the city of Tucson. The construction of the canal began in 1973 (starting at Lake Havasu City) and was completed in 1993 (reaching Tucson). The CAP canal extracts approximately 18.5 km3 (1.5 million acre-feet) of water per year from the Colorado River to meet the water demands of people living in Central Arizona. The Colorado River Compact of 1922 initiated the “Law of the River,” which ultimately separated the Colorado River Basin in two parts, upper and lower. The split was agreed upon by the seven basin states and federal government to meet growing demands for water in the lower basin states. Each half (upper and lower) was granted rights to 7.5 million acre-feet (maf) of water annually from the Colorado River (U.S. Bureau of Reclamation, 2008). The Boulder Canyon Project Act of 1928 ratified the Colorado River Compact of 1922 and allocated water to the lower basin states. Arizona received 2.8 maf of the 7.5 maf of Colorado River water.

Before construction of the CAP, many environmental impact assessments were conducted and their recommendations were implemented in the canal's construction. Several of these studies focused on disturbance of biology and archeological sites (CAP Environmental Section, 2009). To protect desert wildlife, several precautionary measures were implemented in the construction of the CAP, such as constructing special bridges for migratory land animals to cross the canal safely, avoiding bald eagle nests, fencing the canal to keep large animals away, and constructing a rough surface texture on the upper 1.5 m (5 ft) of the canal wall for smaller animals to safely crawl along the wall to drink water (CAP Environmental Section 2009). In the case of ephemeral streams that would be cut off by the canal, culverts and tunnels were built into the canal to allow larger washes to drain downstream.

The CAP canal blocks flow along numerous smaller ephemeral washes, blocking water and sediment from downstream movement; however, studies quantifying the effects of the CAP canal on the biogeomorphology of ephemeral washes in Arizona do not exist. In most cases, these desert washes extend for kilometers from their origins as overland flow on mountain fronts or steeply angled slopes, ultimately resulting in channel formation that extends to the valley floor. Most of the course of the CAP canal is built on alluvial fans and piedmont slopes, mainly avoiding the valley floor where most of the agricultural and urban areas are located. As an example of channel bisection by the CAP canal, to the south of Phoenix (Apache Junction to Tucson), the channels drain east-west where the concrete-lined canal is oriented north-south, causing a hydrological split of these channels.

Desert washes in Arizona exhibit rainfall runoff typically during the Arizona monsoon season and during winter storm events that generate sizable rainfall amounts. When a measurable amount of precipitation occurs, the channels of these washes flow downslope. In cases where the canal has blocked the connectivity of these washes to their downslope counterpart, water begins to pond and, in some locations, slowly flows laterally along the canal's embankment edge. From qualitative inspection, lateral flow seems to occur where there is more precipitation and depends on the size and closeness of adjacent washes. Washes that are closer together are more prone to lateral flow and become hydrologically connected to adjacent washes. Lateral flow may extend to a couple hundred meters from the canal's embankment. Storm systems that generate consecutive days of precipitation can cause ponding to occur over several days until the water has evaporated and/or infiltrated. Ponding of water over decades of storms in the desert has created "anthropogenic playas" where the channel artificially terminates due to the barrier of the canal, which causes both ponding and sediment deposition. The term anthropogenic playa will be used in this article to describe the upslope areas that receive deposition of sediment and ponded water (i.e., playa) that is human-caused by the canal barrier.

Characteristics of Dryland Rivers

Research on dryland river systems is complex due to the many natural variables that affect erosion, deposition, and plant growth, and contribute to dryland fluvial processes (Graf 1988). Two fundamental factors, precipitation and gravity, are well-known elements of morphologic change to a landscape (Harden and Scruggs 2003). Moreover, four additional major factors affecting erosion and deposition rates are rainfall intensity, topography, lithology and vegetation cover (Evans 1980; Reid and Laronne 1995; Nichols and Renard 2003; Bracken and Kirkby 2005; Griffiths et al. 2006). These variables are not easily measured because ephemeral river basins can have great spatial variability of these erosion controls. Rainfall varies more, spatially and temporally, in arid regions than in humid ones (Pilgrim et al. 1988). Furthermore, a simple correlation between rainfall and erosion cannot be easily demonstrated because all of the factors listed above contribute to sediment transport. In general, coarser sediment will have a greater infiltration capacity, whereas finer soils that are less permeable will produce more surface runoff. Typically, soils with high clay content are more resistant to erosion (Graf 1988) because clay is very cohesive. Surface runoff, as Horton overland flow, can erode surface material downslope, creating rills, gullies, and channels. Steeper slopes will cause faster runoff velocities, which increase erosion capabilities. Sediment is transported downslope and usually deposited on the gentler concave-up morphological domain of hillslopes. In channels, sediment can be deposited along channel bends where water slows down.

Sediment transport analyses are critical to quantifying erosion and understanding fluvial processes in dryland regions. Larger drainage basins, defined as > 1 km^2, have lower rates of sediment yield than smaller basins (Nichols and Renard 2003; Griffiths et al. 2006). In the Mojave Desert of southern Arizona, and in the Southwest U.S., studies have shown a relationship of increased drainage area to decreasing sediment yield specific to each region (Renard 1972; Strand 1975; Dendy and Bolton 1976). That is, drainage areas of the same size in southern Arizona and the Southwest U.S. have different sediment yields. This occurs due to the spatial variability of factors controlling erosion and deposition. Sediment transport is important to understanding and examining downstream changes and channel geometry. Understanding sediment yield through fluvial processes remains underdeveloped in arid regions (Reid and Laronne 1995; Griffiths et al. 2006). In the Southwest U.S., Merritt and Wohl (2003) showed that ephemeral rivers had higher than average rates of increase of channel width downstream after flooding when compared to the mean values for rivers across the world.

Interdependencies of Rivers and Vegetation

River systems and vegetation depend on one another for many symbiotic-like relationships in achieving or maintaining (quasi) steady state. Disequilibrium may occur when river systems are altered by humans, resulting in the breakdown of the interdependent relationship between fluvial systems and riparian areas (Hupp and Osterkamp 1996). The breakdown, which may be caused by human-induced system disturbance, can be considered a threat to the existence of the surrounding ecosystem and fluvial landscape. Many interdependent relationships exist in dryland rivers between vegetation processes and hydro-geomorphological dynamics. Vegetated riparian areas help stabilize streambanks and hillslopes from erosion in two ways: (1) slowing the velocity of water through drag; and (2) holding soil together through root systems. One study based on aerial photographs found agricultural floodplains to be 80%–150% more eroded than riparian forest (Micheli et al. 2004). Many researchers have concluded that root systems affect the rate of soil erosion and that, together with soil type, root architecture is a primary factor in vegetation- mediated stability (Ghidey and Alberts 1997; Mamo and Bubenzer 2001; Gyssels and Poesson 2003; Zhou and Shangguan 2005; De Baets et al. 2007).

River processes can provide the conditions of successful vegetation establishment. Several studies have examined seedling establishment and success of survival in relation to hydro-geomorphological conditions (Bendix and Hupp 2000; Levine and Stromberg 2001; Stromberg et al. 2007). Hydrological conditions allow for seed transport, whereas substrate alterations that aid in seed burial are attributed to geomorphological settings. Both play roles in seedling development. Unlike the distribution of riparian vegetation in river systems in humid areas, the spatial distribution of riparian vegetation in dryland river systems develops mainly as a function of water availability (Hupp and Osterkamp 1996). In arid basins, larger basins tend to have more vegetation on valley floors than uplands and support species specific to the valley floor (Zimmermann 1969).

Research needs to be carried out on the effects of human impacts on dryland river systems. With our limited knowledge of anthropogenically altered ephemeral systems, how do scientists and engineers determine the suitability of human-constructed features such as canals along desert washes? More field work and image analyses of human-obstructed river systems will be needed to understand the long-term effects and changes potentially caused by humans. Very little research has been conducted on the long-term or short-term biogeomorphological effects of canals in arid landscapes. Although some limited research has been conducted—e.g., Beshay and Sallam (2001) on the effects of the Ismailia Canal in Cairo, Egypt on changes of physical and chemical soil characteristics and Krausman et al. (1993) on the effects of the CAP canal on desert mule deer populations—I have not encountered any studies quantifying the effects of canals on the biogeomorphology of ephemeral streams.

STUDY AREA

The study area is located at 33°12’15.17” N, 111°29’32.85” W near Apache Junction, Arizona. The site was chosen based on the following main criteria (Fig. 1): (1) the ephemeral stream under investigation did not have a tunnel or culvert that released flow downstream via the CAP canal; (2) no urban areas were directly above the wash; (3) aerial photographs were available for the site before and after construction to quantify change that may have occurred to the landscape due to the canal; (4) the study site could be accessed by motorized vehicle; and (5) the wash was relatively undisturbed, meaning that no urbanization occurred in the period between canal construction and the present. Due to the lack of a tunnel or culvert into the CAP canal, sediment and runoff are impounded upslope from the canal during storm events. Ephemeral washes in the Apache Junction area are situated on alluvial fan deposits approximately 13.7 km long against the base of the Superstition Mountains. To the southwest of the study area are agricultural lands downslope from the canal. Plant species identified in the field were native Arizona desert trees and shrubs, mainly mesquite (Prosopis juliflora), desert broom (Baccharis sarothroides), and a few creosote bushes (Larrea tridentate).

Documents from the CAP canal office detail the years sections of the canal were built; construction of the stretch of the canal under investigation was completed between 1986 and 1987. The field site is characterized by an average regional slope of approximately 0.004. The drainage basin area of the studied ephemeral wash is small, estimated at 0.28 km2. As estimated from a 1973 aerial photograph, the approximate length and width of the main channel are 240 m by 1.3 m, respectively. Within the drainage basin area, the field and mapping studies were conducted within and around the anthropogenic playa (0.023 km^2), which was visually outlined from current aerial photographs that depicted a more vegetated and darker (i.e., moist) area down-channel as the wash approached the canal boundary (Fig. 2). Parts of the area are owned by the State Trust, Maricopa Flood Control District, U.S. Bureau of Reclamation, and the Central Arizona Water Conservation District (CAWCD).

METHODS

A mixed-method approach, involving field and aerial photographic analyses, was used to answer the research questions. High-resolution aerial photographs were used to quantify changes in vegetation canopy cover and in the spatial distribution of vegetation upslope from the canal for the studied ephemeral wash. Change detection techniques were implemented on temporally varying aerial photos using ArcMap to observe changes in riparian vegetation areas along this wash. The aerial photos were also used to delineate the position of the ephemeral channel before and after canal construction. The current channel position was also ground truthed in the field after a winter storm event.

The soil stratigraphy upslope and downslope of the canal were examined to determine the pre-canal soil layer and measure the upslope sediment deposition that occurred after canal construction. The depth of sediment accumulation behind human-made obstructions was measured by shoveling a cross-section through the soil to obtain a stratigraphic section to compare sediment layers behind and below the obstruction (Griffiths et al. 2006). Theoretically, a barrier that hampers flow will cause sediment to accumulate upslope. As a result, a sediment layer will be present upslope, where sediment accumulates, but not downslope, as observed in the field. The holes dug to examine sedimentation based on soil stratigraphy were chosen in and around the anthropogenic playa to determine a distinct depositional boundary zone; that is, to delineate the boundary between desert floor and playa. Most of the sediment deposition was speculated to be within the anthropogenic playa, with less sediment deposition expected at point locations within the playa farther from the canal boundary. Holes were excavated at random locations within the study area because of the difficulty maneuvering a tape measure through the dense thorny shrubs. A total of 77 stratigraphic soil sections were examined in the field. The depth of sedimentation and GPS location of each hole were recorded to overlay sedimentation amounts on the aerial photos for analysis in ArcMap. The digitized vegetation layer was overlain onto sediment deposition totals to determine whether or not a relationship exists between aggradation and the spatial distribution of vegetation. Sedimentation data were used to examine changes in channel geometry and the depth of sediment to indicate the direction of water flow.

A distinguishable whitish-grey clay layer with little or no laminations was present upslope from the canal, but absent downslope from it. The layer below the “post- canal depositional layer” was a reddish sandy layer marked with flow laminations, and some sites contained coarser sediments (~4 mm) embedded within the laminations. The uppermost whitish-grey clay layer was distinguishable from the layer below it by color differences, grain size, and texture (Fig. 3). The whitish-grey layer had a silky feel, while the reddish layer had a rough texture. These holes were brushed with a fine goat-haired paintbrush to locate the textural boundary and determine the unit’s thickness. In holes where unit boundary lines were difficult to determine, the end of the brush was used to scrape the sedimentary units. Magellan Promark 3 GPS system with sub-meter accuracy was used in the field to record latitude and longitude coordinates of each hole. These points were then used to interpolate the sediment depth of the study area in ArcMap.

Ordinary kriging is a random function model used to predict unsampled neighboring values through spatial correlation and weighted linear combination of known point values. Many studies have used kriging techniques to interpolate flow, such as groundwater movement (Cameron and Hunter 2002; Ta'any et al. 2009) and sediment transport direction (Lucio et al. 2006). In this study, ordinary kriging was implemented to develop the spatial representation of interpolated sediment depths that was then used to examine flow patterns and relationships between vegetation and sediment aggradation. ArcMap was used to produce a kriged map of sediment deposition using 73 random sample points (four points below the canal were excluded from interpolation).

The four aerial photographs used in this analysis were from years 1973, 1993, 2007, and 2009. Two of them were single-frame, high-resolution aerial photos acquired from the U.S. Geological Survey (USGS); both images had been taken at a height of 4572 m (15,000 ft) and a ground scale of 9144 m (30,000 ft). They were taken during Arizona summer months, one in September 1973 and the other in June 1993. Both images were of high quality—quality 8 and zero cloud cover. Also, both images had been captured at a vertical cartographic angle. A 3° tilt on a 1:20,000 scale image can cause a 60-m horizontal inaccuracy (Crowell et al. 1991). This was avoided by selecting aerial photos that were captured at the same angle. Only two aerial photos were found from the USGS archive that had been taken before and after 1986/1987 (CAP construction) that were of the same pixel resolution and angle. Pixel resolution for both images is 0.762 m (2.5 ft). The other two aerial photographs, for years 2007 and 2009, were acquired through Maricopa County Flood Control District. These images have a higher pixel resolution: 0.2438 m (0.8 ft) for both images. The images were taken in November 2007 and October 2009. These images were projected in Stateplane NAD 83 HARN and rectified by Maricopa County with a positional accuracy of ±1.524 m (5 ft).

The 1973 and 1993 images acquired through the USGS Earth Explorer website were rectified using digitized ground control points (secondary control points) of features present in those and present-day images (Thieler and Danforth 1994). Latitude and longitude coordinates for the four corners of the unrectified images were known points given in the USGS Earth Explorer website. The four corners of the image, along with ground control points from agricultural crop land corners and roads, were added as points into ArcMap 9.3. These points, along with the pre-rectified aerial photo from Maricopa County, were used to rectify the image in ArcMap using the georeferencing tool.

Aerial photos were used in this study for change detection analysis (Jimenez et al. 1997; Bailey and Pearson 2007; Fletcher et al. 2009). The aerial photos were manually digitized in ArcMap 9.3 using the stream mode method, allowing objects such as vegetation and channels to be traced, which is ultimately less time-consuming than clicking each vertex (Bailey and Pearson 2007). The tolerance was set to a 0.3 m (1 ft) mapping unit and to group 50 points together when streaming.

The area selected for mapping environmental changes had a basin area approximately 0.28 km^2 (3,013,895 ft^2), in which the anthropogenic playa area of the basin area was approximately 0.0234 km2 (251,813 ft^2). The basin area was calculated using a 10 m digital elevation model (DEM) by utilizing Spatial Analyst algorithms within ArcMap 9.3. The study area's extent, a portion of the total basin, is approximately 213 m (700 ft) in length and 120 m wide (394 ft) (Fig. 2). The extent of the anthropogenic playa area used to detect riparian vegetation change was arbitrarily determined from the earliest image of 1973 (Fig. 2). That same area was digitized for aerial years 1993, 2007, and 2009 to quantify vegetation changes. The extent was drawn based on two criteria: (1) the surface was much darker, indicating higher moisture content in soils; and (2) vegetation cover was greater than in the surrounding area. Figure 2 illustrates the extent within the perimeter line that has a higher cluster of vegetation and darker surfaces than seen outside of the line.

The lower resolution aerial photos for 1973 and 1993 were digitized by photographic interpretation of the display of vegetation in terms of albedo, shape, and shadow displayed in the aerial image. Vegetation in these images was distinguished by examining specific vegetative attributes such as linear bands, concentric clusters, darker reflectance of vegetation than desert floor, and shadows cast by vegetation canopies. In some cases, sediment deposits have an albedo similar to that of vegetation; however, by the rounded shapes, coarser textures, and shadows of vegetation, these two features were distinguishable. Because these images are too coarse for individual tree detection, vegetated areas were mapped as regions or clusters. That is, maps of the images for years 1973 and 1993, with coarser spatial resolutions, were based on total amount of vegetation canopy cover, where mapping individual trees was not necessary because the goal was to estimate the percent of vegetation change over time. To classify individual plant species, 10 to 50 cm pixel resolution would be necessary (Murden and Risenhoover 2000). The

2009 aerial photo has a pixel resolution of 0.2438 m (24 cm), while the aerial photo for 1973 has a pixel resolution of 0.762 m (76 cm). A method to compare the two was formulated by deleting any vegetation digitized in the 2009 image that had an area less than 0.58 m^2 (0.762 m × 0.762 m), because the smallest area that could theoretically be detected in the 1973 image with a pixel resolution of 0.762 m is no less than 0.58 m^2. One assumption was that all mapped vegetation had equal length and width. In the 2009 and 2007 images, vegetation areas that are 0.0594 m^2 (0.64 ft^2) or greater could be detected, but for a fair comparison after digitizing, polygon areas between 0.0594 m^2 and 0.58 m^2 were deleted. Furthermore, individual trees were mapped in the 2009 and 2007 images rather than mapping clusters of vegetation, to ensure vegetation area accuracies.

When mapping vegetation, shadows cast by the vegetation were not mapped as part of the vegetated area. Individual trees were also mapped by carefully examining any spaces or shadowing between trees. After digitizing the four aerial photos, the total areas covered by vegetation were subtracted to calculate the amount of change from 1973 to 1993, 1993 to 2007, 2007 to 2009, and 1973 to 2009. Analysis tools in ArcMap were used to create a better visual representation of spatial changes of vegetation over time.

RESULTS

The percent increase of vegetation was greatest from for the period 1973–2009, at 477% (Table 1). The spatial distribution of vegetation also changed considerably in those 36 years (Fig. 4A). Percent vegetation decreased only between 1973 and 1993, by 2.3% (Table 1), reflected by the fact that the number of vegetation-containing polygons mapped for 1973 was greater than for 1993 (Table 2). Vegetation distribution and changes in vegetation cover from 1973 to1993 are also shown in Figure 4B. Vegetation cover increased in 2007 and 2009 when compared to earlier years; from 1993 through 2007, percent vegetation increased by 318.2%, and grew by 41.5% from 2007 to 2009 (Table 1).

Upslope from the canal, sediment accumulation depths were greatest farther downstream closest to the canal boundary, whereas sediment accumulation depths for the same unit downslope from the canal measured zero (Figs. 5A and 5B). Depths of sediment accumulation ranged from 0 to 5.7 cm in and around the upslope study area. However, no clear playa boundary was determined due to lateral flow along the canal (Fig. 6). In this study area, the larger washes were laterally connected with smaller ones so that sediment yield per wash could not be calculated. Figure 5A shows a decrease in sediment deposition outside the boundary to the northwest, but only one sample hole measured zero deposition. The amount of sediment deposited by lateral flow remains unknown. However, the results reveal that the main ephemeral channel in this study supplies sediment, as seen in the northeast section of Figure 5A (above the dirt road).

Statistics for the kriged sediment depth output map are given in Table 3. In general, the output map shows the path in which water flows (Fig. 7). The path defined by the contours in the kriged map appears to follow the same path as that examined in the 1973 photo (Fig. 8). Sediment accumulation depths follow the original channel's path, whereas vegetation distribution within the anthropogenic playa does not exhibit such a distinct pattern. In the field, the channel becomes shallower and narrower farther downslope, until it disappears. The channel stops where the greatest amount of sediment has accumulated (Fig. 8). The channel length has shortened by approximately 13.7 m (45 ft) since 1973 (Fig. 8).

DISCUSSION

Along the northwestern and southwestern boundaries in Figure 4A, closely clustered vegetation marks the presence of flow. The vegetation near the center of the figure has larger tree canopies than the tree/shrub canopies mapped closer to the study area boundaries. This is most likely due to the channel's original and current location, which is mainly in the center of the study area. Because water has been flowing in the center longer, it was expected that vegetation areas would be larger in and around the main channel. The percent increase of vegetation calculated for 2007–2009 is mainly due to individual vegetation units growing larger and thereby producing a greater canopy cover (Fig. 4C). The mapped vegetation displays concentric bands of single vegetation units, which shows that vegetation growth was mapped along the boundary of pre-existing vegetation.

The greater number of vegetation polygons in 1973 than in 1993 indicates that fewer individual trees were present in 1993 than were mapped in 1973. This unforeseen result is most likely a consequence of construction. Approximately 7 years after the canal was built, in 1993, vegetation cover would have been expected to have increased upslope from the canal where water pools after runoff events. Visual inspection of vegetation changes from 1973 to1993 showed that vegetation decline also occurred along neighboring washes. It is possible that this vegetation was removed or run over by construction vehicles, causing vegetation to diminish in some spots. There was no field evidence suggesting that the loss of vegetation was natural. There were no signs of buried twigs or bio-layers in the sediment that would have been caused by a natural episode such as a massive flood event. Also, there were no unusually large quantities of dead tree debris that could have been caused by the inundation of trees for long periods of time, causing them to die. Thus, ecological disturbance through the canal's construction is the most probable cause in this case of tree decline seen from 1973 to1993 (Fig. 4B). However, after 1993, vegetative cover increased significantly in the intervals 1993–2007 and 2007–2009, likely owing to moisture retention upslope from the canal. Overall, from 1973 to 2010, the vegetative cover upslope from the canal increased by 477%. The percent increase of vegetation calculated in the last 35 years appears to be primarily a function of water availability. The presence of riparian vegetation in dryland river systems is controlled mainly by the quantity of water available (Hupp and Osterkamp 1996). This control variable for desert vegetation helps explain the lack of a spatial pattern between sediment aggradation and vegetation distribution (Fig. 7). In this study, it is clear that water availability has been the primary factor in vegetation growth.

The presence of the CAP canal diverts runoff along the canal boundary upslope from the study area due to the restrictive barrier it has created. Water impounded by the canal pools and moves laterally (Fig. 6). Soil color reveals this horizontal water line, with soils having higher water contents exhibiting a darker surface in the aerial image. Due to the lateral motion of surface water along the upslope canal boundary, density and distribution of vegetation are relatively uniform outside of the main channels within the water-line border. In the study area within the anthropogenic playa, vegetation cover decreases with increasing distance upslope from the canal boundary beyond the water line (Fig. 6). Within the active main channel of the ephemeral wash, vegetation cover remains relatively constant upslope from the canal.

Because all of the washes in the area become laterally continuous at a level upslope from the canal where water pools, sediment could have been carried by and deposited laterally from other washes, skewing sediment yield calculations. A study conducted by Griffiths et al. (2006) measured the amount of sediment yield along small drainage basins in the Mojave Desert where railroad beds blocked flow. Their measurements of point-specific sediment deposition, ranging from 0 to 38 cm over a 94-year period, indicate that deposition measurements over an estimated 24 years in this CAP study are within reason. Sediment accumulation is not a linear function because it is controlled by lithology, rain intensity, vegetation cover, and slope, all of which affect transport in each catchment differently. The interpolated map of sediment accumulation depths aids in the visual context of spatially distributed sediment accumulation (Fig. 7), whereas the point-specific measure of sediment aggradation (Fig. 5A) represents an expected range of values for a small ephemeral wash, in this case is 0 to 5.7 cm.

At the end of a channel, sediments will usually be deposited in a depression; for a channel to end and deposit sediment on sloped ground is not typical in natural washes. In this location, the channel stops because the CAP canal blocks flow (Fig. 8), restricting sediment from naturally moving downstream and causing the channel length to have decreased by ~13.7 m since the construction of the canal. The presence of the canal causes backwater in the channel, which slowly infiltrates the surface over time, deposits suspended sediments, and causes the channel to ultimately fill with sediment. Stormwater impounded upslope after a winter storm event was also documented in the field (Fig. 9B). Over time, the channel should slowly become shorter, as sediments fill the channel from the canal boundary onward toward the northeast.

CONCLUSION

The goal of this paper was to examine the following questions: (1) How much sediment is trapped upslope from the canal over time? (2) Are sediment deposition patterns related to changes in the spatial distribution of woody vegetation canopy cover? (3) What are the effects on channel geometry, changes to vegetation spatial distribution, and changes to total amount of vegetation over time due to the presence of the canal, which causes water retention upslope?

At 77 sites, analyzed for sediment accumulation, depths ranged from 0 to 5.7 cm within the studied anthropogenic playa boundary. Aerial images for years 1973, 1993, 2007, and 2009 were obtained to digitize vegetation patterns and densities. Changes in vegetation for these years were quantified using change detection techniques in ArcMap. The most notable vegetative change was a 477% increase in vegetated area between 1973 and 2009. This green-up in vegetation upslope from the canal is mainly attributed to the conditions of increased moisture caused by the restriction of water runoff downslope. Because runoff fills the anthropogenic playa during substantial rainfall events, vegetation is relatively dense within the playa. Larger, more mature trees are located in the center of the playa along the main channel.

The flow path of the main channel has seemingly not changed since the canal was constructed. The interpolated sediment depth map represents flow direction where measured sediment accumulation resides along the original flow path. However, the main channel within the anthropogenic playa has been shortened by approximately 13.7 m due to sediment deposition. This was determined by field surveying after a winter storm event when the upstream end of the channel was recorded using a GPS and compared to the length of the original channel in the 1973 aerial photograph.

Sediment accumulation and woody vegetation distribution do not exhibit a predictable relationship within this study area. The 2009 mapped vegetation was overlaid onto the sediment deposition map in ArcMap to determine the possibility of a spatial relationship between woody vegetation and sediment accumulation or distribution. The increase in vegetation cover is primarily attributed to the ponding of water after storm events due to the land barrier created by the CAP canal. This research lays the groundwork for understanding ways in which canals affect the surrounding desert environment by presenting a general understanding of the environmental impacts of bisecting a desert wash. This study may guide future research in better understanding biogeomorphological processes in drylands affected by existing canals and proposed canals.

Table 1. Percent of vegetation increase and decrease between different time ranges.

Period:	1973–2009	1973–1993	1993–2007	2007–2009
Percent increase	477	–2.3	318.2	41.5
Change in area (m^2)	5397.2	–26.2	3514.0	1916.8

Table 2. Number of polygons mapped for each year and total area occupied by vegetation.

Year:	2009 All	2009 > 0.58 m^2	2007 All	2007 >0.58 m^2	1993	1973
N of	710	680	451	442	208	380
Total area	6539.4	6527.8	4622.6	4618.4	1104.4	1130.6

Table 3. Statistics from ordinary kriging of sediment depth in study area.

