University of Nevada, Reno

Estimating Groundwater Evapotranspiration for Tamarisk-Dominated Riparian Communities through Satellite Imaging, Virgin and Muddy Rivers, Nevada

A thesis submitted in partial fulfillment of the requirements for the degree of
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by

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Abstract

Southern Nevada features very high water demands and very low water availability. Tamarisk is a significant user of surface and groundwater supplies but uses significantly less water when it is defoliated by the northern tamarisk beetle. Because the ability to account for the water conserved by tamarisk defoliation would be helpful to water managers, I attempted to measure the difference in evapotranspiration rates before and after defoliation using remote sensing. Estimations of annual groundwater evapotranspiration rates were made using remote-sensing data from the Landsat 5 satellite for the Virgin and Muddy River systems in Southern Nevada for the years of 2007 through 2011 at various points in the northern tamarisk beetle's diapause cycle. Comparisons were then made between the evapotranspiration rates of tamarisk groves that had or had not been defoliated to estimate the water total water saved. Results suggest that for the year 2011, the reduced transpiration rate of tamarisk due to defoliation saved an estimated 2,205 ac-ft of water.

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Introduction

Fresh water is an essential resource for both human life and many ecosystems. Modern agriculture requires the largest portion of our fresh water resources, but it must compete with the growing need of fresh water for industry and urbanized living. Because of the continued growth of the human population as a whole and the continued migration from rural to urban centers, there is a forever-increasing demand on our limited freshwater sources. Currently Nevada features a population growth higher than the average of the United States (U.S. Census, 2010), and is also the driest state in the nation, meaning the only sources of fresh water available for our growing populations are our groundwater sources.

Groundwater, which can come in the form of a river, lake, or underground aquifer, is in constant motion between recharge and discharge areas. The amount of recharge a groundwater source receives is subject to both seasonal patterns and long-term climatic trends, and should the amount of water discharged exceed the amount that is recharged, the groundwater resource can be depleted. Failing to maintain equilibrium in groundwater systems can cause land subsidence, as the water pressure that normally supports the land becomes reduced by the groundwater being mined.

The groundwater basin used by Las Vegas has been over-appropriated for almost 50 years (Las Vegas Valley Groundwater Management Program, 2013). Currently, Southern Nevada obtains 10 percent of its water from groundwater aquifers, and the other 90 percent from the Colorado River (Las Vegas Valley Water District, 2013). The Virgin and Muddy Rivers are major tributaries of the Colorado River, and thus impact the amount of amount of recharge going into the Colorado River system.

The Virgin and Muddy Rivers are of special significance because they feature both extensive riparian communities and endangered species along their banks. The dominant species of these riparian communities is *Tamarix ramosissima*, or tamarisk. Tamarisk is an invasive species from Eurasia that has outcompeted the natural riparian species of willow and cottonwood across the Southwestern United States.

In 2001, the USDA released *Diohabda carinulata*, the northern tamarisk beetle, as a biocontrol agent for limiting the spread of tamarisk (Deloach et al., 2006). The northern tamarisk beetle feeds on the foliage of tamarisk, to the point of complete defoliation to the host plant. Tamarisk is a phreatophyte, a deep-rooted plant that is capable of obtaining water from the groundwater table and capillary fringe, and consumes a large amount of groundwater. However, when tamarisk is defoliated, its rate of transpiration is severely reduced (Snyder et al., 2010), thereby freeing up water for the Colorado River system.

Because Southern Nevada is so limited in its water resources, it is necessary to account for every source of variation in surface and groundwater recharge. Accounting for the amount of water saved through the defoliation of these tamarisk communities in the Virgin and Muddy Rivers allows for policy makers and watershed managers to better account for the actual water available, with the possibility of drawing more water from the Colorado River System. The goal of my research is to estimate the amount of groundwater saved by the defoliation of the tamarisk in the Virgin and Muddy Rivers through remote sensing. Remote sensing is well suited to this task, as it involves obtaining the estimation of hydrological variables across a large-scale area. For my research, I used remote sensing to estimate groundwater evapotranspiration (ETg), which is the combined water loss from soil evaporation and plant transpiration from groundwater sources.

Literature Review

This project investigates the effects that tamarisk defoliation has on the groundwater evapotranspiration for the Virgin and Muddy Rivers. Tamarisk has existed in these areas for quite some time; however the beetle did not arrive to the study area until 2011. My research requires knowledge of remote sensing techniques and the physiology of both tamarisk and the northern tamarisk beetle. Therefore, it is necessary to review the previous studies done in these areas.

