FLUVIAL GEOMORPHIC HISTORY OF THE VIRGIN RIVER IN RESPONSE TO TAMARISK COLONIZATION AND REMOVAL

by

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THESIS ABSTRACT

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Title: Fluvial Geomorphic History of The Virgin River in Response to Tamarisk Colonization and Removal.

Perennial rivers in the southwestern United States are rare sources of consistent water supply and biodiversity in otherwise water-stressed environments. Tamarisk, an invasive shrubby tree, has colonized vast portions of floodplains on these river systems, leading to channel incision, bank stabilization, and reductions in water supply and biodiversity. Much research has been done on the adverse geomorphic effects of Tamarisk colonization; however, little research has been done on the effects of post-removal. The Virgin River in southwestern Utah, provides a case study to measure channel reaction to Tamarisk colonization and removal. Historic aerial imagery is obtained from 1953 to 2017 and georectified to imagery from the National Agricultural Imagery Program (NAIP). Vegetation communities, the active channel, the channel centerline, and width measurements were digitized for each year of imagery. This research provides a way to test multiple hypotheses of how the channel may react over time to removal.

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CHAPTER I

INTRODUCTION

Riparian Ecosystems in Dryland Environments

Dryland regions are areas with little precipitation and scarce naturally-occurring water resources. The southwestern United States is one of these regions (Steele et al., 2018). The few perennial river systems that exist in this region provide critical sources of water for both human settlement and native vegetation. Agriculture in the region is dependent upon the streamflow of these perennial rivers, with few other irrigation options available to them (Steele et al., 2018). Additionally, the riparian zones along these major perennial river systems host the most densely vegetated and biodiverse zones in these dryland environments (Graf, 1982; Stromberg, 2013; Tooth, 2000).

The Tamarisk Problem

Tamarisk (*Tamarix Chinensis)* is an invasive woody tree species that has colonized most riparian zones of the major river systems in the southwestern United States (Birken & Cooper, 2006; Graf, 1978; Harms, 2006; Jaeger & Wohl, 2011). Originally brought to the United States as an ornamental plant and a railroad windbreak, tamarisk has quickly spread throughout fluvial systems within the American Southwest (Graf, 1978). Colloquially known as saltcedar, tamarisk secretes salt through its needles, which in turn fall as leaf litter to the valley floor and increase soil salinity within the soil profile (Barrows, 1996; Ladenburger, 2006; Meinhardt, 2012). Native riparian vegetation in the American Southwest, such as Fremont cottonwoods, typically cannot withstand this saline soil, and thus monostands of tamarisk develop (Shafroth et al., 1995). This not only lowers biodiversity, but also leads to reductions in groundwater and streamflow due to tamarisk's high water consumption, potentially costing hundreds of millions of dollars per year (Zavaleta, 2000).

Another way that tamarisk propagates is by colonizing areas of bare soil that is left behind from the removal of native vegetation by said flood (Graf, 1982; Keller et al., 2014). Native riparian vegetation in the American Southwest, such as Fremont cottonwoods (*Populus fremontii)* and black willows (*Salix nigra)*, are more prone to being ripped out of the soil by floods due to their weaker root system (Birken & Cooper, 2006; Camporeale et al., 2019). These newly formed areas of bare soil are then colonized by tamarisk seedlings, which grow at a faster rate and are more tolerant of geomorphic and hydrologic changes than native vegetation (Birken & Cooper, 2006).

Tamarisk also has widespread geomorphic effects as well. The lateral root system of tamarisk is larger and more pervasive than that of native cottonwoods. This can lead to bank stabilization, reductions in bank erosion, channel incision, channel narrowing, reduction in sediment transport, and a reduction in bare-soil areas and in-channel bar formation (Birken & Cooper, 2006; Graf, 1978; Keller et al., 2014). This reduces the geomorphic complexity of the colonized river system and can have negative implications for native fish and amphibian species (Keller et al., 2014). A common management response to these issues is to attempt to mechanically remove tamarisk from colonized riparian zones, with the aim of increasing biodiversity and water storage (Keller et al., 2014; Jaeger and Wohl, 2011).

Given that tamarisk colonized most major southwestern river systems in the late 19th century and into the mid-20th century (Graf, 1978), sources of quantitative data (such as aerial imagery) before mass tamarisk colonization are difficult to find. Thus, many studies only focus on the conditions of a river in an already disturbed state. This presents analytical limitations as a pre-colonization reference condition is largely unavailable for most river systems in the region. The Virgin River presents a unique scenario in this case, with qualitative accounts from Hughes et al. (1993) claiming that tamarisk did not colonize until after World War II. This fact paired with available aerial imagery that dates back to 1953 allows us to gather quantitative data about the conditions of the Virgin River before and during colonization, and post-removal.

Despite its pervasiveness and detrimental effects, studies on the geomorphic impacts of tamarisk removal are scarce. Outside of Keller et al. (2014) and Jaeger and Wohl (2011), the author was unable to find more studies that analyzed the geomorphic effects of tamarisk removal. Nevertheless, the results of these studies are invaluable and aid the analysis of this paper. Keller et al. (2014) had found that areas of channel movement on the San Rafael River in Utah were significantly larger in tamarisk removal areas than in non-removal areas. Similarly, Jaeger and Wohl (2011) found that the main geomorphic response to tamarisk removal on a small stream in Canyon De Chelly in Arizona was channel widening but does not mention channel movement. The differences in response from these two sites that are both in the American Southwest showcases a need for more studies to be performed on the subject. This study aims to contribute to this by using the removal sites on the Virgin River in St. George, Utah as another case study to add to the existing literature on tamarisk removal in the region. The gage used for this study will be USGS gage #09413500, which is conveniently located at the western edge of the study area under the I-15 overpass.

Research Goals

Given the amount of tamarisk removal projects that occur within the southwestern United States, this presents a significant gap in our understanding of how tamarisk geomorphically impacts a river system. For example, the Pecos River in Texas underwent a 289-mile-long removal effort from 1999-2005 in order to restore peak streamflow levels (Sher & Quigley., 2013).

Undertaking large-scale tamarisk removal efforts, such as those done on the Pecos River, with little literature on the topic is problematic and needs to be addressed. This study seeks to add to the scarce literature on the geomorphic effects of tamarisk removal by using a case study done on the Virgin River in St. George, Utah, where a tamarisk removal effort is being conducted by the Utah Department of Natural Resources. This site is unique in that qualitative accounts of tamarisk colonization do not occur until the 1950's, allowing the chance to see the river system evolve in response to both colonization and removal. Thus, this research asks three questions:

Question #1: When did tamarisk colonize the Virgin River in St. George?

Question #2: How has the channel width, area, and curvature of the Virgin River responded to tamarisk colonization?

Question #3: How has the channel width, area, and curvature of the Virgin River responded to tamarisk removal?

Obtaining historical aerial imagery from the United States Geological Survey (USGS) EarthExplorer from the earliest date available (1953) to the latest (2018) is done to achieve this. Digitizing vegetation communities is done at each site to verify the claim made in Hughes (1993) that tamarisk did not colonize the Virgin until the 1950's. This allows us to answer research question #1 and pin down a rough time period when tamarisk colonized the study area. Digitizing the active channel allows for the measurement of the active channel width, area, and curvature. Dividing the study site into equal-length 200m bounding boxes allows for the detection of spatial variability in geomorphic response. These boxes fall into equal-length categories, labeled 1, 2, and 3. Boxes for the years 2009-onward are categorized as removal or non-removal sites. This allows us to answer research questions #2 and #3 by visualizing and analyzing changes in channel width, area, and curvature.

CHAPTER II

BACKGROUND

Literature Review

While there is ample literature on tamarisk colonization of major southwestern rivers, none have been performed on the Virgin River to the best of the author's knowledge. Dryland rivers are difficult to cross-compare due to their highly dynamic nature (Graf, 1988; Knox, 1978; Powell, 2009; Schumm & Hadley, 1957), and thus this study looks to fill the hole that exists in the literature for the Virgin River in regards to tamarisk colonization. This topic is also highly relevant as the Virgin River is the main source of water for the region, and tamarisk management is a top priority for many agencies actively managing the river (Virgin River Master Plan, 2007).

Fluvial geomorphic theory behind tamarisk colonization is well-established. tamarisk has a deep and pervasive root system that stabilizes channel banks and promotes channel narrowing, incision, and a loss of habitat complexity (Birken & Cooper, 2006; Birkeland, 2002; Graf, 1978; Graf 1982; Dean & Schmidt, 2011). tamarisk appears to more quickly colonize dammed river systems, as native cottonwoods and willows are more sensitive to flow alterations than tamarisk (Everitt, 1998; Graf, 1982). This may explain why accounts of tamarisk colonization of the Virgin River are later than most other rivers in the region, as the Virgin River is mostly undammed.

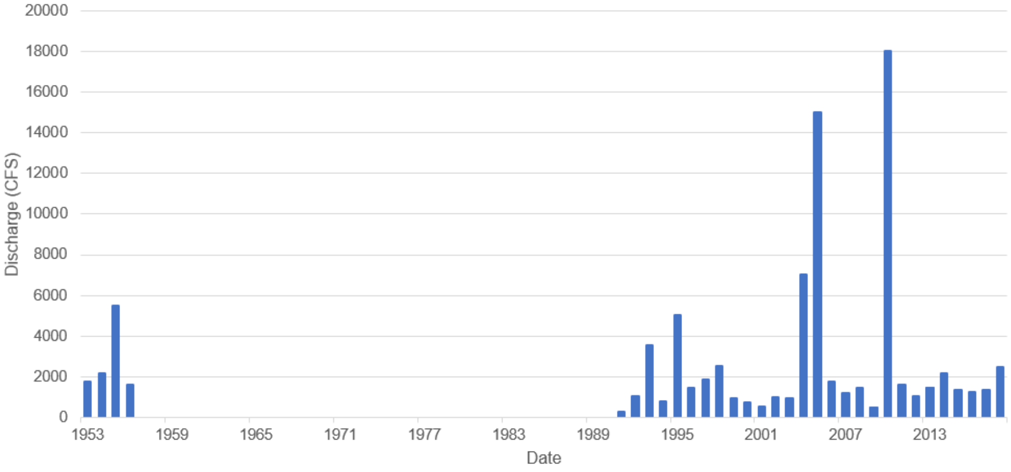
While the literature on the geomorphic effects of tamarisk colonization are of great use, there is a gap in that these studies have taken place on river systems that are already colonized. This is largely due to the fact that most river systems were colonized by tamarisk before during the 19th century and early 20th centuries, long before the capabilities to perform in-depth historical studies on this topic existed. As such, the effects that tamarisk had during colonization of these systems is largely unstudied. This paper seeks to help fill this gap by using aerial imagery as a medium to achieve this.

Despite being a pervasive problem, limited studies have been done on the geomorphic effects of tamarisk removal, and even fewer have been done from the viewpoint of long-term change using historical aerial imagery. The lack of studies that have been done on post-removal effects is troubling, given that over $80 million was allocated by the Department of The Interior for tamarisk removal along riparian zones in 2005 (Jaeger & Wohl, 2011). Jaeger and Wohl (2011) and Keller et al. (2014) looked at the geomorphic changes that occur post-tamarisk removal, however the study only looked at the first four years of removal, and did not frame the analysis from a long-term historical perspective. These studies generally found that the channel widened post-removal and that the channel had a higher rate of lateral migration than pre-removal. The results from these papers will be instrumental in formulating hypotheses for the removal effects that may materialize on the Virgin River. Without extensive literature on the topic of tamarisk removal, hypotheses on its geomorphic effects can be formulated by studying the documented effects in the existing papers that are available. Specifically, the effects of colonization may be reversed when the tamarisk is removed.

Another factor in tamarisk removal are floods. In dryland environments, flooding has a large effect on vegetation community composition and can promote an increase in bare soil areas, which generally favor tamarisk seedlings over cottonwood and other native vegetation (Birkeland, 2002; Graf, 1978; Keller et al, 2014; Meinhardt, 2012). For example, Birkeland (2002) found that, between 1922-1998, an increase in active channel flood power coincided with an 86% increase in riparian vegetation growth. This is largely the result of native vegetation being more susceptible to being ripped out by the increased flows of floods, whereas tamarisk is more likely to withstand flood events (Graf, 1978). Specifically regarding flooding and tamarisk, Keller et al. (2014) found that a greater area of vegetation was removed post-flood in areas that were not colonized by tamarisk compared with those that were. All this suggests that flooding can play a major role in which areas become colonized by tamarisk, specifically by leaving behind large areas of bare soil that tamarisk seedlings can take advantage of. The most notable flood for this study is the one that occurred in 2010, which had a peak discharge of 18,000 cubic feet per second (CFS). The only other recorded large flood occurred in 2005, with a peak discharge of 15,000 cubic feet. See figure 1 for details.

Figure 1

Discharge Graph for USGS gage #09413500 near St. George, UT



Note the largest floods are in 2005 and 2010, and that the gage was offline for an extended period of time.

Most papers on tamarisk colonization view it through a historical lens. Perhaps the most famous of these papers is Graf (1978), which analyzed the spread of tamarisk throughout the American Southwest and the fluvial effects that had on channel morphology. In a similar vein on a smaller scope, Birkeland (2013), Birken & Cooper (2006), and Cadol et al. (2011) analyzed changes in channel morphology over the 20th century in response to vegetation change in Utah and Arizona, mainly with tamarisk colonization. These papers provide baseline patterns for how dryland rivers in the southwest generally react to tamarisk colonization, with bank stabilization, channel narrowing, and bed incision being the most prevalent effects. Although the Virgin River has not been studied in this regard and is its own unique system, the methodologies and results from these papers can provide guidance when analyzing how the Virgin River reacted to tamarisk colonization. While the literature on tamarisk colonization is useful, the inverse question of what happens post-removal has not been thoroughly researched. For example, can the opposite geomorphic effects be expected when tamarisk is removed? Will the channel begin to retake the shape before colonization? These remain unanswered.

This paper seeks to add a more temporally holistic view of tamarisk colonization and the effects it has post removal. Methodologies that account for the long-term trends of a fluvial system allow for a richer analysis and a greater overall perspective when considering restoration efforts. Given that removal of tamarisk and the recolonization of native vegetation are common restoration goals, information on channel characteristics pre-colonization can help inform long-term goals and expectations. Studies such as Birkeland (2013), Birken and Cooper (2006), Cadol et al. (2011), and Graf (1978) have examined long-term historical changes in regards to tamarisk colonization and changes in riparian vegetation, however they do not analyze changes post-removal. Conversely, the studies by Jaeger and Wohl (2011) and Keller et al. (2014) have looked at the effects of removal, but do not compare the results to pre-colonization conditions.

The Virgin River presents a unique opportunity to blend the methodologies of the aforementioned papers. Pre-colonization conditions can be used as a baseline of comparison to post-removal conditions, rather than having separate papers that look at these conditions apart from one another. The synthesis of these two approaches allows for a more complete historical view of how tamarisk colonization affected the Virgin River, which can aid in the assessment of how successful a restoration project has been. Assessment of how a river is responding to tamarisk removal would be difficult if one did not know the channel characteristics pre-colonization. Most major rivers in the region were already colonized by tamarisk by 1940 (Graf, 1982), before the advent of widely-available aerial imagery. As colonization of the Virgin River didn't begin until the 1950's, this presents a unique case that allows us to see how the river channel changed in detail in response to tamarisk colonization. To the best of the author's knowledge, no study has been written that generates empirical data on channel conditions of a major southwestern river system pre-tamarisk colonization that was later colonized.

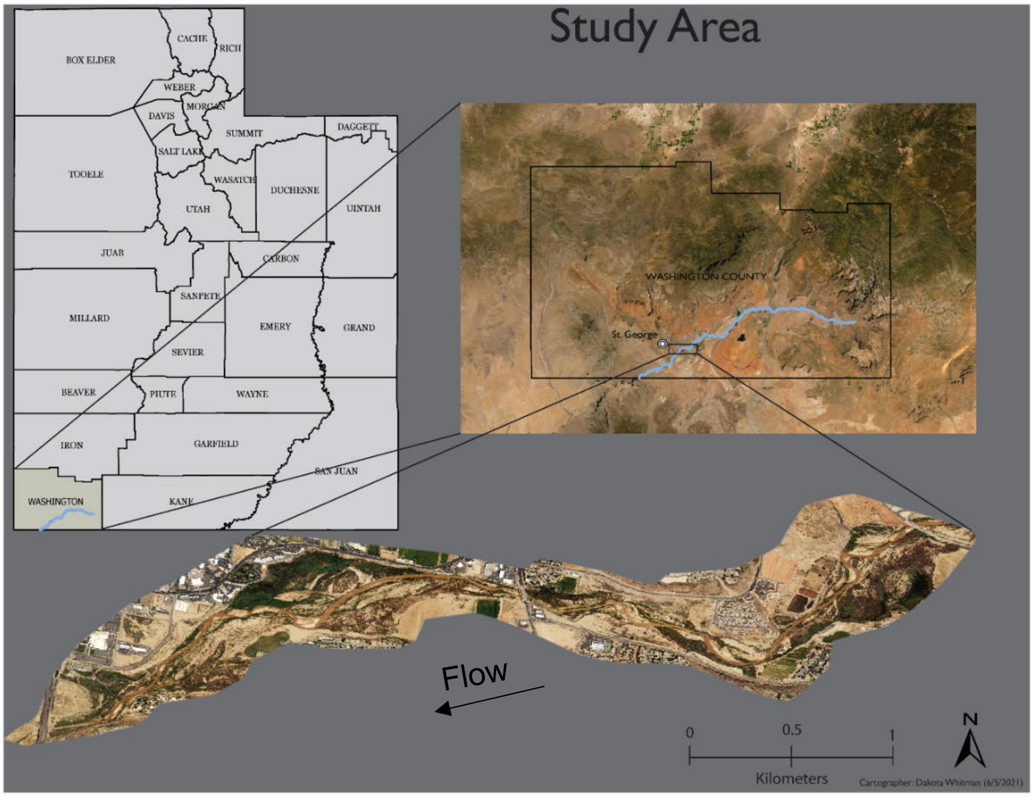
Study Area

The study site for this project is a 5km reach of the upper Virgin River that is located in St. George, Utah (figure 2). This site was selected for three main reasons: availability of historical images and documents, availability of high quality historical aerial imagery, and the recent tamarisk removal projects done by the Utah Department of

Natural Resources. Tamarisk removal is of high priority for the Virgin River, mainly in efforts to recolonize native vegetation and aesthetic purposes (Natural Channel Design, 2007).