Root-Mean-Square	Average Standard Error	Mean	Mean Standardized	Root-Mean-Square Standardized	N of Samples
0.9747	0.9499	0.009525	0.0001434	1.033	73 of 73

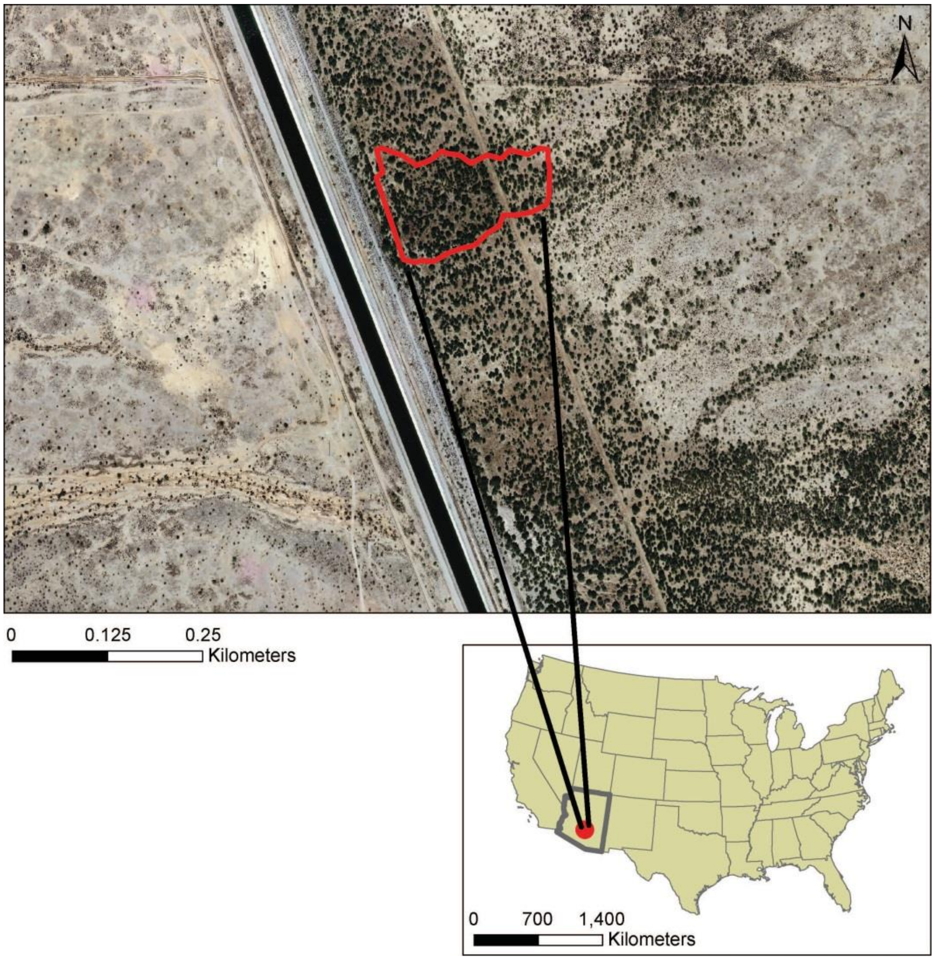


Figure 1. Location of the study area. There are no culverts or overchutes that connect the upper channel to its downstream section, as seen in the aerial photograph.

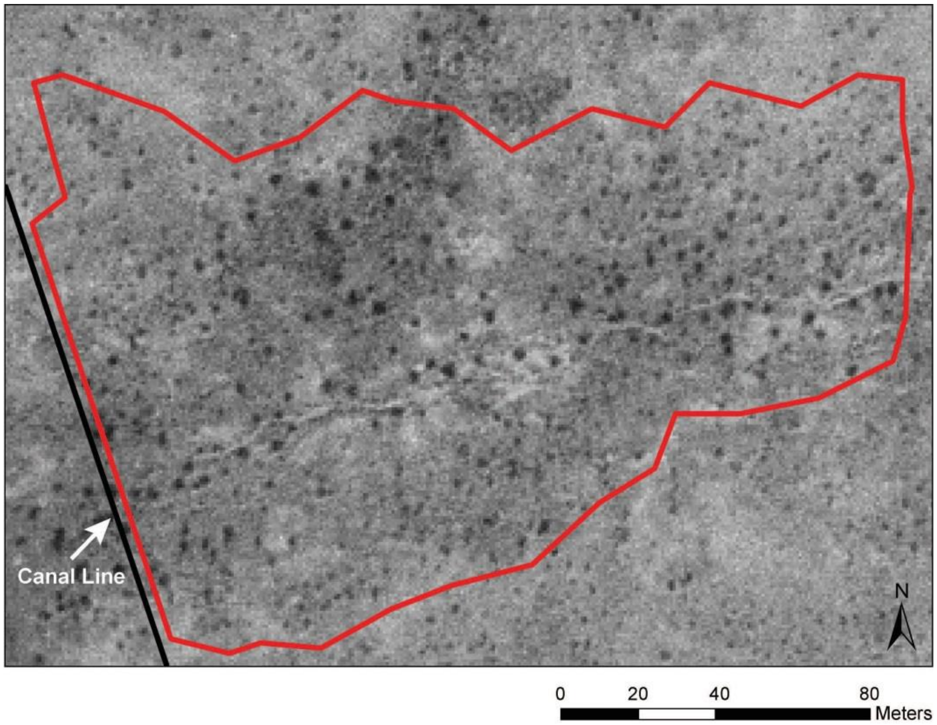


Figure 2. Aerial photo of the mapped area taken in 1973, prior to canal construction in 1986/1987. The wash channel is in the middle of the outlined area. Location "A" was a secondary channel that connected to the main wash in the outlined study area.

Figure 3. Layers of sediment in the study area. The uppermost (whitish-grey clay) layer is distinguishable by a subtle color change; its boundary with the reddish sandy layer below is marked by the black line adjacent to the ruler.

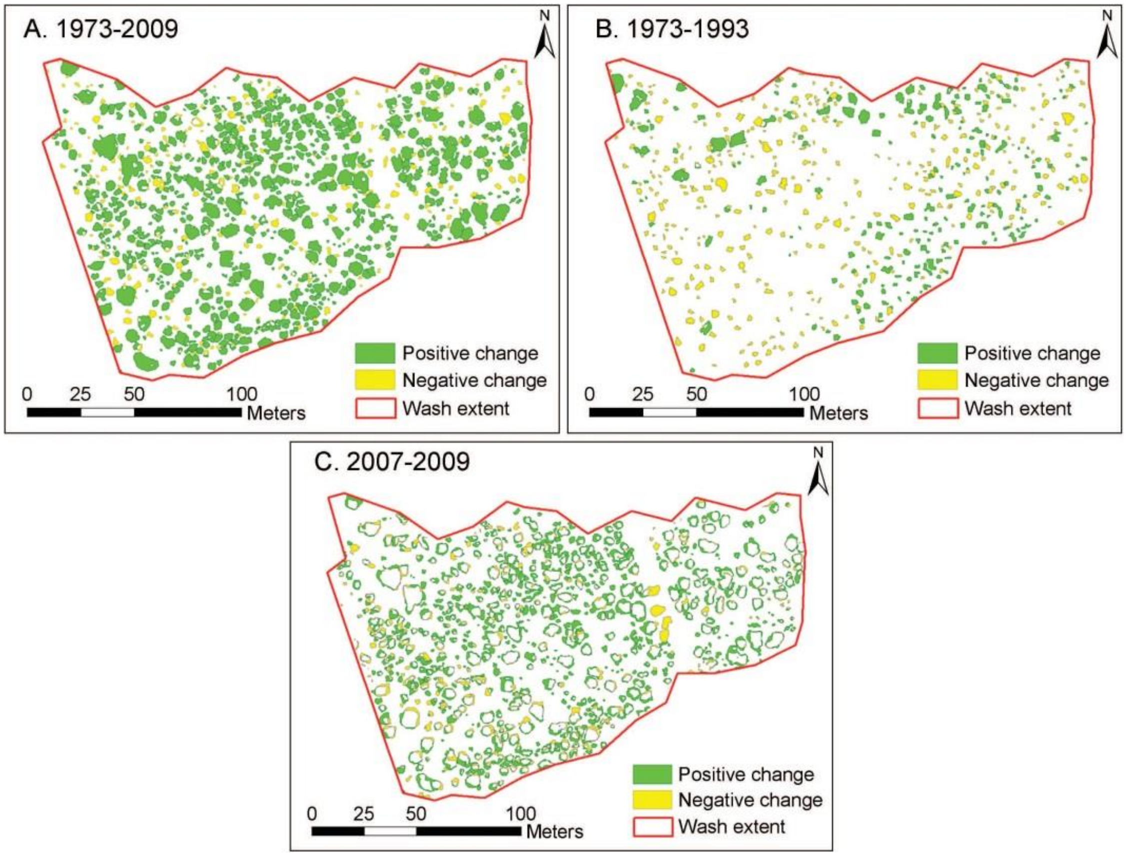


Figure 4. The spatial distribution of vegetation change in the study area. Green patches in A and B show sites where vegetation that had not been present in 1973 appeared later; yellow represents vegetation present in 1973 but not in the later year. A. Changes between 1973 and 2009. B. Changes between 1973 and 1993. C. The spatial distribution of vegetation change between 2007 and 2009. Green shows vegetation that had not been present in 2007 and yellow represents vegetation what was present in 2007 but not in 2009. The four larger yellow patches near the center are locations where vegetation was believed to be removed to expand the dirt road that cuts through the study area. The dirt road was wider in 2009 than in 2007.

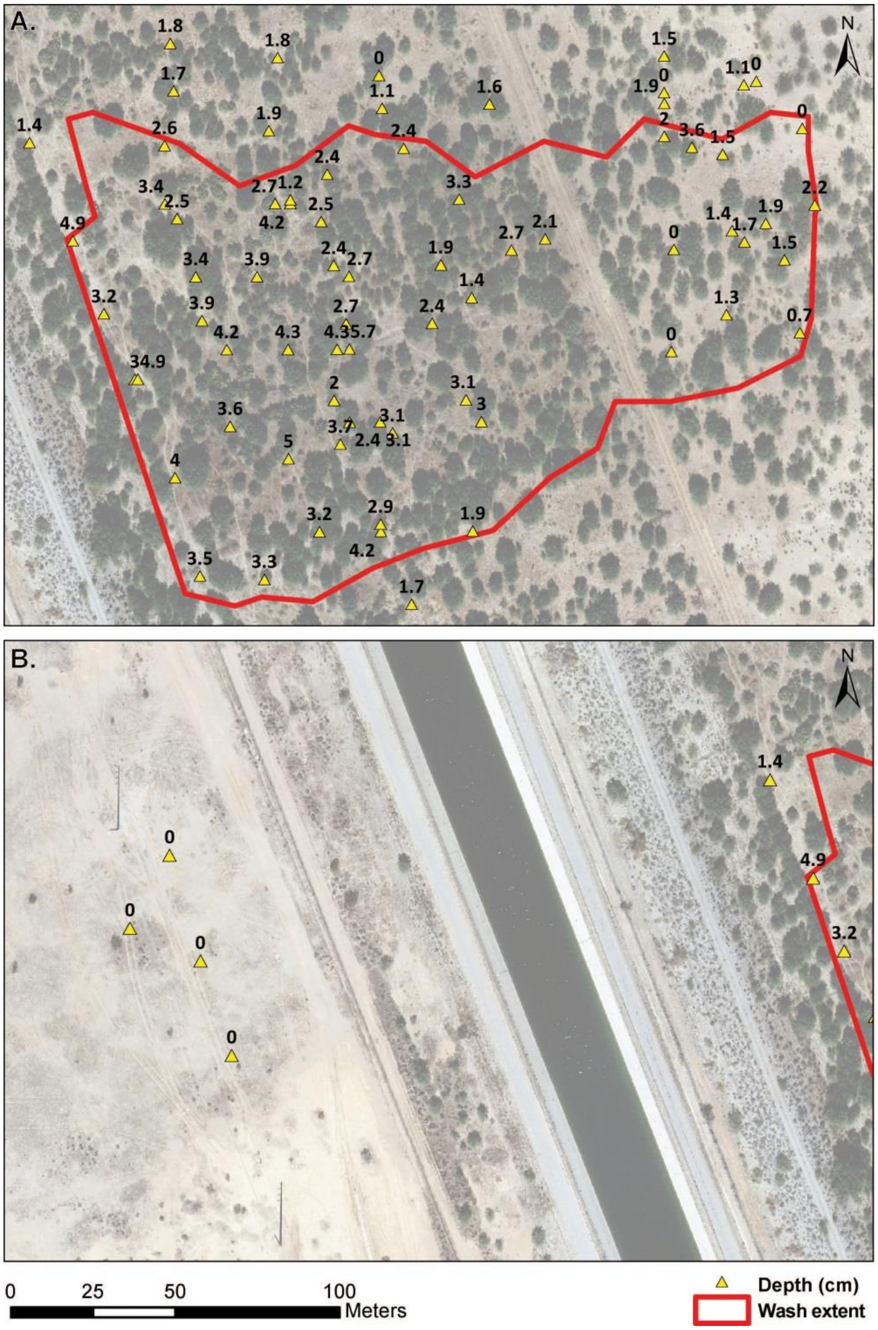


Figure 5. Depths of sediment accumulation (in cm) collected in holes dug at 77 random points within and outside the study area boundary to determine the playa extent of the study wash. A. Upslope from the canal; numbers are depth of deposited sediment in cm. B. Downslope from the canal; no sediment accumulated.

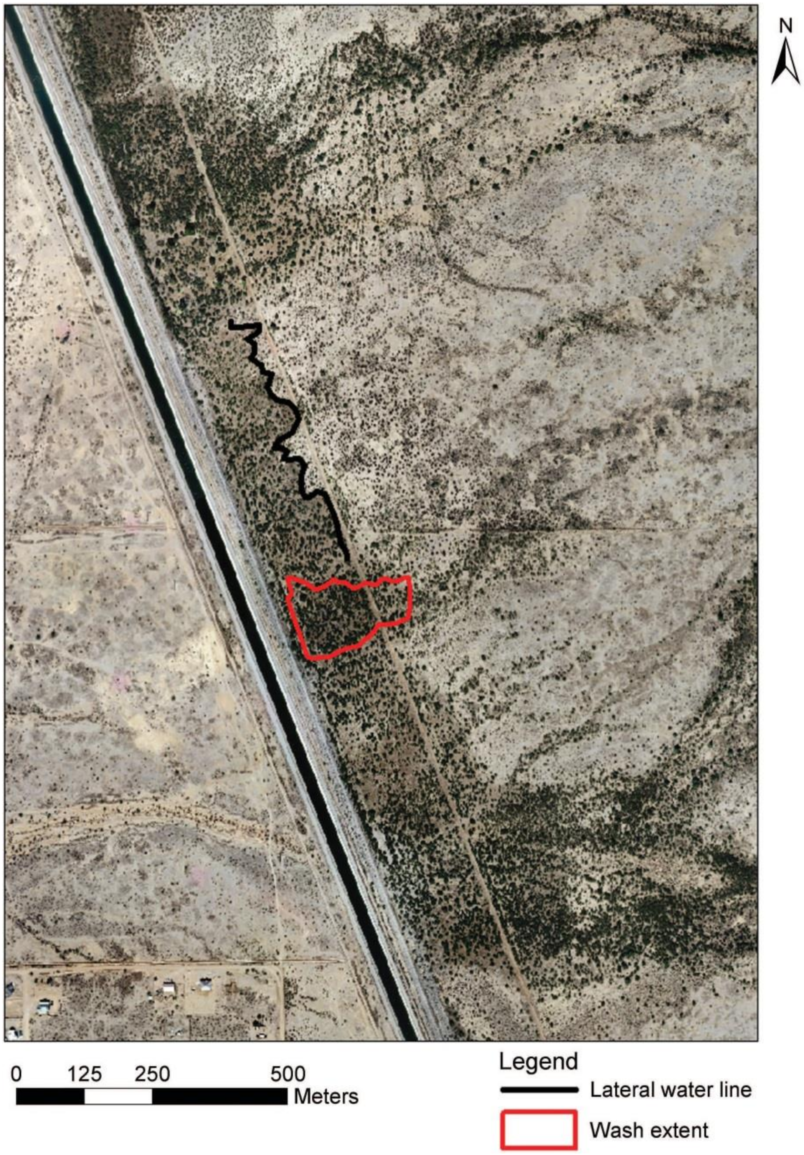


Figure 6. The CAP canal and the study area. The black line shows the uphill boundary of lateral overland flow, "the water line." The darker color of moist soil can also be seen to the southeast of the study area.

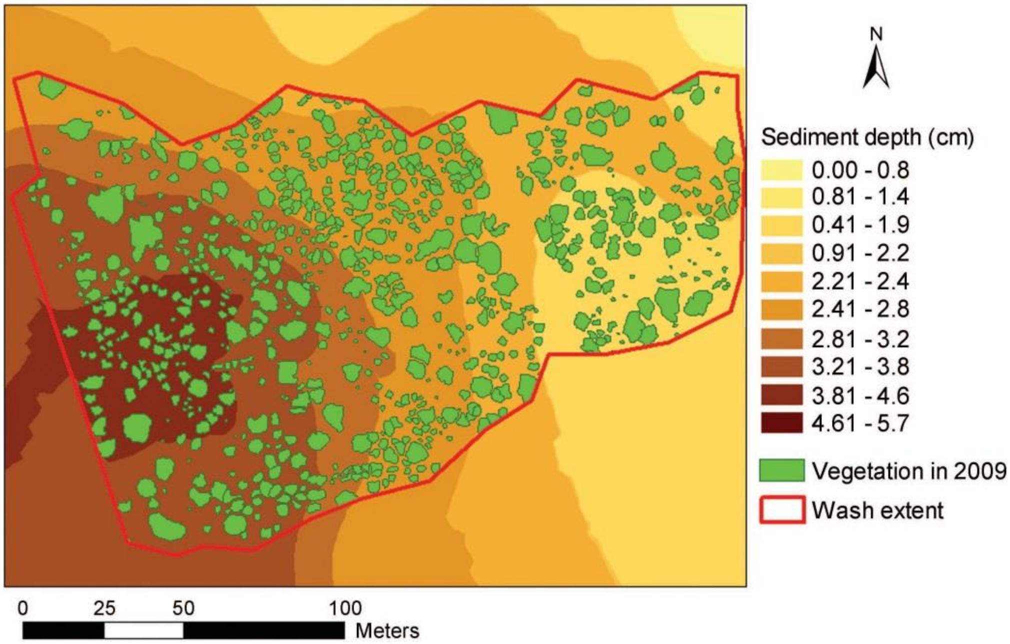


Figure 7. Interpolation map of sediment accumulation depths. The mapped vegetation (green) illustrates that sediment accumulation is not a dominant variable for the growth of riparian vegetation in this dryland river system.

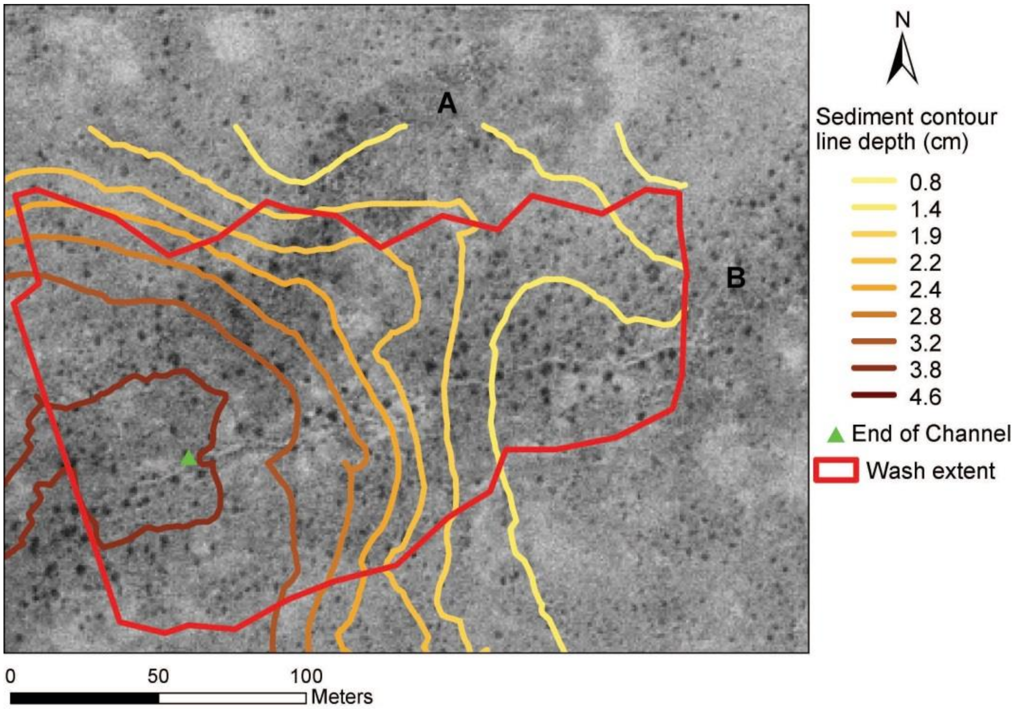


Figure 8. Comparison of the 1973 flow channel and depths of aggraded sediment. This map overlays the kriged map of current sediment depth on the 1973 aerial image. The green triangle marks the lower limit of the present channel. The distance between the green triangle and the end of the 1973 channel is ~13.7 m.

Figure 9. A. View facing southwest of storm water flows into the anthropogenic playa on January 23, 2010. The green triangle marks the end of the channel. B. Closer view, facing north, of water impounded by the canal.

3. BIOGEOMORPHIC RELATIONSHIPS AND RIPARIAN VEGETATION CHANGES ALONG ALTERED EPHEMERAL STREAM CHANNELS: A REMOTELY-SENSED ANALYSIS

ABSTRACT

In this study, we examine the effects of human impact on desert ecological systems due to altered stream flows. This study specifically examines riparian vegetation changes along ephemeral channels due to the emplacement of the Central Arizona Project (CAP) canal, which transects hundreds of streams in its path. The CAP canal is a land barrier that creates, otherwise unnatural, pooling conditions on the upstream side of the intersected channel. Two research questions examined are: 1) How has riparian vegetation changed over the course of 28 years due to altered flow conditions created by the CAP canal? 2) How has channel morphology affected changes in vegetation canopy cover? Five Landsat TM images acquired over the study area in 1982, 1989, 1996, 2003 and 2010 were classified using an object-oriented approach to examine changes in vegetation over time. The average change of vegetation per 0.5 km section over the 28 year period is approximately 100,436 m^2 over 25.5 km length of the canal that was examined. The results of this study can be applied to other semi-arid desert environments that are subjected to similar human disturbances.

INTRODUCTION

The emplacement of human-constructed obstructions on land and in water can be viewed as ecologic and geomorphic barriers. A physical barrier alters ecologic function and geomorphic form causing the system to respond and/or adjust due to changes in processes. The types and sizes of barriers vary and can include obstructions such as, roads, fences, dams and canals. Studies conducted on the effects of terrestrial barriers on surrounding ecology typically deal with understanding changes to wildlife diversity, genetic diversity and migratory changes (e.g. Epps et al. 2005; Holderegger and Di Giulio 2010; Krausman et al. 1993). Moreover, research regarding the geomorphology and hydrology of a dammed river system mainly focuses on changes to channel structure, sediment transport, erosion and deposition (Dawdy 1991; Webb et al. 1999). The majority of these studies are conducted on perennial river systems whereas little research has been conducted on anthropogenically altered habitats and/or morphology in drylands. Understanding biogeomorphological changes, in this case, the alteration of ephemeral streams and habitat due to anthropogenic activity is a critically important subject. Multi-disciplinary work from both geomorphology and ecology must be applied to achieve a holistic understanding of the changed system (Corenblit et al. 2008; Hupp 1992). In general, the main goal of this paper is to understand how barriers across desert landscapes impact the surrounding riparian vegetation along altered ephemeral streams.

The foreseeable increase in the need for water supply caused by a rapidly growing population on a global scale, coupled with the likelihood of more people expected to live in urban environments, will enhance the need for water delivery systems especially in dryland regions. Approximately 33 percent of the Earth’s land masses are characterized as drylands, which is home to 15 percent of the world’s population (Parsons and Abrahams 2009). As we utilize Earth’s natural resources, water being the most precious, it is imperative that we understand the effects on our surroundings in order to properly embrace environmental stewardship. To support Arizona’s population growth, a large canal known as the Central Arizona Project (CAP) canal was constructed to transport water for municipal and agricultural use to cities throughout Arizona. Hundreds of ephemeral channels have been transected in the canal's path. In this paper, we examine how the surrounding desert riparian vegetation has changed due to the intersection of the canal across these desert streams.

The CAP canal begins at Lake Havasu City and stretches over 336 miles to its terminus in southeastern Arizona near Tucson. The construction of the canal began in 1973 starting at Lake Havasu City near the western Arizona-California border and was completed in 1993 in Tucson. The CAP canal extracts approximately 1.5 million acre-feet of water a year from the Colorado River to meet water requirements for people living in Central Arizona. The canal has built-in culverts or overchutes for larger ephemeral streams to flow downstream, whereas smaller streams are dammed causing stormwater runoff to pool upslope behind the canal wall/berm. The CAP canal creates two situations: 1) completely impounds the upstream-downstream connectivity of ephemeral channels or 2) modifies flow regimes of ephemeral channels through culverts and overchutes.

The pooling of water on the upslope side of the canal has led to noticeable vegetation changes, referred to in this paper as green-up areas. Semi-arid regions have sensitive thresholds where a small change in water supplied can produce substantial changes. Some changes in vegetation are so extreme that xeric regions have become drier leading to desertification, while other areas alter into more mesic environments on the upslope end near the canal's boundary. In one study, the amount of vegetation along one small ephemeral channel that was cut off by the CAP canal increased by 477 percent in the 36 year period analyzed (Hamdan 2012). The primary cause of this vegetation increase was due to increased water availability; sedimentation accumulation was not related to vegetation spatial distribution (Hamdan 2012). Less than 1% of lands in the western US consists of riparian vegetation zones supported along stream channels (Knopf et al. 1988). These dryland riparian zones are essential in supporting wildlife habitats and vegetation that merit further studies in ephemeral research (Crawford Zimmerman et al. 1999); it is important to understand the impacts and influences humans cause by constructing barriers across present and future desert landscapes.

This study is specifically aimed at examining the spatial pattern of vegetation with the following research questions: 1) How has riparian vegetation changed over the course of 28 years due to altered flow conditions created by the CAP canal? 2) How has channel morphology affected changes in vegetation canopy cover? We hypothesize an increase in vegetation along both completely closed off channels and altered channels (i.e. with overchutes or culverts). However, more vegetation biomass increases are expected where there is greater ponding, which mainly relies on the size of the catchment and whether it is completely impounded by the canal. This is the first study to date that quantifies vegetation changes along ephemeral channels on a broad scale and examines the relationship between vegetation changes and channel morphology due to a canal barrier.

STUDY AREA DESCRIPTION

The study area is situated within a section of the Basin and Range Province in southern Arizona. The mountain ranges consist of the characteristic Basin and Range orientation, which is northwest-southeast trending. This orientation causes most of the mountain drainages to runoff in the general northeast-southwest or southwest-northeast directions. The selected study area consists of numerous anabranching ephemeral streams being transected by the CAP canal in which all of the streams flow from northeast to southwest and the canal is positioned north-south (Figure 10). The darker areas that are on the northeast side of the canal are green-up areas from ponded runoff during storm events due to the CAP canal.