The Introduction and Success of Tamarisk

Tamarisk was introduced from Eurasia to the United States in the early 1820s to serve as a windbreak and ornamental shrub. The tamarisk soon escaped cultivation and began to invade the riparian communities of the Southwestern United States. Tamarisk has spread across to these communities with rapidity, growing from an estimated 360,000 hectares in 1965 (Robinson, 1965) to an estimated 600,000 hectares in 1987 (Brotherson and Field, 1987). Those estimations would indicate that over 10,000 hectares of natural riparian habitat is outcompeted and replaced by tamarisk each year. Both the Virgin and

Muddy Rivers feature extensive tamarisk populations that cover over 2,140 hectares of riparian habitat.

Tamarisk is a halophytic facultative phreatophyte, allowing it to tolerate saline soils and drought conditions. Tamarisk has a much higher tolerance for saline conditions than the native vegetation of cottonwoods and willows, and utilizes soil salinity as an allelopathic mechanism. A study by Su et al. (2012) found that tamarisk draws salt out of the groundwater and secretes the salt from its leaves. When the leaves are shed, this greatly increases the salinity of the topsoil, reducing the fertility of the soil near the tamarisk. In addition to this mechanism, tamarisk is also able to regrow and reestablish more readily than native riparian species following a fire, which have been occurring at increasing rates due to human activity (Busch, 1995).

Another factor contributing to the success of tamarisk in riparian communities is the extreme fecundity of the species. Tamarisk seeds are wind-dispersed, feature rapid maturation, and lack a dormancy requirement. In addition, a mature tamarisk can flower for the entirety of its growing season, allowing a single specimen to produce an estimated 500,000 seeds per year (Di Tomaso, 1998).

The Northern Tamarisk Beetle and Tamarisk Control

In 2001, the USDA-ARS released *Diohabda carinulata*, the northern tamarisk beetle, as a biocontrol agent for tamarisk. The beetle is a herbivorous specialist of tamarisk foliage, and lives its entire life cycle on tamarisk plants (DeLoach et al., 2006). After reproducing and eating during the summer, the beetle will enter diapause for the winter underneath the fallen tamarisk foliage. The beetle uses an aggregation pheromone to draw other beetles towards tamarisk plants, promoting the formation of beetle populations near food sources (Cosse, 2005). Tamarisk occurs in Eurasia as isolated specimens, not as expansive, concentrated populations. This change, in combination with the aggregation pheromone, causes the beetle to form stable populations that completely defoliate tamarisk populations year after year. Although the tamarisk will regrow during the period of beetle diapause (Bean et al., 2012), the loss of foliage during the longest days of the year is a severe setback to the plant.

Both the herbivory and oviposition of the northern tamarisk beetle have severely negative effects on the photosynthetic rates of tamarisk (Snyder et al., 2010). The reduction in photosynthetic rate also reduces the amount of water the tamarisk uses. In addition, the wounds from herbivory cause an accelerated rate of water loss in tamarisk tissues, causing desiccation and early leaf drop. The early onset of leaf senescence occurs so rapidly that tamarisk affected by northern tamarisk beetle herbivory are unable to retranslocate essential nutrients out of the leaves before they are dropped (Snyder et al., 2010). While tamarisk can quickly recover from a single defoliation event, repeated defoliations will cause the depletion of stored nutrients and eventual starvation of the plant (Snyder et al., 2012).

Because the leaf senescence of tamarisk can be detected through remote sensing, we can use remote sensing methods to obtain the difference in ETg rates between tamarisk that has been defoliated versus tamarisk that has not been defoliated. A study done by Meng et al. (2012) successfully used the Landsat 5 satellite to track beetle movement using disturbed vegetation indices (VIs), but the study did not take into account the impact the defoliation had on hydrologic zones.