Figure 2

Study area map



Location of study reach in St. George, Utah.

The Upper Virgin River is a low gradient, mixed sand-and-gravel bed perennial river whose headwaters flow out of the section of Dixie National Forest that is on the

Navajo reservation and then south through Zion Canyon, and then flows southwest through St. George, Utah. The bed material is poorly sorted and spatially variable, having higher gravel content in reaches that flow through canyons and higher sand content in open alluvial valleys (Andrews, 2000; Hereford, 1996). The Virgin was Utah's first designated wild and scenic river, and one of the few perennial rivers in the region that doesn't have a major dam. The riparian zone of the upper Virgin River is a source of high biodiversity in an otherwise dry environment, and an important stop for migrating birds (Whitmore, 1975). Given that the Virgin River is a major tributary of the Colorado River and flows through Zion National Park, one of the most visited national parks in the country, it is also of economic importance to the local tourism industry and regional economy.

Additionally, St. George is the largest city in southern Utah with a fast-growing population and an area of great economic importance to the region. As mentioned earlier, tamarisk uses considerably more surface and ground water than cottonwoods and other native riparian vegetation, which can be costly (Zavaleta, 2000). Given that the population of the St. George metro area doubled between 2000 and 2020 (U.S. Census Bureau), this loss of water in an arid region can potentially add further stress to already in-demand water resources.

Unlike other major southwestern rivers, qualitative accounts of tamarisk colonization on the Virgin River are relatively recent. Whereas tamarisk colonization began in the general region in the late 19th and early 20th centuries (Graf, 1982), local accounts of tamarisk along the Virgin River do not begin until the 1950's (Hughes, 1993). Given that there is historical aerial imagery for the Virgin River that dates back to

1953, this presents a unique opportunity to analyze how the channel has changed in response to tamarisk colonization. Research on the geomorphic effects of tamarisk has not been performed on the Virgin River, making it a suitable site.

Environmental History

The Virgin River has a uniquely long history of management by humans. Native American tribes built canals and other irrigation structures for agricultural purposes centuries before Euro-American colonization, with corn and melons being the most common crop (Larson, 1996). Upon settlement by Mormon Euro-Americans, the irrigation of the Virgin River for expanded agriculture remained a top priority for white settlers. In contemporary times, the booming population of the St. George metro area has led to a strong dependence on the flow of the Virgin River to support this growing population (Kutz, 2018).

Native American Usage of The Virgin River

The valley of the Upper Virgin River where St. George is located was originally inhabited by the Ancestral Puebloan peoples. The group located on the Virgin River Valley were the westernmost group of the Ancestral Puebloan peoples, sometimes referred to as the western Puebloans. The Ancestral Puebloans relied on the Virgin River for corn agriculture and fish, constructing canals and check-dams to increase agricultural production (Larson, 1996). The Ancestral Puebloans occupied the Virgin River Valley until around 1100-1200 A.D., when the Southern Paiute tribe colonized the area. Like the Ancestral Puebloans, the Southern Paiutes continued to irrigate the Virgin River for agricultural purposes, mainly for dryland-friendly crops such as corn and melons. Both the Ancestral Puebloans and Southern Paiutes were nomadic and mainly occupied the

Virgin River Valley in the winter months, as summer temperatures were too harsh, and the river was prone to flooding.

Although the geomorphic effects that resulted from Ancestral Puebloan and Southern Paiute colonization are not directly relevant to the analysis of this study, it is important to recognize the history of extensive human use of the Virgin River by the Ancestral Puebloan and southern Paiute tribes.

Euro- and White American Settlement of the Virgin River Valley

The first Euro-Americans to arrive to the Virgin River Valley were led by Atanasio Domínguez and Silvestre Vélez de Escalante of the Dominguez-Escalante expedition of 1776. While the expedition only had ten men and was mainly for finding an overland route across the region, it opened up a route for future Euro-American settlers to enter the Virgin River Valley ("Washington County Historical Society", n.d.). Despite this opening, the population of Euro-Americans in the Virgin River Valley remained relatively small until further explorations by Euro-Americans were conducted.

Jedediah Smith was the first Mromon to follow the Virgin River in 1826, with John C. Fremont mapping the entirety of the river in 1844. Large-scale settlement of the Virgin River Valley by Euro-Americans began with the Mormon migration. In 1849, Brigham Young sent a group of fifty men to the Virgin River Valley to survey its suitability for agriculture and Mormon settlement. Mormon missionaries and farmers began to settle the valley over the following decades, with Washington County being established in 1892 ("Washington County Historical Society", n.d.).

The manipulation of the Virgin River by mostly Mormon settlers was more wide-ranging and invasive than that done by the Ancestral Puebloans and Southern Paiute tribes. Mormon settlers built dozens of miles of canals and ditches along the Virgin River to cultivate wheat, alfalfa, and oats, which require more water than the previously farmed corn and melons (Teele, 1908). Stream bottoms and high bench areas were extensively tilled, which likely led to the deforestation of many riparian cottonwood forests (Teele, 1908). Multiple attempts to dam the Virgin River were performed in the late 19th/early 20th centuries, however these all failed to withstand major floods (Teele, 1908).

On-the-ground imagery from the late 19th/early 20th centuries provides some insight into historical channel conditions. Figures 3 and 4 show a single thread meandering channel shape with a floodplain that is dominated by shrub and scrub, with some large trees being prevalent in figure 4. These trees are most likely native cottonwood and willow, however the images are too grainy to be certain. Conversely, figures 5 and 6 show a larger, more open and braided channel shape that differs from images 3 and 4. While unknown variables such as discharge and flood events can limit analysis between images, we are able to get a general idea of the channel and riparian vegetation conditions for the Virgin River during this time period.

The population of St. George and the upper Virgin River Valley continued to grow into the 20th century, and so did the demand for water from the Virgin River. The population of St. George increased from 1,700 to 50,000 over the 20th century (U.S. Census Bureau, 2018) and transformed from a small farming community to the largest city in the region.

Figure 3

Virgin River South of St. George, early 20th Century

The channel is a single-thread, meandering shape with a floodplain that's dominated by shrubs and scrub (Washington County Historical Society, n.d.)

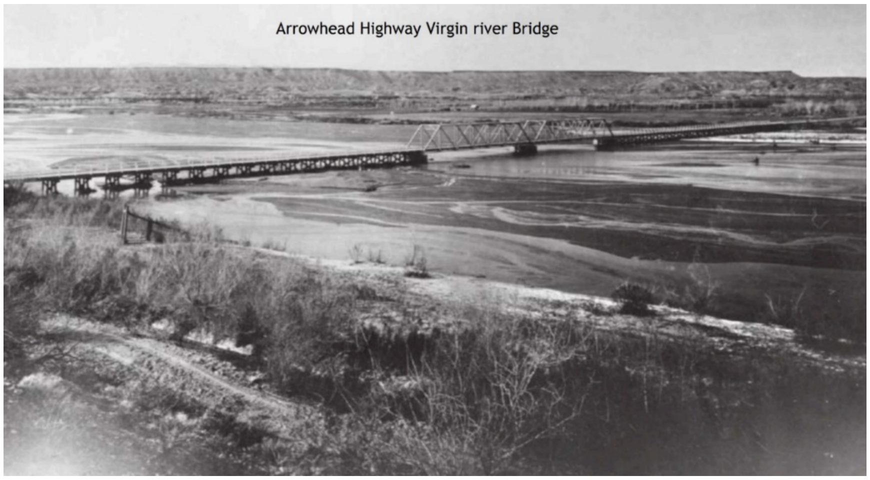
Figure 4

Virgin River near Hurricane, 1900

Like figure 3, the channel has a single thread, meandering shape. Large trees are prevalent across the riparian zone. (Washington County Historical Society, n.d.)

Figure 5

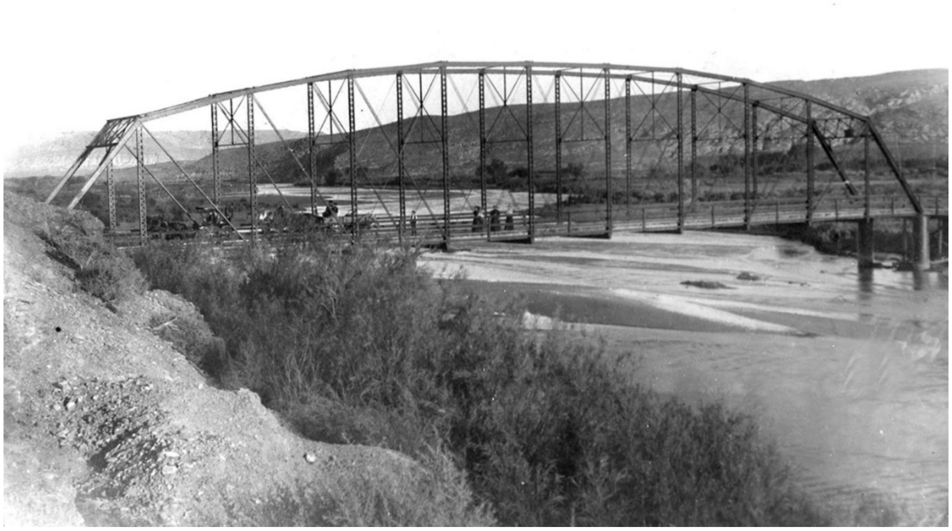
Virgin River bridge in St. George, early 20th Century



Note the braided pattern of the channel. (Washington County Historical Society, n.d.)

Figure 6

Virgin River bridge in St. George, 1912.



Like figure 4, the channel is more of a braided pattern with large shrubs dominating the floodplain. (Washington County Historical Society, n.d.)

As such, the land cover shifted from mostly agriculture to suburban communities and business districts. To supply water to this booming population, Quail Creek Reservoir was built in 1985 by damming Quail Creek and supplementing water from the Virgin River via a buried pipeline. While this led to increased water supply, there was a large dike failure on the reservoir in 1989 that led to a discharge record of over 60,000 cubic feet.

During this time period, tamarisk also began to colonize the Virgin River starting around the 1950’s. One long-time resident of Mesquite on the lower Virgin River states: "When I was a boy in the 30's and 40's the Virgin River was open, no brush on its banks. Then in the late 40's and in the 1950's the tamarisk just seemed to roll down the river" (Hughes, 1993). Colonization of riparian zones by tamarisk typically has wide-ranging effects on fluvial systems. This can include channel narrowing, colonization of bars within the channel, decreasing biodiversity, reduction in discharge, and a reduction in groundwater levels (Graf, 1978; Zavaleta, 2000).

During the 21st century, the boom of population and tamarisk has continued, and thus the management of the Virgin River remains active. The population of St. George and its suburbs doubled between 2000-2020, rising from 91,000 to 188,000 between 2000-2020 (U.S. Census Bureau, 2018). In response to this skyrocketing demand for water, neighboring Kane County has proposed to dam the Virgin River upstream of Zion National Park to aid local farmers (Maffly, 2020). Tamarisk management has also become the number one priority of agencies that are managing the Virgin River (Natural Channel Design, 2007). For example, a large-scale removal project of tamarisk was performed by the Utah Department of Natural Resources on the St. George stretch of the Virgin River in 2014 to promote the recolonization of native vegetation.

As the population of St. George has boomed and moved away from being an agricultural community, local perception of the river appears to have also shifted. Per the Virgin River Master Plan, the two main management goals of the river are to attenuate floods risk and remove tamarisk for ‘aesthetic and recreational purposes’. Given the attention that tamarisk management receives on the Virgin River, this study is highly relevant and potentially useful to local agencies in charge of these management efforts.

The removal effort done in 2013 at the study area was designed with the goal in mind to promote biodiversity and the re-colonization of native species (Wadsworth, 2014). Removal was done discontinuously along the river in the areas that were dominated by Tamarisk with little-to-no other species present (Wadsworth, 2014). This is consistent with on-the-ground observations of the study area, which showed that Tamarisk colonization is highly spatial. To the best of the author’s knowledge, no monitoring efforts have taken place, which adds to the relevancy of this study.

CHAPTER III

METHODS

Methodological Goals

The overall goal of these methodologies is to quantitatively assess the geomorphic changes that the active channel of the Virgin River has experienced in response to tamarisk colonization and removal. To achieve this, historical aerial imagery allows for analysis of the time period from 1953 to 2018, which is the most recent year data is available. Non-orthorectified imagery is georectified to acceptable levels of error, per the methods outlined in Hughes et al. (2006). Visual inspection of historical aerial imagery allows for quantitative digitization of vegetation communities, as done in Hooke & Chen (2015) and Garófano-Gómez et al. (2013).

The research questions in this study are historical in nature, and thus require data that may not be readily available from traditional, on-the-ground methods. To the best of the author's knowledge, there is no historical data on channel characteristics or riparian vegetation composition of the Virgin River. Aerial imagery provides a suitable resource in which to generally extract this data and answer the research questions. Specifically, the capabilities to analyze channel characteristics and riparian vegetation composition over a period of time are invaluable. A remote sensing-based approach also allows for more data collection on a longer stretch of river, as opposed to the greater amount of time and money a traditional, on-the-ground assessment would require.

The research questions boil down to tracking changes in the outlined channel characteristics pre- and post-removal of tamarisk over a period of time. The aerial imagery approach allows us to collect this data both historically and contemporarily, and to also easily delineate which areas have had removal and which haven't. This allows for a larger set of data that can be analyzed and allows us to explore the understudied effects of tamarisk removal by directly comparing the results of removal sites to non-removal sites.

Aerial Imagery

The use of aerial imagery for this analysis allows us to view tamarisk colonization and channel response through a historical lens, by providing a means with which to collect data from time periods where on-the-ground measurements are unavailable. Obtaining imagery was done for the years 1953, 1976, 1993, 2009, 2011, 2014, 2016, and 2018 (see table 1 for details). Obtaining of all imagery for this study was done using the United States Geological Survey (USGS) EarthExplorer tool.

Projecting the imagery was done in NAD UTM Zone 12 with a NAD 1983 coordinate system. Resampling the images to 1x1m using cubic convolution was done to ensure accuracy, per the methods outlined in Hughes et al. (2006). Georectification was only necessary for the 1953 and 1976 imagery, as the other years are already orthorectified.

Whiles Hughes et al. (2006) used a 2nd order polynomial transformation for georectification, this is not ideal for the non-rectified imagery for this site. The 1976 and 1953 imagery are off-nadir, and using the 2nd order polynomial transformation leads to unacceptably high levels of error (~9m). Using the spline rather than the 2nd polynomial transformation allowed for greater minimization of error. Using the methods outlined in Hugh et al. (2006) allowed for higher accuracy when measuring error, mainly by using hard points such as roof corners and fence posts for georectifying the images to the 1993 DOQ image. The orthorectified imagery obtained from the EarthExplorer tool do not provide error metrics, and thus their respective errors are not available to input into table 1. A consistent minimum mapping unit was used for all vegetation communities as they were discernable from one another on all years of imagery. Identifying different vegetation stands, rather than a consistent area, allows for a more flexible identification when deciding a minimum mapping unit. Quantifying this leads to a minimum mapping unit of roughly six square meters.

Table 1

Imagery Details

Year	Date	Scale	Resolution	Error (m)	Imagery Type	Imagery Source
1953	June 14th	1:37,400	4m	3.15	Aerial Photo Single Frames	USGS EarthExplorer
1976	August 13th	1:80,000	2m	2.5	Aerial Photo Single Frames	USGS EarthExplorer
1993	July 24th	1:12,000	1m	No Metrics Provided	Digital Orthoquad (DOQ)	USGS EarthExplorer
2009	August 9th	1:12,000	1m	Not Metrics Provided	National Agriculture Imagery Program (NAIP)	USGS EarthExplorer
2011	June 20th	1:12,000	1m	No Metrics Provided	National Agriculture Imagery Program (NAIP)	USGS EarthExplorer
2014	June 18th	1:12,000	1m	No Metrics Provided	National Agriculture Imagery Program (NAIP)	USGS EarthExplorer
2016	July 10th	1:12,000	1m	No Metrics Provided	National Agriculture Imagery Program (NAIP)	USGS EarthExplorer
2018	August 10th	1:12,000	0.6m	No Metrics Provided	National Agriculture Imagery Program (NAIP)	USGS EarthExplorer

Details on the imagery obtained for this study.

Vegetation Communities

The author is unable to find a previously used set of criteria for vegetation communities along the Virgin River. Visual inspection of aerial imagery and on-the-ground observations provides a basis for vegetation community classification, as outlined in Garófano-Gómez et al. (2013) and Hooke and Chen (2015). Digitizing these communities allows us to answer the first research question on when tamarisk colonized the study area, and also allows us to classify which areas have had tamarisk removal. Heads-up digitizing of vegetation communities was done using ArcGIS Pro. Ground truthing polygons using the 2018 imagery, the most recent year of data which was available, allowed for the determination of vegetation community types.