METHODS

Data

Landsat 4-5TM consists of seven bands in which all bands for the exception of the thermal band has a 30 meter spatial resolution. The spectral ranges of these bands are: 0.45-0.52µm, 0.52-0.60 µm, 0.63-0.69 µm, 0.76-0.90 µm, 1.55-1.75 µm, 10.40-12.50 µm, and 2.08-2.35 µm; respectively.

In total, five Landsat 4-5 TM images were used, beginning with the year 1982 proceeding in 7 year intervals leading to image year 2010. Image years consisted of 1982, 1989, 1996, 2003, and 2010. The specific dates of these images are: 21 Nov 1982, 15 Oct 1989, 18 Oct 1996, 22 Oct 2003, and 9 Oct 2010. The satellite images were available cloud-free and of high quality during the fall months of October/November from the USGS online server. The reference image captured in 1982 is the pre-canal construction image used to analyze changes of riparian vegetation after 1982. Approximately 82 km of the canal was constructed after the reference image, which spans from the cities of Florence (33° 0'4.23"N, 111°23'32.23"W) to Marana (32°30'39.42"N, 111°14'12.72"W) (Figure 11). The CAP canal is the black center line in Figure 11. The study area is approximately 4 km wide; a 2 km buffer from each side of the CAP canal was created.

Object-Based Image Analysis

The satellite images were classified in order to perform change detection analysis of riparian vegetation over time. A 2 km buffer around the canal boundary was used to examine the changes. The images were classified using a multi-resolution object-oriented approach. Multi-resolution segmentation also known as fractal net evolution approach (FNEA) is a bottom-up, region merging algorithm that begins with one pixel and merges contiguous spectrally similar pixels (homogenous) as well as considering other pixel qualities such as compactness and smoothness (Baatz and Schäpe 2000). The user can apply weights to the bands within an image for segmentation; that is, if the analysis focuses on band 1 and band 2 of a 5 band image, the user can assign greater weights to bands 1 and 2 during the segmentation process. There are three main criteria that are entered for segmentation procedures which are: scale (size), compactness and smoothness (shape). Compactness and smoothness are based on the smoothness of boundaries and compactness of edges. Based on the weighted image bands, scale is referred to as the maximum allotted heterogeneity for a single object, a larger scale parameter results in larger pixel-merged objects (Definiens 2008). There are no standardized methods for scale and shape settings, rather they are based on the user's decision through trial and error inputs (Yan et al. 2006; Walsh et al. 2008; Myint et al. 2011).

In object-based classification, an object is considered as a collection of pixels which contain spectral and spatial properties that are alike (Myint et al. 2008); whereas traditional per-pixel classification excludes analyzing spatial comparison of neighboring pixels such as texture, shape and general context within an image (Laliberte et al. 2004). Per-pixel classifiers have resulted in significantly lower overall accuracies when compared to object oriented classification methods (Walsh et al. 2008; Yan et al. 2006). Myint et al. (2011) reported a 22.8% increase in overall accuracy when classifying urban land cover using an object-based classification over per-pixel classification. An object-oriented image analysis software package known as Definiens Developer or eCognition, is increasingly used amongst environmental scientists in studies that map changes, identify riparian species, shrub detection, mapping forested areas and determining bank stability (Myint et al. 2008; Laliberte et al. 2004; Walsh et al. 2008; Johansen et al. 2008; Johansen et al. 2007; Bontemps et al. 2008; Gilmore et al. 2008; McGlynn and Okin 2006). This study uses Definiens Professional 8.0 to classify the image pixels.

Three classes within each Landsat image were classified using an object-oriented approach. The respective classes mapped were riparian vegetation, agriculture and xeric/lowland areas. Mountains that encompassed a small portion of the images were masked. The canal was unable to be accurately identified in Definiens, because the width of the canal was spatially smaller than the Landsat pixel size. Rather, the CAP canal was digitized in ArcMap 10.0 software package using the Landsat images as a reference. In classifying the images, each image was segmented at a scale level of 20 in order to classify larger objects, which were agricultural areas. Then, the images were further segmented to a scale level of 3 to classify smaller objects, in this case, riparian vegetation, xeric lowland areas and bare agricultural areas (Figure 12). The objects were classified in the following respective order: green agricultural patches, riparian vegetation, xeric/lowands and drier/less green agricultural patches. The values assigned to shape factor, compactness and smoothness were all constant for each image at both scale levels and were determined through trial and error. The bands were all weighted the same during the segmentation process. NDVI was used to classify riparian vegetation and agricultural areas using expert decision rules for all images (Figure 12). Furthermore, Nearest Neighbor Rule using the mean bands (i.e. layers in Definiens) in the decision process was implemented in classifying xeric/lowland areas and dry agricultural patches

(Figure 12). Also, manual editing was performed on these classes to achieve the highest possible classification accuracies.

The accuracy assessment test of these classified images was implemented using ERDAS Imagine software. Accuracy results of 85 percent or greater is the general standard for accurate mapping used in most resource management studies (Anderson et al. 1976; Townshend 1981). Seventy-five equalized random points for each class were assigned to each classified image. The original Landsat TM image was used as the reference image in the accuracy testing of the classified image using ERDAS Imagine software. Google Earth and several field observations on multiple site locations also aided in accuracy testing. Pixels in the original Landsat TM image that was used in the accuracy test were matched visually to fine resolution aerial and remotely sensed imagery in Google Earth to verify land cover classes. Thus, land cover pixels within the five classified Landsat TM images were identifiable based on current aerial photography in Google Earth and field surveying. After the accuracy assessment tests, the classification results from Definiens were imported into ArcMap 10.0 in the form of polygon shape files. ArcMap was used to quantify changes in vegetation areas over time. The canal's length was segmented into 0.5 km sections in order to examine average vegetation changes (m^2) per a 0.5 km length of the canal (Figure 13). Several sections were not included in the analysis due to suspected vegetation clearing, which was evident from the lack of vegetation detection within the 0.5 km sections in image years 1989 and/or 1996. In addition, some sections of the canal remained barren throughout time mainly due to the absence of channels or riparian zones. In all, 51 sections, approximately 25.5 km, were analyzed.

Channel Measurements

Lastly, average channel widths were measured using Google Earth to determine a relationship between vegetation green-up and channel widths. In this part of the analysis, the green-up zones suspected of having vegetation cleared were avoided. Seventeen completely cut off channels and six altered channels were used in this analysis, which were the maximum possible observations obtained in this study area. The altered channels consisted of having one overchute connecting the channel to flow downstream. Assuming uniform channel depths, the greater the channel's width the greater the amount of storm water flowing through it. Due to the anabraching nature of these ephemeral channels, each adjoining channel that fed into the pool (i.e. green-up zone) was summed to calculate the total average channel width. This formula can be expressed as:

$$\sum \bar{\mathbf{W}}_{\mathbf{Total}} = \bar{\mathbf{W}}_{\mathbf{1}} + \bar{\mathbf{W}}_{\mathbf{2}} + \bar{\mathbf{W}}_{\mathbf{3}} + \ldots \bar{\mathbf{W}}_{\mathbf{n}}$$

RESULTS

Accuracy Assessment

The classification accuracy results of the Landsat TM images were all fairly high in which all were above 85 percent accuracy (Table 4). The overall accuracy of classifying riparian vegetation, agriculture and xeric lowland areas were 95.0% (Yr 1982), 93.3% (Yr 1989), 96.0% (Yr 1996), 94.6% (Yr 2003), and 94.2% (Yr 2010). Producer's and user's accuracy results for the riparian vegetation class ranged from 90.6% to 98.5% depending on the image year (Table 4).

In some cases, the accuracy results for riparian areas are not as high as agriculture and xeric/lowland classes due to some signature confusion between both: agriculture and riparian vegetation, and riparian vegetation and xeric/lowland desert areas (Table 4).

Agricultural areas provide some signature confusion between riparian vegetation when the two classes are adjacent to one another. In some infrequent cases, streams intersect agricultural plots in which case riparian vegetation grows next to agricultural crops, and since the two classes rely on the same bands 3 and 4 to detect vegetation this can produce signature confusion. Riparian vegetation and xeric desert areas may also exhibit signature confusion due to fuzzy boundaries and the mixing of adjacent pixels between riparian vegetation and xeric areas. It is visually clear that vegetation cover has increased over the 28 years from 1982 to 2010 (Figure 14). Figure 14 illustrates a small representation of the study area, which visually displays the changes in vegetation area of the classified images. In the 2010 image, there is a clear indication of the situation of the CAP canal from the way in which the vegetation is laterally connected north to south along the canal. Vegetation growth is localized to the canal boundary in areas of ponding after storm events. That is, the length of green-up areas from the canal's boundary does not extend very far upslope along the channel. The average length of green-up zones from the canal's boundary is approximately 188 meters over a 28 year period. Furthermore in some cases, vegetation growth became laterally connected over time as impounded waters were inhibited from flowing downstream.

Change and Spatial Analysis

Figure 15 illustrates the changes in vegetation area within each 0.5 km section. In total, there were 51 half-kilometer sections that were analyzed (x-axis). Overall, the change in vegetation cover increased substantially from 1982 to 2010; however, vegetation cover decreased consistently in the 0.5 km sections analyzed from years 1996 to 2003 (Figure 15). The greatest changes in vegetation area within the 7-year intervals are from years 1982 to 1989 and from 2003 to 2010. The time between 1996 to 2003 was the only interval that underwent a negative change (Figure 15). The total average change in vegetation within each section varied with image year intervals (Table 5). Overall, vegetation increased within each section over the 28 year period, which can be visually examined in Figure 15. The average change of vegetation per 0.5 km section over the 28 years is approximately 100,436 m^2 over 25.5 km of the canal. This equates to a vegetation increase of roughly 200,872 m^2 per kilometer of the CAP canal over a 28 year period. The total amount of vegetation green-up in the 28 years over the 25.5 km length of the canal is approximately 5,122,239 m^2.

There is a significant linear relationship between changes in vegetation cover and channel widths from 1982 to 2010 (Figure 16). There is a greater correlation between this relationship when comparing the channels with connectivity (i.e. overchutes) than streams without connectivity (Figure 16). There is a greater overall increase in vegetation along channels that are completely impounded than channels that are semi-connected denoted by the steeper sloped regression line for impounded channels. Both data display a relationship of expected increase in vegetation cover on the upslope side of the canal with larger channel widths. The coefficient of determination for impounded channels is approximately 0.7027 (n=17), whereas the connected channels value is about 0.93 (n=6). We understand that the number of samples is relatively low. Within the 25.5 km stretch of the study area along the CAP canal, this was the maximum sample number of streams that were discernible. Nonetheless, the relationship is statistically significant.

DISCUSSION

On average, vegetation increased by 200,872 m^2 per kilometer of the CAP canal over a 28 year period; and a total increase of approximately 5,122,239 m^2 was analyzed along the 25.5 km length of the canal. There is substantial increase in riparian vegetation due to the emplacement and bisection of the CAP canal on ephemeral streams over the 28 year period (Figure 13). Unlike riparian vegetation in humid environments, water availability is the primary factor for vegetation growth and abundance of riparian vegetation along dryland channels (Hupp and Osterkamp 1996). The spatial distribution of vegetation along perennial rivers is controlled mainly by fluvial landforms (e.g. floodplain, terraces) and hydrolologic processes (e.g. flood frequency, flow period, inundation length) where sediment size is not as influential on plant distribution (Hupp and Osterkamp 1985). In dryland ecosystems, water resources is crucial for maintaining species richness (Hancock et al. 1996) and aids with the understanding for reasons of species distribution in or along channels (Tooth and Nanson 2000).

In this study, riparian vegetation cover seemed to gradually increase over time. Table 5 shows that the average green-up per 0.5 km section was greater in the first 7 year interval than the proceeding 7 year interval from 1989-1996. However, there remains a steady increase in vegetation. The analyzed years from 1996 to 2003 exhibited a large and consistent decline in vegetation cover within each 0.5 km section (Figure15). This decrease in vegetation cover is associated with the severe drought period in 2002 in which Phoenix, AZ received 2.82 inches of precipitation, 4.68 inches below average. The average amount of precipitation for that year was the lowest in over two decades. It is very likely that vegetation did not die off within this timeframe, but instead experienced a dramatic decrease in photosynthetic pigments. Drought tolerant vegetation can undergo photosynthetic pigment reduction during dry spells and can recover when re-watered (Kyparissis et. al 1995). Thus, riparian vegetation that has brown or less green leaves due to drought would be difficult to detect using NDVI, as believed to be the case in image year 2003, which relies on the reflectance of green vegetation. Another reason it is suspected that vegetation cover did not actually decrease from 1996 to 2003, is due to the enormous increase in vegetation cover from 2003 to 2010 (Figure 15 and/or Table 5). It is more than double that of the previous years: 1982-1989 and 1989-1996. It is much more probable that a substantive portion of the quantified vegetation increase from 2003 to 2010 is a combined number from the undetected vegetation in image year 2003. Moreover, it is remarkable that plant phenology was affected on such a large scale due to drought conditions and, even more so, that vegetation was able to recover.

Vegetation increases varied from section to section (Figure 15). Figure 16 represents the relationship between changes in riparian vegetation green-up area from 1982 to 2010 with respect to average channel widths. Sections that were completely impounded and had no connectivity via overchute displayed a greater increase in vegetation than channels that had connectivity (Figure 16). Also, sections experienced a greater increase in vegetation where the main channel(s) were positioned in or near the center of the 0.5 km sections (i.e. more ponding). Furthermore, larger channels displayed a greater amount of vegetation increase. In summary, segments that contained larger channels, completely impounded and positioned near the center of the section exhibited the greatest amount of vegetation increase.

The linear relationships posed in Figure 16 are speculated to possibly over-estimate vegetation increase based on channel widths. This is mainly due to measuring channels in Google Earth. The width of the inner channel is distinguishable in Google Earth, but the bank is difficult to determine especially if the banks are sloped and have similar colors and textures. It is more likely that the channels are larger in the field than measured in Google Earth, which may over-estimate the predicted vegetation area values using the regression formula.

Vegetation downslope of the CAP canal could not be accurately detected using the coarse spatial resolution of Landsat TM images. The spatial extent of the streams downslope of the canal is smaller than one 30-meter pixel unit within the Landsat TM image. However, it is visually clear through field and aerial examination that there is less dense vegetation downslope along channels that are completely impounded in contrast with channels that are longitudinally connected (Figure 17). The scales of the riparian vegetation along streams located downslope of the canal are too small to be detected using Landsat TM images. For example in Figure 17, stream channel A has an average riparian zone width of approximately 18 meters. Also, note the scales of the green-up zones upslope of the canal are clearly large enough to be detected within the 30 m spatial resolution Landsat TM images. Along with less vegetation cover on impounded channels downslope of the canal, there are also immediate barren zones along channels that occur directly downslope of the canal. These barren zones along streams, which indicate vegetation die-off, typically extend for a short distance downslope from the canal’s boundary.

A quasi-linear relationship exists between channel widths and vegetation growth for altered and impounded channels (Figure 16). The channel widths are the summed widths of every channel flowing into the green-up area. In some cases, there were 3 channels while in others there were 8 channels terminating into the green-up areas. These linear regression equations can be used to estimate the amount of vegetation green-up over time that could be expected in future canal projects in desert environments. A similar style canal project is underway in Jordan to connect the Red Sea to the Dead Sea; this study can aid in forecasting potential changes to riparian vegetation. Furthermore, there is a need for more research to be conducted on altered ephemeral channels due to human constructed barriers. Krausman et al. (1993) conducted a study to examine desert mule deer behavior in response to altered vegetation along a section of the CAP canal. Further studies on how wildlife is affected by channel and vegetational changes along canals built in desert environments are necessary to understanding how to maintain a healthy desert ecosystem. Ephemeral channel research is under-studied compared to studying perennial systems, and even more so, the human effect on these systems.

CONCLUSION

Along hundreds of streams, the canal has completely impounded or altered channels leading to disconnecting or altering the surface flow regime of the channels in relation to their downslope counterpart. In analyzing Landsat TM images from pre and post canal construction dates, vegetation increased considerably over the 28 year period upslope along both completely impounded and semi-impounded channels (i.e. altered through overchutes or culverts). Vegetation loss downslope from the canal was not quantifiable using Landsat TM images, which contain pixel sizes that are larger than the riparian zones located downslope of the canal. However, decrease vegetation cover downslope of impounded channels can be visually examined through field and aerial photographs.

The spatial extent of vegetation green-up from the canal's boundary averaged 188 meters upslope. Larger streams experienced a greater increase in vegetation cover upslope than smaller streams. In addition, streams of similar width dimensions that were completely closed-off resulted in greater vegetation increases than streams that were semi-connected. A significant relationship between changes in vegetation green-up and channel widths were examined. Results from this study suggest that there is a quasi-linear relationship between channel widths and vegetation growth for altered and impounded channels due to the presence of the CAP canal. These linear regression models can be used to predict the amount of vegetation green-up over time that could be expected in future canal projects in desert environments. Understanding anthropogenic influences on desert riparian ephemeral systems is under-researched and needs to be given greater attention. With increasing global populations worldwide including deserts, human effects on the landscape is inevitable. Nonetheless, we must understand these effects and changes to desert riparian systems in order to better prepare through strategic planning and development, and predict future outcomes for a sustainable future in desert environments.

Table 4. Accuracy assessment results for each class: Riparian Vegetation, Agriculture and Xeric/Lowland Desert areas.

Classified (YEAR 1982)	Reference				Producer's Accuracy (%)	User's Accuracy (%)
	Riparian Vegetation	Agriculture	Xeric/Desert Lowlands	Total		
Riparian Vegetation	71	0	4	75	91.0	94.6
Agriculture	0	75	0	75	100.0	100.0
Xeric/Desert Lowlands	7	0	68	75	94.4	90.6
Column Total	78	75	72	225		

Overall Accuracy 95.0%
Kappa Statistic 0.93

Classified (YEAR 1989)	Reference				Producer's Accuracy (%)	User's Accuracy (%)
	Riparian Vegetation	Agriculture	Xeric/Desert Lowlands	Total		
Riparian Vegetation	68	1	6	75	90.6	90.6
Agriculture	1	73	1	75	98.6	97.3
Xeric/Desert Lowlands	6	0	69	75	90.7	92.0
Column Total	75	74	76	225		

Overall Accuracy 93.3%
Kappa Statistic 0.90

Classified (YEAR 1996)	Reference				Producer's Accuracy (%)	User's Accuracy (%)
	Riparian Vegetation	Agriculture	Xeric/Desert Lowlands	Total		
Riparian Vegetation	74	0	1	75	91.3	98.6
Agriculture	3	71	1	75	100.0	94.6
Xeric/Desert Lowlands	4	0	71	75	97.2	94.6
Column Total	81	71	73	225		

Overall Accuracy 96.0%
Kappa Statistic 0.94

Classified (YEAR 2003)	Reference				Producer's Accuracy (%)	User's Accuracy (%)
	Riparian Vegetation	Agriculture	Xeric/Desert Lowlands	Total		
Riparian Vegetation	70	1	4	75	97.2	93.3
Agriculture	2	71	2	75	94.6	94.6
Xeric/Desert Lowlands	0	3	72	75	92.3	96.0
Column Total	72	75	78	225		

Overall Accuracy 94.6%
Kappa Statistic 0.92

Classified (YEAR 2010)	Reference				Producer's Accuracy (%)	User's Accuracy (%)
	Riparian Vegetation	Agriculture	Xeric/Desert Lowlands	Total		
Riparian Vegetation	69	0	6	75	98.5	92.0
Agriculture	0	71	4	75	97.2	94.6
Xeric/Desert Lowlands	1	2	72	75	87.8	96.0
Column Total	70	73	82	225		

Overall Accuracy 94.2%
Kappa Statistic 0.91

Table 5. Average change in vegetation area per 0.5 km section within each time interval.

Image Years	1982-1989	1989-1996	1996-2003	2003-2010	1982-2010
Average Total Change (m^2/0.5km)	32,130	20,003	-23,007	71,586	100,436

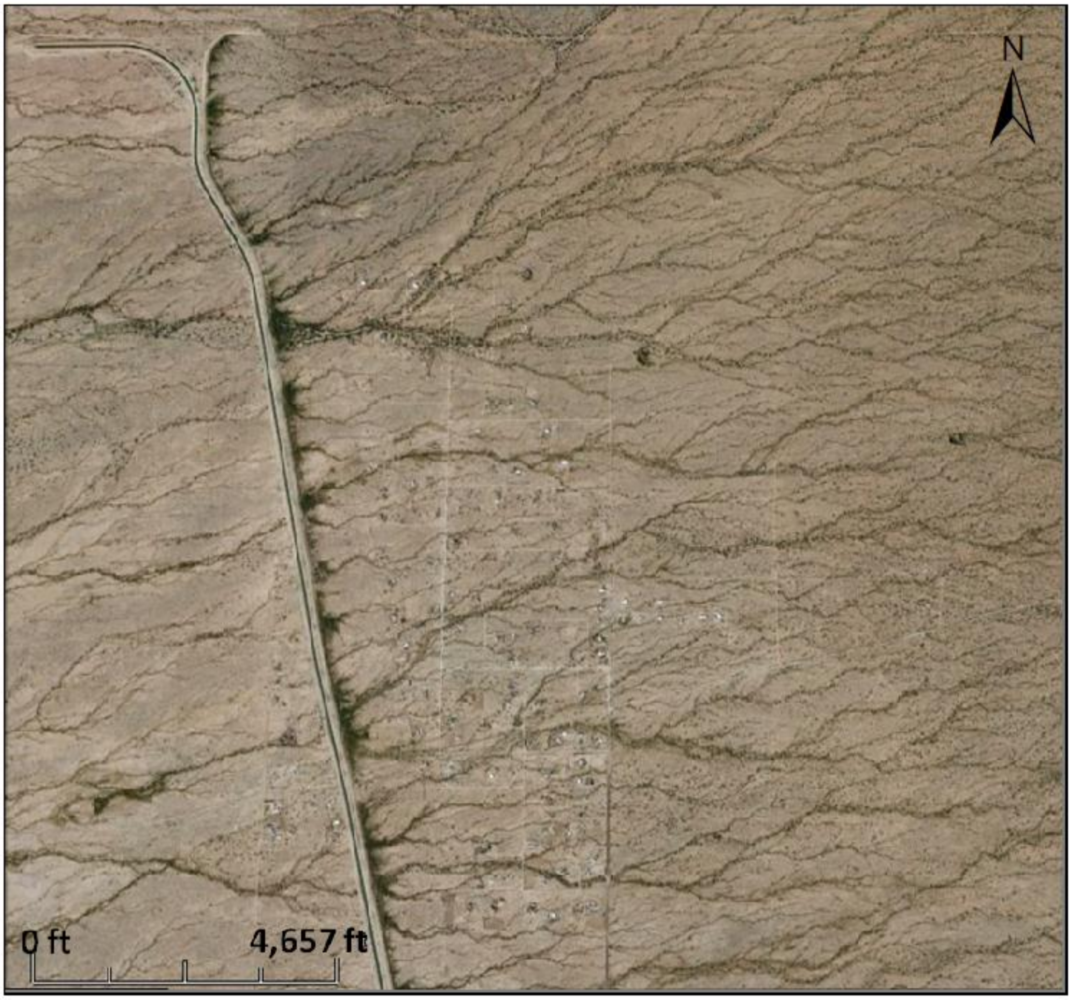


Figure 10. Aerial perspective of study area: the image represents a small section of the study area captured from Google Earth.

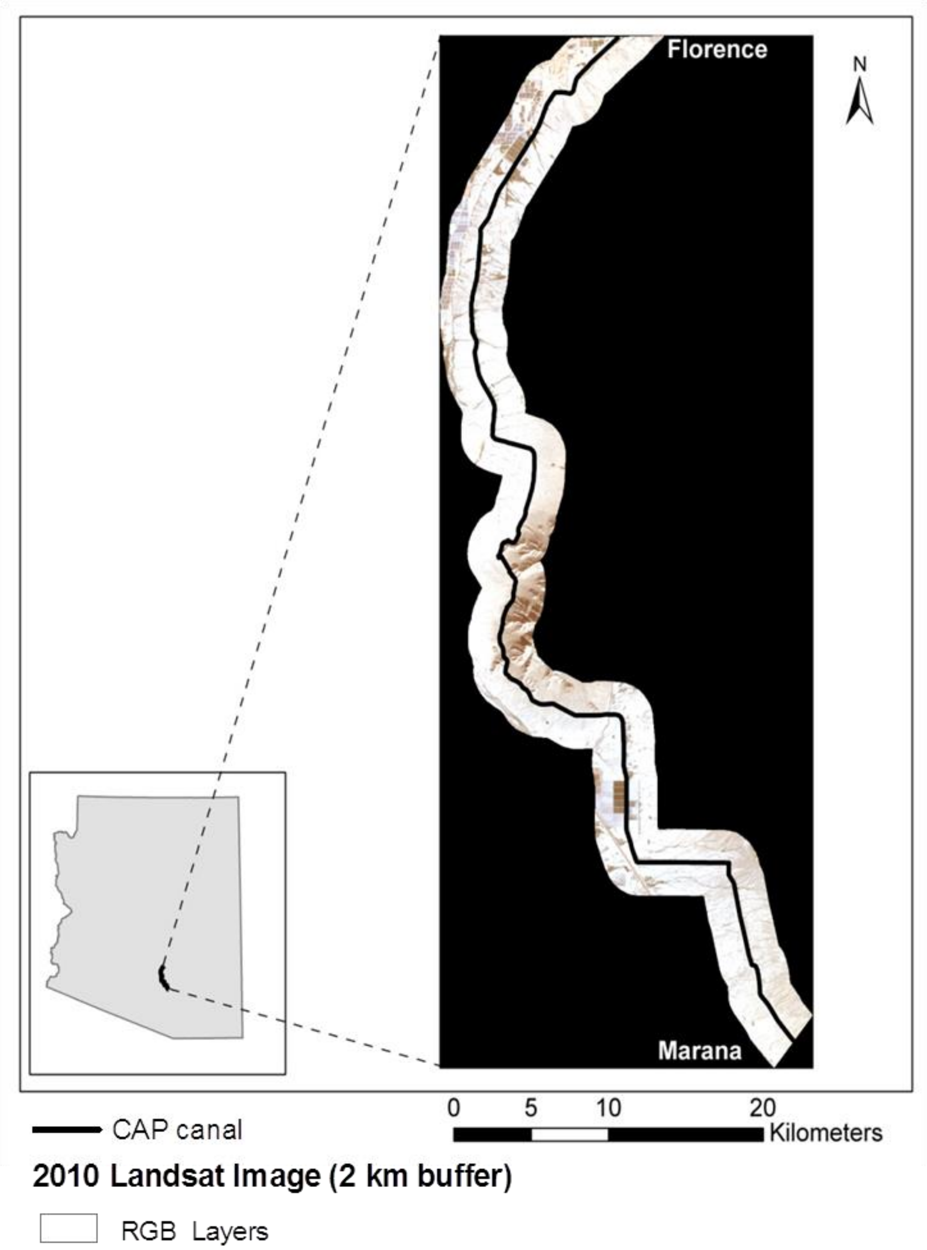


Figure 11. Study area: a 2 km buffer around the canal shown as a black line.