Estimating Annual Evapotranspiration from a Single Mid-Summer Scene

A method for estimating annual actual evapotranspiration, ETa, from only remote sensing and weather data was published by Groeneveld et al. (2007). Beamer et al. (2013) refined this method, producing a specialized version for obtaining annual ETa and ETg estimations and groundwater discharge estimates from phreatophytic species in Nevada. In both studies, the correlation between the remote sensed VI and the measured annual ETa were very robust, with Groeneveld et al. reporting an R^2 value of 0.95, and Beamer et al. reporting an R^2 value of 0.97. Because my research involves the defoliation of phreatophytic species in Nevada, I use the method published by Beamer et al. to estimate the annual amount of groundwater conserved by defoliation. Furthermore, because both of these prior studies have shown mid-summer VI's to be such a robust indicator of annual ETa, we can safely assume our remote sensing data to be accurate estimations of annual ETg. The northern tamarisk beetle became established in the Virgin River system in 2011, but has not yet moved into the Muddy River. Thus, using the Beamer et al. (2013) method, I was able to compare the estimated annual rates of ETg for defoliated tamarisk groves in the Virgin River to the estimated annual rates of ETg for the healthy tamarisk groves in the Muddy River. This comparison allows me to approximate the amount of groundwater conserved by the reduced transpiration rate of the defoliated tamarisk in the Virgin River.

Methodology

The method put forth by Beamer et al. (2013) requires the annual total precipitation (PPT) and annual reference evapotranspiration (ETo) (Allen et al., 2005) for the study area. ETo is a function of solar radiation, temperature, humidity, and windspeed, and serves as a measure of the atmospheric demand for water. Annual ETo was calculated from an automated weather station located in Overton, Nevada at 36.588°N,-114.324°W.

Precipitation Data

Daily precipitation data for the study area was provided by a co-operative weather station located at 36.551°N,-114.458°W in Overton, Nevada. Instances of missing Overton precipitation data were filled in by data from a nearby co-operative weather station in Bunkerville, Nevada, and instances of missing data entries from both stations were filled in by a tipping bucket located in Overton.

Overall, there were 69 instances of Bunkerville data being used to fill missing points, and 71 instances of tipping bucket data being used to fill missing points. After the precipitation data was filled, the sum total precipitation for each water year was calculated.

Specifications of Remote Sensing Data

The remote sensing data used for this study was obtained from NASA’s Landsat 5 satellite. Landsat 5 features an Enhanced Thematic Mapper, and collects both visible and infrared spectra at a 30m resolution, with repeating coverage every 16 days. The study area for this research occurs at path 39, row 35 for the satellite (Figure 1).

Requirements of Scene Selection

The method used in this study requires a mid-summer Landsat image that is both free of clouds and doesn't have preceding precipitation events. A mid-summer image is used because mid-summer features peak tamarisk growth and vigor. Because the focus of this study is on evapotranspiration from groundwater sources, choosing a scene that hasn't had precipitation occur in the prior two weeks prevents non-phreatophytic vegetation from greatly impacting our estimation of enhanced vegetation indices. Three scenes were selected for each year from 2007 to 2011, using a scene that occurred around July 1st, then August 1st, and then finally September 1st (Table 1). These dates were chosen to account for the diapause cycles of the northern tamarisk beetle (DeLoach et al., 2006).

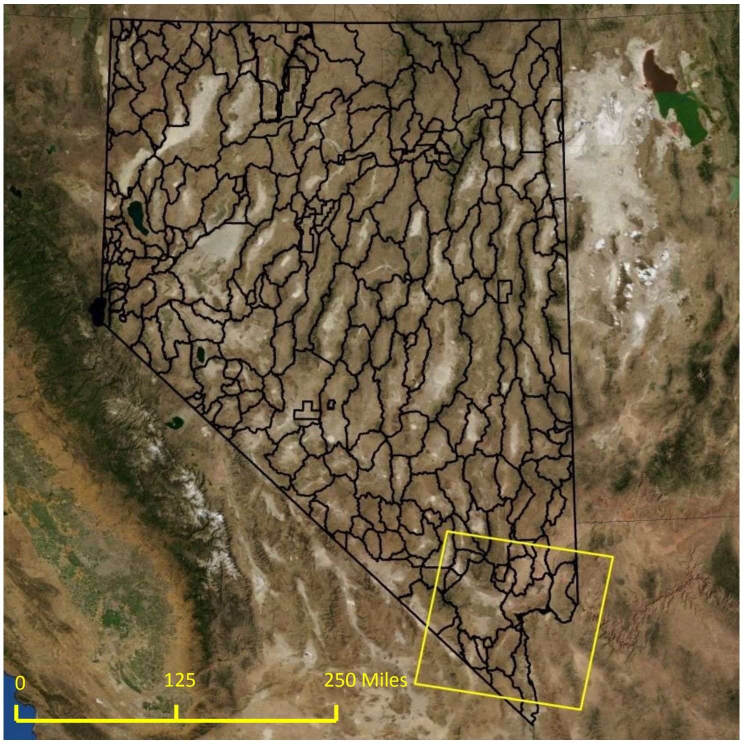

Figure 1. Location of the study area. The yellow box represents the area covered by the Landsat 5 scene at path 39, row 35. The black polygons represent the different hydrographic areas of Nevada.