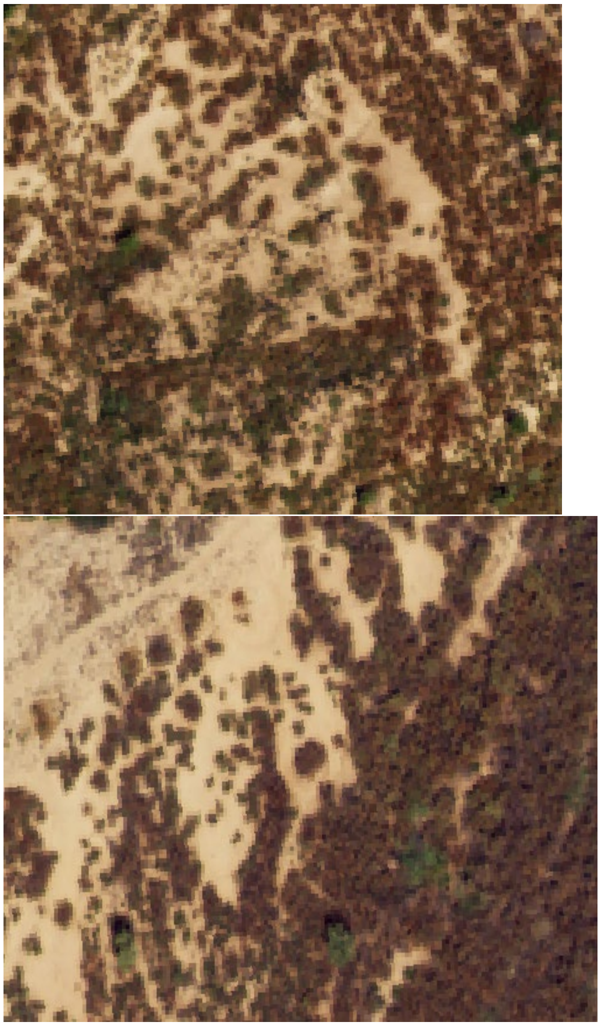
Identifying vegetation communities leads to six community types: Non-Tamarisk Large Woody Vegetation; Sparse, Non-Tamarisk Woody Vegetation; Shrubs/herbaceous; Bare Soil; and the River Channel.

Tamarisk

Due to its unique characteristics, identifying tamarisk is possible on a species level. On aerial imagery, tamarisk has a clumped pattern of canopies of individual plants separated by open ground, that is different from the more closed canopy appearance of the non-tamarisk woody vegetation. The tendency of tamarisk to grow in dense monostands (Harms, 2006; Meinhardt, 2012) aids in identifying communities from aerial imagery (Figure 7).

Figure 7

Visual example of tamarisk from aerial imagery



Aerial view of Tamarisk using on-the-ground observed sites from the 2018 NAIP imagery.

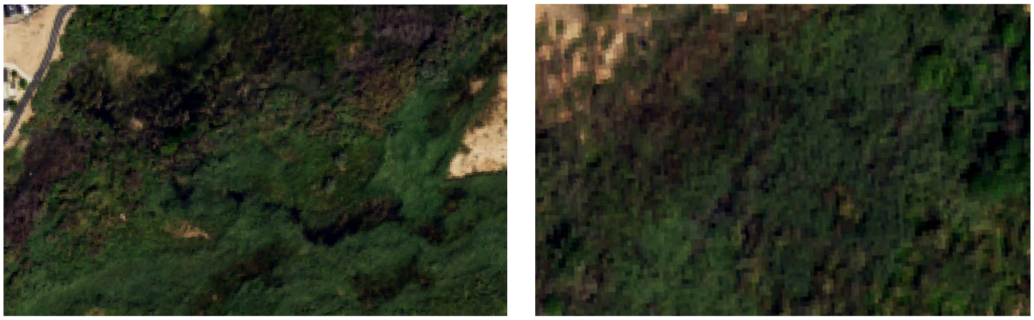
On-the-ground observations of tamarisk communities are largely consistent with the literature. Mature tamarisk stands are homogenous and cover the soil surface in salt-secreted needles. Areas where native cottonwoods and willows dominate generally do not have tamarisk growing in the understory. This is consistent with the observations of Meinhardt (2012).

Dense, Non-Tamarisk Woody Vegetation

Dense, Non-Tamarisk Woody Vegetation (DNTWV) is distinct from tamarisk mainly in its texture and density. Unlike tamarisk, DNTWV grows in a moss-like appearance with no discernable bulbs and is usually a more diverse mix of species. On-the-ground observations showed that these areas are a mix of cottonwoods (*Populus fremontii)* and willows (*Salix nigra*), with other native vegetation such as catclaw acacia (*Senegalia greggii)* and Apache bloom (*Fallugia)*. Like tamarisk, DNTWV tends to spatially cluster (figure 8).

Figure 8

Visual example of dense, non-tamarisk woody vegetation from aerial imagery



Aerial view of DNTWV using on-the-ground observed sites from the 2018 NAIP imagery.

Sparse, Non-Tamarisk Woody Vegetation

Identifying Sparse, Non-Tamarisk Woody Vegetation (SNTWV) is similar to DNTWV, however the key difference is in spatial organization. Whereas DNTWV is moss-like and spreads across a large area, SNTWV is sparse and not closed canopy, although the vegetation type may be continuous over a large area (figure 9). On-the-ground observations showed that these areas tended to not be dominated by large native woody vegetation such as cottonwoods and willows, but by smaller native woody vegetation.

Figure 9

Visual example of SNTWV from aerial imagery

Aerial view of SNTWV using on-the-ground observed sites from 2018 NAIP imagery.

Shrubs/herbaceous

The least-common vegetation group is shrubs/herbaceous. Shrubs are characterized by their small size and dotted appearance on the landscape, typically appearing in smaller patches than the other classes (figure 10). Areas of shrubs typically begin as an area of bare soil and then become shrubs over time.

Figure 10

Visual example of shrubs/herbaceous communities from aerial imagery

Aerial view of shrubs/herbaceous using on-the-ground observed sites from 2018 NAIP imagery.

Bare Soil

Identifying bare soil is accomplished by the lack of vegetation and a bald and bright appearance (figure 11). Most of the bare soil areas were directly adjacent to the channel, and on-the-ground observations showed that the few seedlings present on bare soil areas were dominated by tamarisk.

Figure 11

Visual example of Bare Soil from Aerial Imagery

Aerial view of bare soil using on-the-ground observed sites from 2018 NAIP imagery.

Active Channel Banks

The active channel banks of the Virgin River are dynamic and have undergone considerable amounts of change over the time period of this study. While identifying banks can be more difficult when using on-the-ground techniques, channel banks are usually more visible on aerial imagery (Lauer, 2017). The active channel banks of the Virgin River are visible on the imagery for the majority of the reach, delineated by areas of mature vegetation (figure 12). However, certain areas are more ambiguous, and thus some interpretation was necessary when defining an area as active channel or as bare soil.

Figure 12

Visual example of the active channel from aerial imagery

Examples of easily identifiable active channel margins using 2018 NAIP imagery.

Dividing Reach into Bounding Boxes

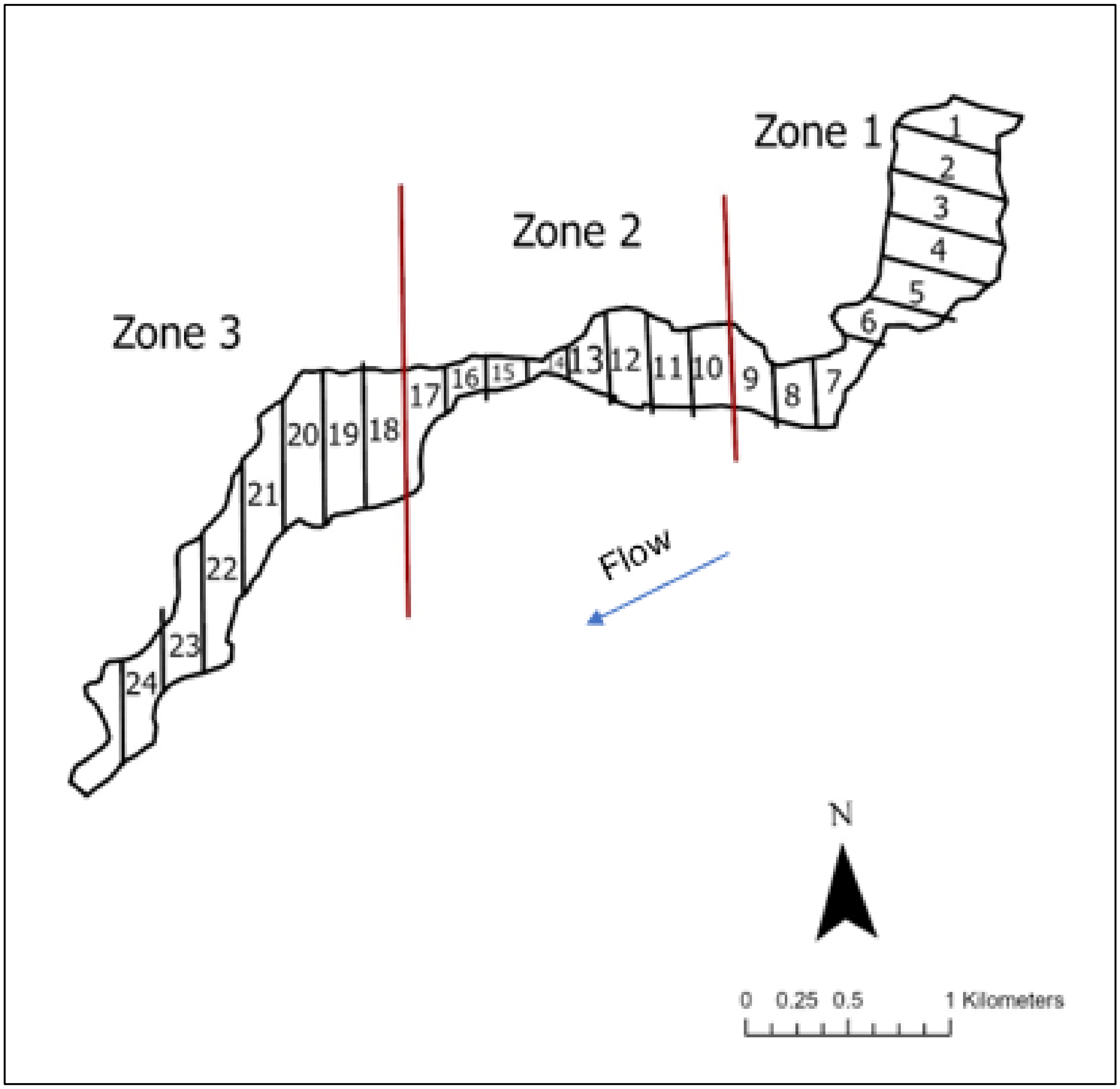
Dividing the study reaches into equal-length 200-meter bounding boxes down the channel centerline is done following the methodologies of Proctor (2017) and Zanoni (2008). The outer boundary of the boxes is defined based on the active floodplain of the study site, which is clearly demarcated from upland areas by the presence of small cliffs to the south and human developed areas to the north. The total number of bounding boxes for this reach is 25, and determining box category relies on if the site is a site of tamarisk removal or non-removal (figure 13). The purpose of the bounding boxes is twofold: one is to account for any spatial variability that occurs in channel and vegetation changes, and the other is for easy classification of removal and non-removal sites. Given the dynamic nature of the Virgin River, it's possible that a disproportionate amount of change may largely occur over a smaller area, and thus overall results of channel change for the entire reach would not capture this spatial variability. The boxes also make it convenient to classify sections of the reach as removal or non-removal sites for tamarisk, which aids in analysis of channel morphology change. Using zones is preferable to individual boxes, as boxes that are close to one another geographically will show similar response, which would add redundancy in the results. When plotted by boxes rather than zones, boxes that were close to one another (for example, boxes 1-4) showed similar values and did not add to the analysis. This is due to the relatively short length of each box (200m). Zones 1, 2, and 3 make up 34%, 24% and 42% of the total study area, respectively. Comparing removal and non-removal boxes allows for the detection of differences in channel changes between the two categories. Since tamarisk removal only occurs post-2009, comparing changes in channel morphology is only pertinent for the 2009 imagery onward.

Vegetation Change Through Time

Dividing the imagery into three time periods allows us to assess the geomorphic effects that occur at varying phases of tamarisk colonization. These three periods are pre-colonization (1953-1976), post-colonization (1993-2011), and post-removal (2014-2018). The classifying of these time periods revolves around the qualitative accounts of tamarisk colonization as outlined in Hughes (1993). To assess changes in the different time periods, calculating the area of each vegetation community type allows for direct comparison with which to gain insight on how the channel reacts to the changing riparian vegetation makeup.

Figure 13

Map of Bounding Boxes



Bounding Boxes used for the study site at equal-length 200m intervals.

Channel Variables

The channel variables measured for this study are width, area, and curvature. Heads-up digitizing of the channel centerline allows for easier measuring of channel width and curvature, per the methodologies outlined in Keller et al. (2014), Laurer et al. (2017) and Gendaszek et al. (2012). The channel centerline only encompasses the primary channel of the Virgin River and not any tributaries.

A common issue with fluvial geomorphic studies that rely on remote sensing is that of discharge levels. Large differences in discharge values between images can be a confounding factor during analysis and lead to inaccurate digitizing of channel variables, such as area and curvature. For this study, the discharge values between images are reasonably close together, as outlined in table 2, with the exception of the 1976 imagery, when the gage was not operating for an extended period of time.

Table 2

Discharge Values for Each Imagery Date

Year	Date	Discharge (cfs)
1953	June 14th	21.4
1976	August 13th	n/a
1993	July 24th	35.0
2009	August 9th	41.0
2011	July 20th	65.2
2014	June 18th	12.8
2016	July 10th	58.2
2018	August 10th	26.9

Table 2: Discharge data from USGS Gage (09413500) for each date of imagery obtained.

Channel Width

Generating points along the channel centerline at equal-length 20-meter intervals allows for easier measuring of the channel width with the ‘measure’ tool in ArcGIS Pro. Categorizing points allows for further analysis in Microsoft Excel, where comparing points in removal and non-removal sites can aid in gaining further insight into removal trends.

Channel Area

Channel area and channel width are linked – as channel width increases, so too will the area. Given that channel width is spatially variable, comparing overall trends of channel width and area can help gain a sense of how localized widening in the study reach is. At each bounding box interval in the digitized channel, using the ‘split’ tool in ArcGIS Pro allows for calculating the area of each box. Calculating the area of each bounding box is done in square meters. Categorizing the channel segments in relation to their bounding box number is done in Microsoft Excel.

Channel Curvature

Given the short length of the study reach (~5km), sinuosity is not an appropriate method of measuring changes in lateral channel migration. Instead, measuring the radius of curvature between points every 20 meters down the channel centerline. However, given that a radius of curvature value can get infinitely higher, curvature values greater than 2400 are not included in this analysis. This number represents the value at which 95% of measurements fall below it. Figure 14 gives a visual example of radius of curvature.

Figure 14

Diagram of Radius of Curvature Values

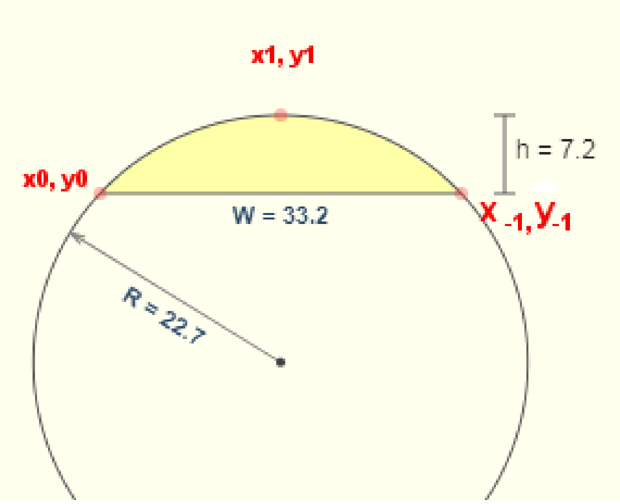


Diagram that visualizes radius of curvature (Unknown author, n.d.)

To calculate curvature, we use the following formula:

$$\frac{H}{2}+\frac{W^2}{8H}=R \qquad (1)$$

Where H is the height, W is the width, and R is the radius of curvature. To calculate H, we use the following equation:

$$H=\sqrt{(x_1-\frac{(x_{-1}+x_0)}{2})^2+(y_1-\frac{(y_{-1}+y_0)}{2})^2}$$

Where X_0 is the beginning x-coordinate point, X_1 is the middle x-coordinate point, X_{-1} is the ending x-coordinate points, Y_0 is the beginning y-coordinate point, Y_1 is the middle y-coordinate point, and Y_{-1} is the ending y-coordinate point (Williams, 1986). To calculate W, the following equation was used:

$$W=\sqrt{(x_{-1}-x_0)^2+(y_{-1}-y_0)^2}$$

Using the same variables as equation H.

Changes Post-Removal

Categorizing the bounding boxes as either removal or non-removal sites is done only with imagery from 2009 onward. Comparing channel width, area, and curvature from each bounding box is done on boxes status as a removal or non-removal site. The goal of this is to identify any changes in these variables between removal and non-removal sites.

Analysis Methods

For the vegetation data, ArcGIS Pro was used for digitizing and visualizing the vegetation communities and river channel into maps. Each vegetation community and the river channel was assigned a certain color. All quantitative data derived from vegetation communities and channel variables was analyzed and visualized into bar charts using Microsoft Excel.