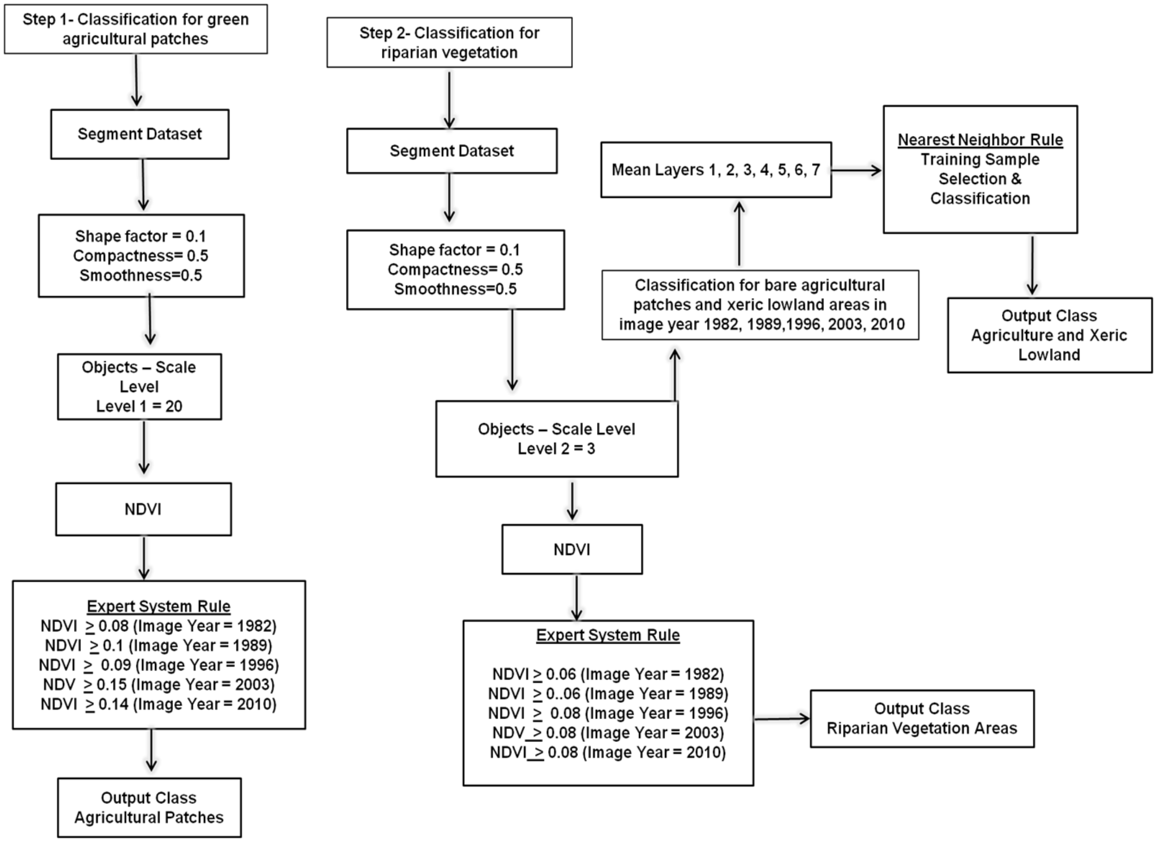


Figure 12. Research design: steps executed in object-based analysis.

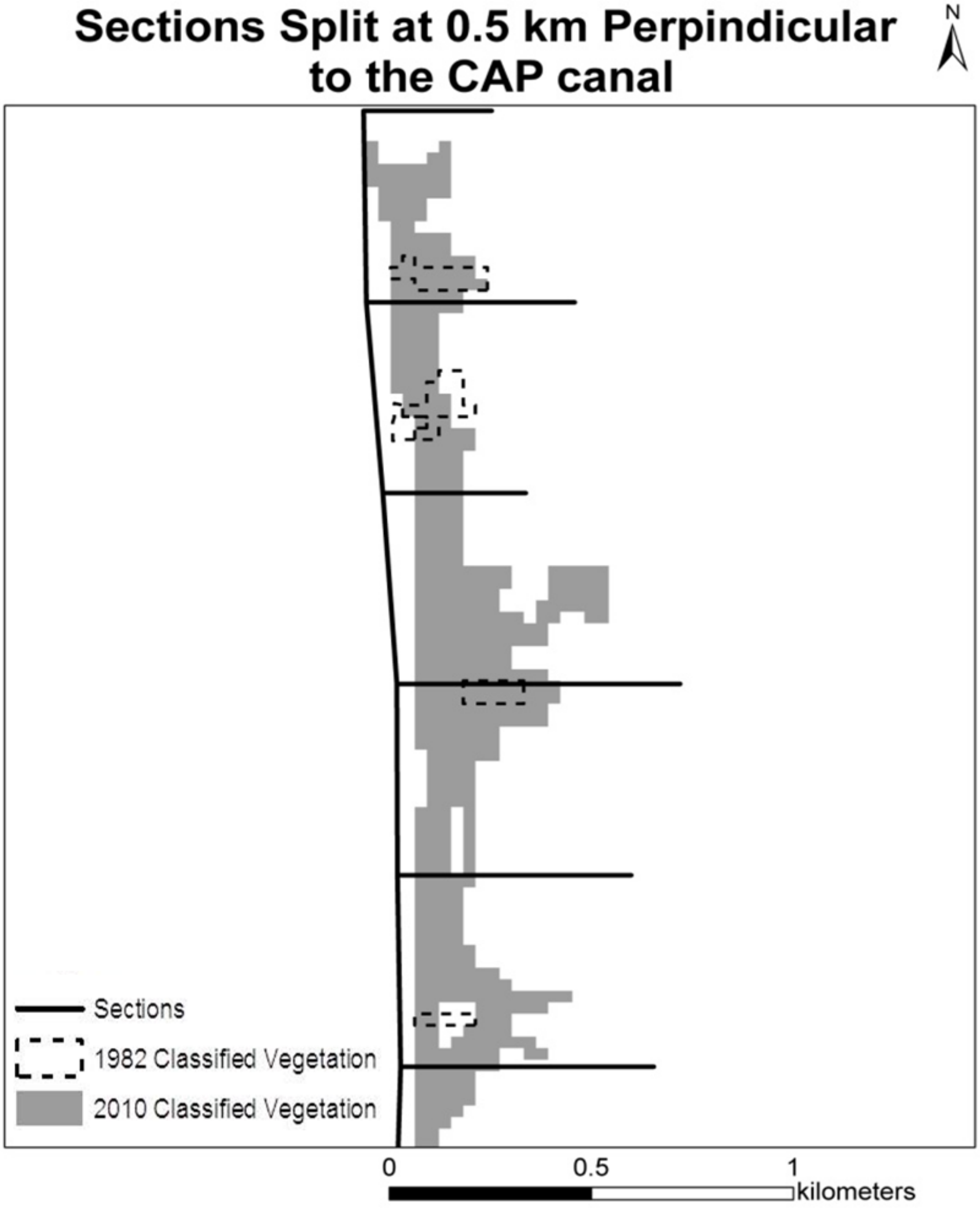


Figure 13. Vegetation change: the change was analyzed in 0.5 km sections along the canal.

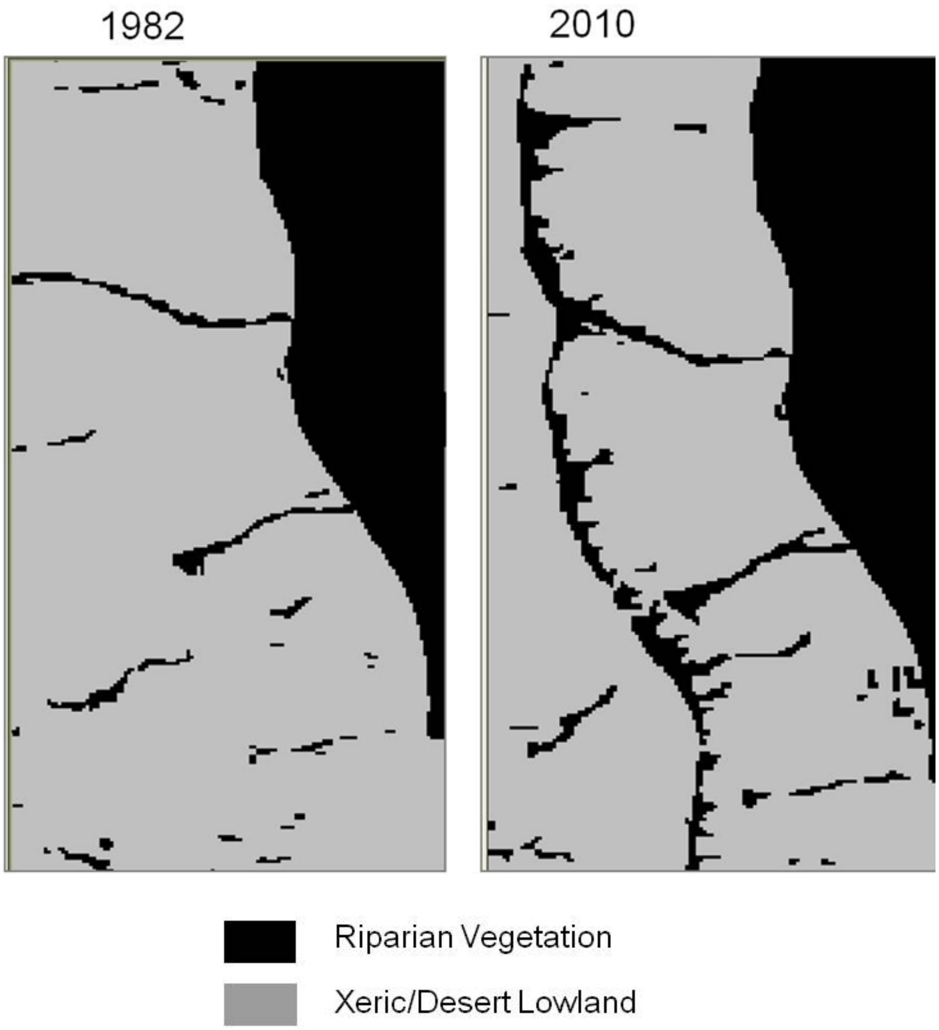


Figure 14. Classified image detection: an example of the change from 1982 to 2010.

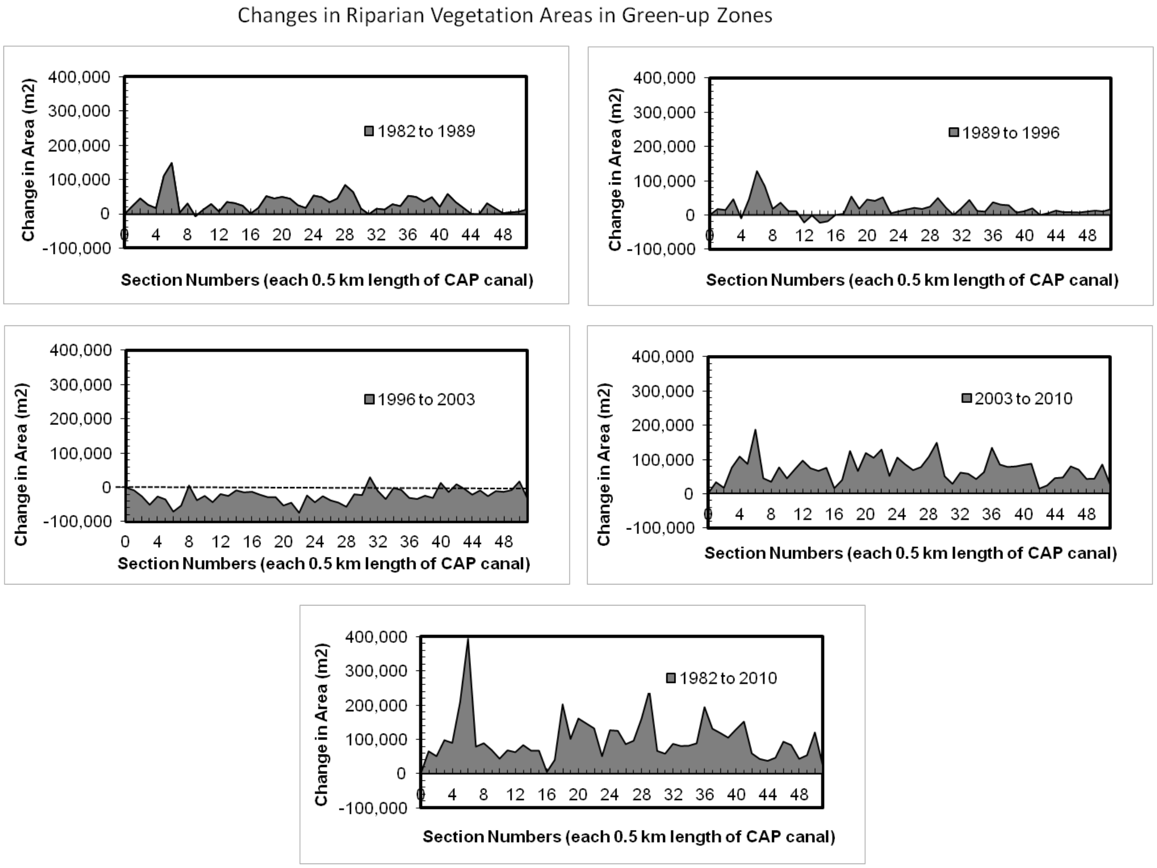


Figure 15. Vegetation change over time: graphical representation of change detection.

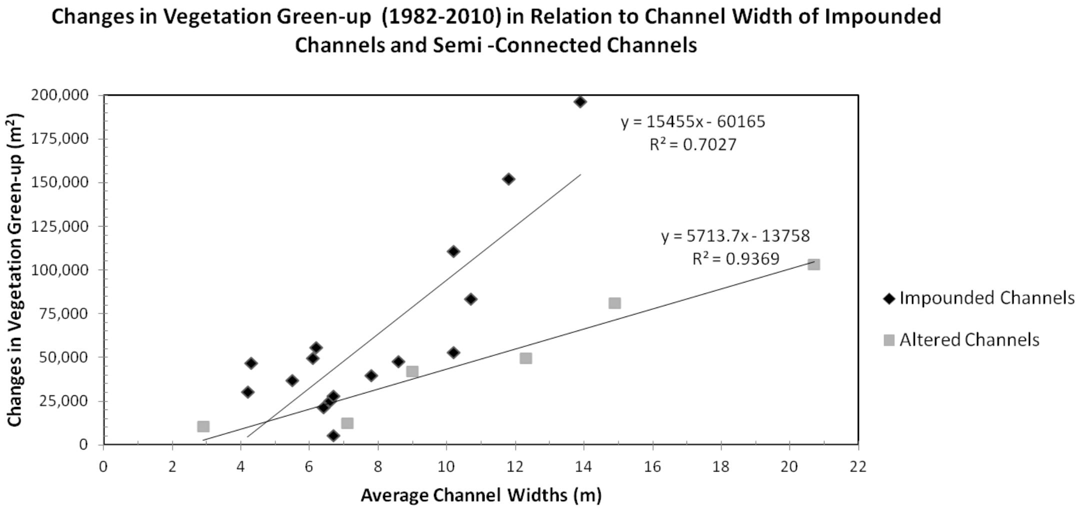


Figure 16. Quasi-linear relationship: vegetation change vs. channel widths relationship.

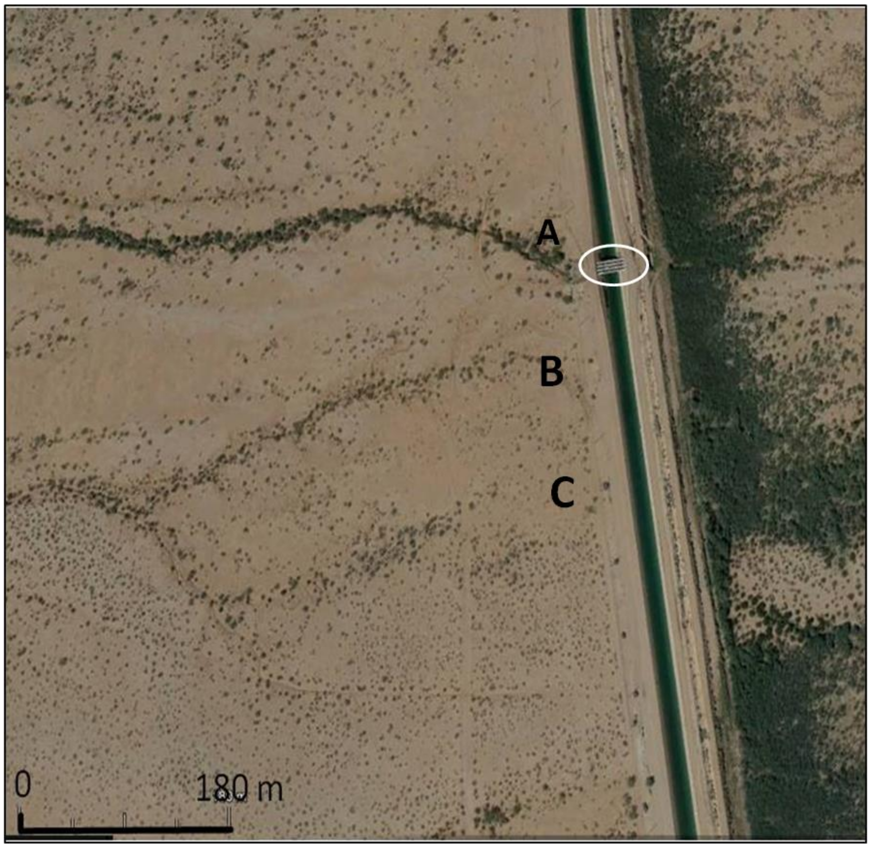


Figure 17. Downstream vegetation: the Google Earth image displays the difference in vegetation cover downslope from the canal: Section A is denser than sections B and C, because channel A is connected by overchutes (circled in white).

4. BIOGEOMORPHIC ANALYSIS OF RIPARIAN AREA GROWTH OF DAMMED EPHEMERAL STREAMS IN THE SONORAN DESERT

ABSTRACT

In this study, we compare two ephemeral streams intersected by the Central Arizona Project (CAP) canal. The purpose of this study is to understand the biogeomorphic processes that lead to green-up evolution upstream from the canal’s berm. Green-up zones are created on the upstream section of completely and partially dammed ephemeral streams where water and sediment are fully or partially restricted from moving downstream. The two chosen stream sites are longitudinally connected via culverts to their downstream counterpart. Channel transects conducted in the field reveals that the culvert size for one of the streams is underestimated in relation to the stream’s bankfull discharge. Consequently, over the 36 year period sedimentation and waterlogging have created the development of a green-up zone. Whereas, the other ephemeral stream examined did not develop a green-up zone mainly because the culvert’s peak discharge, 435 cfs, coincides with the measured main channel’s average bankfull discharge, 380 – 475 cfs.

Green-up zones slowly enlarge over time as sediment is deposited causing the floodplain (i.e. green-up zone) to laterally increase due to overbank flooding. It is estimated that the green-up area for the partially dammed stream will increase by approximately 1,570 m^2 over the next 36 years. In this paper, we make suggestions for urban and agricultural development in relation to these dynamic green-up zones. Understanding biogeomorphic processes along dammed ephemeral streams lends

valuable insight to riparian conservation efforts and future urban development plans in desert regions.

INTRODUCTION

The damming of rivers dates back centuries. Documented studies regarding the understanding of human impacts due to damming rivers began within the early 20th century. Primarily, perennial and intermittent rivers have been the focus of river research typically along large rivers. Anthropogenically-caused changes due to damming include hydrologic, geomorphic and ecologic ones. As water and sediment are shifted within the fluvial system, vegetation responds by adjusting to geomorphic and hydrologic shifts, which in turn affects fluvial processes. Decades of environmental studies from multiple disciplines on the effects of damming perennial rivers has been conducted (e.g. Dawdy 1991; Webb et al. 1999). In many instances, controlled flooding is practiced to achieve "environmental goals" of rehabilitation, restoration or maintenance of specific vegetation or wildlife species (Stevens et al. 2001; Lee et al. 2013). The human impacts of dammed perennial rivers have been in the past and remain to be of great environmental concern (e.g. Humborg et al. 1997; McCully 1996; Raymond 1979; Schmidt et al. 1998; Graf 2006; Huang et al. 2013). However, less commonly studied are the effects of damming ephemeral streams in dryland environments.

In this paper, we present one of the first few studies of biogeomorphic responses and effects to, in essence, damming ephemeral streams (other studies include Hamdan 2012; *in review*: Hamdan and Myint 2014). Biogeomorphic responses in drylands are complex but necessary in understanding human impacts to desert environments. Drylands contain sensitive thresholds and interactions between geomorphology, hydrology and the biological fabric of that place or region. Land degradation is prone to occur in drylands that are mismanaged due to the lack of understanding between the multi-part interactions of the system as a whole (El Bastawesy et al. 2013). Ma et al. 2009 concluded that a decline of native vegetation inhabiting desert oases was mainly due to the overuse of groundwater. It is clear that a relationship between vegetation and water availability exists, especially in drylands. It is critical to understand the biogeomorphic interactions between the system in order to ensure a minimal impact and better planning in desert environments.

Youssef et al. (2011) proposes to dam ephemeral streams (also known as wadi) as a way to control flooding and road damage in Egypt. Some measures of ephemeral damming are more indirect and related to canals. Israel, Jordan and the Palestinian territories have proposed a canal known as the Red-Dead Canal that will transect many ephemeral streams causing longitudinally discontinuous or altered streams. Understanding biogeomorphic interactions due to damming ephemeral streams is essential to making informed decisions to proposed canals or dams in desert regions. The Central Arizona Project Canal (CAP) serves as a gateway to understanding biogeomorphic processes along dammed ephemeral streams to apply to future projects.

The CAP canal is 540 kilometers long and traverses the Arizona Desert, while intersecting hundreds of ephemeral stream channels. Canal construction began in 1973 and ended in 1993, delivering water from the Colorado River to municipal and agricultural areas throughout Arizona. In some lengths along the canal, 12 to 15 feet high berms were constructed to protect the canal from ephemeral stream runoff. The ephemeral streams that intersect the canal can be categorized as being completely dammed, partially dammed or not dammed. During flow events, partially and completely dammed streams are inundated with stormwater runoff and trap sediment upstream of the canal's berm. Hamdan (2012) quantified vegetation green-up and sedimentation on a completely dammed ephemeral channel due to the CAP canal and found that riparian vegetation increased by a total of 477 percent over time. These vegetation increases are called "green-up" zones, which occur on the upslope side of the canal. Green-up zones occur on both, completely dammed and partially dammed ephemeral streams. Streams that have a culvert or overchute built into the canal for stream connectivity are partially dammed or not dammed depending on the culvert's discharge capacity to stream discharge rates. This research paper examines partially dammed and non-dammed ephemeral streams caused by the CAP canal. In this study, we compare a partially dammed ephemeral stream to a non-dammed ephemeral stream. The unaltered sections serve as the research controls in which case, Sections far upstream from the canal are considered unaltered due to the presence of the canal; these unaltered sections are used as research controls in this study. The main purpose of this study is to understand the geomorphic processes that lead to the development and growth of green-up zones over time.

The research questions addressed in this paper are: 1*) how has sedimentation and form changed along the two intersected stream sites? 2) how do green-up zones evolve?* 3*) are the channels still adjusting to reach a new equilibrium condition from being dammed? 4) how do biogeomorphic processes along dammed ephemeral channels affect urban planning?* We hypothesize that similar changes occur in partially dammed channels as they do in dammed perennial rivers. We expect fine-grained sediment accumulation on the upstream section of the channels causing changes to the stream’s structure, processes and riparian vegetation. The factors are examined on both a partially dammed and a non-dammed stream in order to answer the following research questions are: bankfull discharge rates, sediment accumulation, upstream morphological changes and green-up volume.

Riparian zones constitute a relatively small percentage of land area, but are of regional, international and national importance (Knopf et. al, 1988). For instance, riparian zones in the southwest US support breeding grounds to a fairly large percentage of various avian species; the loss of these zones can cause large declines in breeding and populations as a whole (Knopf et. al, 1988). The riparian areas along the ephemeral streams that are intersected by the CAP canal are zones of biodiversity situated within a vast landscape of urbanization and xeric lowlands. As it is critically important to understanding the effects of damming the Colorado River, it is of equal importance to understand the damming of these sensitive desert riparian systems. Understanding human caused changes of ephemeral systems will enable better predictions for future projects in desert environments of dammed ephemeral streams.

STUDY AREA

The section of the CAP canal in this study area was built in 1977. In essence, changes along these streams have occurred over a thirty-six year period. We selected two ephemeral stream channels for comparison, both located on the same alluvial fan, on the southern slope of the Hieroglyphic Mountains. The study area is located at approximately 33°44'53.09" N, 112°28'27.93" W near Wittmann, AZ. In this area, there are numerous ephemeral stream channels carved into the alluvial fan that are intercepted by the CAP canal. These channels have anabranching characteristics and channel widths vary from approximately 1m to 10 m across. Stream 1 has a basin area of approximately 1.1 km^2, whereas Stream 2 has a basin size greater than 10 km^2. Stream 2 has an official name, Picacho Wash, because it is a large wash that initiates from the Hieroglyphic Mountains. Measuring the basin area of Picacho Wash is difficult due to the anabranching nature of the streams. Upstream sections of the streams become profoundly intertwined with other channels making it difficult to delineate a distinctive catchment boundary. The main channels of both site locations are characterized by a sandy to cobble-sized substrate, but as the channels approach the canal barrier particle size become much smaller as fines are trapped upslope of the canal. Finer sediments are deposited on the upslope side of the channel during periods of inundation as sediment laden waters pond upslope to eventually pass through overchutes.

In the case of the selected dammed ephemeral stream, stormwater collects in the green-up zones during periods of intense and prolonged precipitation events, even with the longitudinal connectivity through overchutes. Stormwater no longer follows the same path as it did along the pre-canal stream channel. The stream channels are confined to drain through a pipe of a fixed diameter (72 inches), which causes waterlogging in the green-up zone. This ultimately causes water to flow laterally onto the desert floor, which widens the floodplain of the ephemeral stream. As seen in Figure 1, the partial damming caused by the CAP canal creates a wider green-up zone for Stream 1 (i.e. floodplain), which increases in width as it approaches the canal’s boundary. The green-up zone contains the main channels and a newly-created floodplain. However, inundation due to the CAP canal is not exclusive to the green-up zones only, inundation also occurs in the main stream channels beyond the green-up zones. Sections of the channels upstream from the green-up zones (i.e. ponded areas) also fill with water as the area below is ponded. The effect of inundation due to the CAP canal ends upstream beyond the waterlogged channels, which will serve as the control sites. The non-dammed ephemeral stream, Stream 2, selected for this study has a 72 inch pipe diameter as well, but a green-up zone has not developed as in the partially dammed stream (Figure 18).

METHODS

Bankfull Discharge

Williams (1978) description of “bankfull” -a filled channel to the top of its banks- was used in the field to delineate “bankfull”. Channel cross-sections were measured in the field in order to calculate bankfull discharge rates. There were at least two representative channel cross-sections surveyed for each channel. Many previous studies have used channel cross section surveys to monitor or assess channel changes over time (e.g. (Merritt and Wohl 2003; Vanacker et al. 2005; Neave et al. 2009).