Table 1. List of scenes used for each year for the study area and the point in the northern tamarisk beetle diapause cycle the scene occurs in.

Year	Exiting Diapause		Peak Activity		Entering Diapause	
	DOY	Date	DOY	Date	DOY	Date
2007	183	July 2nd	215	August 3rd	247	September 4th
2008	170	June 18th	234	August 21st	250	September 6th
2009	188	July 7th	220	August 8th	252	September 9th
2010	175	June 24th	223	August 11th	255	September 12th
2011	178	June 27th	226	August 14th	242	August 30th

Calculation of Enhanced Vegetation Index

The enhanced vegetation index (EVI) is a remote-sensed measurement of vegetation vigor that is calculated from the different bands of surface reflectance. The equation used for calculating EVI is as follows:

$$EVI = 2.5(\rho_{NIR} - \rho_{Red})/(\rho_{NIR} + 6\rho_{Red} + 7.5\rho_{Blue} + 1)$$

where ρ is the at-surface reflectance, NIR is the near-infrared waveband from 0.76 μm to 0.90 μm, Red is waveband from 0.63μm to 0.69μm, and Blue is the waveband from 0.45μm to 0.52μm**.** The red and near-infrared wavebands are representative of the health of surface vegetation, and the blue waveband compensates for any interference due to atmospheric conditions (Beamer et al., 2013).

Calculation of ET and ETg Values*

Once we obtain EVI values for our scene we then calculate ET*, or normalized annual evapotranspiration, for each pixel using the polynomial model equation:

$$ET^* = -0.196 + (2.904 * EVI) + (-1.592 * EVI^2)$$

where EVI is the enhanced vegetation index for each pixel (Beamer et al., 2013). From there, ET* is then used to estimate annual ET_g through the equation:

$$ET_g(annual\ estimated) = (ET_o - PPT)ET^*$$

where ET_o is the annual reference evapotranspiration and PPT is the annual precipitation (Beamer et al., 2013). These series of equations give us the estimated annual groundwater evapotranspiration rate for each pixel in the study area.

Selection of Polygons and Calculation of Water Saved

The estimations of annual ETg are then spatially averaged across the areas of known tamarisk stands (Figure 2). The comparison of the ETg rates between our control group of tamarisk in the Muddy River, which does not get defoliated, and the defoliated groups of tamarisk in the Virgin River (Figure 3), allows us to determine the amount of water not consumed due to reduced tamarisk transpiration from defoliation.