CHAPTER IV

RESULTS

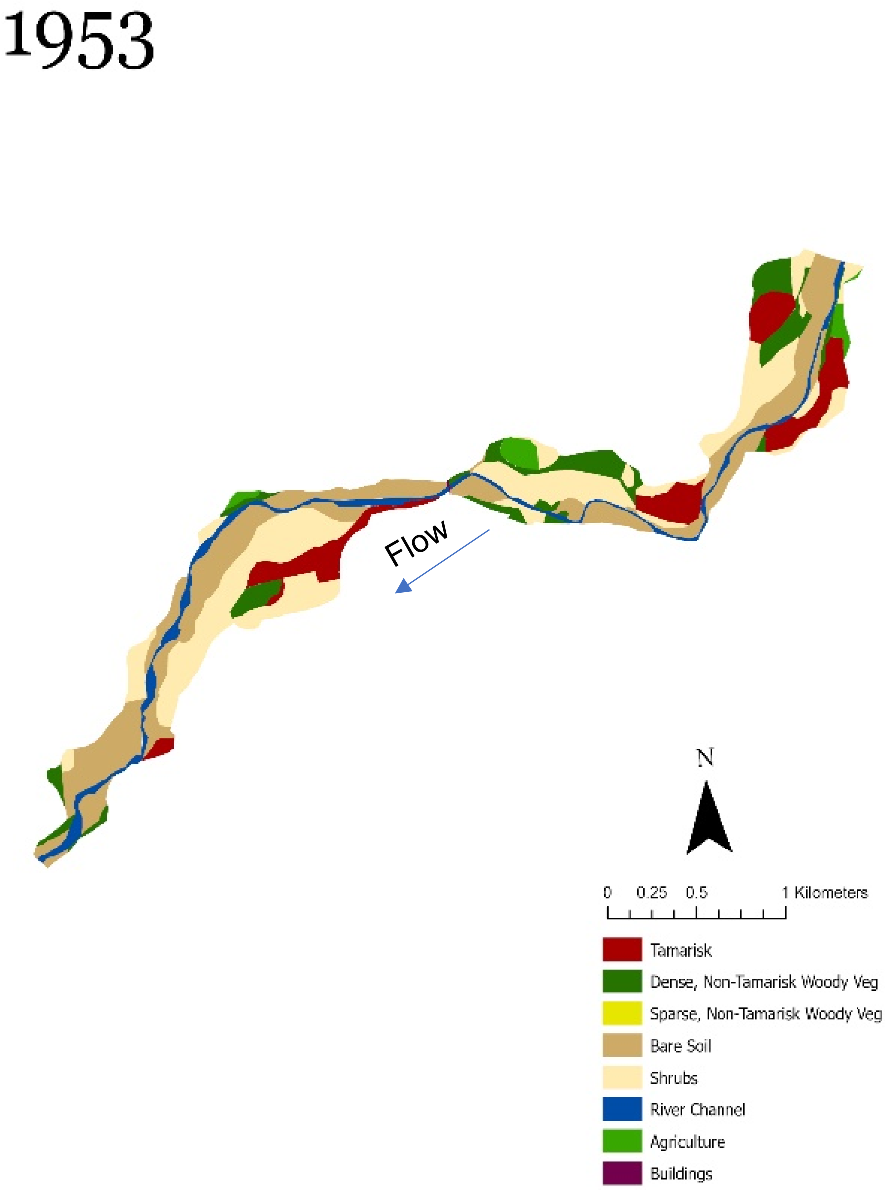
Overall Vegetation Change Through Time

From the earliest pre-colonization imagery in 1953 and 1976, we see that tamarisk stands are limited, with shrubs and bare soil being the two more common vegetation communities. Large stands of DNTWV are not as present in 1953 as they are in future years (figures 15 & 16). By 1976, the vegetation makeup of the reach changes substantially, with DNTWV becoming the dominant community type along with a small increase in tamarisk cover and a large decrease in areas of bare soil and shrubs (figures 17 & 18). There is also a notable decrease in bare soil over this time period in all zones, largely being replaced by stands of DNTWV. The lack of widespread tamarisk in this area is largely consistent with the qualitative accounts put forth by Hughes (1993) in which tamarisk did not reach the lower Virgin River until the 1950's. As a result, most of the vegetation remained native, with only smaller stands of tamarisk present. The changes in vegetation makeup are highly spatial, with the downstream boxes (20-25) experiencing high changes in percentage of area that becomes dominated by DNTWV, rather than bare soil or shrubs (figures 16 & 18).

During the colonization period (1993-2011), tamarisk becomes the largest dominant community and is present in almost every box on the reach (Figures 19 & 20). Areas of bare soil, shrubs, and SNTWV see the largest declines, while DNTWV remains prominent.

Figure 15

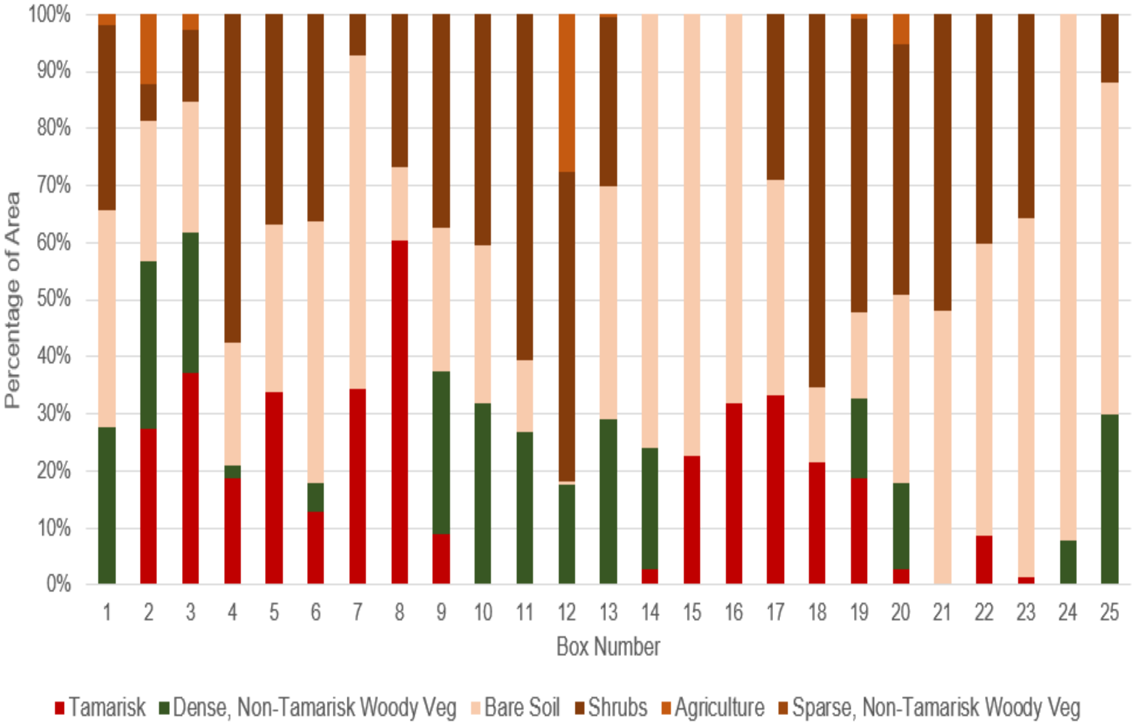
Map of vegetation communities for the 1953 imagery



Vegetation community composition of the study site from 1953 imagery. Bare soil and shrubs are the dominant communities, while relatively small patches of tamarisk remain.

Figure 16

Vegetation community area (1953)

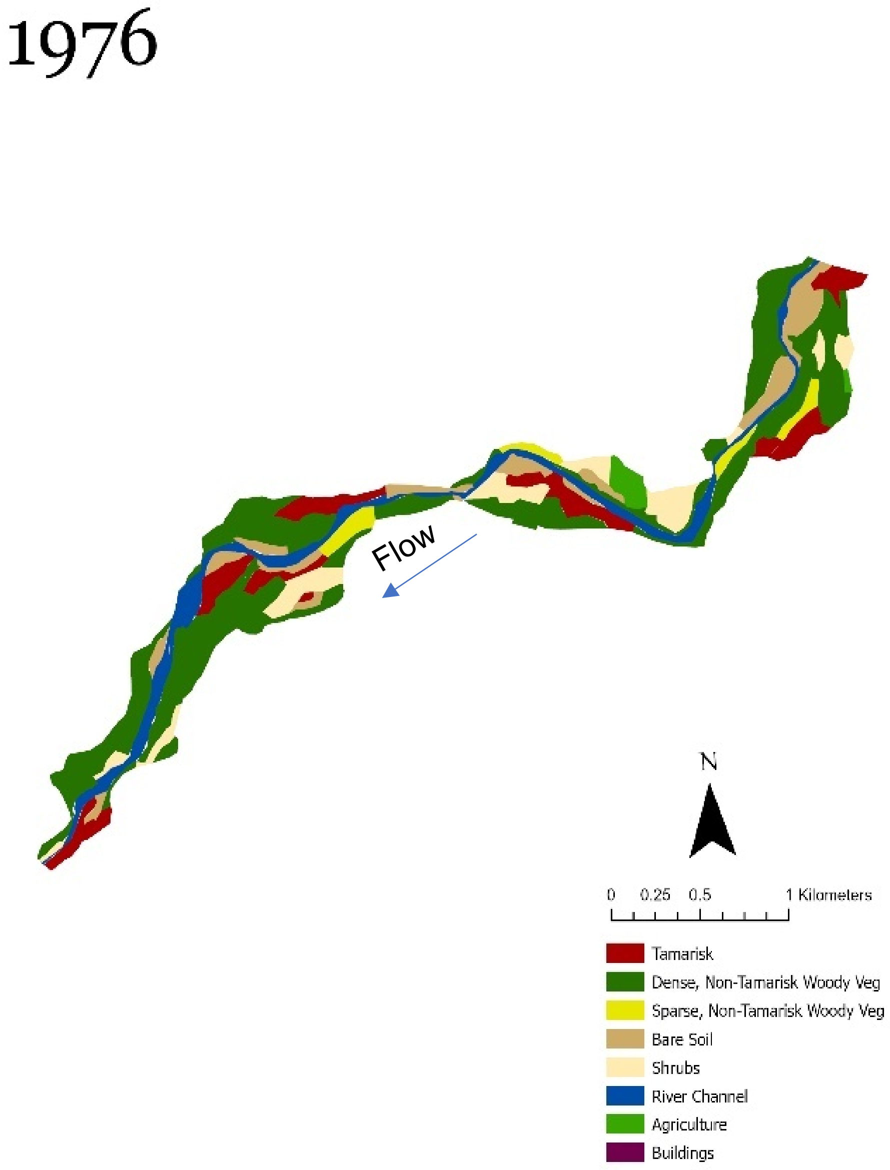


Vegetation community area of the St. George reach in 1953, excluding the river channel. SNTWV is not present for this year and is not included in the legend.

There are notable changes between 1976 and 1993. The largest difference being the increase in area that is classified as Tamarisk that occurs between the two years of imagery, along with a sharp decline in area classified as DNTWV (Figures 19 & 20). The continued decline of bare soil from 1953-1976 also appears to be continuing. Like the previous years, this change is highly spatial, with downstream boxes accounting for a disproportionate amount of the change.

Figure 17

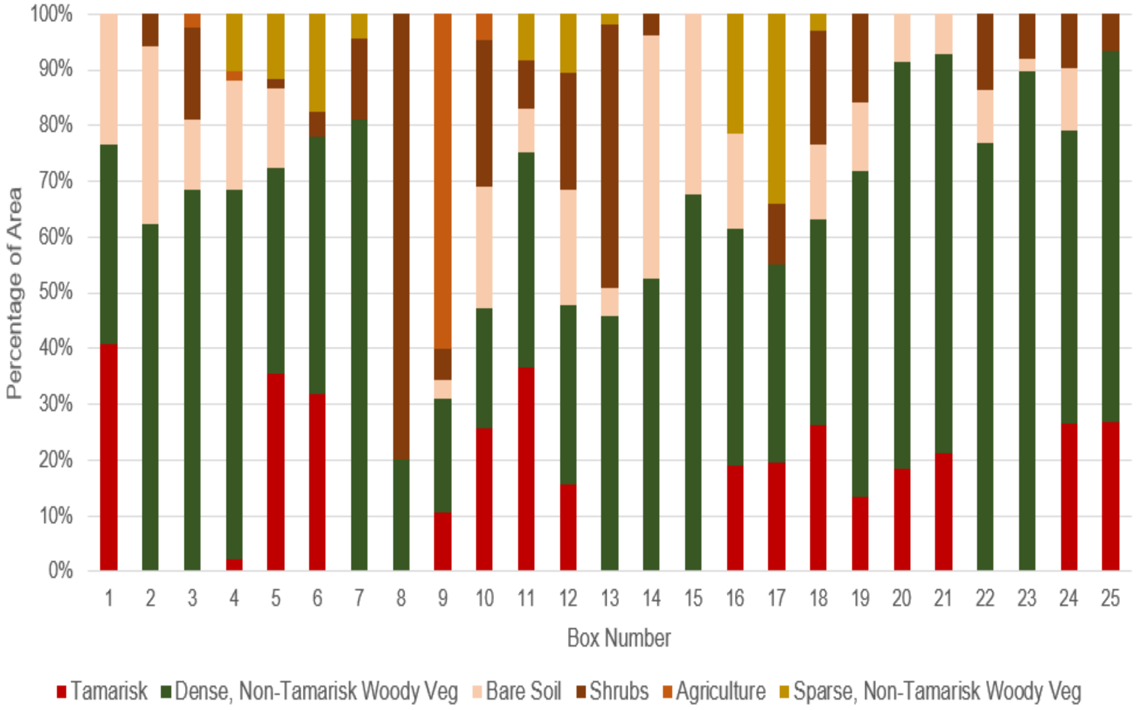
Map of vegetation communities for the 1976 imagery



Vegetation community composition of the study site in 1976. DNTWV has colonized the area, while tamarisk communities have grown in size but are still not the dominant community.

Figure 18

Vegetation community area (1976)



Vegetation community area of the St. George reach in 1976, excluding the river channel.

The imagery for 2009 appears to be the year of peak tamarisk colonization with an overall area of about 800,000 square meters (Figures 21 & 22), with a noticeable decline from 2011 onward. Larger stands of DNTWV and tamarisk are present for these years in greater numbers than in previous years.

By 1993, tamarisk has become nearly as large as the DNTWV vegetation community on the Virgin River in St. George (Figure 19). Areas of DNTWV saw the largest decline as these stands began to be replaced by tamarisk. This is also around the time that larger-scale tamarisk removal projects began to be implemented by state and local agencies, with the 2007 Virgin River Master Plan highlighting tamarisk removal as one of the top management goals.

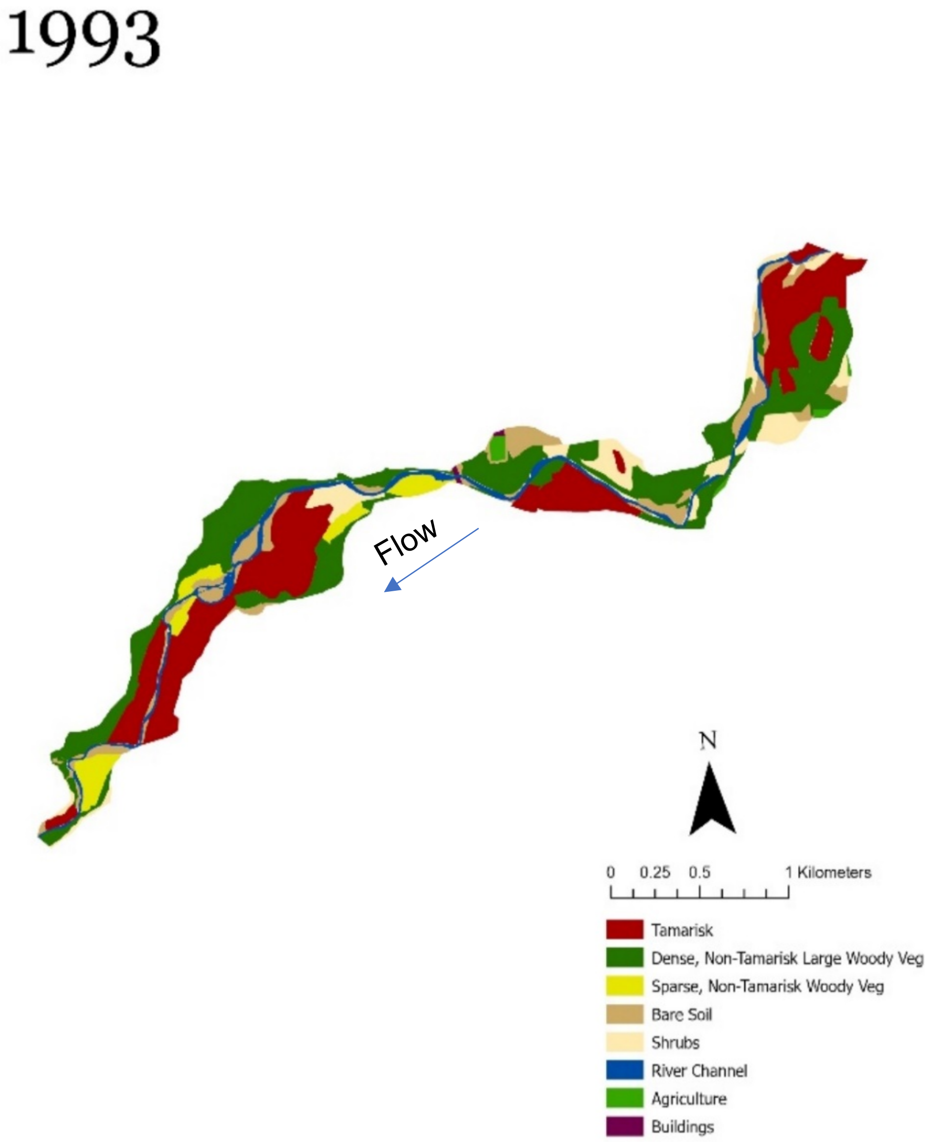
Of note is the sharp increase in bare soil area between 2009 and 2014. Gage data from the United States Geological Survey (USGS) gage near St. George (Gage number 09413500) shows that there were abnormally high discharge values between December 20th 2010 and December 23rd 2010, with the highest discharge value being 18,000 cubic feet per second on the 21st. To the best of the author's knowledge, there were no other large-scale removal projects on the Virgin River in St. George at this time. Thus, the sharp change in vegetation composition is most likely a result of this flood.