For stream 1, there are 8 anabranching channels that led into the green-up zone of which a minimum of two channel surveys per channel were conducted (Figure 19). However, Stream 2, the non-dammed stream, had a single main channel. We used a Trimble GeoXH 2008 GPS system to gather data in measuring channel cross sections. The GPS system was set to a threshold of not recording data points with greater than 1 m vertical accuracy. Along with GPS data, a measuring tape was used to verify the GPS data collected. The tape was laterally positioned from one end of the bank to the other, while ensuring the tape was taut. Cross-sectional area, wetted perimeter and mean channel depth were calculated from the detailed cross-sections. The Gauckler-Manning flow equation was used to calculate the range of discharge rates. The Gauckler-Manning flow equation is:

$$Q = VA = \frac{1}{n} A\, R^{\frac{2}{3}}\ S^{\frac{1}{2}} \quad \text{(SI units)}$$

The variables in this equation are the non-dimensionless roughness coefficient, n, the cross-sectional area, A, the hydraulic radius, R, and the slope, S. Discharge rates were calculated using mean reach slope that was surveyed instream along the bed using the GPS system and a range of n-values using methods presented in Arcement and Schneider (1989). In general, Mannings n-values were determined based on mean grain size distribution in the surveyed channels. Bankfull discharge is reported as a range rather than a single value, because of subjective nature of the n-value determined by the researcher (Radecki-Pawlik 2002).

Sedimentation

The erosion and transport of sediment mainly occurs during large storm events, but can also take place to a lesser extent during smaller storms in semi-arid regions (Hooke and Mant 2000). As stormwater travels downstream, sediment laden waters pool upslope behind the canal’s berm causing the deposition of fine sediment in the Stream 1 location. Stream 2, non-dammed, has no evidence of channel fill or sedimentation; thus, stratigraphic analysis was not conducted on Stream 2. Total sediment accumulation over the 36 year period was measured using methods presented in Hamdan (2012) and Griffiths et al. (2006). The stratigraphic soil layers were examined upslope and downslope of the canal boundary to determine the depth of sediment layers deposited post-canal construction. A total of 148 holes were excavated to measure the total sedimentation over a 0.048 km^2 (~48,000 m^2) area; this area encompassed the green-up zone and the outer boundary to determine where the sedimentation boundary ended.

The interpolation of spatial data using kriging methods in a GIS is widely used in environmental studies (e.g. Forsythe et al. 2004; French et al. 1995). The sedimentation data was interpolated using simple kriging in ArcMap 10.1 software. The interpolated sedimentation map was one of the maps used in calculating a predicted surface to model the green-up zone's evolution over time. That is, the sedimentation map was added to the current Digital Elevation Map (DEM) to obtain the height of the future surface assuming that the sediment depth doubles in the next 36 years.

Upstream Morphological Changes & Green-up Basin Volume

Morphological changes are often analyzed using DEMs, which can be created in ArcMap through interpolating elevation points surveyed in the field (Hooke and Mant 2000). We surveyed the topography using the Trimble GeoXH 2008 GPS system to create a DEM surface. On average, the points were recorded at a 1 meter distance from its neighboring point. A total of 1050 points were surveyed over a 0.0266 km^2 (26,600 m^2) area to create a DEM surface within the green-up zone (Figure 20). Points of elevation were also collected outside of the boundary totaling 1699 points. The DEM was used in calculating average net volume of water that could potentially pond within the green up area. The sedimentation boundary was used to delineate the boundary of the green-up area. That is, locations of zero sedimentation are where the green-up zone ends and marks the end of the flow boundary. A total of 20 cross sections, extracted from the interpolated map, within the green-up zone were analyzed and the average area was calculated. The mean area was multiplied by the average length of the green-up area to estimate volume

(Figure 21). The volume represents the maximum amount of water, peak volume, that is retained upslope within the green-up zone.

As the channels within the green-up zone fill with sediment, water laterally flows out farther onto the desert floor. The maximum volume of water that exceeds the peak outflow of the culvert will be retained behind the canal’s berm. The maximum volume that can be retained essentially remains constant through time; it is the continual deposition of sediment within the green-up zone that causes water to laterally migrate. Over time, stream flow onto the desert floor laterally increases causing vegetation cover to increase as well.

Thus, a prediction map of vegetation growth within the green-up zone was estimated based on current sedimentation measurements and the stream’s DEM. We assumed that the sedimentation would double in the next 36 years. The interpolated raster files, sediment accumulation and DEM, were added in ArcMap 10.0 to obtain a “future” topographic surface. In general, the elevation height of the predicted DEM is relatively higher than the current DEM surface; thus, further increasing the lateral flow of water onto the desert floor over time. The same 20 cross-sections as with the present-day volume estimation mentioned above were used to estimate future maximum volume within the green-up zone. This resulted in obtaining an estimate of the excess volume of water that would laterally flow onto the desert floor causing an increase in vegetation growth. Cross-sections on the eastern and western boundary of the green-up zone were analyzed using the interpolated map to determine the average length and width of vegetation growth.

RESULTS

Discharge Rates

Stream 1 has 8 anabranching channels of various geometric dimensions and channel characteristics. The bankfull discharge rate for Stream 1of the combined 8 anabranching channels that flow into the green-up zone range from approximately 1,031 – 1,318 cfs (Table 6). These 8 channels vary in bed sediment-sizes and channel geometry; thus, some channels such as channels 3, 5 and 8 contribute higher discharge rates than channel1, 2, 6 and 7 (Table 6). Channels 1 and 2 have relatively high fluctuations in discharge rate calculations along individual transects mainly due to changes in channel width, which caused the majority of the variability (Table 6). However, channels 3, 4, 5, 6, 7 and 8 have relatively uniform channels that did not experience similar discharge rate variations (Table 6). Stream 2 was also fairly uniform in which discharge rates among transects did not fluctuate far from the mean value. Stream 2 consists of a single channel that has a bankfull discharge range of 380 – 475 cfs (Table 6).

Interpolated Map Statistics

In general, low values of root mean square errors (RMSE) less than 1 have good data accuracy in which the smaller the number the more accurate the predictive model. The root mean square error (RMSE) for the sedimentation map is 0.791 and 0.592 for the interpolated DEM surface.

Sedimentation

Significant amounts of sedimentation have accumulated behind the canal’s berm even with the partial connectivity of the 72-inch pipe overchute. The ephemeral stream, Stream 1, with a basin area of approximately 1.1 km^2 (0.42 mi^2), has been partially dammed since 1977. Approximately 0.09 $AF/mi^2 \cdot YR$ of sediment has accumulated in the partially dammed stream, Stream 1. The interpolated sedimentation map reveals the expected general path of flow based on sedimentation. Flow paths are evident from sedimentation, which in this case shows flow from the northwest (Figure 22). The greatest amount of sediment accumulation is closest to the canal's berm and towards the center of the green-up zone (Figure 22). Within the greatest amount of sediment aggradation, the maximum accumulation measured in the field was a 48 cm thick layer of very fine sand to silt-sized particles (Figure 22). Sedimentation ended approximately 231.9 meters upstream from the partial dam. Currently, the estimated total aggradational area, which is the green-up zone, is 26,560 m^2 .

Morphological Changes & Green-up

Stream 2, Picacho Wash, has no evidence of sedimentation upstream of the canal's berm. Thus, the morphology of the stream channel has remained unaltered due to the canal, which was also examined in historical aerial photographs. The stream has a similar path and structure as interpreted in the 1949 aerial photograph (Figure 18). However, Stream 1 has undergone significant channel changes due to pooling and sedimentation caused by the canal. The green-up zone consists of dense vegetation, a finer substrate, enlargement of floodplain and shallower channels. The green-up zone will continue growing based on the results of the future predicted gain in topography through sedimentation processes in the next 36 years. The maximum water volume that pools behind the canal is approximately 34,784 m^3 (374,412 ft^3). As sedimentation rates increase in the next 36 years, the baseline topography rises causing the same area to only hold 32,339 m^3 (348,094 ft^3) of water retention. This amounts to an excess of 2,445 m^3 (26,318 ft^3) of water to move out laterally onto the desert floor. It is estimated that the green-up area will increase by approximately 1,570 m^2 over the next 36 years on the western end of the green-up boundary, which has lower topography than the eastern edge causing water to flow west along the canal (Figure 23). If the excess water volume flowed to the east, the green-up area growth would be 4 times greater (~5,463 m^2) than the western edge.

DISCUSSION

Green-up zone evolution

Bankfull discharge rates for Stream 1 was approximately three times greater than the culvert's discharge capacity emplaced for that stream. The culvert has a peak flow of 435 cfs whereas Stream 1 could experience 1,031 – 1,318 cfs at bankfull. Stream 2, Picacho Wash, also has a 72 inch culvert with the same peak discharge outflow, 435 cfs. The calculated bankfull discharge of the main channel for Picacho Wash ranges from 380 – 475 cfs. The properly suited culvert to Picacho Wash is the primary reason that this site is referred to as the non-dammed site. The culvert size matches the bankfull discharge rate of the channel; thus, water is not pooling upstream of the canal's berm. Furthermore, Picacho Wash has no field evidence of increased vegetation density, overbank flooding, sedimentation or remanent high water marks caused by the canal. However, Stream 1 is partially dammed during storm events and experiences overbank flooding, sediment deposition and increased vegetation densities upstream from the canal's berm.

Stream 1 is prone to flooding during steady, low rainfall events unlike Stream 2. Stream 1 has less transmission losses than Picacho Wash, which has a smaller basin area with smaller multiple channels when compared to Picacho Wash. Transmission losses in dryland regions is mainly characterized by water seepage into the banks and bed of an ephemeral channel, which is very high causing total discharge rates to decrease downstream and eventually approach zero (Graf 1988). Stream 1 had significant flow during a steady, low intensity rainfall on November 22, 2013 unlike Picacho Wash which had zero stream flow (Figure 24). Picacho Wash is likely to experience bankfull discharge rates during high intensity and high magnitude storms, which are less frequent in drylands (Hooke and Mant 2000; Bull 1997). On the other hand, Stream 1 may flow even during low intensity but steady rainfall events leading to sediment deposition and water ponding in the green-up zone.

Water availability is the essential element limiting plant growth and distribution in desert environments (Lazaro et al. 2001; Hupp and Osterkamp 1996; Noy-Meir 1973). Evidently, inundating the green-up zone is the fundamental aspect to the increase in seedling establishment and vegetation biomass. However, the enlargement of the green-up zone over time is due to sediment deposition. Sedimentation has caused bed levels to artificially rise upstream directly above the canal’s berm; thus, causing excess water to flow onto the desert floor expanding the floodplain and in turn expanding the green-up zone. Hence, over time the lateral migration of water (i.e. green-up zone development) will reach equilibrium when sedimentation reaches a maximum and the channels are completely filled.

Predicting the amount of sediment yield per basin area is difficult mainly due to differences in lithology, vegetation densities, topography, spatial variability of storms, and differences in storm intensity, magnitude and duration (Bautista et al. 2007; Nearing et al. 2007; Griffiths 2006; Nichols and Renard 1999). Sediment yield can vary within watersheds located in the same region. The Walnut Gulch Experimental Watershed (WGEW) located in Tombstone, AZ had varying sediment yields between four different sites (Figure 25). Our estimation for Stream 1 lies alongside the lowest sediment yield measured at one of the WGEW sites (Figure 25). Sediment yield for Stream 1 is lower because suspended sediment still passes through the culvert. Since Stream 1 is partially dammed, it is unknown the percentage of sediment that passes in relation to the amount that is deposited. It may be possible to better predict the amount of vegetation green-up over time along the completely dammed ephemeral streams since all of the sediment will be trapped instead of partially trapped. Nonetheless, without better predictions of sediment yield, it would remain a difficult task even along the completely dammed streams. One would still need to field survey the ephemeral streams before predicting the sediment yield of a basin.

Thirty-six years has passed since the construction of the CAP canal near Wittmann, AZ. Within this timeframe, sediment has been steadily increasing upstream to raise bed levels, laterally increase the flooplain zone, and increase vegetation extent. The effect of this process is more prevalent on completely dammed ephemeral streams. Hamdan and Myint (2014) analyzed increases in vegetation canopy cover using remotely sensed images over time, which revealed that completely dammed ephemeral streams have a much greater increase in vegetation than partially dammed ephemeral streams. We speculate that completely dammed ephemeral streams will reach equilibrium, in which the green-up zone is at a maximum, sooner than the partially dammed streams.

Planning Strategies & Considerations

There are many long-term factors to consider when damming ephemeral streams in desert environments, which include the environmental goals set for that area and ensuring proper infrastructure development around the canal. We imagine two common scenarios that a new canal project may want to implement into the canal's design, which are: 1.) ensuring that most or all ephemeral streams follow the "non-dammed" stream model 2.) intentionally implementing the "partially or completely dammed" stream model. The first case would ensure that streams are preserved and that little to no change would occur to the system. The second case could serve as increasing biodiversity along desert riparian zones and may potentially offset a portion of the riparian areas and habitats lost or altered by urbanization. In southern California, a considerable amount of riparian areas have been replaced with urban infrastructure and agriculture (Katibah 1984). In some cases, urban development attempts to incorporate riparian areas to maintain the "natural" landscape. A study conducted by Green and Baker (2003) in Phoenix, AZ conclude that areas of riparian zones that are left within the urban environment do not maintain their past ecological identity in which the urban environment negatively influences native bird populations. In general, the green-up zones created upstream may help compensate for some of the riparian deforestation in drylands.

The second case could also support agrarian societies living in deserts. The Red-Dead Canal is a proposed canal that will transport water from the Red Sea to the Dead Sea: its proposed path will transect ephemeral streams in Jordan. These potential green-up zones could be used as agricultural areas with the type of crop that can withstand periods of inundation and sedimentation. Horticulturalists should be engaged to make informed decisions regarding suitable crops. Future canal design in desert regions is critical to the desert environment and to the humans that live in them. We must first understand the biogeomorphic responses to anthropogenically altered ephemeral streams, then, the system can be manipulated depending on the planners' and societies goals for the site.

As these green-up zones develop and migrate upstream over time, it is critical to ensure housing and development is not as risk of flooding from being too close to the canal's berm. Hamdan and Myint (2014) concluded that the average length of the green-up zones from the canal's boundary is approximately 188 meters. We would advise that homes should be at least double that distance from the canal's berm and three times the average distance when taking extra precaution, if living upstream near small to medium sized ephemeral streams. Because green-up evolution is a relatively slow process it can go unnoticed by the planner. Homes located near Marana, AZ on the upslope side of the canal seem to be in the "safe zone" (Figure 26). All of the homes are located greater than 330 meters from the canal's berm. However, one particular house near Wittmann, AZ (33.740984, -112.504320) may experience significant flooding during large storm events due to poor planning. Maricopa County public record shows that this house was built in 1981, which was about 3 years after the construction of the canal. This house was constructed upstream about 223 meters away from the canal's berm (Figure 26). Without understanding the underlying processes of green-up zone development, it could have been easily over looked and deemed a suitable site for housing especially since after three years of canal construction the green-up zone was in its initial stage of development.

CONCLUSION

Perennial river research regarding dams is conducted to maintain ecosystem integrity and, in some cases, assess potential risks involved to homeowners (e.g. Lewis et al. 2008). As it is important to understand these anthropogenic effects along perennial rivers, it should be of equal importance along dammed ephemeral streams. The main purpose of this research was to understand the anthropogenically-caused impacts to the surrounding desert environment and humans.

The CAP canal has altered the geomorphology and ecology along ephemeral streams. In sections along the canal that have a culvert sized to less than the bankfull discharge rate, green-up zones develop due to the pooling of water and sediment deposition during storm events. This process is relatively slow on a human scale. After thirty-six years, the green up zone is still evolving and has not reached a steady-state. The repeat process of sediment deposition slowly builds the topography upstream, in so doing, causing water to flood out laterally onto the desert floor and essentially widen the green-up zone. This slow process is the main reason that homes built on the upstream side should avoid construction within a minimum of 375 meters and preferably 550 meters from the canal's berm when living along a small to medium sized stream. Research regarding the damming of ephemeral streams is in its infancy. This study provides a fundamental baseline of understanding biogeomorphic processes along dammed streams in dryland environments.

Table 6. Discharge values for Stream 1 and Stream 2.

Stream 2	Discharge (cfs) (middle n-value = 0.04)	Discharge (cfs) (upper n-value = 0.05)
1 single main channel		
Channel 1 (n = 0.03-0.05)		
Transect 1	454.91	363.93
Transect 2	422.79	338.21
Transect 3	595.24	476.18
Transect 4	463.29	370.45
Transect 5	436.05	348.84
Transect 6	452.59	362.08
Transect 7	499.7	399.83
Average Discharge for channel 1 (cfs)	**474.94**	**379.93**
Stream 1	**Discharge (cfs) (middle n-value)**	**Discharge (cfs) (upper n-value)**
8 anabranching channels		
Channel 1 (n = 0.026-0.035)		
Transect 1	129.3	110.82
Transect 2	167.96	143.96
Transect 3	57.22	49.02
Transect 4	82.98	71.3
Average Discharge for channel 1 (cfs)	**109.365**	**93.775**
Channel 2 (n = 0.026-0.05)		
Transect 1	43.47	30.43
Transect 2	76.27	53.4
Transect 3	114.67	80.3
Average Discharge for channel 2 (cfs)	**78.137**	**54.71**
Channel 3 (n = 0.026-0.035)		
Transect 1	397.06	340.34
Transect 2	390.91	335.06
Transect 3	230.75	138.45
Average Discharge for channel 3 (cfs)	**339.57**	**271.28**
Channel 4 (n = 0.026-0.035)		
Transect 1	108.36	92.89
Transect 2	151.37	129.75
Average Discharge for channel 4 (cfs)	**129.865**	**111.32**
Channel 5 (n = 0.026-0.035)		
Transect 1	206.8	177.26

Transect 2	249.41	213.78
Transect 3	246.36	211.16
Average Discharge for channel 5 (cfs)	**234.19**	**200.73**
Channel 6 (n = 0.026-0.05)		
Transect 1	77.44	54.21
Transect 2	116.77	81.73
Transect 3	127.94	89.56
Average Discharge for channel 6 (cfs)	**107.38**	**75.17**
Channel 7 (n = 0.026-0.05)		
Transect 1	82.19	57.53
Transect 2	75.34	52.73
Average Discharge for channel 7 (cfs)	**78.765**	**55.13**
Channel 8 (n = 0.026-0.05)		
Transect 1	252.06	176.43
Transect 2	229.24	160.47
Average Discharge for channel 8 (cfs)	**240.65**	**168.45**
Total (Bankfull) Discharge: Sum of Channel Averages	**1317.93**	**1030.57**

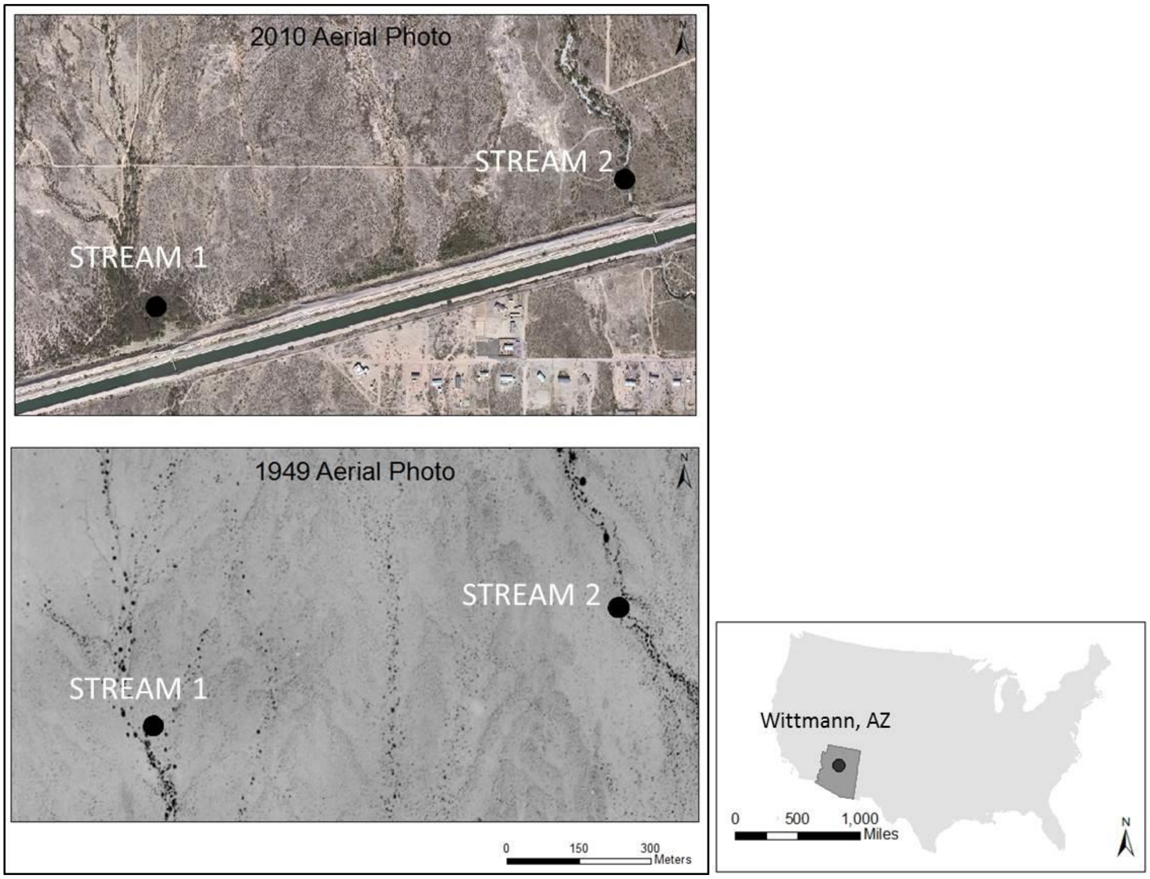


Figure 18. Stream 1 has had significant vegetation growth upstream from the canal as interpreted from the 1949 to 2010 aerial photograph. The canal barrier restricts water and sediment movement causing the floodplain and green-up zone to widen. Stream 2 has not developed a green-up zone and maintains similar geometry through time.

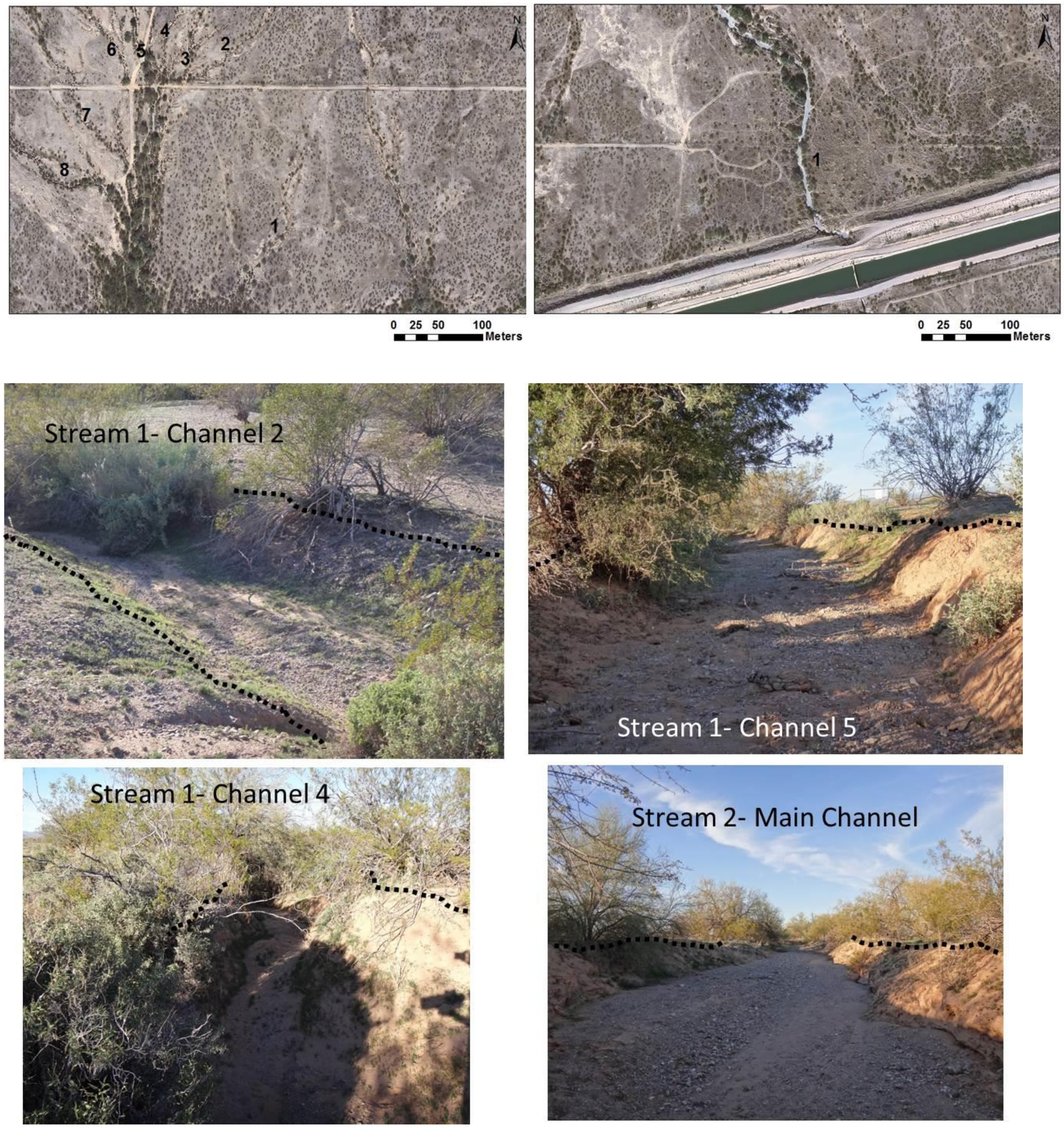


Figure 19. The above aerial photograph displays the channels that were surveyed in the field to calculate bankfull discharge rates. Stream 1 had eight channels (numbered in the aerial photo above) and Stream 2 had one channel. The photographs are examples of channel characteristics of the two sites where the dotted black line denotes the bank.

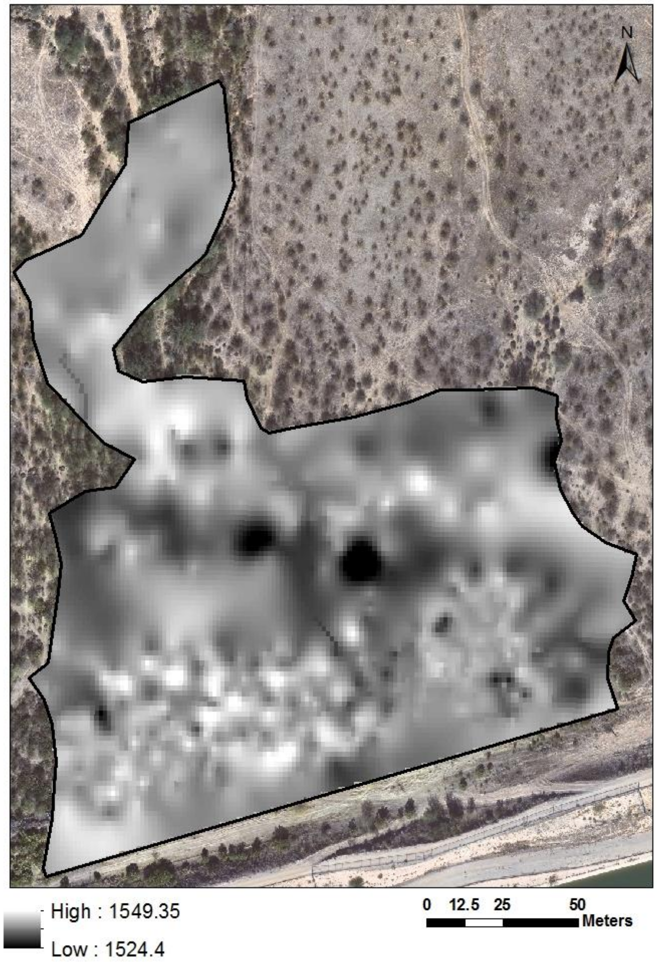


Figure 20. The topography of the green-up zone illustrates the numerous sources and sinks.