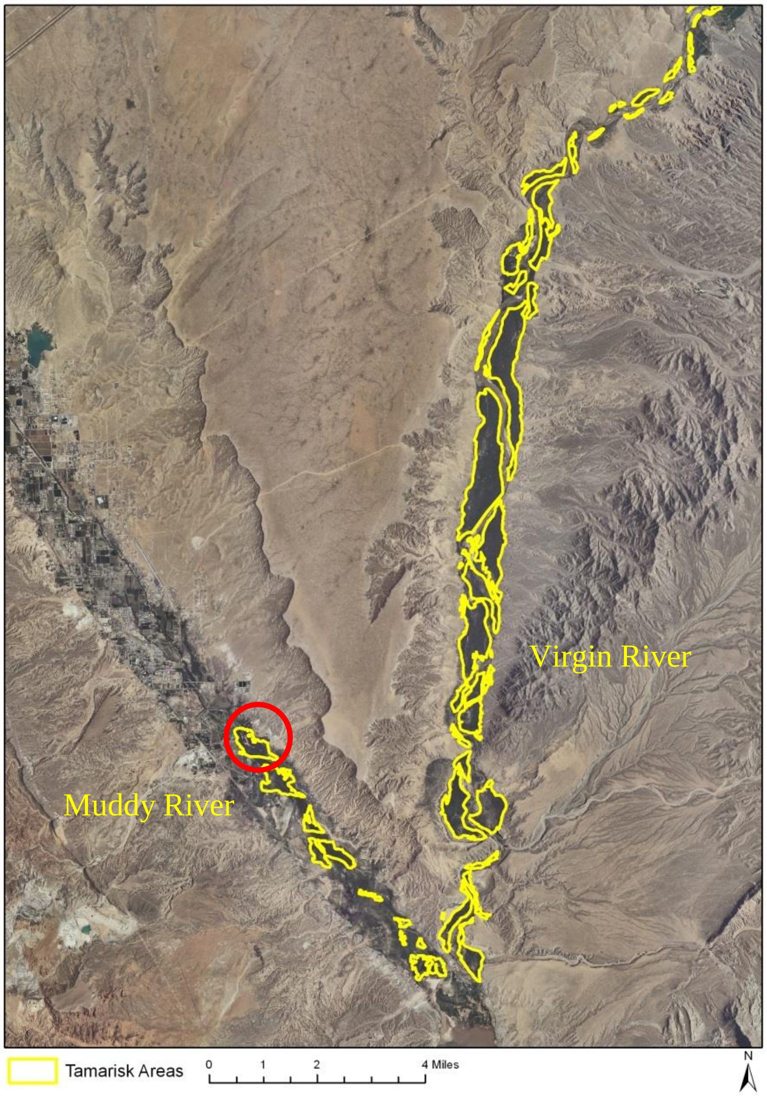

Figure 2. Study area with superimposed tamarisk polygons. Each yellow polygon is representative of an uninterrupted group of tamarisk. The polygon circled in red is the tamarisk population that was used as the un-defoliated control group.

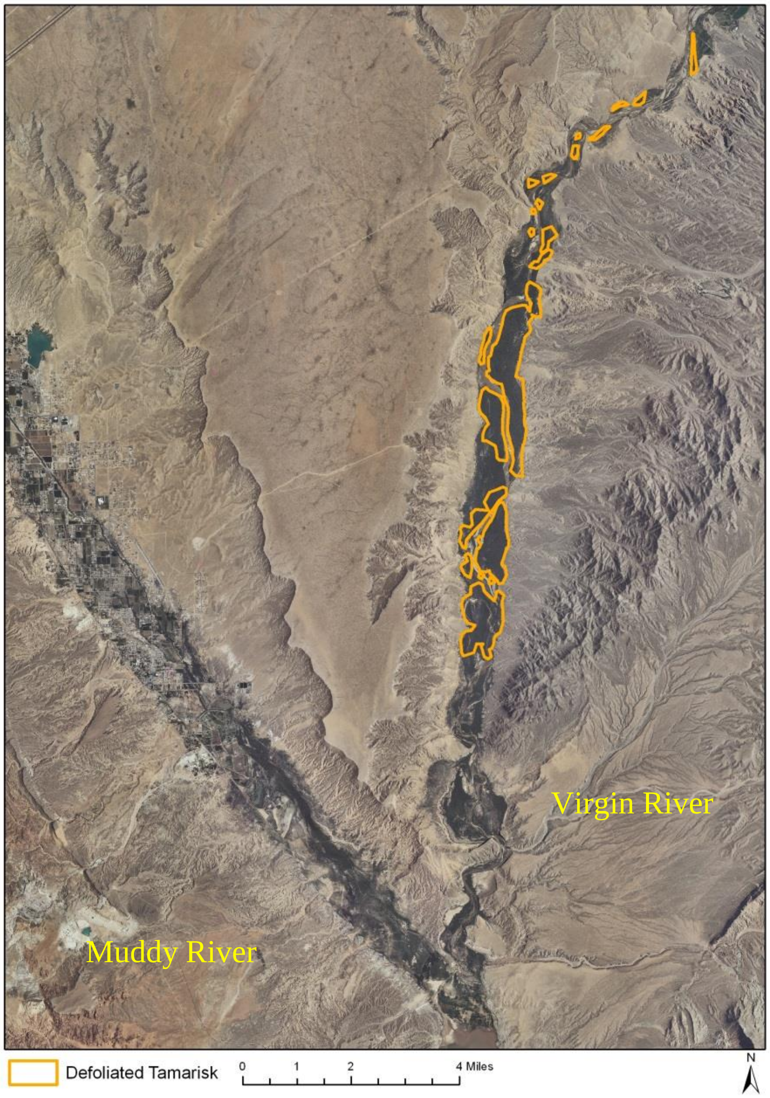

Figure 3. Study area with superimposed defoliated polygons. The polygons represented in this figure refer to groups of tamarisk that are defoliated by the northern tamarisk beetle.