The post-removal period doesn't see many dramatic changes in vegetation composition over time. This is unsurprising given the short timeframe of this period. The large increase of bare soil areas that were left behind from the 2010 flood largely ended up becoming tamarisk stands, however overall the vegetation communities appear to be stable during this time period (Figures 25, 26, 27, & 28). While tamarisk stands are less abundant than in the peak year of 2009, the area of tamarisk post-removal is still greater than in the pre-colonization period (Figure 31).

Over the period of analysis, there is a shift in vegetation community composition from bare soil and DNTWV to tamarisk and DNTWV. While the earliest 1953 imagery showed an area dominated by bare soils and shrubs, large woody vegetation colonizes the area between 1953 and 1976.

Figure 19

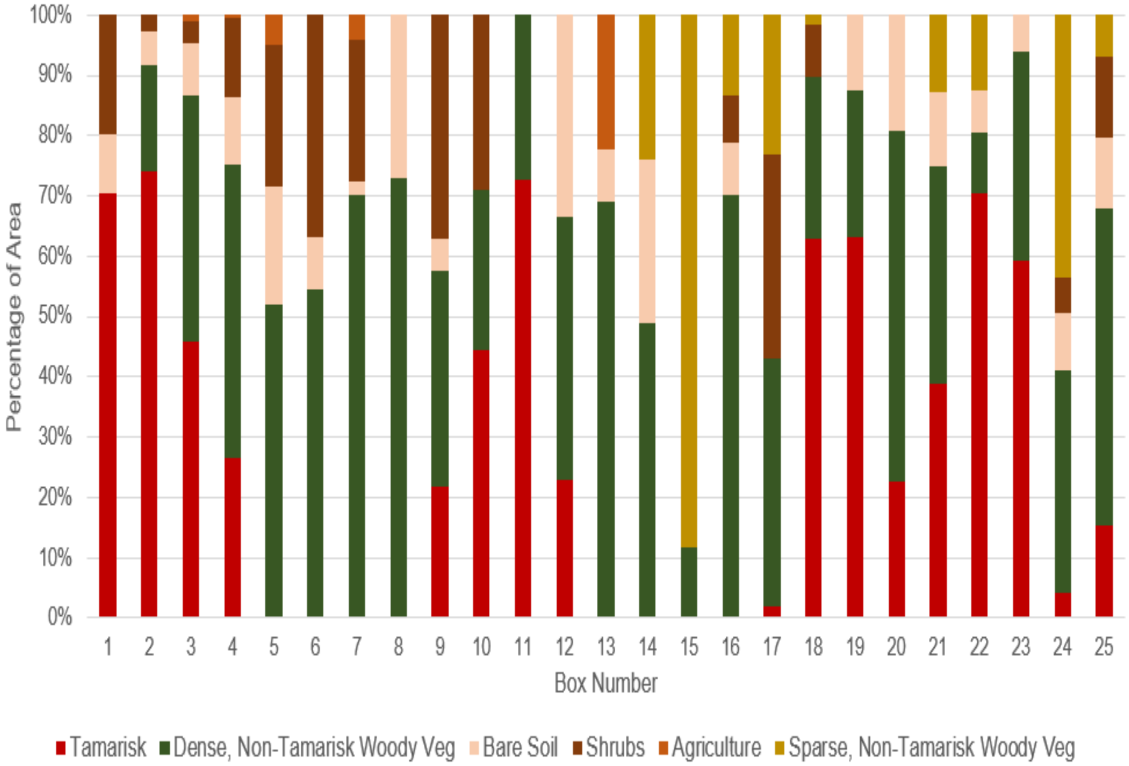
Map of vegetation communities for the 1993 imagery



Vegetation community composition of the study site in 1993. Tamarisk is now the largest vegetation community type, with DNTWV and bare soil areas declining.

Figure 20

Vegetation community area (1993)

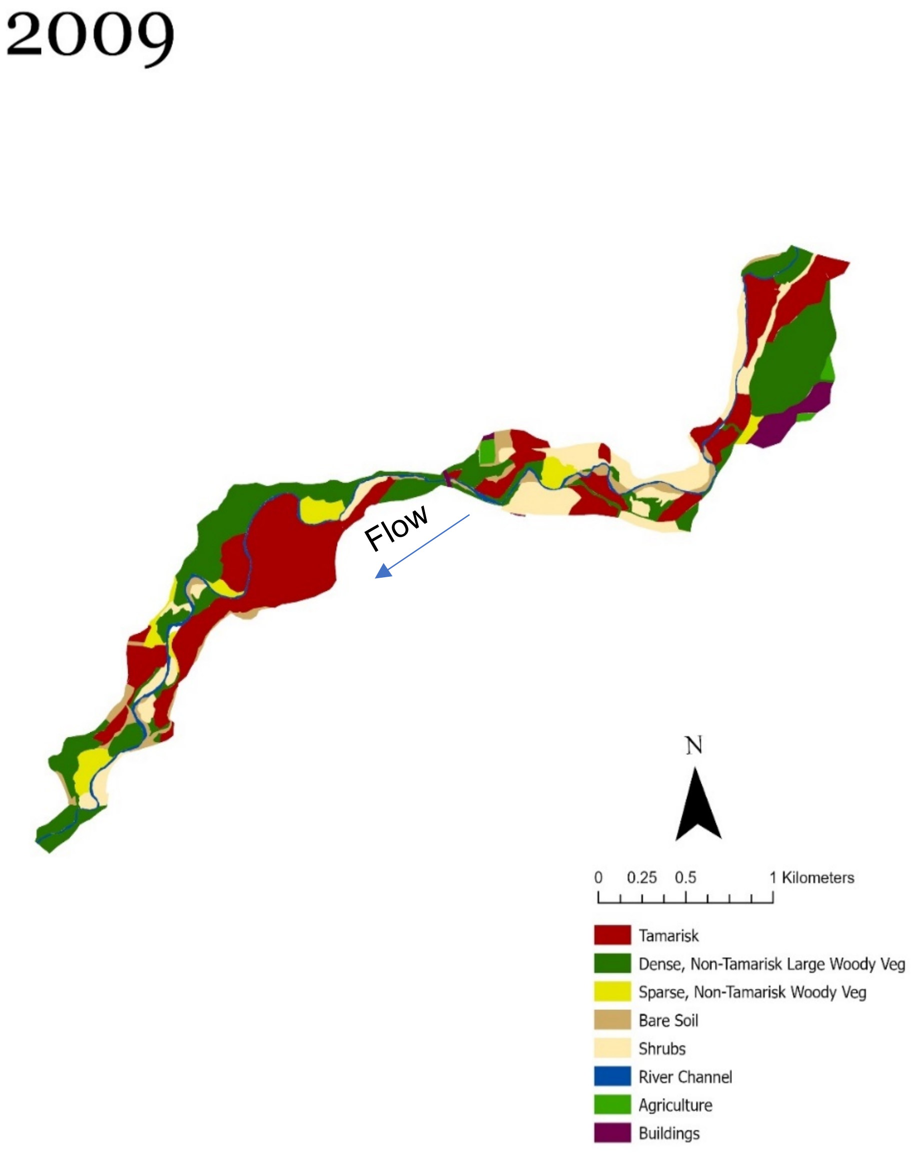


Vegetation community area of the St. George reach in 1993, excluding the river channel.

Of note are the changes in bare soil, which decline from 1953-1993, and then increase from 2011-2014. This is of note as tamarisk generally is able to colonize bare soil areas more efficiently than cottonwoods and other native vegetation in the region (Meinhardt, 2012). Tamarisk stands peak around 2009 and see a decline from then onward but remain one of the dominant vegetation community types.

Figure 21

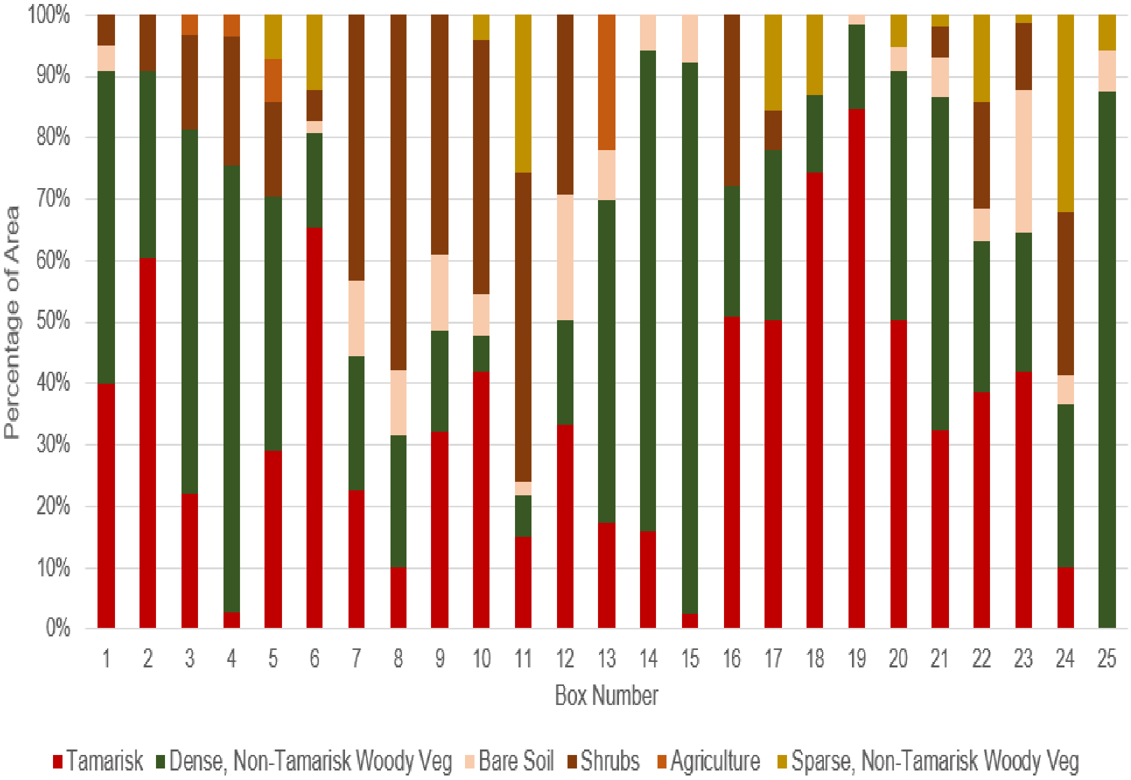
Map of vegetation communities for the 2009 imagery



Vegetation community composition of the study site in 2009, the year of peak tamarisk colonization.

Figure 22

Vegetation community area (2009)



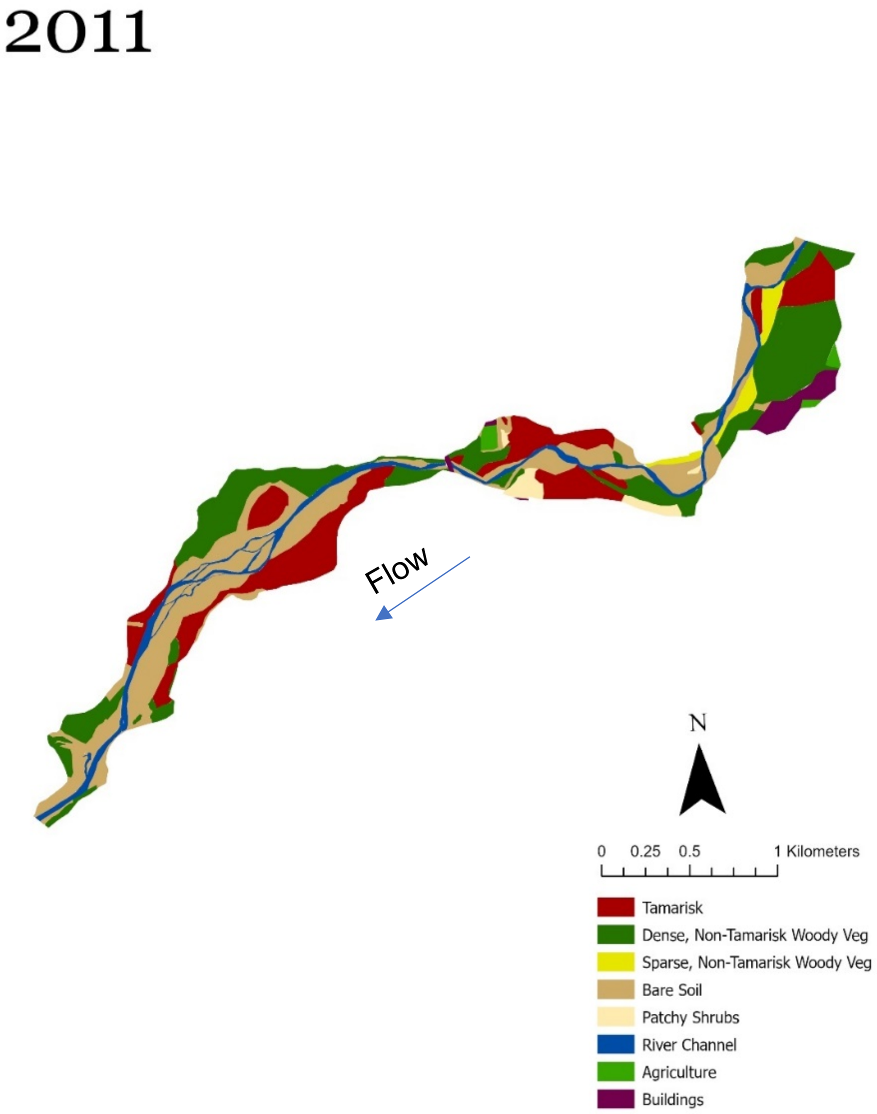
Vegetation community area of the St. George reach in 2009.

Overall Channel Width Change Through Time

The active channel of the Virgin River has been dynamic over this period of analysis, Pre-colonization, there is an open, broad channel pattern that peaks in 1976 with an average width of ~42m. By 2009, the width average decreases considerably to only 11m, coinciding with the mass colonization of tamarisk on the reach. Channel width greatly increases by 2011, mostly likely due to the abnormally large flood that occurred from Dec 21-23rd of 2010. Post-removal, the channel narrows to an average of about 8m in 2014, with a steady increase up to about 15m in width by 2018 (Figure 32).

Figure 23

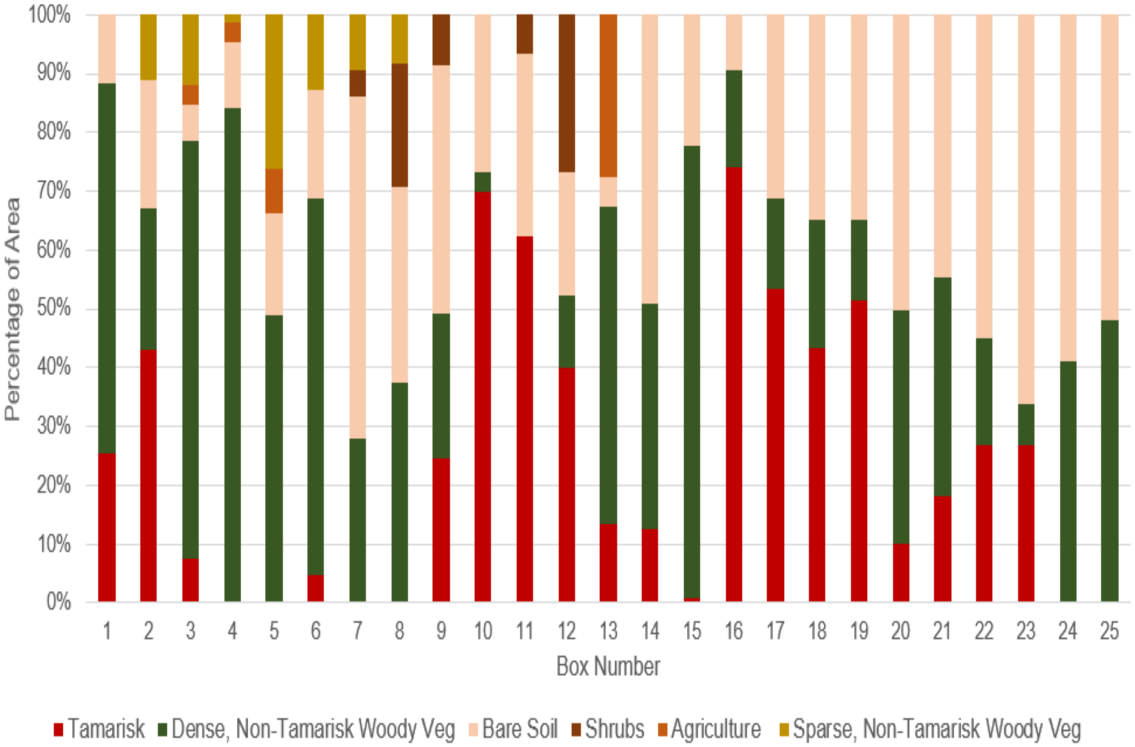
Map of vegetation communities for the 2011 imagery.



Vegetation community map of the study site in 2011, the year after the major flood at the end of 2010.