Figure 21. The figure displays the 20 transects used to calculate the total average volume contained in the green-up zone when flooded. The black boundary signifies the green-up zone boundary.

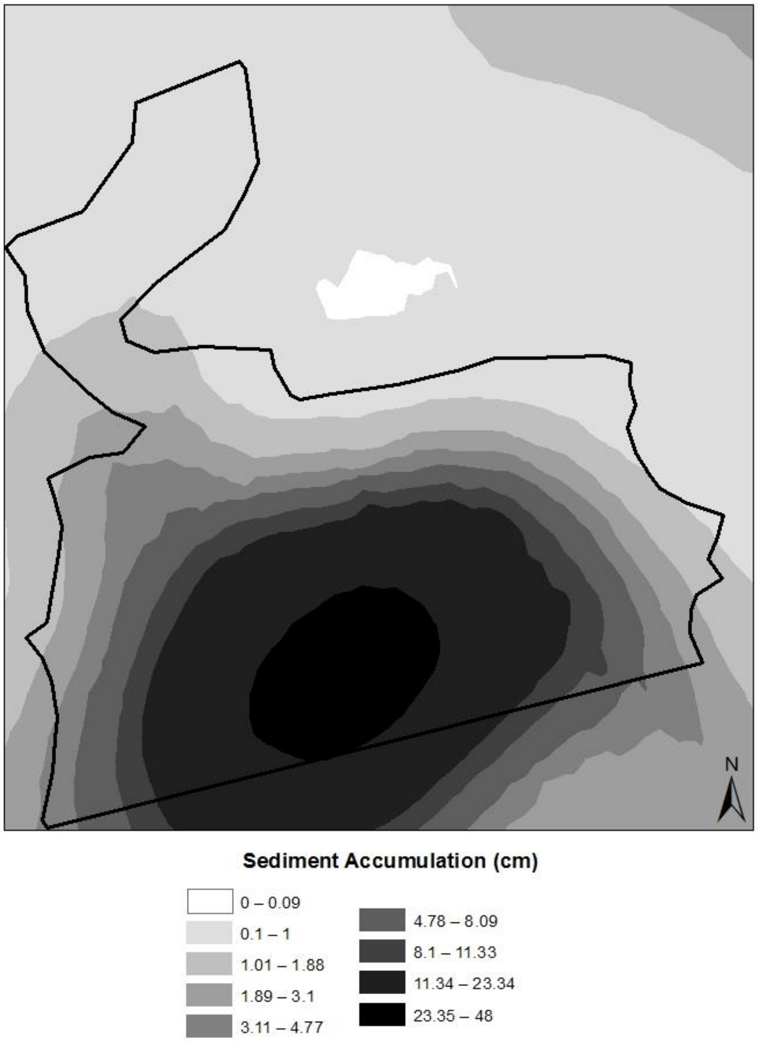


Figure 22. Sediment accumulation upstream from the canal within the green-up zone of Stream 1.

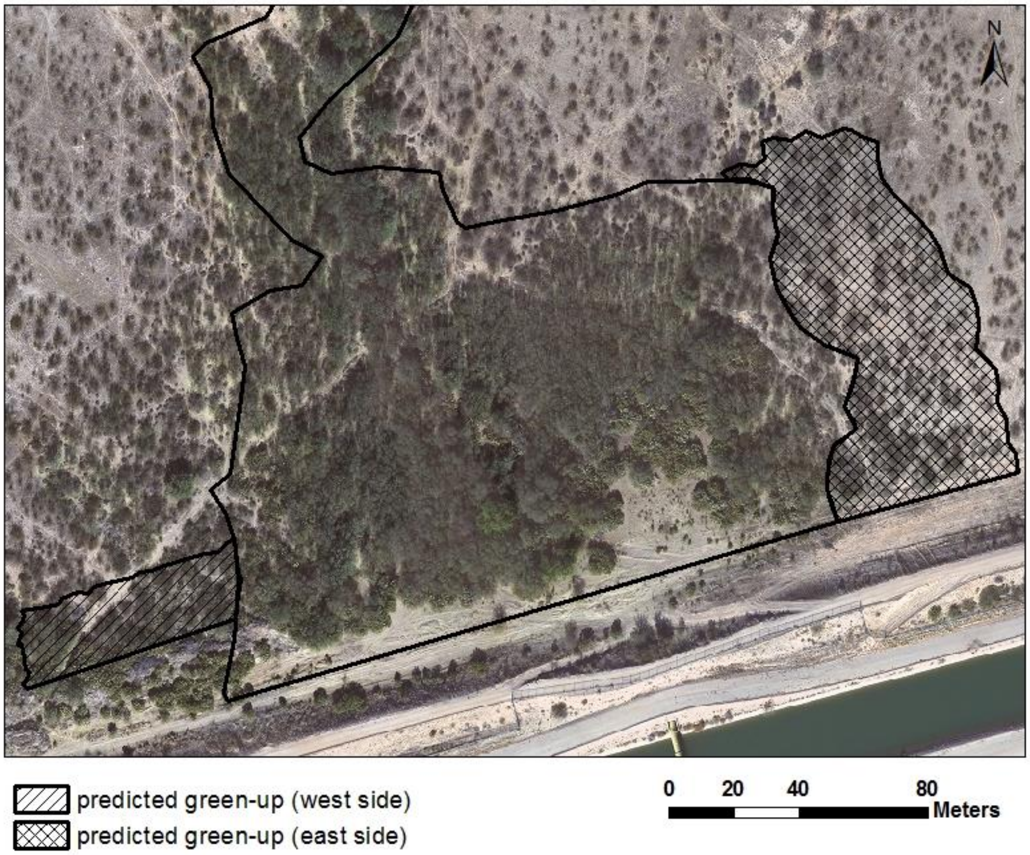


Figure 23 – The west side of the canal is likely to have the majority of vegetation growth, because it is lower in elevation than the east side. Note: if the growth were on the east side, the area of green-up would encompass a much larger area because the topography is less deep than the west side.

Figure 24. The images are all captured facing upstream (northward). Images A, B and C are in order from the canal's boundary (upstream) to approximately 350 meters upstream. No flow was present in the Stream 2 shown in image D. Precipitation data downloaded from the FCDMC shows this area received approximately 0.04 inches of rain about every half hour totaling to about 1 inch of rain during the time the pictures were taken in the field.

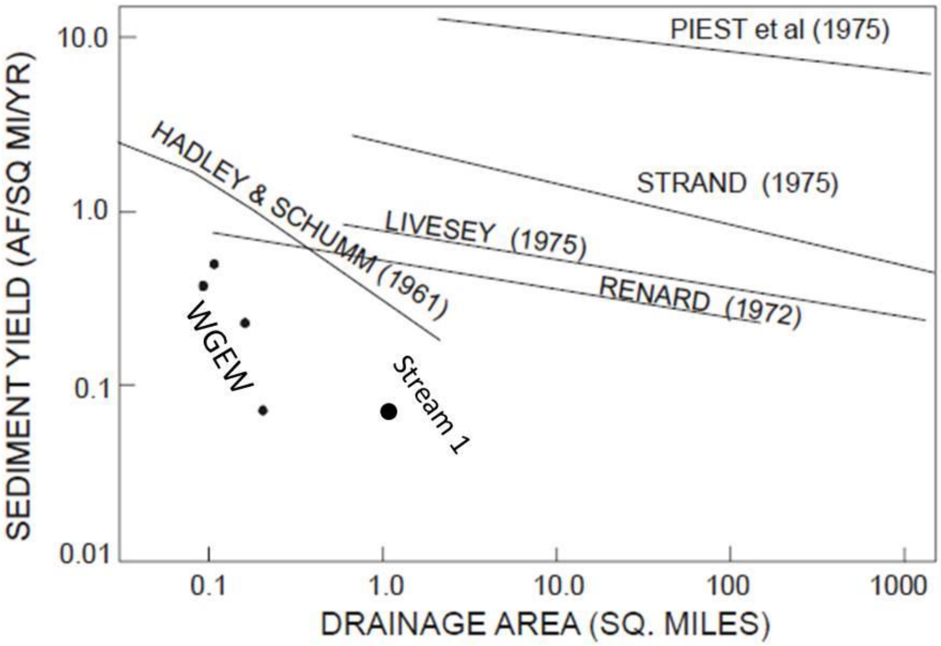


Figure 25. Sediment yield estimates vary with differing sites. The WGEW site varies by an order of magnitude between the four sites. Our estimated sediment yield for the partially dammed stream is closer in value to the WGEW sites. Figure adapted from Nichols and Renard (2003).


Image A
road culvert
0
72 m
237 ft
© 2013 Google

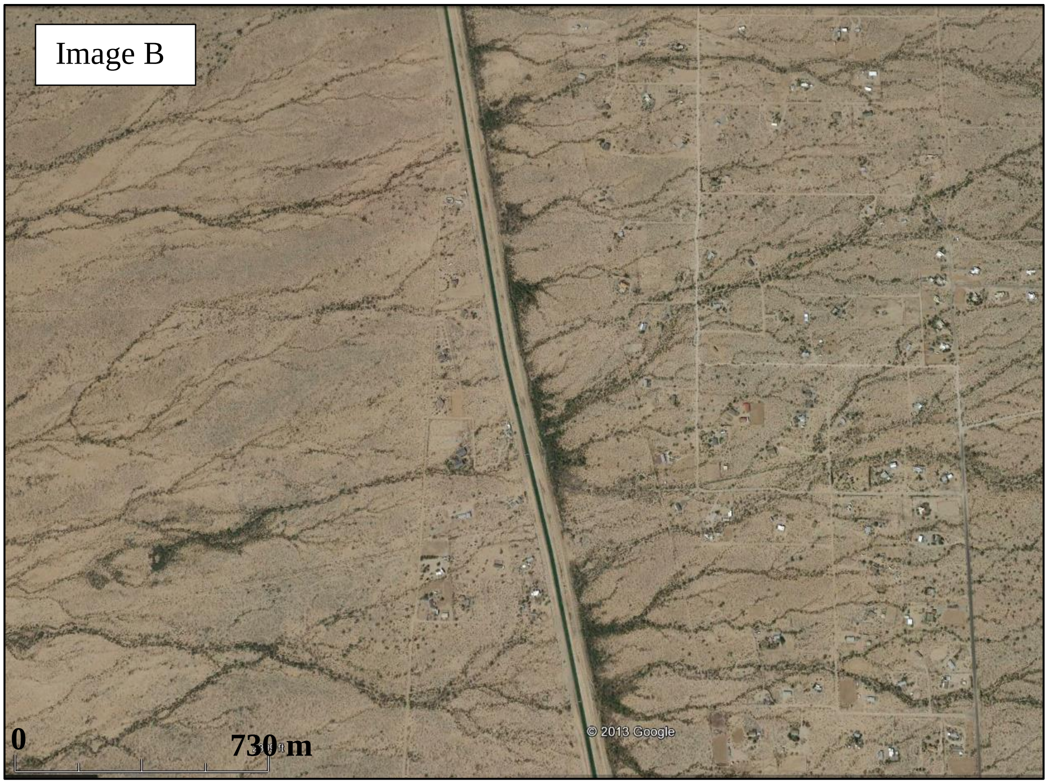


Figure 26 – The above aerial photographs have been extracted from Google Earth. In image A, it is apparent that during large precipitation events water floods the upstream side of the canal that is completely dammed to where the flooding extends up the road culvert to the house on the left (black dotted line is estimation of high water mark). In image B, the homes are constructed or existed previously to canal construction and are safe from flooding.

5. CHANGES IN ABUNDANCE, STEM SIZES AND DENSITIES OF RIPARIAN VEGETATION DUE TO A CANAL BARRIER TRAVERSING EPHEMERAL STREAM CHANNELS

ABSTRACT

The effects of damming perennial rivers have been well-studied in multiple disciplines. Both the upstream and downstream reaches of dammed rivers are affected where connectivity has been disrupted. The aim of this study is to quantify changes to riparian vegetation due to the Central Arizona Project (CAP) canal, which serves as a longitudinal barrier to ephemeral streams. The CAP canal traverses ephemeral channels, and alters flow during runoff events essentially ponding water upslope behind the canal's wall. The research question asked in this study is: What vegetational shifts have occurred within riparian plant communities over the course of 35 years in response to the construction of the CAP canal? Three ephemeral streams near Wittmann, AZ were selected for examination. Field data was collected to compare differences in plant stem density, vegetation volume and plant size between locations upstream and downstream of the canal with respect to unaltered control sites.

By ponding water, the CAP canal has created areas that contain denser riparian vegetation than existed prior to canal construction. Vegetation composition within the wettest zone has shifted from a mix of tree and shrub cover to more of a tree and herb mosaic of which velvet mesquite (Prosopis velutina) trees have become the predominant tree species. Creosote shrub (Larrea tridentata) densities are approximately 90 percent lower within the wettest abovementioned zone (R-A1), whereas densities of mesquite trees are approximately six times greater than the control zone. In general, areas that are

not heavily ponded have preserved their species composition to resemble the control area. L. tridentata shrubs in wetter areas have larger stem diameters and greater height than in the riparian control site (R-C). Mean L. tridentata heights and dbh values have increased by 0.6 m and 0.76 cm respectively, when compared to the control site, due to increased water availability caused by the CAP canal. These species-specific and community level changes across the desert landscape have been caused by the presence of the canal. This research aids in greater understanding of human impacts due to canal barriers on sensitive desert riparian vegetation, and can be used to predict future outcomes of newly proposed canal-building in desert environments.

INTRODUCTION

Barriers such as roads, fences, dams and canals affect landscapes and their various components. Studies conducted on the effects of terrestrial barriers (e.g. roads) typically deal with understanding changes to wildlife abundance, genetic diversity and migratory patterns (Epps et al. 2005; Holderegger and Di Giulio 2010; Krausman et al. 1993). Research on impacts of aquatic barriers, largely associated with damming perennial rivers, focus heavily on the migration and population dynamics of fishes and changes to riparian vegetation dynamics (Bergkamp et al. 2000). In dammed perennial rivers, controlled flooding and less sediment availability downstream from a dam can have major effects on seedling establishment, and plant survival given that species have different thresholds for survivorship of flooding and sedimentation (Levine and Stromberg 2001; Stromberg et al. 2007).

The spatial distribution of vegetation along perennial rivers is controlled mainly by geomorphic processes (e.g. sedimentation) and hydrologic processes (e.g. flood frequency) (Hupp and Osterkamp 1985). Yet, for ephemeral stream settings in arid to semi-arid regions, water availability is the predominate factor regulating vegetation spatial abundance and distribution (Hupp and Osterkamp 1996). In dryland regions, water resources are crucial for maintaining high productivity (Hancock et al. 1996) and exert strong influence on species distribution in or along channels (Tooth and Nanson 2000). Our current understanding of desert plant communities' responses and adjustments to human-constructed barriers along ephemeral streams is in its infancy.

This study focuses on a longitudinal barrier- the Central Arizona Project (CAP) canal- that traverses ephemeral streams. This barrier causes changes to stream hydrology and thus to riparian desert plant communities along longitudinal (upstream to downstream channel) and lateral (channel to upland) directions of the stream channel. The CAP canal also affects vertical conductivity (surface to groundwater) (Boon 1998; Blanton and Marcus 2009; Brierley et al. 2006). In this study we examined how the longitudinal barrier affects the lateral and longitudinal aspects of the vegetation, thereby providing a much needed understanding of plant community changes in response to anthropogenically altered ephemeral channels.

CAP canal construction was initiated in 1973 in order to establish a concrete lined canal to meet the growing water demands of municipal and agricultural areas in Arizona's desert. This twenty-year long project was one of the most costly (approximately 4 billion US dollars) and largest (336 mile) canals built in the United States. Currently, the CAP canal intersects hundreds of desert ephemeral rivers, which are locally referred to as washes or arroyos. The larger washes remain connected to their downslope counterparts through overchutes or culverts that were built into the canal's design. However, smaller streams are in most cases dammed causing stormwater runoff to pool upslope behind the canal wall/berm. Thus, the CAP canal can either completely disrupt upstream-downstream connectivity of ephemeral stream channels or can modify their flow regimes through culverts and overchutes.

The CAP canal is an ecological barrier that not only fragments habitats, but also alters landscape processes to create different environments. Remotely sensed studies indicate that pre-existing xeroriparian vegetation on the downslope end has become even drier, leading to desertification, while areas on the upslope end become seasonally ponded and more mesic. These ponded areas are referred to as green-up zones or anthropogenic playas (Hamdan 2012). In this study, we conduct field studies to ask: What vegetational shifts and spatial adjustments have occurred to xeroriparian plant communities over the course of 35 years in response to the construction of the CAP canal? To address this question, we focus on four main variables: vegetation volume, canopy height, woody stem density, and herbaceous cover. Four specific research questions are: 1*) Have vegetation volume, canopy height, and stem density of the xeroriparian vegetation increased in the altered areas upstream and downstream of the canal barrier relative to the unaltered control sites? 2) Has the increased ponding created by the CAP canal induced greater growth of herbaceous vegetation? 3) Are changes evident in the desert upland vegetation, owing to increased lateral flow of water?* 4) *Have composition and structure both changed within the green-up zones, with shifts from shrub-dominated communities to tree-dominated communities? 5) How has changed hydrology caused by the canal influenced the different responses in vegetational changes along different sections of the altered stream channel?*

There has been little research conducted on riparian vegetation response to longitudinal barriers in desert environments. As years pass, global populations and urbanization will increase, which consequently adds to the need for greater water demands. An estimated 33 percent of the Earth's continents are characterized as drylands of which 15 percent is inhabited by people (Parsons and Abrahams 2009). Riparian vegetation along ephemeral channels comprises a small portion of these drylands (Knopf et al., 1988). However relatively small these areas seem, they support an abundance of desert wildlife and vegetation. Understanding the effects of the CAP canal on riparian vegetation is critical to upholding environmental stewardship as well as having the potential to aid in implementing sustainable practices in desert environments.

STUDY AREA AND EXPERIMENTAL DESIGN

In this study, we compare altered sections of stream channels (such as the green-up zones) to unchanged sections of the stream channels. The unaltered sections serve as the research controls. We selected three ephemeral stream channels, all located on the same alluvial fan, on the southern slope of the Hieroglyphic Mountains. The study area is located at approximately 33°44'53.09" N, 112°28'27.93" W near Wittmann, AZ **(**Figure 27a.**)**. In this area there are numerous ephemeral stream channels carved into the alluvial fan that are intercepted by the CAP canal. These channels have anabranching characteristics and channel widths vary from approximately 1m to 6 m across. The main channels are characterized by a sandy to gravely substrate, but as the channels approach the canal barrier particle size become much smaller as fines are trapped upslope. Finer sediments are deposited on the upslope end of the channel during periods of inundation as sediment laden waters pond upslope to eventually pass through overchutes.

The three study streams are not completely impounded by the canal; rather, they have connectivity via overchutes. However, even with the longitudinal connectivity through overchutes, backfill of stormwater collects in the green-up zones during periods of intense and prolonged precipitation events. Stormwater no longer follows the same path as it did along the pre-canal stream channel. The stream channels are confined to drain through a pipe of a fixed diameter (72 inches), which causes waterlogging in the green-up zone. This ultimately causes water to flow laterally onto the desert floor. This widens the floodplain of the ephemeral stream channel as stormwater approaches the canal's boundary (Figure 27a & 27b). As seen in Figure 27, this creates a widening of the green-up zone (i.e. anthropogenic floodplain), which increases in width as it approaches the canal's boundary. The green-up zone contains the main channel and a newly-created floodplain. However, inundation due to the CAP canal is not exclusive to the green-up zones only, inundation also occurs in the main stream channel(s) directly upstream from the green-up zones. Sections of the channels upstream fill with water as the area below is ponded as well. The effect of inundation due to the CAP canal ends upstream beyond the abovementioned section.

The main species of woody plants at these three ephemeral stream sites are *Larrea tridentata* (LATR), *Prosopis velutina* (PRVE), *Ambrosia ambrosioides* (AMAM), *Ambrosia deltoidia* (AMDE), *Parkinsonia florida* (PAFL), *Baccharis sarothroides* (BASAR), and *Baccharis salicifolia* (BASAL). Additionally, many herbaceous plants are present, collectively referred to as H.

METHODS

Site Naming and Characteristics

The ephemeral channels have distinct zones that we delineated by aerial and field observations (Figure 28). Six unique areas within each stream channel are sampled that are mainly differentiated by the amount of runoff received and substrate composition. The six areas are named accordingly: Desert Control (D-C), Desert Altered 1 (D-A1), Riparian Control (R-C), Riparian Altered 1(R-A1), Riparian Altered 2(R-A2) and Riparian Altered 3(R-A3).

There are two control sites in this study. The first of these is the Riparian Control (R-C) which serves as a control site for the altered sections of the stream channel. R-C is the portion of the channel that lies sufficiently far upslope from the canal's boundary to be unaffected by ponding events. The altered sections of the channel are separated into three areas, R-A1, R-A2 and R-A3. R-A1 is the wettest area. It is directly upslope of the canal's boundary and is inundated (ponded) with runoff after large storm events. Fine sediments are deposited in R-A1, which we attribute to ponding within this area. R-A2 is the section of the main channel that is directly upslope from R-A1. This section of the channel backfills as the ponded area (RA-1) drains slowly through the overchute. R-A3 is the downslope section of the channel immediately below the canal. This section of the channel has a constant discharge rate of ponded water flowing upstream to downstream through the overchute

The second control area (D-C) is an unaltered area of the Sonoran Desert, beyond the area of influence of the canal. The desert floor is altered (D-A1) due to the lateral flow of runoff that occurs as the ponded area fills, inundating the desert floor. D-A1 is the perimeter of the ponded area/green-up zone. It is not a part of the channel rather it is an area of spill over once the ponded area has exceeded its retention limits.

Field Sampling- (Density, Herbaceous Cover, Vegetation Volume, Stem Sizes)

Field data was collected in mid-November to early December (2012). We collected data on vegetation volume (by species), vegetation height (by species), woody plant stem density (by species), woody plant stem diameter (by species), and herbaceous cover. To measure total vegetation volume (TVV) and species-specific vegetation volumes (VV), we used the vertical line intercept method with a telescoping pole (MacArthur and Horn 1969; Mills et al. 1991). Ten points within each zone of each of the three streams were randomly sampled except for R-A1 in which we randomly sampled 18 points, because of its larger area. This amounted to a total of 30 points for R-C, D-C, D-A1, R-A2, and R-A3 and 55 points for R-A1.

At each point, we recorded the volume of woody and herbaceous vegetation along the vertical pole within sub-sections of a meter. Any part of the vegetation that would lie within the pole's boundary was recorded as a "hit" at that decimeter (dm) within a specified meter layer. A 1 dm radius was chosen for the pole's boundary to include vegetation that fell within that radius. The unit of measure is vegetation within 1 dm vertically by 1dm radially. The number of "hits" for each meter layer ranged from 0 to 10.

TVV and VV were calculated using the following:

$\mathrm{TVV} = \sum h / 10n$ and $\mathrm{VV} = \sum hs / 10n$

Where:

h – number of hits per meter within a zone
hs – number of hits per meter within a zone for a particular species
n - total number of sample points within a zone

At each point we also recorded the maximum vegetation height. The points also served as locations for sampling vegetation within a 1m by 2 m plot. The variables measured in the plots were number of stems per shrub or tree, stem diameter (DBH), and visual estimates of the percentage of herbaceous cover.

We calculated average density, D, of each species within each zone per hectare was calculated using: D = (Total species count in zone/sum of sampled zone areas) * 10,000. Basal Area per zone was calculated with the standard formula: BA = πr^2 /plot area. Median values for herbaceous cover were calculated using the measured values of herbaceous cover for all quadrats per zone.

Stem Changes - Statistical Analysis using Welch's t-test

We used Welch's two sample t-test (also referred to as the unequal variance t-test) (Whitlock and Schluter 2009) to compare the height and DBH of common woody species in each zone to their respective control sites. We conducted this analysis only for *L. tridentata*; the sample size for other plant species, including *P. velutina,* was too small to reasonably perform statistical analysis. We also performed Welch's two sample t-test to compare the mean values for total vegetation volume within each zone. Welch's t-test assumes unequal variances within the data and does not require a normal distribution (Ruxton, 2006). Welch's t-test was conducted in R programming software. We set alpha at 0.05.

VV, Stem Density, & Herbaceous Cover - Statistical Analysis using Two-way ANOVA

We used a two-way Analysis of Variance (ANOVA) using Tukey post-hoc tests (Whitlock and Schluter 2009) to detect significant differences between vegetation volume of *L. tridentata* and *P. velutina*, stem densities of *L. tridentata* and *P. velutina*, and herbaceous cover. These were the three types of vegetation that had sufficient sample size to perform statistical analyses. The statistical analyses were performed to detect differences between the three ephemeral streams and the zones within these stream areas, and to determine if there were interaction between the two factors. ANOVA was executed using SPSS version 19 software. We considered population means of at least one group to be significantly different if the p-value is less than 0.05 (Whitlock and Schluter 2009).

RESULTS

Vegetation Volume

The altered riparian areas (R-A1, R-A2, and R-A3) have greater total vegetation volume than the riparian control site, R-C (Figure 29). R-A1 is the only riparian zone to show a statistically different mean from the control (Welch's t-test, t = -2.1006, df = 77.233, *p* = 0.0389); its total vegetation volume was 40 percent greater compared to the control (Figure 3). There is no significant difference for TVV between the riparian control and the altered zones, R-A2 (Welch's t-test, t = -1.5811, df = 56.437, *p* = 0.1194) and R-A3 (Welch's t-test, t = -0.975, df = 49.449, *p* = 0.3343). For the desert altered, D-A1, and the desert control areas, D-C, there is a significant difference for TVV (Welch's t-test, t = -4.1296, df = 41.555, *p* = 0.00017). Total vegetation volume for D-A1 is almost four times greater than the desert control (Figure 29). The desert altered area, D-A1, and the riparian altered zone, R-A1, were the two locations that revealed a significant difference in TVV from their respective control sites.

Vegetation Volume, by Species

The mean differences for vegetation volume, VV, of *P. velutina* trees across the three sampled streams are not statistically significant (two-way ANOVA, $F = 2.647$, $p = 0.074$). However, the zones within the streams occupied by *P. velutina* are statistically significant (two-way ANOVA, $F = 11.420$, $p < 0.001$). Specifically, R-A1 had statistically greater *P. velutina* tree volume when compared to the control (HSD, $p = 0.003$), and was different from all other zones including R-A2 (HSD, $p < 0.001$), R-A3 (HSD, $p < 0.001$), D-C (HSD, $p < 0.001$) and D-A1 (HSD, $p < 0.001$). Vegetation volumes for both *P. velutina* and palo verde trees are greater within each stratigraphic 1 meter layer of R-A1 as compared to R-C (Figure 30). *P. velutina* is present within the 5 to 6 m layer in R-A1 and has a greater vegetation volume throughout each meter layer when compared to the control area where it reached only to the 4 to 5 m layer (Figure 30). In contrast, vegetation volumes for *L. tridentata* decline considerably in R-A1 compared to the control (Figure 30).