Results

Using the Beamer et al. method and mid-summer Landsat 5 scenes, I was able to estimate annual groundwater evapotranspiration for the tamarisk populations of the Virgin and Muddy Rivers and how the rate of evapotranspiration changes in response to tamarisk defoliation (Table 2). As is expected, in the summer of 2011 the established beetle population defoliated the tamarisk found in the Virgin River (Figure 4B) but not in the Muddy River (Figure 4A). As can be seen in the graph, the annual estimated rate of ETg for 2011 reaches its lowest point at the time of peak beetle activity and begins to recover as the beetles enter diapause.

The estimated amount of water saved from tamarisk defoliation in 2011 is displayed in Table 3. The rates of ETg for this calculation were obtained by averaging the three annual ETg estimates for the year 2011.

Table 2. Annual ETg (mm/yr) estimates for both the control group and defoliated groups of tamarisk each year.

Year	**Exiting Diapause**			**Peak Activity**			**Entering Diapause**		
	Defoliated Etg	Control Etg	**Ratio**	Defoliated Etg	Control Etg	**Ratio**	Defoliated Etg	Control Etg	**Ratio**
2007	1025.33	963.60	**1.06**	937.24	932.13	**1.01**	998.22	983.92	**1.01**
2008	1049.56	902.45	**1.16**	1037.74	942.21	**1.10**	1027.86	936.01	**1.10**
2009	836.70	827.01	**1.01**	901.93	801.41	**1.13**	983.71	854.11	**1.15**
2010	951.47	846.43	**1.12**	953.20	886.18	**1.08**	968.93	798.33	**1.21**
2011	855.03	842.41	**1.01**	376.08	808.39	**0.47**	405.58	756.91	**0.54**

Table 3. Estimated amount of water saved by tamarisk defoliation.

	ETg (ft/yr)
Muddy River (Control Group)	2.6
Virgin River (Defoliated)	1.8
Difference	0.8
Acrage of Defoliated Tamarisk:	2,616
Total Water Saved by Defoliation (ac-ft):	**2,205**