Figure 24

Vegetation community area (2011)



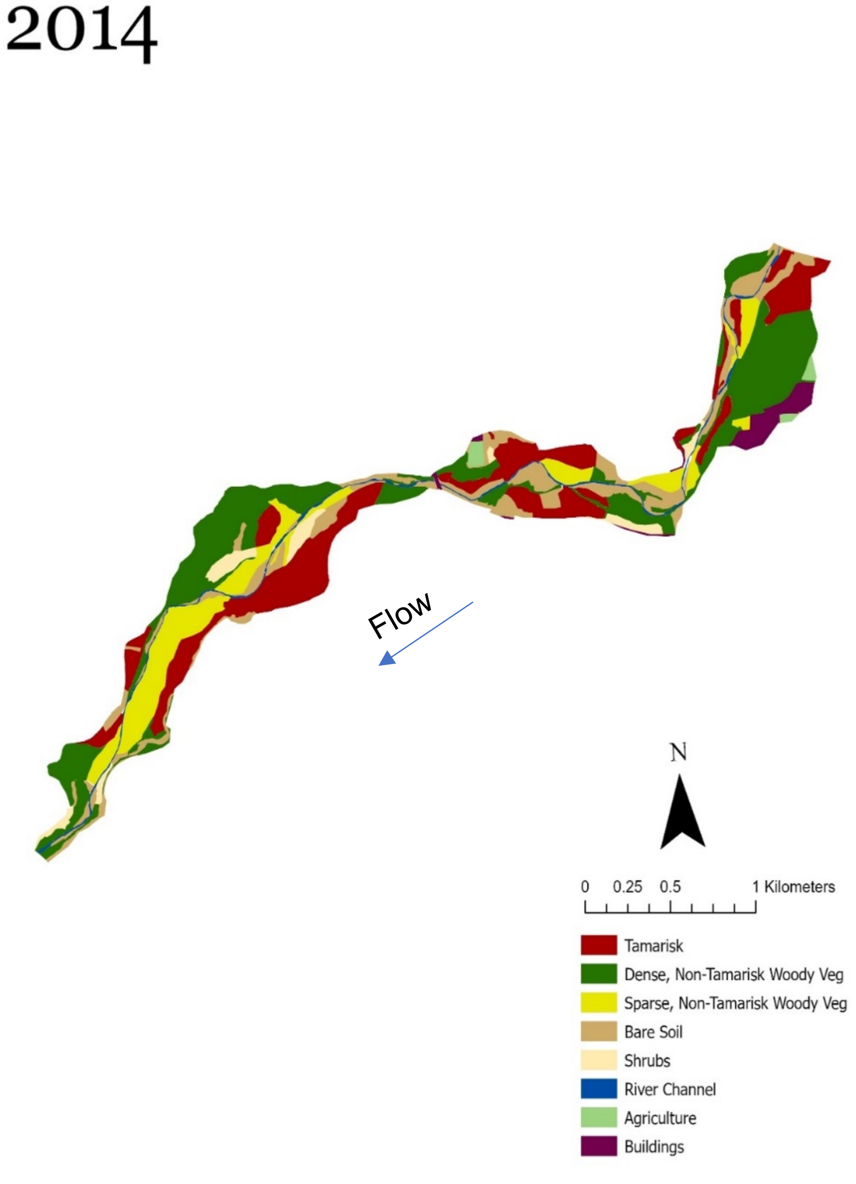
Vegetation community area of the St. George reach in 2011.

Channel Width Change by Zone

Changes in channel width can be spatially variable along a reach. While overall changes in channel width are useful for broadly assessing if a reach is widening, breaking up the reach into zones, as done by Proctor (2017) and Zanoni (2008), helps identify if any areas are experiencing a disproportionate amount of change. As outlined in the methodology section, the twenty five boxes of the study site are split up into three zones, with boxes 1-8 being zone 1, boxed 9-17 being zone 2, and boxes 18-25 being zone 3.

Figure 25

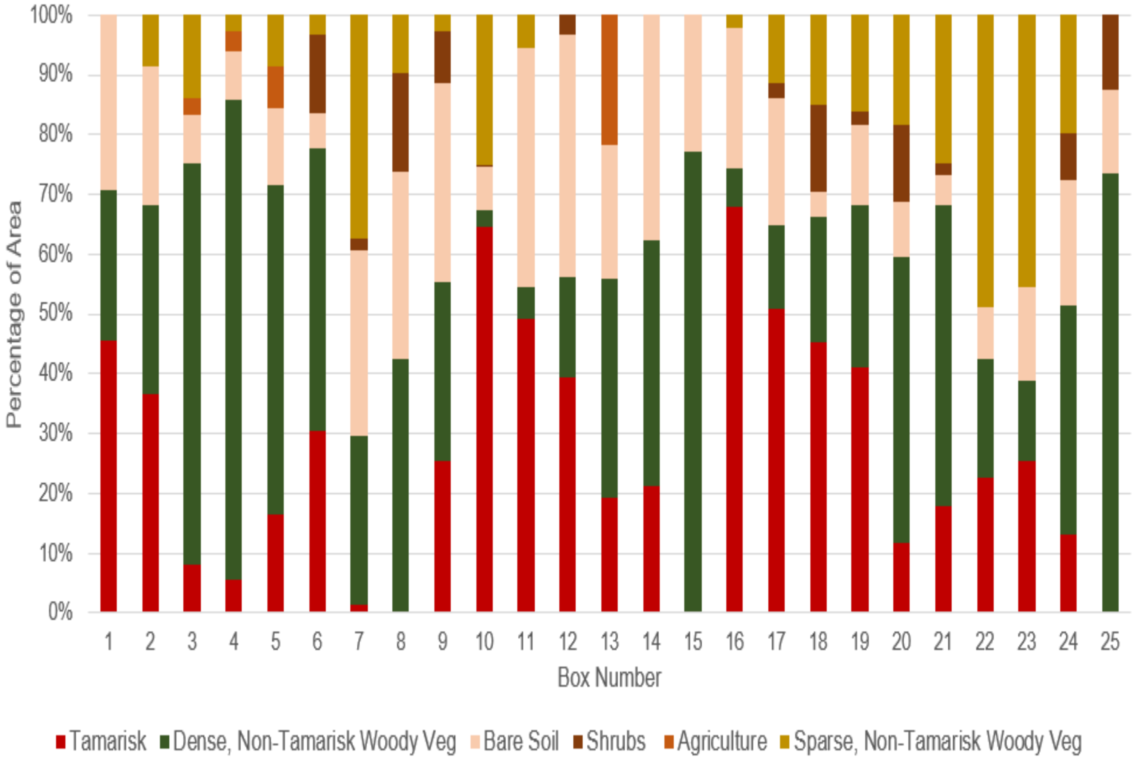
Map of vegetation communities for the 2014 imagery



Vegetation community map of the study site in 2014, the first year of removal.

Figure 26

Vegetation community area (2014)

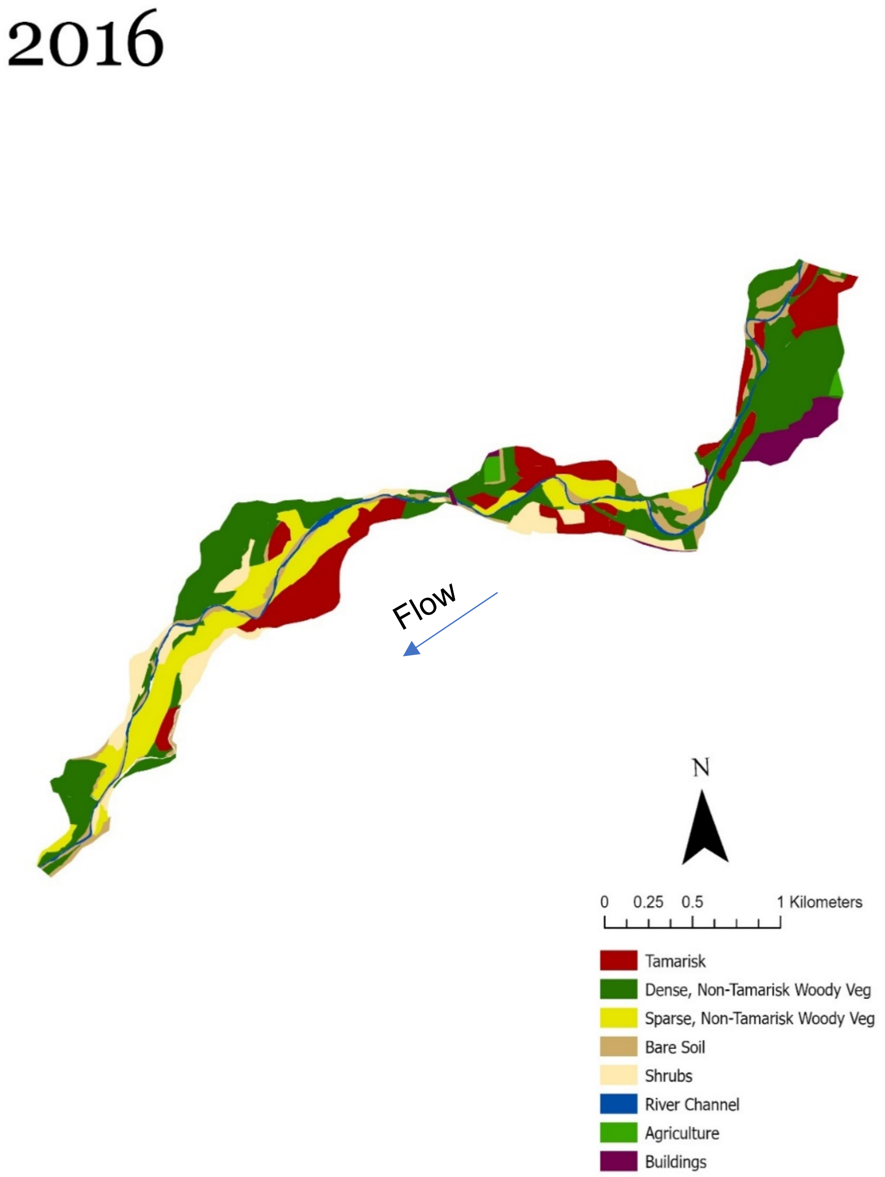


Vegetation community area of the St. George reach in 2014, excluding the river channel.

Changes in channel width have been disproportionately experienced in zone 3, which experiences by far the largest changes. Zones 1 and 2 are closely linked together in terms of changes, having relatively similar values for each year of imagery (Figure 33). Zone 3 also has the least amount of removal sites, with only two boxes (18 and 19) containing them. After the 2010 flood, the largest flood of record for the USGS gage near St. George (09413500), which is the overwhelming majority of channel width change occurred in zone 3.

Figure 27

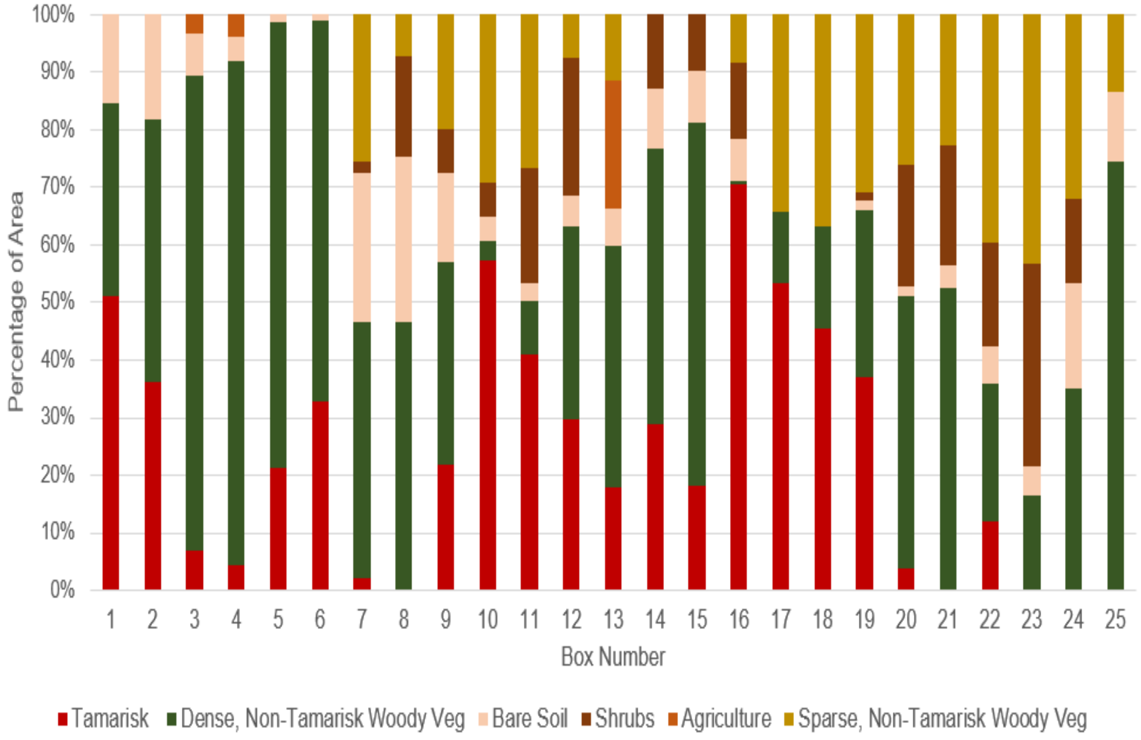
Map of vegetation communities for the 2016 imagery.



Vegetation community map of the study site in 2016.

Figure 28

Vegetation community area (2016)



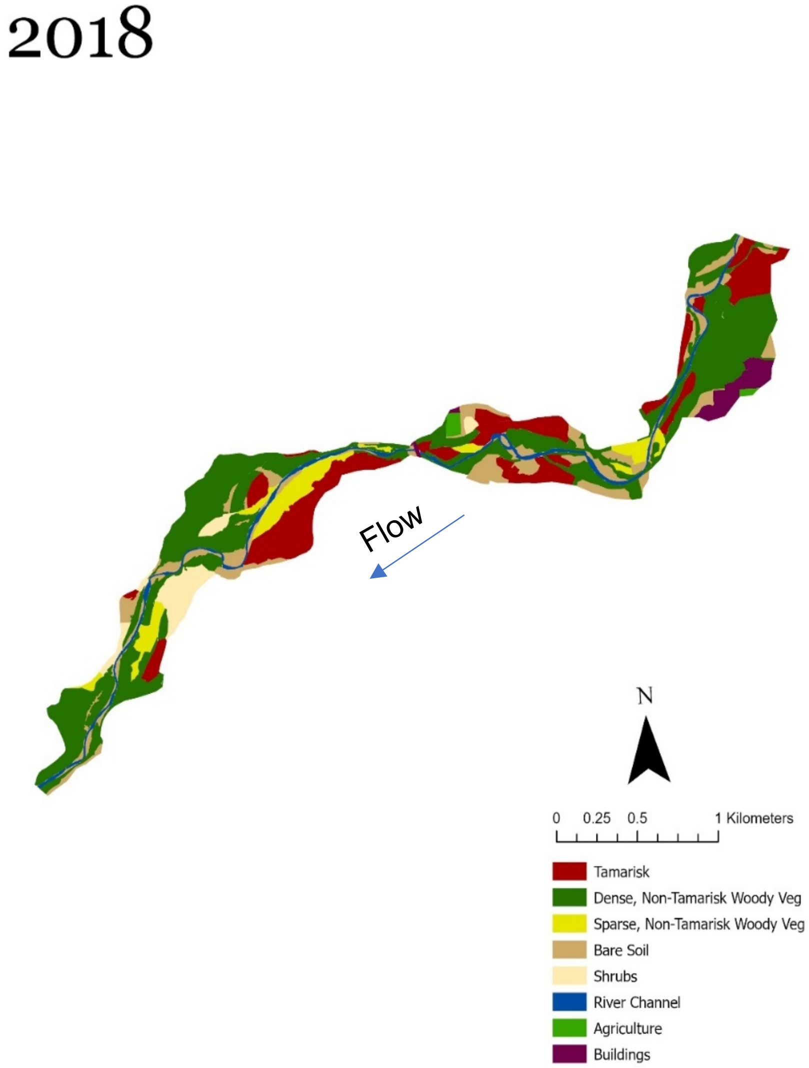
Vegetation community area of the St. George reach in 2016.

Channel Width Change by Removal Status

To see if there are any differences in channel width changes from tamarisk removal, classifying boxes was based on the presence of removal sites. This is to help 'untangle' the spatial differences that may occur in channel width changes. The uniform channel narrowing that occurs from 1976-onward can most likely be attributed to the increase in tamarisk area (Figure 32). However, channel widening has occurred for all areas post-2010 flood.

Figure 29

Map of vegetation communities for the 2018 imagery



Vegetation community map of the study are in 2018, the last year of available NAIP imagery.