L. tridentata volume differs significantly by zone, but not by stream (two-way ANOVA, $F = 9.829$, $p < 0.001$). R-A2 has statistically greater *L. tridentata* volume than the control (HSD, $p = 0.005$), with *L. tridentata* volume particularly abundant in the 2 to 3 meter layer of R-A2 (Figure 30). R-A3 and R-C are fairly similar in the species present and their associated vegetation volumes. The altered desert zone (D-A1) does not have a significant difference of *L. tridentata* volume when compared to the desert control (D-C) (HSD, $p = 0.244$).

Stem Density, by Species

As in the case for vegetation volume, stream sites are not a significant factor in controlling *L. tridentata* stem densities (two-way ANOVA, $F = 1.281$, $p = 0.280$), but are significant for *P. velutina* densities (two-way ANOVA, $F = 8.442$, $p < 0.001$). Zone areas are significant for both *L. tridentata* (two-way ANOVA, $F = 6.510$, $p < 0.001$) and *P. velutina* (two-way ANOVA, $F = 5.523$, $p < 0.001$).

The mean density for *P. velutina* in stream 2 does significantly vary from that of stream 1 and stream 3 (HSD, $p < 0.001$ for both). In comparisons of zones, stem density for *P. velutina* trees is greatest in R-A1 (Figure 31), and values in this zone statistically differ from the control site (HSD, $p = 0.003$) and other zones (R-A2, D-C, D-A1; HSD, p ≤ 0.002 for all zones). Densities of *P. velutina* were approximately six times greater within R-A1 (2,182 individuals/ha) than R-C (345 individuals/ha). R-A1 also has greater stem density of *B. salicifolia* and *B. sarothroides* than the control (Figure 31). At the same time, densities of *L. tridentata* have declined in R-A1 to 182 individuals/ha from 1,897 individuals/ha estimated in the control zone (Figure 5). R-A1 has statistically differing means for stem density of *L. tridentata* compared to R-A2 (HSD, $p = 0.005$), R-A3 (HSD, $p < 0.001$), D-C (HSD, $p < 0.001$) and D-A1 (HSD, $p < 0.001$), but not compared to R-C (HSD, $p = 0.149$). Even though R-A1 and R-C are not statistically different, R-A1 and R-A3 are statistically different. *L. tridentata* populations may have been closer to the value for R-A3 (2,167 individuals/ha) mainly due to its closer proximity to R-A1 than the control site and since R-A3 has been statistically similar to R-C for all variables.

The small desert shrub *A. deltoides* was not present within R-A1 whereas R-C contained a fairly large density of this species with about 1,552 individuals/ha. Densities of *L. tridentata* were greater in D-A1 and R-A2 when compared to R-C and D-C, which were 2,833 individuals/ ha, 2,333 individuals/ha, 1,897 individuals/ ha, and 2,069 individuals/ha; respectively (Figure 31). *A. ambrosioides* exhibited the greatest density within R-A2 in relation to R-C. R-A1 contained the highest value for basal area of woody vegetation whereas R-A3 displayed the lowest basal area change relative to R-C (Figure 32).

Herbaceous Cover

Herbaceous cover was influenced by the stream site (two-way ANOVA, F= 5.995, $p = 0.003$) and the stream's zones (two-way ANOVA, $F = 15.271$, $p < 0.001$). The third stream channel, the smallest stream of the three, had statistically more herbaceous cover than the other two larger streams: stream 1 (HSD, $p = 0.027$) and stream 2 (HSD, $p = 0.001$).

The mean values for herbaceous cover in R-A1 and D-A1 are statistically greater than in their respective control sites, R-C (HSD, p = 0.004) and D-C (HSD, p < 0.001). From the 30 plots sampled in R-C, only one plot contained any herbaceous cover (Figure 33). D-C did not contain herbaceous cover in any plot. Both R-A1 and D-A1 had relatively high percentages of herbaceous cover and displayed a significant increase compared to their control sites. Approximately two-thirds of the entire area of D-A1 had a median value of 60 percent herbaceous cover whereas about half of R-A1 area had a median value of 40 percent herbaceous cover (Figure 33). There was very little herbaceous cover present within the other zones.

Overall, the interaction between the three stream sites and zones reveal no interaction between the two subjects (stream sites * zones) in performing the two-way ANOVA on vegetation volume of *L. tridentata* and *P. velutina*, stem densities of *L. tridentata* and *P. velutina*, and herbaceous cover.

Stem Size Changes for L. tridentata

In one of the three altered riparian zones, zone R-A2, *L. tridentata* had significantly greater height ($p<0.01$) and stem diameter ($p<0.01$) compared to the control, based on Welch's test R-C (Table 7a and Table 8a). *L. tridentata* mean height in R-A2 was approximately 2.4 m compared to 1.8 m in R-C (Table 7a). R-A2 contains the widest range of height values and a maximum height value of 3.7 m (Figure 34). The mean stem diameters for *L. tridentata* in R-A2 and R-C are 1.97 cm and 1.21 cm, respectively (Table 8a). Once more, R-A2 had the greatest range of DBH values and the highest maximum of 4 cm (Figure 35).

Within the desert areas, *L. tridentata* had statistically larger size in D-A1 than in D-C with p-values less than 0.05 (Table 7a and 7b). *L. tridentata* heights averaged 1.7 m in D-A1 and 0.9 m in D-C (Table 7b). DBH mean value increased from 0.71 cm in D-C to1.16 in D-A1 (Table 8b).

DISCUSSION

Wettest Zone, Green-up Area (R-A1)

Water availability is the primary factor limiting plant growth and distribution in desert environments (Lazaro et al. 2001; Hupp and Osterkamp 1996; Noy-Meir 1973). In cases of prolonged drought, desert shrubs may experience canopy die-back and individual shrub mortality (McAuliffe and Hamerlynck 2010; Hamerlynck and McAuliffe 2008).

The wettest area of all zones in this study, not unexpectedly contains the greatest density of woody plant stems, the greatest vegetation volume, and a high percentage of herbaceous cover (Figure 31). Using a different methodology, remote sensing, Hamdan (2012) documented a 477 percent increase in vegetation cover along one ephemeral stream channel, which is primarily attributed to increased water amounts due to ponding from the CAP canal barrier.

The wettest zone contains the greatest uniformity of vegetation volumes throughout the vertical stratigraphic column (Figure 30). Comparing the vegetation volumes and the species associated in the riparian control area and the wettest zone clearly illustrates the importance of water availability in the desert (Figure 30). Vegetation volumes are consistently greater in the higher portions of the stratigraphic column within the wettest zone than all other zones. This zone also contains the highest basal area and the greatest total vegetation volume than all other zones (Figure 29 and Figure 32). Vegetation-type also contributes to the reasons of the wettest zone resulting in the highest total vegetation volumes and basal area. The wettest area has more trees as the other zones contain more shrubs. Hence, comparing tree barks to shrub stems (basal area) and comparing tree heights to shrub heights (TVV) affect the outcome of these values as well. Nevertheless, the wettest zone displays the greatest total vegetation volume and basal area.

Even though vegetation cover is evidently greater in the green-up area, the abundance of specific species has changed from pre-existing conditions before the construction of the canal. Desert vegetation spatial distributions and responses are associated with a complex system that includes climatic variables as well as geomorphic factors and the understanding of plant traits (Sponseller et al. 2012). Within the wettest zone, a decline in more drought-tolerant plants such as *L. tridentata* bush and *A. deltoidia* has occurred when comparing it to the control (Figure 31). The canal has caused the substrate of the wettest zone to change from sandy to a finer clayey surface, which decreases the infiltration capacity and, in turn, causes longer periods of inundation. Such conditions are not favorable to drought-tolerant plants that grow better in well drained and well aerated soils.

We speculate that the lack of *L. tridentata* in the wettest zone is possibly due to many reasons. Because this area is heavily inundated during storm events, the critical annual range of precipitation for seed germination is exceeded, which may inhibit seed germination. Similar to the characteristics of the majority of plants on Earth, densities of *L. tridentata* shrub cover increase with increasing rainfall (Woodell et al. 1969). However, there is a critical average rainfall range of 160-183 mm for high success rates of *L. tridentata* seed germination (Beatley 1974). Higher or lower annual precipitation resulted in 0 to 20 percent success in *L. tridentata* seed germination (Beatley 1974). Furthermore, Sharifi et al. (1988) found that reproductive growth of *L. tridentata* was least successful in watered *L. tridentata* when compared to non-irrigated shrubs. The wettest zone is essentially ‘irrigated’ during storm events throughout the year. Secondly, the inundation of *L. tridentata* for unnaturally long periods makes this shrub possibly susceptible to die off. Also, it was qualitatively examined in the field that water lines reached a maximum of 2 meters within the ponded area. The frequency and duration of water reaching this height over the course of 36 years is unknown, but exposing *L. tridentata* to anoxic conditions that completely submerge the shrub could also lead to die-off of pre-existing *L. tridentata*. Lastly, an increased density, which has been documented to slow growth rates with increasing neighbor densities, could have also contributed to *L. tridentata* die-off in the wettest zone (Cody 2000).

As *L. tridentata* and *A. deltoida* have declined in the wettest zone, *P. velutina* and herbaceous cover have increased (Figure 33 and Figure 31). Unlike some other types of vegetation that tend to have a narrowly limited geomorphic threshold for growth, Prosopis *sp*. can grow in a wide range of geomorphic settings. Prosopis *sp*. has been documented growing in and along ephemeral rivers, canyons, sand dunes, alluvial fans, wide floodplains and even on mine tailings with harsh soil chemistry (Nagaraju et al. 2006; Simpson 1977). Seed germination can occur on the surface of the soil, but requires burial of 1 to 2 cm for seedling survivorship (Simpson 1977). This wettest zone area has the greatest amount of sedimentation due to the canal boundary making it conducive to *P. velutina* seed burial. Also, *P. velutina* seeds may generally germinate in temperatures ranging from 20°C to 40° C, and can germinate within 6 hours of deposition at 34 °C with proper moisture availability (Simpson 1977). The wettest zone is conducive to providing these conditions as evident by the new young growth of *P. velutina* trees that are ubiquitous in this zone.

Backfill Channel (R-A2) & Anthropogenic-floodplain zone (D-A1)

The anthropogenic-floodplain zone (perimeter of the wettest zone) and the backfill channel (upstream section directly above the wettest zone) contain the most abundant and largest *L. tridentata* shrubs; both zones are less moist than the main ponded area and the substrate composition is different. The conditions associated with these zones are favorable to the largest shrubs in terms of dbh, height and vegetation volume

(Figure 30, 34 & 35). This observation of larger *L. tridentata* is primarily due to greater water availability and the presence of sandy soils. Hamerlynck et al. (2002) examined *Larrea* on various alluvial fan surfaces concluding that soil type is an important factor in plant population and community-level processes. The zone with the largest creosotes is a section of the main channels that backfills and ponds when the ponded area is flooded causing the advancement of water upstream. This channel section consists of well-drained soils due to the fine-medium sandy surfaces on which *L. tridentate* shrubs reside, which differs from the fine clayey surface of the ponded area. The heights of the *L. tridentata* shrubs from the control site increased on average by approximately 0.6 m (Table 7a & Figure 34). Stem growth of *L. tridentata* in the Sonoran Desert is associated with the summer monsoon season; high growth rates were reported during wet summer years whereas low growth was recorded during dry summer years (Sponseller et al. 2012). Furthermore, *L. tridentata* shoot growth rates have been documented to increase with increasing water availability (Sharifi et al. 1988), which is also supported in this study. Stem diameters of *L. tridentata* increased by approximately 0.76 cm in the backfilled channel compared to the drier riparian control zone (Table 8a & Figure 35).

Further evidence in the importance of water to *L. tridentata* growth is apparent when comparing their growth on the desert floor to growing in riparian zones, which receive more water (Table 7a & 8a). It is also supported in the comparison of height and dbh values for the desert control site to the desert altered area (Table 7b & 8b). The desert altered area is essentially the anthropogenically-induced floodplain that resembled the desert pre-canal construction. The main channel over-fills causing ponding upslope from the canal barrier and disperse water laterally onto the desert floor (i.e. anthropogenically-induced floodplain). Mean height changed from 0.9 m in the unaltered desert to 1.7 m on the anthropogenic-floodplain; furthermore, mean dbh increased by 0.45 cm within the altered desert zone (Table 7b & 8b). Hence, the reason for increased growth is increased water availability.

Downstream Altered Channel (R-A3)

None of the measured variables were statistically different from the control zone. Due to the connectivity of the streams to their downstream counterpart via overchute, little change has occurred downstream. The downstream channels have maintained their general characteristics of a main channel with a narrow band of vegetation along the banks. The main difference between the control and the downstream section is that water is discharged at a slower rate through the overchute during ponding events, which may increase transmission through the soil downstream. This may explain the reason for greater TVV compared to the control (Figure 29); specifically, greater vegetation volume of *L. tridentate* (Figure 30). Nevertheless, this zone is remains very similar to the control site.

Herbaceous Cover

In perennial river systems, a reduction of water in the main channel can cause a decrease in herbaceous diversity and density (Stromberg et al. 2007). Herbaceous cover has significantly increased in the wettest zone and the perimeter of the ponded area (anthropogenic-floodplain) from their respective control sites due to increased water and sedimentation. These two zones contain the highest values for herbaceous cover that is within the 0 to 1 meter height range (Figure 30). In addition herbaceous percent cover is greatest in the anthropogenic-floodplain, which is speculated to mainly be due to having less sedimentation than the wettest zone. The primary herbaceous species surveyed in the field is Malva *parviflora* (Little Mallow). Seed germination of this particular species is not photoblastic (Michael et al. 2006; Chauhan et al. 2006) and can germinate within a wide range of temperatures with an optimal temperature between 15°C – 20°C (Michael et al. 2006).

The seeds of *M. parviflora* have an impermeable seed coat that enables the seeds to remain physically dormant until the seed is scarified through various physical processes (Michael et al. 2006). One method of scarification are periods of fluctuating temperatures (>15°C) documented in Mediterranean regions characterized by warm dry summers and wetter winters (Michael et al. 2006; Chauhan et al. 2006). Our study area, located within the Sonoran Desert, regularly experiences large diurnal temperature fluctuations capable of scarifying the seed of *M. parviflora*. A critical factor in seed emergence of *M. parviflora* is the burial depths of seeds. Burial depth of 0.5 to 2 cm is the optimal range in which seeds that are buried deeper have a precipitously declining rate of emergence and showed no emergence when buried 8 cm or greater (Chauhan et al. 2006). For this reason, the wettest zone has less herbaceous cover than the anthropogenic floodplain, because the anthropogenic floodplain receives less sedimentation causing seeds to be potentially buried with the optimum threshold for emergence. This explanation is also supported by the fact that herbaceous cover is statistically higher in the wettest zone of the smaller third stream than the other two wettest stream zones. The smaller stream will have less runoff, hence, less sedimentation causing the preferred shallow burial of M. parviflora seeds. Herbaceous cover is double in the wettest zone area of the smaller stream than the other two larger streams. As burial is critical to seed germination and emergence, water availability plays a critical role in seedling survival, which is the primary reason seed germination occurs mainly with winter rainfall in order to avoid seedling death during mostly dry hot summers (Michael et al. 2006).

CONCLUSION

It is clear that increased water availability in desert environments can drastically change the densities of species, stem sizes and species abundance. Overall, wetter zones displayed greater densities of vegetation cover and volume. These wetter zones were closer to the canal's boundary on the upslope sections of the canal. The riparian vegetation on the downslope end of the canal's boundary was similar to that of the control section (R-C) located far upslope mainly because connectivity remained on all three wash sites through the use of overchutes built into the canal. The most notable differences in riparian vegetation were increased *P. velutina* and herbaceous cover in the wettest zone R-A1. Moreover, R-A1 has changed from a mixed shrub and tree landscape to exhibit a more tree and herb cover. Greater water availability has led to the increase in *L. tridentata* height and stem diameter in the backfill channel (R-A2) and the anthropogenic-floodplain (D-A1) in comparison to their associated control sites R-C and D-C, respectively. Sections of the altered stream channels displayed different changes mainly due to the amount of water available, substrate composition, inundation duration and vegetation structure.

The greater environmental implications of these changes in vegetation are indirectly hypothesized from previous ecologic studies. Many ecologic studies show significant correlations with increased vegetation volumes to house greater bird densities (e.g. Mills et al. 1991). In addition, studies have found relationships between specific bird species to be associated with a particular plant species (e.g. Meents et al. 1982) as well as finding changes in bird communities due to changes in vegetation areas (Ambuel and Temple 1983). Vegetation structure can be used as an indicator for understanding bird diversities and their selection of specific vegetation structures used for habitation (Cody 1981). Plant species, abundance and volume are important indicators of bird populations. In studies mentioned above, greater densities of vegetation and volume have been shown to be correlated with greater bird densities. Since the wettest zone contains the highest overall density and vegetation volume, we speculate that this area may house greater bird densities and greater avian species richness than pre-existing conditions and compared to all other zones.

This research aids in greater understanding of human impacts due to the construction of the CAP canal on sensitive desert riparian vegetation. This study can be used to predict future outcomes of newly proposed canal-building in desert environments. Further research needs to be conducted on the implications to desert wildlife with these vegetational changes. It is essential that we understand human-related changes to landscapes in order to ensure and maintain a sustainable future for all living beings.

Table 7. a - Statistical results for mean heights of LATR to control site Riparian Control (R-C). b - Statistical results for mean heights of LATR to control site Desert Control (D-C).

7a

Larrea *tridentata*	Sample Area ID	Mean Height for Control R-C (m)	Mean Height (m)	t-value	p-value	df
	R-A1	1.8 ± 0.3	1.6 ± 0.8	0.8522	0.4224	6.991
	R-A2	1.8 ± 0.3	2.4 ± 0.6	3.4808	0.00176	26.19
	R-A3	1.8 ± 0.3	2.2 ± 0.6	1.9306	0.06621	22.53

7b

Larrea *tridentata*	Sample Area ID	Mean Height for Control D-C (m)	Mean Height (m)	t-value	p-value	df
	D-A1	0.9 ± 0.3	1.7± 0.6	4.7825	5.03E-05	27.988

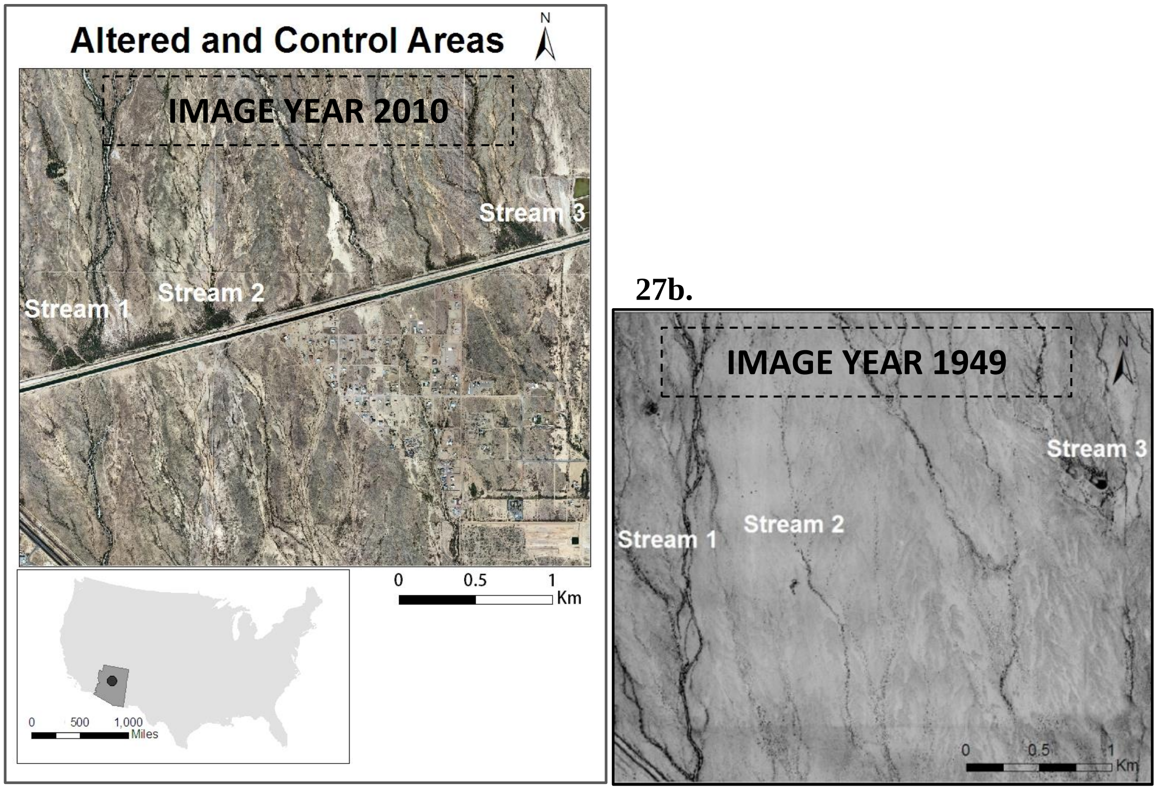
Table 8. a - Statistical results for mean DBH of LATR to control site R-C. b - Statistical results for mean DBH of LATR to control site D-C.

8a

Larrea *tridentata*	Sample Area ID	Mean DBH for Control R-C (cm)	Mean DBH (cm)	t-value	p-value	df
	R-A1	N/A	N/A	N/A	N/A	N/A
	R-A2	1.21 ± 0.48	1.97 ± 0.95	2.6846	0.01314	23.326
	R-A3	1.21 ± 0.48	0.955 ± 0.34	1.4915	0.1583	13.849

8b

Larrea *tridentata*	Zone ID	Mean DBH for Control D-C (cm)	Mean DBH (cm)	t-value	p-value	df
	D-A1	0.71 ± 0.32	1.16 ± 0.51	3.2918	0.002325	34.027



27a.

27b.

Figure 27. a – Study area. Stream channels are flowing from the northwest to the southeast, image captured in 2010. b – A historical photograph of the study area before the construction of the CAP canal.

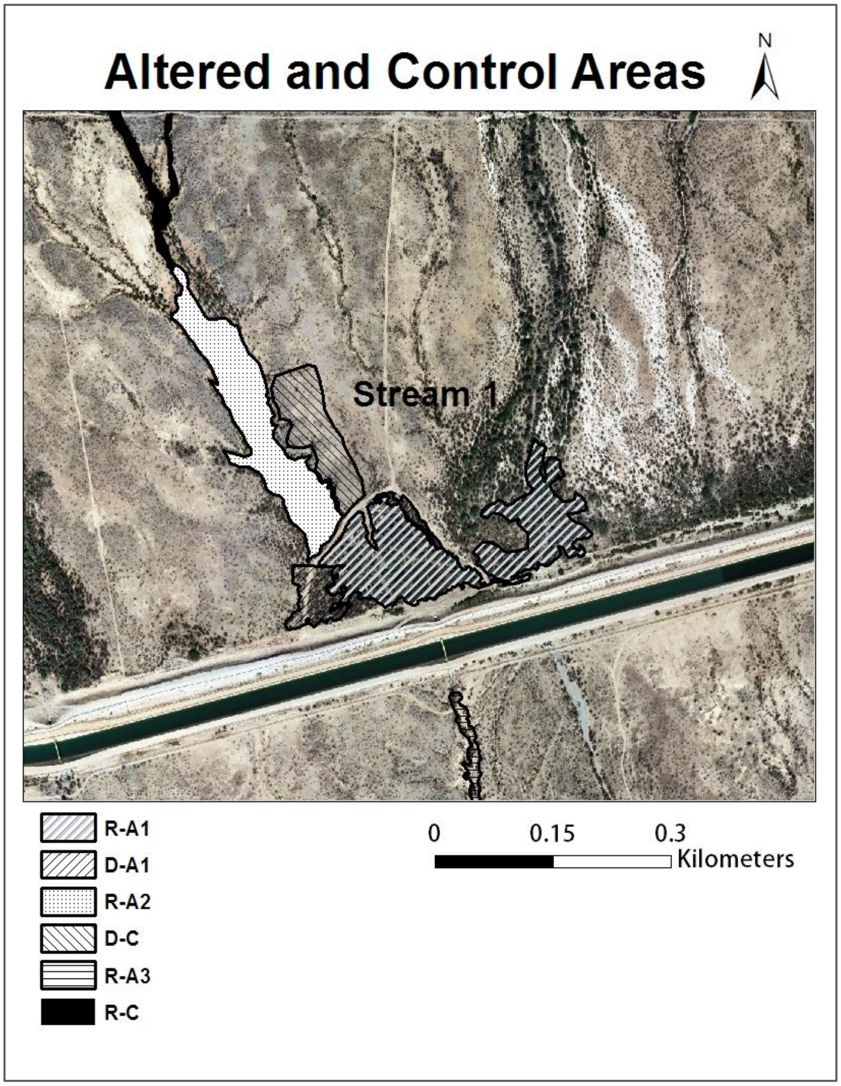


Figure 28. An example of channel delineation and assigning names D-C, D-A1, R-C, R-A1, R-A2, and R-A3 for stream channel 1.

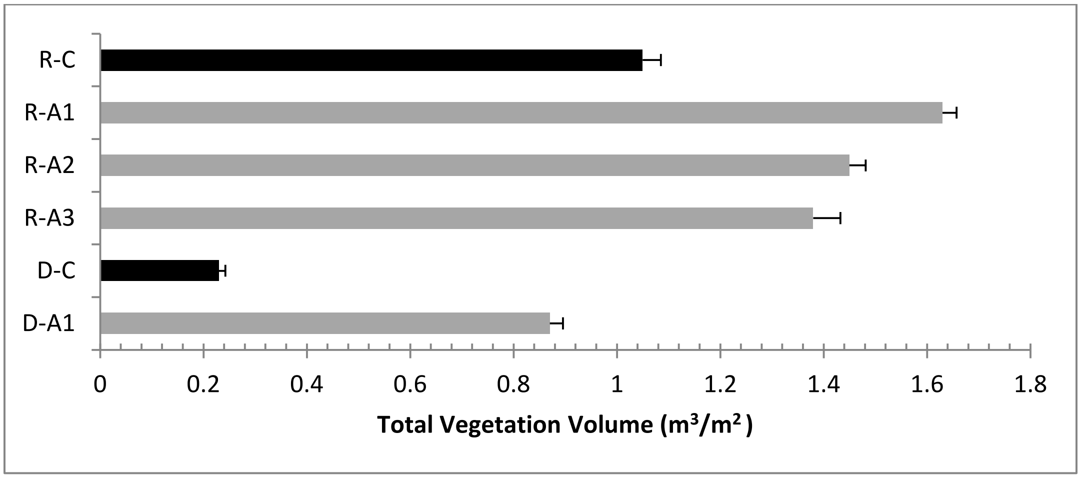


Figure 29. Total vegetation volumes for each zone.