Figure 30

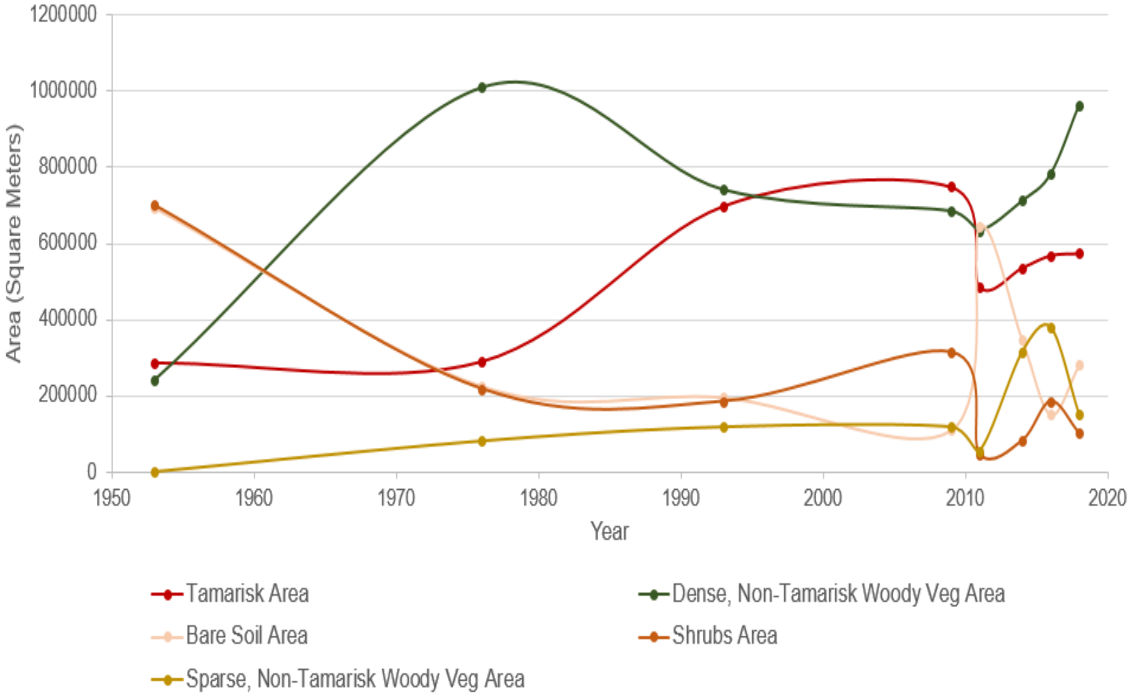
Vegetation community area (2018)

Vegetation community area of the St. George reach in 2018.

A potential explanation for this is the removal of native vegetation in the non-Tamarisk areas, which leaves channel banks susceptible to erosion and channel widening. Areas of removal, however, would widen faster as the removal of Tamarisk would leave the banks and the nearby floodplain completely bare. Table 3 shows box numbers and the corresponding classification. Since this section is only concerned with changes post-removal, only imagery from 2009, the year of peak tamarisk colonization, and onward is used. This is to help 'untangle' the spatial differences that may occur in channel width changes. The uniform channel narrowing that occurs from 1976-onward can most likely be attributed to the increase in tamarisk area (Figure 32). However, channel widening has occurred for all areas post-2010 flood. A potential explanation for this is the removal of native vegetation in the non-Tamarisk areas, which leaves channel banks susceptible to erosion and channel widening. Areas of removal, however, would widen faster as the removal of Tamarisk would leave the banks and the nearby floodplain completely bare. Table 3 shows box numbers and the corresponding classification. Since this section is only concerned with changes post-removal, only imagery from 2009, the year of peak tamarisk colonization, and onward is used.

Figure 31

Change in total area of each vegetation community over time

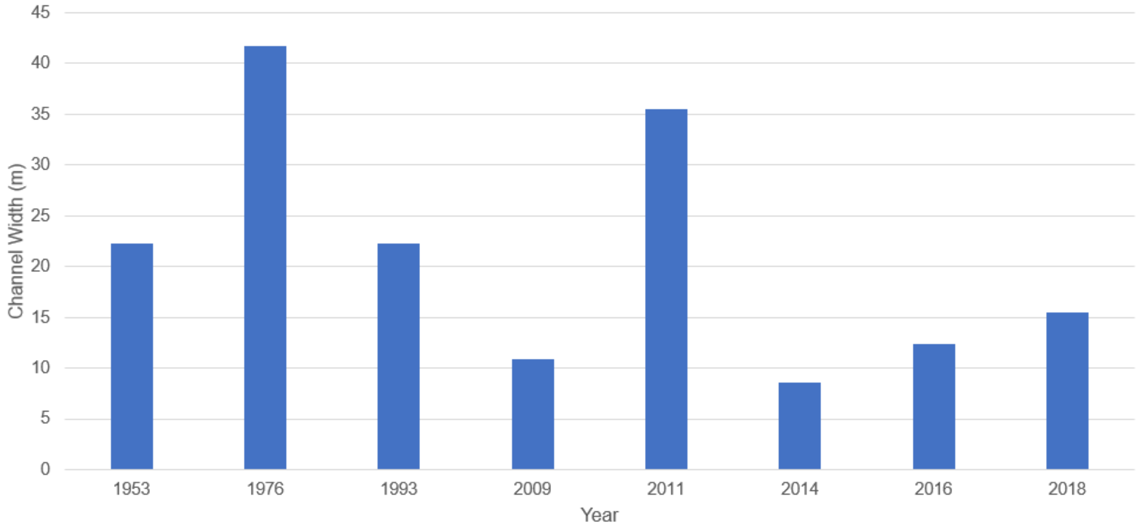


Changes in each vegetation community over time.

Compared to 2009, the year of peak tamarisk colonization, channel width begins to increase across the reach after 2009. From 2014-2016 the differences between removal and non-removal boxes is negligible, with both sites having an average channel width of about 13m. However, by 2018 the average width of removal sites is larger than in non-removal sites, with removal sites having an average width of about 16.5m and non-removal sites having an average width of 14.5m (Figure 34). This is consistent with findings from Keller et al. (2014), which found greater increases in channel width along removal areas of tamarisk than in non-removal areas.

Figure 32

Average channel width by year



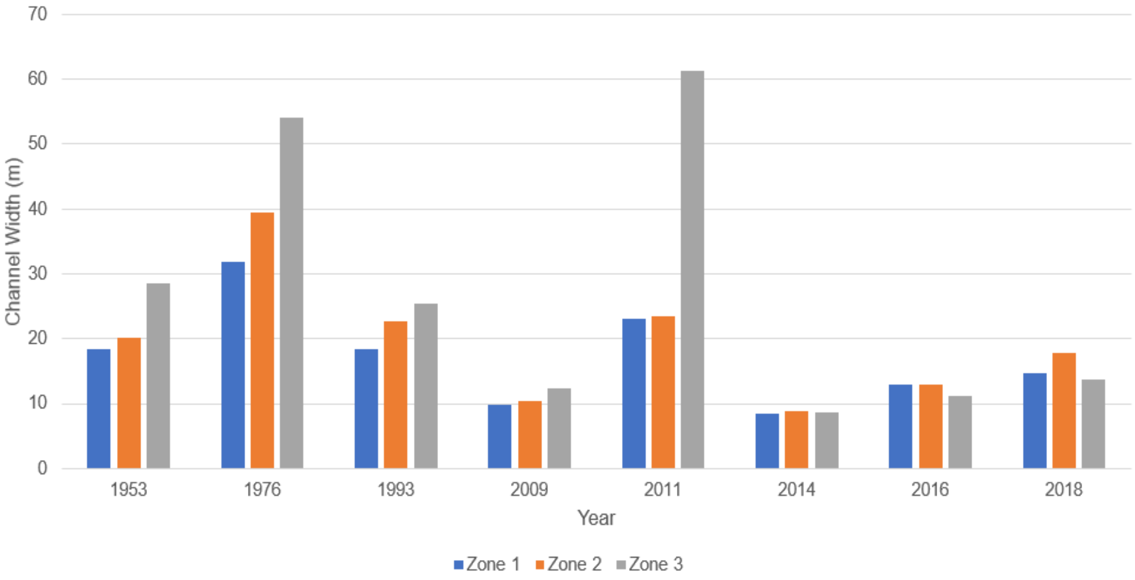
Average channel width by year for the overall reach in St. George.

Overall Channel Area Change Through Time

Measuring channel area allows us to gain an overall perspective on how the channel is widening. Since changes in channel width can be spatially variable, measuring channel area can provide insight into how uniformly the channel is widening along the study area.

Figure 33

Changes in channel width by zone



Channel width change by zone for each year on the St. George reach.

Table 3

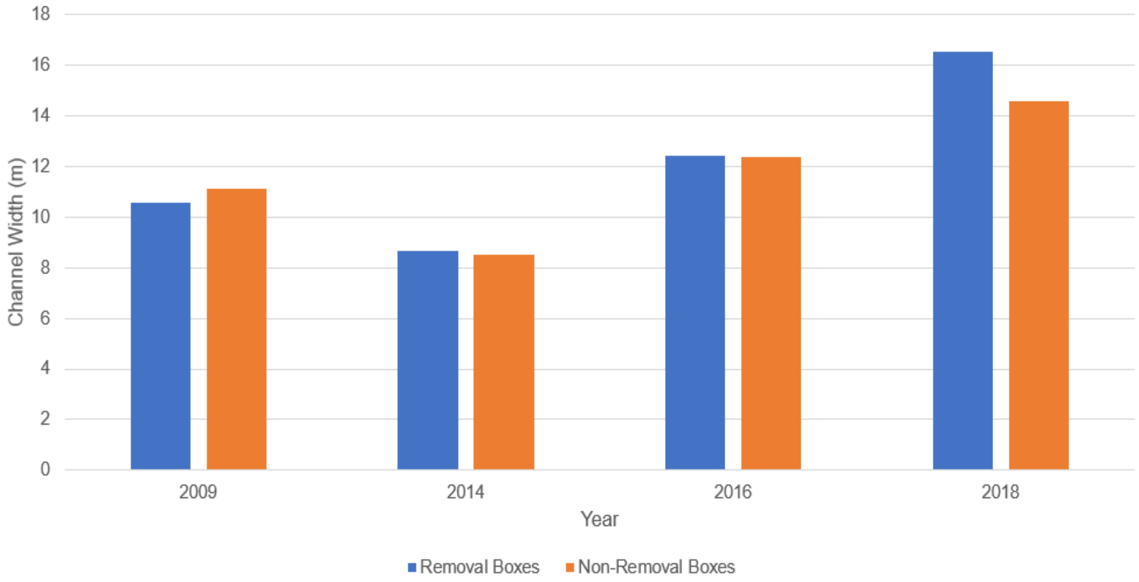
Boxes classified as removal or non-removal Boxes

Removal Boxes	Non-Removal Boxes
1	2
3	4
5	7
6	8
10	9
11	16
12	17
13	20
14	21
15	22
18	23
19	24
	25

List of which boxes have been classified as removal or non-removal.

Figure 34

Changes in channel width by removal status



Changes in channel width by removal status for the pre-removal (2009) and post-removal (2014-2018) years.

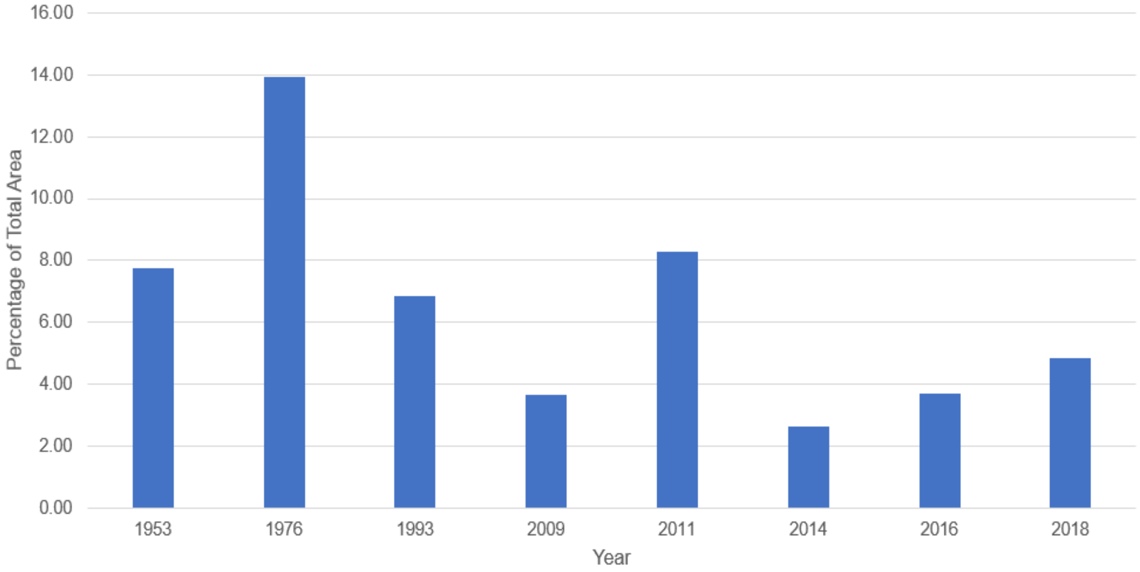
During the pre-colonization period, the channel area was greatest in 1976 and then declines until 2011, when the average area increases to about 5% of the total area (Figure 35). The post-removal period (2014-2018) sees a steady increase in overall channel area for each year of imagery, rising from an average of about 2.2% of total area in 2014 to ~5% by 2018.

Channel Area Change by Zone

Similar to channel width, a disproportionate amount of changes in channel area occur in zone 3 of the reach, peaking in area in the 1976 imagery (Figure 36). Channel area is smallest in 2009, the year of peak tamarisk colonization, and begins to increase from 2014 onward post-removal. Changes in channel area are not as large as changes in channel width, implying that increases in width may be localized to a certain extent.

Figure 35

Average channel area percentage by year



Average channel area percentage by year for the St. George reach.

Figure 36

Changes in channel area percentage by zone

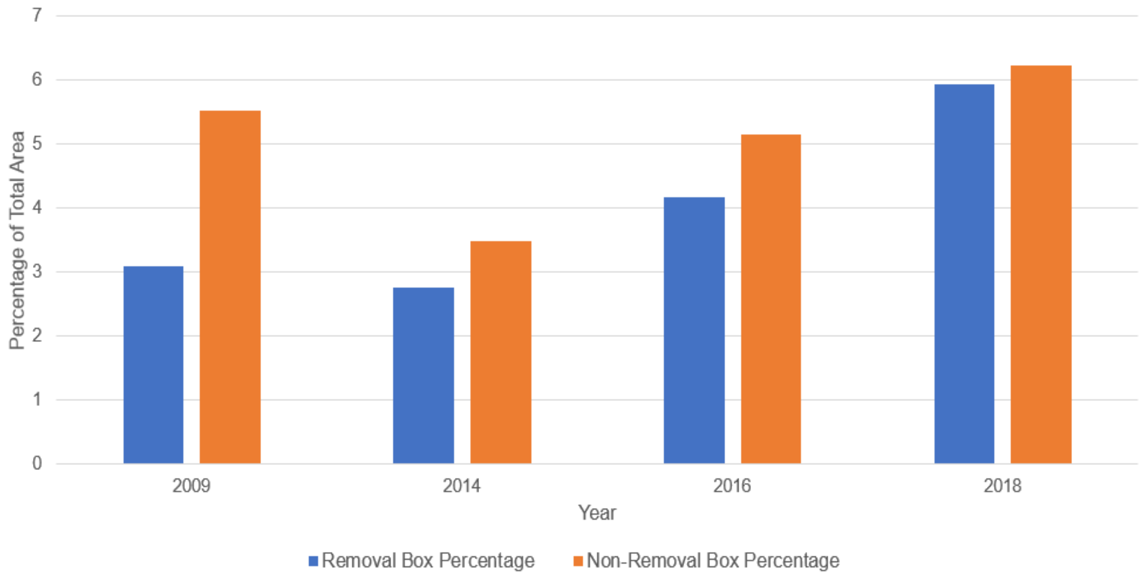
Changes in channel area by zone for each year on the St. George reach.

Channel Area Change by Removal Status

There is a large disparity in channel area pre-removal. In 2009, removal boxes have a noticeably lower channel area than non-removal boxes, with removal boxes having an average of 3.1 percent of the total area and removal boxes averaging around 5.7 percent (Figure 37). Post-removal, the disparity between removal and non-removal boxes begins to decrease every year, with both removal and non-removal boxes making up about 5.9 and 6.1 percent of the total area. Unlike the trends in channel width, channel area in removal boxes does not exceed the value of channel area in non-removal boxes.

Figure 37

Changes in channel area percentage by removal status



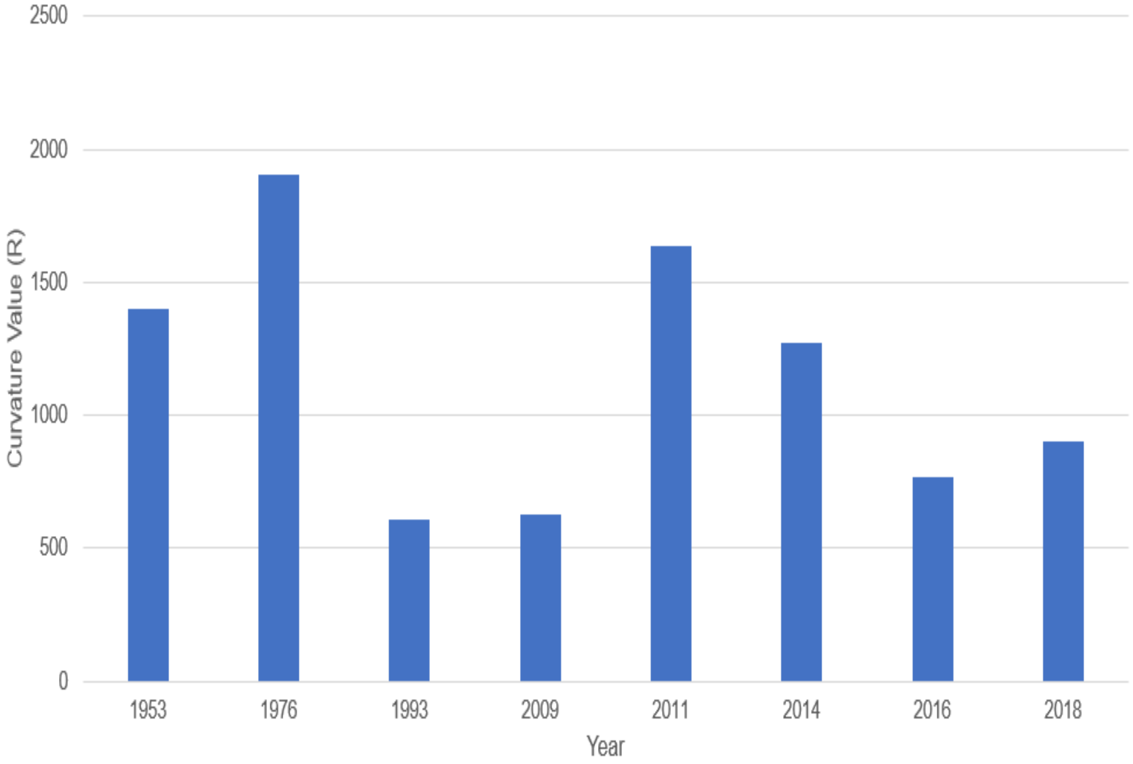
Changes in channel area by removal status for the pre-removal (2009) and post-removal (2014-2018) years.