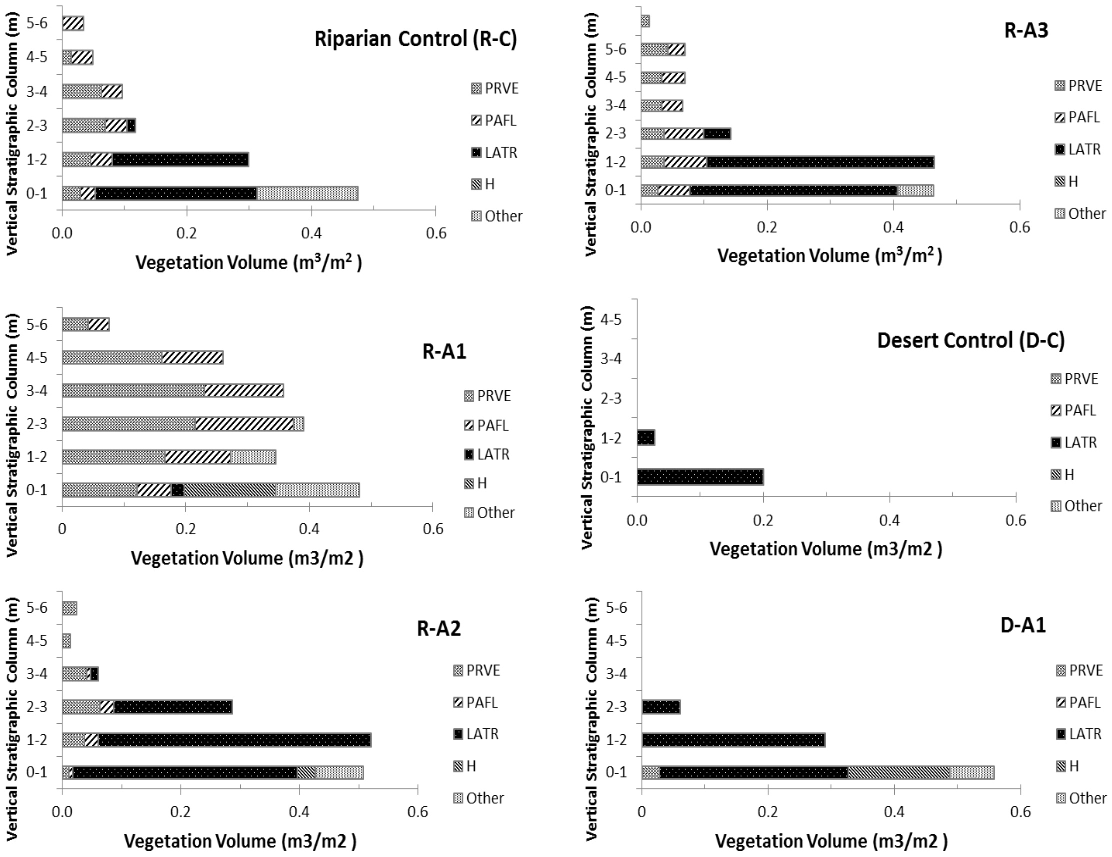


Figure 30. Vegetation volume of species within each sampled zone.

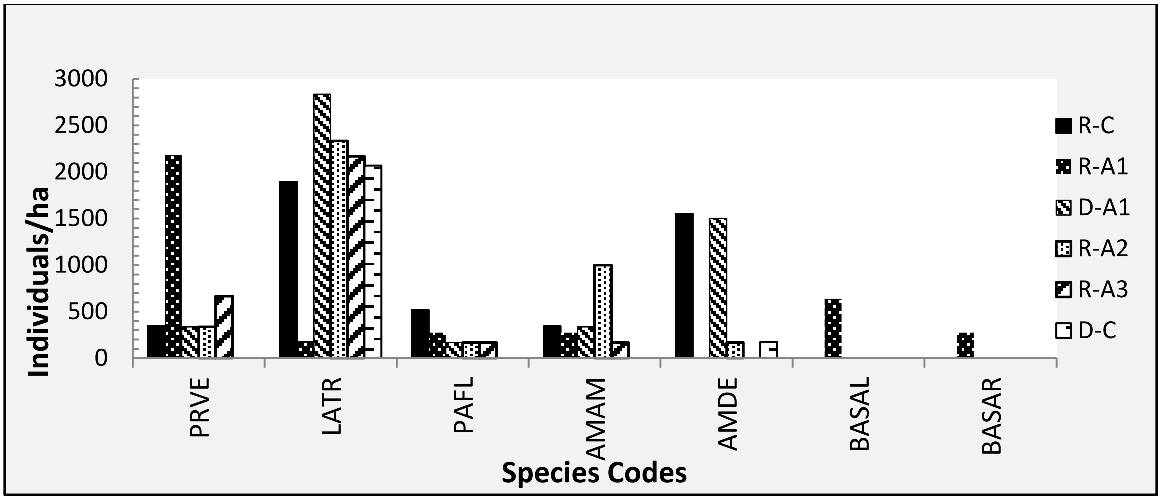


Figure 31. Stem densities of plant species within the six areas sampled compared to control sites R-C and D-C.

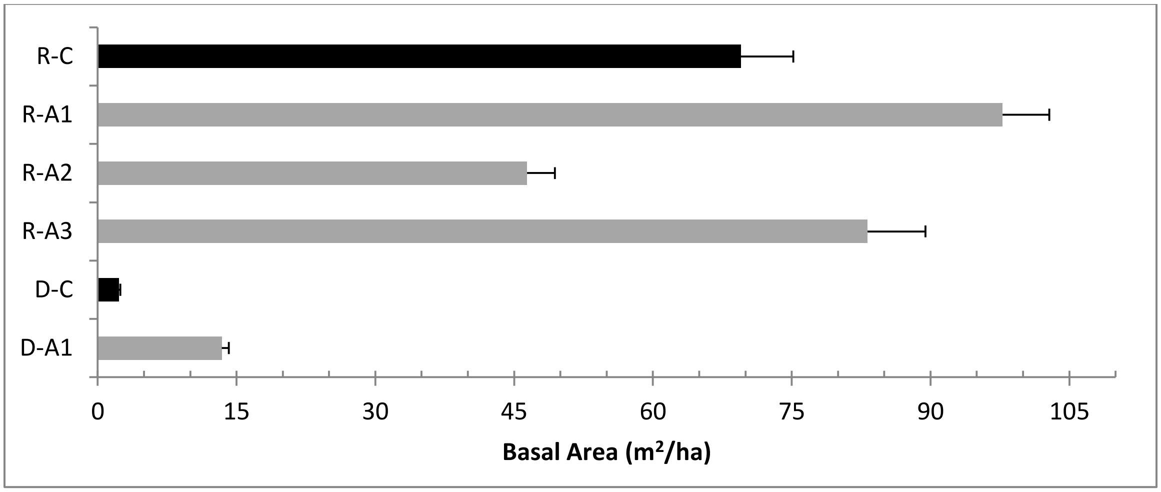


Figure 32. Basal area of woody vegetation across zones.

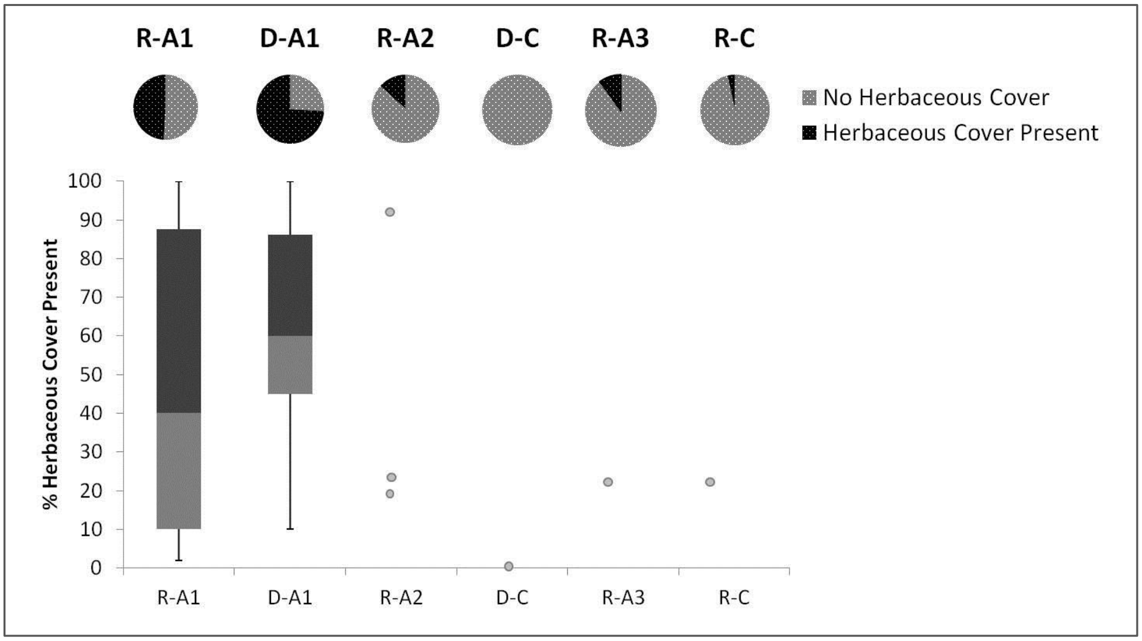


Figure 33. Percent herbaceous cover for each zone.

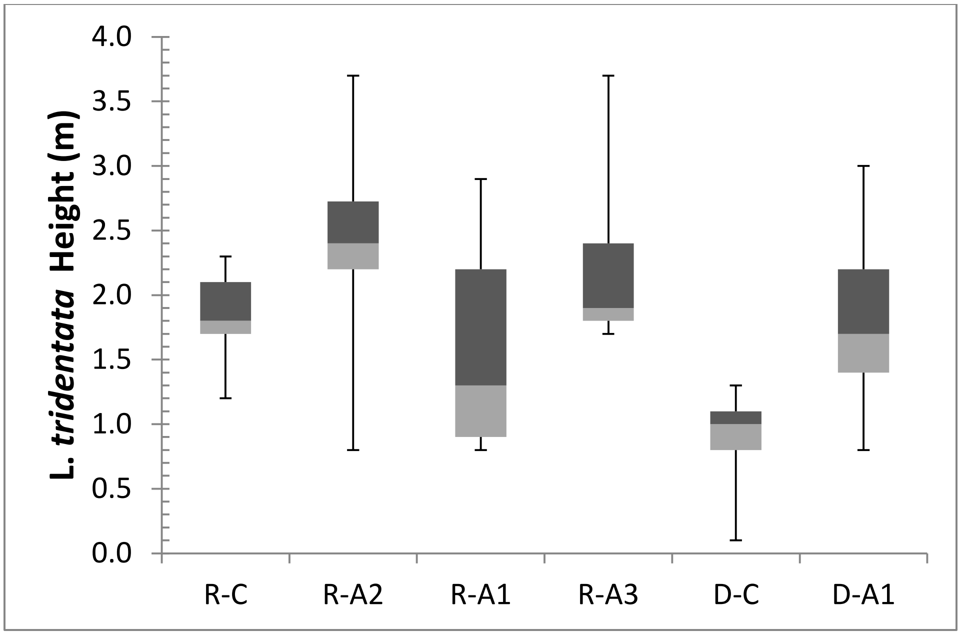


Figure 34. Absolute height of LATR within all sampled areas compared to the control sites R-C and D-C.

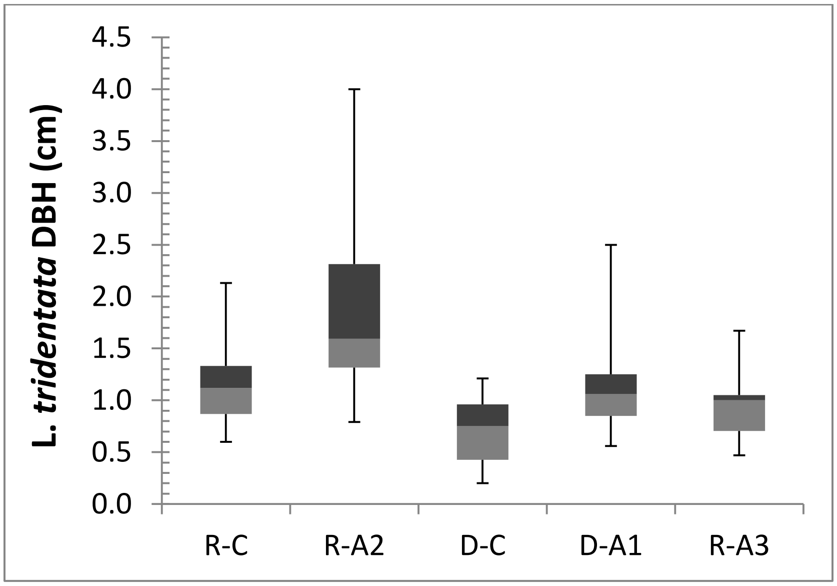


Figure 35. DBH for L. tridentata across sampled areas compared to control sites R-C and D-C. R-A1 is omitted due to low sample values.

6. CONLUSION

Complex processes and adjustments have occurred in studying the dynamics of dammed and partially dammed ephemeral streams due to the CAP canal. It is critical to examine both the geomorphology and ecology of the system to truly grasp the bio-geo interactions that exist within a specific environment. A historical analysis of ways in which we shape and change the landscape around us is a necessary and challenging task that is essential to upholding environmental stewardship and implementing planning strategies through informed decisions.

For decades, ephemeral streams have been dammed (partially or fully) along sections of the CAP canal. Throughout this time period, some years in the Sonoran Desert bring intense heavy rainfalls causing water and sediment to flow through these naturally carved waterways on desert ground. Whereas, other years have records of less intense storm events, which can be perceived as periods of geomorphic rest. In the process of runoff events over the years, the transport of sediment and water along dammed streams has been altered from its pre-canal conditions upstream of the CAP canal's berm. Consequently, changes in water delivery and sediment have altered the riparian vegetation as well.

Runoff pools upslope of the canal's berm along partially and fully dammed ephemeral streams causing the development of a "green-up" zone. The green-up zone constitutes the channels and its respective floodplain. As finer sediment deposits upslope filling the channels, the floodplain widens over time due to overbank flooding. The continual deposition of sediment causes the lateral growth (i.e. floodplain) of the green-up zone over time (Figure 36). The green-up zone is in a transient state until the channels within the green-up zone completely fill with sediment becoming flush with the desert floor (Figure 36). One ephemeral stream studied in this dissertation reveals that the green-up zone has not reached equilibrium. Also, from qualitatively examining other streams surrounding the one studied they too appear to remain in a transient state. Green-up zone development is a relatively slow process that requires decades to eventually reach steady state.

The amount of green-up over time is relative to the stream's size and whether it is partially or fully dammed. Some ephemeral streams have multiple culverts built into the canal whereas other streams may only have one culvert. The amount of green-up over time depends on the streams' sediment yield and discharge rates relative to the sizing of culverts in partially dammed streams. In cases where the culvert is sized to match the discharge rate of the stream, the development of a green-up zone is non-existent. However, in cases where the culvert is sized to half or a third of the bankfull discharge rate of an ephemeral stream, green-up zones develop due to the excess water that pools behind the culvert. Water is the fundamental element to increased vegetation growth in drylands.

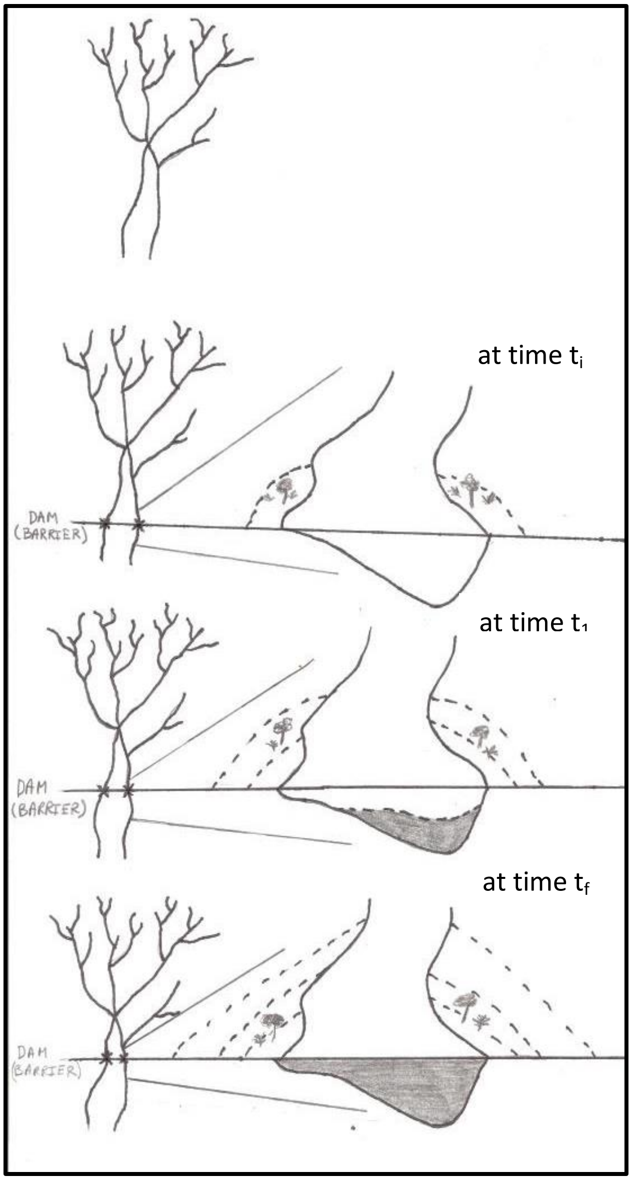
The increase in water availability upstream has created dense woody patches of vegetation with a herbaceous understory in the wettest zone. The types of vegetation that are dominant in the green-up zone and outer sections mainly depend on inundation and/or sedimentation thresholds of specific species. Desert vegetation that is susceptible to long periods of inundation die out, while other species thrive. The abundance and composition of these developed green-up zones are unique to the desert landscape. These zones have increased biodiversity in relation to their surrounding environment.

Green-up zones have a maximum growth length upstream from the canal’s berm that varies depending on stream size. Infrastructure suitability for houses or roads should consider the flood risks if building upstream from a dammed stream. In the initial phases of green-up zone development, it may not be apparent to the planner or developer that there is a risk involved. But, due to the dynamic and slow nature of the growth of the green-up zones they can pose a threat to homes if they are built too close to the canal’s berm (or other barriers). It is proposed that a minimum 375 meter, and preferably 550 meter, rule should apply for building upstream near small to medium sized (<1 km^2) streams to avoid potential flood damage. Proper assessment should be considered first by examining whether the stream is partially or fully dammed and the size of the stream catchment.

The biogeomorphic responses and shifts to damming ephemeral streams should be considered in other dryland regions as well. During the design process for the Red-Dead canal, the abovementioned biogeomorphic responses need to be considered to understand the changes that will occur to the surrounding environment and to avoid potential flood risks to houses and roads. The proposed path of the Red-Dead canal will be perpendicular to several ephemeral streams in Jordan. Using Google Earth, these ephemeral channels are much larger than the streams in this study. They are approximately 3 to 4 times wider. If these streams are partially or completely dammed, similar results found in this study will occur. Furthermore, the canal is proposed to be constructed parallel to a major road (Road 65). The canal should be constructed above the road (west of the road) to avoid being within the green-up zone area that develops slowly over time; to avoid risk of flooding and damage. Depending on the planned goals of this region, damming channels can be beneficial to increasing riparian vegetation (i.e. conservation purposes) or agricultural use upstream within the green-up zone. As noted, certain species can thrive in inundated areas, while others cannot. This means that planting a suitable crop, preferably native, is key to successful crop yields.

Along with planned canals in desert regions, damming ephemeral streams in Egypt to avoid costly re-building of damaged roads during intense storm events need to also examine the geomorphology and riparian ecology before constructing these large-scale projects. Similar processes as examined in this dissertation will occur in these semi-arid to arid regions.

This dissertation research lends valuable insight of biogeomorphic responses to, in essence, damming ephemeral streams. This research can be used as a guide to understanding biogeomorphic responses especially when planning canal or dam projects in drylands. This is the first body of research to present the biogeomorphological effects of damming ephemeral streams. This research paves the way for future work and understanding of ephemeral stream interactions to human-influenced longitudinal alterations.



Ephemeral stream network before canal construction

Green-up initiation along the banks of the channel. The initial boundary of green-up depends on the maximum runoff volume dammed, V_R.

Maximum V_R remains constant. Green-up increases as channel fills with sediment and water is pushed out farther onto floodplain.

Green-up growth is at a maximum when channel completely fills with sediment.

Figure 36. Schematic evolution of green-up zones along dammed ephemeral channels.

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APPENDIX I – VEGETATION DATA 0.5 KM SECTIONS

1982-1989	1989-1996	1996-2003	2003-2010	1982-2010	sections
23347	17150	-7781	32985	65700	1
45768	14431	-25333	16434	51300	2
27075	45639	-50248	75633	98100	3
17671	-9926	-26028	108282	90000	4
111622	46365	-34671	86384	209700	5
148945	127545	-70387	187197	393300	6
4189	83366	-52768	44413	79200	7
30988	17656	6329	34127	89100	8
-5954	35733	-36979	76500	69300	9
13154	11147	-24300	44100	44100	10
29385	11030	-42759	70744	68400	11
7610	-21875	-19036	96300	63000	12
35512	-1312	-24300	73800	83700	13
32117	-22648	-8088	66118	67500	14
24574	-18327	-13929	75182	67500	15
1898	386	-12184	15300	5400	16
18492	3192	-20668	39484	40500	17
52464	53506	-27889	124420	202500	18
45817	17918	-27631	65596	101700	19
50360	44727	-52554	118567	161100	20
45289	41039	-44213	104586	146700	21
26079	51296	-73822	128748	132300	22
18083	4967	-23051	51300	51300	23
54261	10360	-43021	105300	126900	24
49525	15697	-25069	85233	125385	25
34885	20617	-37503	68400	86400	26
45491	17484	-44074	77400	96300	27
84736	24168	-56215	107511	160200	28
64585	49234	-19603	148783	243000	29
16348	21714	-21851	50389	66600	30
0	0	30321	28179	58500	31
16200	19857	-9679	60922	87300	32
13500	43452	-33552	57600	81000	33
28908	11769	-882	42105	81900	34
23472	9838	-7048	62516	88779	35
53610	36932	-30155	134013	194400	36
50109	29916	-33313	84687	131400	37
36799	28185	-23834	77650	118800	38

	49422	6880	-30187	79185	105300	39
	21186	10994	13847	83456	129482	40
	58709	19283	-12924	87146	152215	41
	35473	-9	9866	14070	59400	42
	18316	5084	-3600	23400	43200	43
	900	12600	-20700	45000	37800	44
	0	8100	-8100	46800	46800	45
	31470	7935	-25004	79200	93600	46
	17086	7156	-10279	69738	83700	47
	3353	10029	-12376	42643	43650	48
	5400	12696	-7296	43200	54000	49
	7165	10366	18092	84977	120600	50
	13228	16798	-30998	25200	24228	51
Average	**32130**	**20003**	**-23283**	**71586**	**100436**	

APPENDIX II – CHANNEL SUBSTRATES

CHANNEL 1


CHANNEL 2


CHANNEL 2


CHANNEL 3


CHANNEL 5

APPENDIX III – WETTEST ZONE SUBSTRATE

APPENDIX IV – LARREA TRIDENTATA DBH & HEIGHT DATA

zone	spc_no	DBH (cm)
1	3	2.75
1	3	2.2
2	3	1.1
2	3	1.35
2	3	1
2	3	0.56
2	3	0.63
2	3	1.63
2	3	1.18
2	3	0.8
2	3	1.13
2	3	1.17
2	3	1.25
2	3	1.25
2	3	0.67
2	3	0.77
2	3	2.5
2	3	0.85
2	3	1.04
2	3	1
2	3	1
2	3	2.5
2	3	1.06
3	3	1.37
3	3	1.15
3	3	1.61
3	3	0.79
3	3	1.52
3	3	3.6
3	3	4
3	3	2.06
3	3	3.38
3	3	1.58
3	3	1.95
3	3	2.25
3	3	1.13
3	3	1.52
3	3	2.5
3	3	1.15
4	3	0.5
4	3	1.17
4	3	0.2
4	3	0.93
4	3	0.38

4	3	0.67
4	3	1.21
4	3	0.31
4	3	0.83
4	3	0.95
4	3	0.39
4	3	0.44
4	3	0.88
4	3	1
4	3	0.5
4	3	1
5	3	0.98
5	3	1.57
5	3	0.88
5	3	0.74
5	3	0.47
5	3	0.88
5	3	0.5
5	3	1.25
5	3	0.5
5	3	1.67
5	3	1.1
5	3	1.36
5	3	1
5	3	0.67
5	3	1
5	3	1
5	3	1
5	3	1
5	3	0.58
6	3	1.3
6	3	0.6
6	3	1.91
6	3	0.8
6	3	1.04
6	3	2.13
6	3	1.2
6	3	1.34
6	3	0.98
6	3	0.83

zone	wash_no	Spc_code	Height (m)
1	3	3	1.0
1	3	3	0.8
1	1	3	0.8
1	1	3	1.3
1	2	3	2.0
1	1	3	2.3
1	1	3	2.8
2	1	3	1.6
2	2	3	1.6
2	1	3	1.3
2	1	3	2.0
2	2	3	1.0
2	2	3	2.4
2	2	3	1.4
2	3	3	1.5
2	3	3	0.9
2	3	3	2.1
2	3	3	0.8
2	1	3	2.6
2	1	3	1.7
2	1	3	1.5
2	1	3	1.3
2	2	3	2.9
2	2	3	2.0
2	2	3	2.4
2	3	3	2.1
3	1	3	0.8
3	1	3	2.5
3	1	3	2.4
3	2	3	1.8
3	3	3	2.3
3	3	3	2.9
3	3	3	2.2
3	3	3	2.5
3	1	3	2.2
3	2	3	2.0
3	2	3	2.8
3	2	3	3.3
3	2	3	3.1
3	3	3	2.1
3	3	3	2.4

3	3	3	2.5
3	3	3	2.3
3	1	3	3.7
4	1	3	0.1
4	3	3	1.1
4	1	3	1.0
4	1	3	1.1
4	1	3	1.1
4	2	3	1.3
4	2	3	0.7
4	2	3	0.8
4	3	3	0.8
4	3	3	1.3
4	3	3	1.0
5	2	3	2.7
5	3	3	1.7
5	1	3	2.0
5	1	3	1.8
5	1	3	1.7
5	1	3	1.7
5	1	3	1.9
5	2	3	1.8
5	2	3	2.5
5	2	3	1.8
5	3	3	2.2
5	3	3	2.7
5	3	3	1.9
5	3	3	2.3
5	1	3	3.7
6	1	3	2.1
6	1	3	1.8
6	2	3	1.9
6	3	3	2.1
6	3	3	1.7
6	1	3	1.7
6	1	3	1.5
6	2	3	1.7
6	3	3	2.2
6	3	3	1.2
6	3	3	1.7
6	1	3	2.3
6	2	3	1.9

APPENDIX V- HERBACEOUS COVER DATA

zone	herb%
1	90
1	80
1	90
1	90
1	85
1	100
1	20
1	10
1	5
1	60
1	10
1	40
1	20
1	40
1	5
1	10
1	5
1	5
1	80
1	100
1	2
1	5
1	80
1	90
1	40
1	20
1	90
1	0
1	0
1	0
1	0
1	0
1	0
1	0
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1	0
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1	0
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2	30
2	30
2	50
2	10
2	50
2	80
2	85
2	90
2	50
2	50
2	20
2	20
2	80
2	95
2	90
2	60
2	90
2	70
2	100
2	60
2	0
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2	0
2	0
2	0
2	0
2	0
2	0

3	90
3	10
3	15
3	90
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