Overall Channel Curvature Change Through Time

Channel curvature is dynamic along this reach over time, largely correlating with periods of tamarisk colonization. Overall curvature is highest during the pre-colonization period of 1953 and 1976 (Figure 38). Curvature values are the lowest in 1993 and 2009, the years of peak tamarisk colonization, and increase again in 2011. The post-removal period (2014-onward) does not see major changes in curvature that line up with the removal of tamarisk.

Figure 38

Changes in channel curvature by year



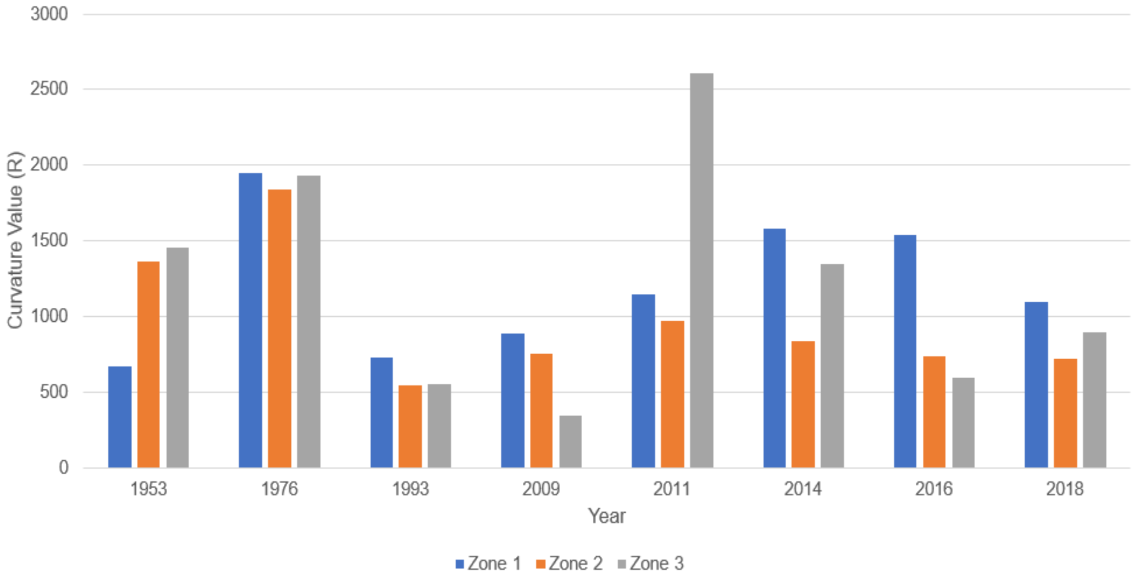
Overall change in channel curvature values for each year of imagery. Higher curvature values indicate less sinuosity.

Overall Curvature Change by Zone

Following a similar pattern to channel width and area, the majority of change occurs in zone 3 of the reach (Figure 39). The pre-colonization period in 1953 and 1976 sees fairly uniform curvature values throughout the entirety of the reach, with lower values (more sinuous channel) dominating during the period of peak tamarisk colonization in 1993 and 2009. The post-removal period sees a shift in curvature values between zones, with zone 1 having higher values than zones 2 and 3. The low curvature values in 1993 and 2009 are consistent with the results from Keller et al. (2014).

Figure 39

Changes in channel curvature by zone



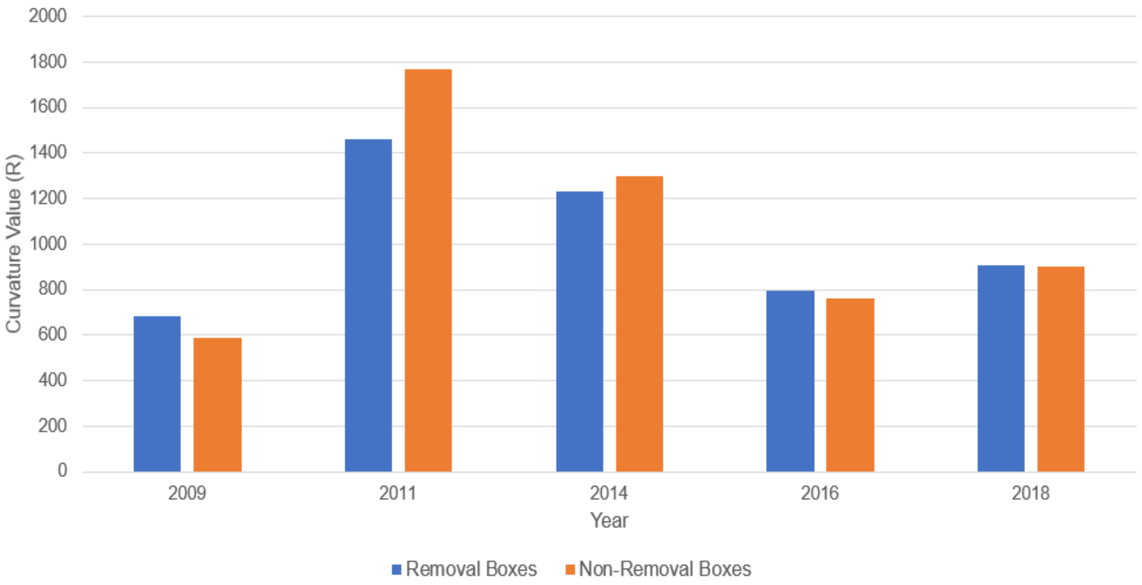
Change in channel curvature by zone for each year of imagery.

Channel Curvature Change by Removal Status

Unlike channel width and area, there aren't major differences in channel curvature values between removal and non-removal sites (Figure 40). While there is an overall increase in curvature compared to the 2009 imagery, which was the peak year of tamarisk colonization, the values for removal and non-removal sites are nearly identical. This is inconsistent with the findings of Keller et al. (2014), who found that channel sinuosity increased in removal boxes at a greater rate than in non-removal boxes.

Figure 40

Changes in channel curvature by removal status



Changes in channel curvature by removal status.

CHAPTER V

DISCUSSION

Vegetation and Channel Change

As stated previously, tamarisk began to colonize most major southwestern river systems roughly around the end of the 19th century (Birken, 2006; Graf, 1978; Hughes, 1993), long before the advent of aerial imagery capabilities. Thus, performing research on the geomorphic effects of tamarisk colonization has been performed when the river was already colonized. However, the interviews with locals along the Virgin River performed by Hughes (1993) implied that tamarisk did not begin to colonize the river until the mid-20th century.

The geomorphic history section of this study is greatly facilitated by tamarisk colonizing the study site later than other major river systems, as this gives the unique chance to see a river system react to tamarisk colonization with aerial imagery. The results from the mapping of vegetation communities largely line up with the findings of Hughes (1993), where a local rancher from nearby Mesquite, Nevada claimed that: “When I was a boy in the 30's and 40's the Virgin River was open, no brush on its banks. Then in the late 40's and in the 1950's the tamarisk just seemed to roll down the river". While this is the account of only one individual, sources that include the general timing of tamarisk colonization are practically non-existent.

As seen in figures 16 and 18, the pre-colonization period has patches of tamarisk, but it is not the dominant riparian vegetation community on the floodplain. However, by 1993, tamarisk has established itself as the largest community by area, largely at the expense of DNTWV, bare soil, and shrubs (Figure 20). This is consistent with other studies findings on how tamarisk colonizes riparian zones, which is mainly by colonizing bare soil areas faster than native Fremont cottonwoods during times of low flow (Harms, 2006; Quigley, 2013; Stromberg et al., 2009).

One of the most common geomorphic changes that occurs with tamarisk colonization are decreases in channel width, area, and lateral channel migration (Graf, 1978; Keller et al., 2014; Jaeger and Wohl, 2011). This is likely a result of bank destabilization, as Pollen-Bankhead et al. (2009) found when analyzing geomorphic changes of invasive species removal in Canyon De Chelly, Arizona. We can see from figures 32, 35, and 38, that the peak years of tamarisk colonization (1993 and 2009 imagery) possess by far the narrowest and most sinuous channel forms of all the years for which analysis was performed.

Pre-colonization, the Virgin has the channel form that was described in Graf (1978) and Hughes (1993) of a wide, straight channel shape with greater overall channel area. The root systems of native riparian vegetation, such as cottonwoods and willows, are not as pervasive and thick as those of tamarisk roots (Sher & Quigley, 2013). Pre-colonization, large floods would generally erode riverbanks at a greater rate due to the lack of bank stabilization (Birken, 2006). When tamarisk colonization occurs, changes in channel migration, curvature, and width all tend to occur less frequently. This coincides with the results in figures 32, 35, and 38, which shows the lowest of all these values occurring during the years of peak tamarisk colonization.

Of note is the fact that while the channel is widening faster in tamarisk removal areas, it is also widening in areas not dominated by tamarisk. This could be due to the removal of some non-native vegetation by the 2010 flood, which allowed for greater bank erosion to occur. Another possibility is that the recent drought this area has experienced has led to the dying off of some native vegetation that is not as drought tolerant as tamarisk, as Chew (2009) notes was a reason the plant was so effective at colonizing the American Southwest.

On a finer scale, the changes that occurred during colonization are spatially variable. Where zones 1 and 2 have similar values for the channel variables, zone 3 showed larger changes in channel variables throughout the years of imagery. It is worth noting that zone 3 is larger than zones 1 and 2, and thus some level of greater change is expected, however the changes seen are not proportional to the area that zone 3 occupies. Analyzing this variability in further detail is difficult with aerial imagery, as there are no large differences in geomorphic or ecologic setting in this zone. To the best of the authors knowledge, no major geomorphic alterations have been made in this zone, which makes the stark differences puzzling.

The differences observed between removal and non-removal sites is mixed. Channel width and area largely supported the initial hypotheses that both would increase faster in removal sites than in non-removal sites, as we see in figures 34 and 37. The loss of the pervasive tamarisk root systems in removal areas likely led to accelerated erosion of the now-bare banks, which is similar to the results found in Keller et al. (2014) and Jaeger & Wohl (2014).

Unlike channel width and area, channel curvature reveal little-to-no differences between removal and non-removal sites. This is inconsistent with the findings of Keller et al. (2014), who found noticeable differences between treated and untreated sites. One possibility is that there was a lack of large floods over the post-removal period on the Virgin, leading to inadequate levels of flow necessary to perform geomorphic work, as was hypothesized by Jaeger & Wohl (2014). Differences in the presence of non-tamarisk vegetation could also affect these differences as well. For example, the studies by Keller et al. (2014) and Jaeger and Wohl (2014) could have measured differences in non-colonized areas that were mainly shrubs, whereas the non-tamarisk areas in this study were mainly DNTWV. However Keller et al. (2014) and Jaeger & Wohl (2014) do not have detailed vegetation data to use for cross-comparison.

While remote sensing is an effective method for this type of study, there are multiple limitations. Lack of fine scale, on-the-ground data can make analysis more difficult when spatial variation exists, such as the stark differences in zones we see in figures 33, 36, and 39 Large time gaps are also an issue for historical aerial imagery, which leads to patchy data that does not include time periods in-between available images. This study was also performed during the COVID-19 pandemic, which severely limited fieldwork capabilities over the summer months as cases were surging.

Implications for Restoration Efforts

Given that tamarisk removal is one of the most common river restoration efforts in the southwest (Jaeger & Wohl, 2011; Zavaleta, 2000), it is imperative for restoration practitioners to have an expectation of the geomorphic changes that occur post-removal. The trends identified in this study, mainly the increase in channel width and the lack of change in curvature in removal areas, can be of use when assessing monitoring data. For example, a faster increase in channel width at removal sites could be a potential hazard to landowners who have riparian property.

The results from this study can also aid in restoration design efforts. Given the spatial variability we see in the different zones on a small study area, practitioners should prepare for considerable differences in geomorphic response to removal. This can be particularly hazardous if there is an unusually large flood shortly after removal, as nearby property could be at risk if in an urban setting. This study also shows that geomorphic response may not be visible in the first four years post-removal, as evident by the lack of difference in change in curvature between removal and non-removal sites. This makes monitoring efforts all the more crucial.

Future Research Efforts

Given the prevalence of tamarisk removal projects, more studies that assess geomorphic changes post-removal should be performed to identify any trends or differences across the southwest. The limited number of studies makes inference difficult due to a lack of data and precedence. With very few river systems in the region being free of tamarisk, the possibilities for studies are vast. For the Virgin, the results of this study can be foundational as more aerial imagery is released in the future, such as the 2020 NAIP imagery.

Historical studies of tamarisk removal are also lacking in the literature. While this study took a broad approach to the effects of tamarisk removal, more in-depth studies that focus on a specific channel variable, such as width, can provide greater insight. This scope was not possible given the time constraints associated with this study.

Studies assessing geomorphic changes post-removal can also be performed in different geomorphic settings. Reaches that have different confinement, bed morphology, and topography have not been extensively studied and compared to one another in regards to tamarisk removal. This presents a real-world challenge to restoration practitioners and land managers, who may implement a removal project and see different results from the few studies that exist due to differences in geomorphic setting.

Longer-term monitoring efforts of post-removal effects is also needed. This study, Keller et al. (2014), and Jaeger & Wohl (2011) have all focused on timeframes that are less than five years. Considering that the Virgin River Master Plan extends around 25 years into the future, acquiring data on the long-term geomorphic impacts of tamarisk removal can greatly aid in the management and design of river restoration projects.

While the main focus of this study is geomorphic, a substantial interdisciplinary component also exists with longer-term monitoring efforts. As outlined in the Virgin River Master Plan, one of the primary goals of tamarisk removal is to have these areas be recolonized by native cottonwood forests. For longer-term removal studies, vegetation assessments that monitor native vegetation regrowth and recolonization by tamarisk are necessary to achieve common management goals. Without this, it is difficult to attribute geomorphic changes to changes in vegetation cover. Changes in soil chemistry are also a crucial aspect to native vegetation replanting, as tamarisk needles greatly increase soil salinity within the soil profile (Barrows, 1996), which can complication revegetation efforts.

CHAPTER VI

CONCLUSION

Tamarisk is an invasive woody tree species that has colonized the riparian zones of most major southwestern river systems. Originally imported as an ornamental plant and wind break for railroads in the mid-19th century, tamarisk quickly spread throughout the region at a blistering pace (Graf, 1973). Tamarisk roots are larger and more pervasive than native cottonwoods, and the salt secreted from the needles leads to soils that are too saline for native vegetation to tolerate. (Birken, 2006; Meinhardt, 2012). With the larger and more expansive root system, colonized areas typically undergo increased bank stabilization, and thus a decrease in bank erosion (Birken, 2006; Graf, 1973; Jaeger & Wohl, 2011). This largely led to a decrease in native vegetation, channel narrowing, and more sinuous channel morphology (Graf, 1973; 1982).

The existing literature on the fluvial geomorphic effects of Tamarisk colonization are extensive, however little research has been done on the effects post-removal. The Virgin River in St. George presents a unique opportunity to confront this gap in the literature. Longtime residents claim that Tamarisk did not colonize the area until the 1950's (Hughes, 1993), and a Tamarisk removal project was done in 2014 by the Utah Department of Natural Resources. This not only allows us to see how the river responded to Tamarisk colonization, but also to removal. This leads to the research questions of the study: When did Tamarisk colonize the Virgin River in St. George? How do changes in channel width, area, and curvature, differ between removal and non-removal sites?

To accomplish this, aerial imagery from seven different years (1953, 1976, 1993, 2009, 2011, 2014, 2016, and 2018) was downloaded from the USGS EarthExplorer, with the 1953 and 1976 imagery requiring georectification. The geomorphic channel and vegetation communities of the reach were digitized, along with measuring channel width, area, and curvature. The site was separated into equal-length 100m bounding boxes to detect spatial variation in geomorphic change. The boxes were separated into three equal-length zones, and labelled as ‘removal’ or ‘non-removal’.

Results show that mass Tamarisk colonization did not occur until sometime between 1976 and 1993, which matches the qualitative accounts given in Hughes (1993). The channel starts out wide with low sinuosity pre-colonization, becomes narrower and more sinuous during peak-colonization, and wider post-removal. This largely lines up with the results of previous studies done by Keller et al. (2014) and Jaeger & Wohl (2011). Spatially, most of the change occurs downstream in zone 3. Removal sites saw greater increases in channel width and area over non-removal sites, while channel curvature saw little-to-no difference.

The results of this study have implications for restoration practitioners and designers. The spatial variability shown in the different zones implies that there can be stark differences in geomorphic response in a relatively small reach. While curvature showed little-to-no difference, the short-term nature of this study means it’s possible that not enough time has passed for any significant changes in curvature to occur.

Future research opportunities exist for this study. With the onset of 2020 NAIP Imagery, a study that adds another two years of geomorphic response post-removal can aid in adding to the literature on longer-term response. Additionally, performing similar studies on other removal sites in the region can add to the scarce literature and provide restoration practitioners with useful data when designing projects. Interdisciplinary efforts also exist, with revegetation efforts and monitoring of soil salinity being common goals among removal projects, along with the geomorphic goals.

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