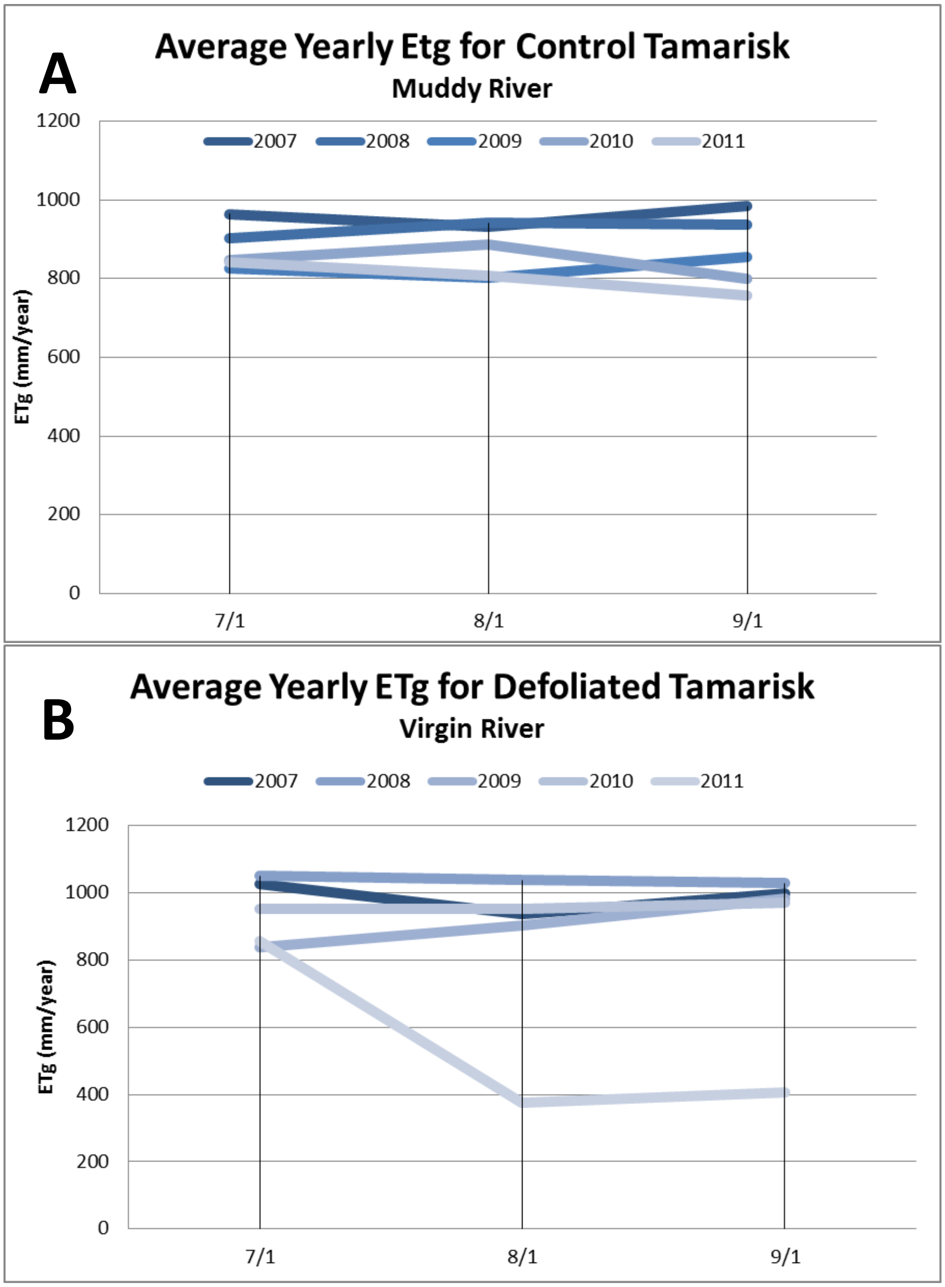

Figure 4. Effect of defoliation on tamarisk ETg rates. A) Annual ETg estimates for the control group for each year. B) Annual ETg estimates for defoliated tamarisk for each year. The three periods sampled are the expected timing of the beetle exiting diapause, reaching peak activity, and then entering diapause again.

Discussion

The data obtained from remote sensing was able to reflect the change in transpiration rate that occurs with tamarisk defoliation. The defoliation by the tamarisk beetle saved an estimated 2,205 ac-ft of water, which then flows into Lake Mead. The knowledge of the existence of this formerly unaccounted water will allow water managers to make better decisions regarding available water resources.

Sources of Error

The goal of this study was to provide estimations of the amount of water conserved by tamarisk defoliation. Due to the nature of remote sensing, it is impossible to obtain perfect calculations, as there are sources of variation in ET rates that aren't reflected in changes to EVI. That being said, it is still important to look at how these estimations can be improved:

The estimations performed in this study compare the remote sensed ETg rates of defoliated tamarisk in the Virgin River to ET rates of tamarisk in the Muddy River. The calculations are made with the assumption that non-beetle conditions in the Virgin and Muddy Rivers are, due to their close proximity, the same. The assumption that the Virgin and Muddy Rivers have the same conditions is proven wrong by Table 2: Before 2011, before the northern tamarisk beetle established itself in the Virgin River, every ratio of estimated annual ETg for the Virgin and Muddy Rivers resulted in a value greater than 1, meaning the tamarisk in the Virgin River were experiencing some condition that caused them to transpire more than their Muddy River counterparts. That being said, because the

Virgin River went from higher rates of ETg than our control group to significantly lower ETg rates in 2011, the estimation of water saved made here is conservative.

In regards to the precipitation data, filling in missing weather station data with data from another close station, is a common practice and doesn't introduce any systematic errors. However this study also had to rely on precipitation data from a tipping bucket. Due to how the tipping bucket functions, the tipping bucket consistently undermeasures the amount of precipitation that actually occurred, which introduces a systematic error into our estimations. By using a small number of tipping bucket data points, 71, compared to the total number of precipitation data, 2750, we minimize the effect of this error.

Finally, the calculation of yearly water saved by defoliation (Table 3) does not fully take into account the regrowth of tamarisk that occurs after the northern tamarisk beetle enters diapause. As seen in Figure 4B, the ETg rate of defoliated tamarisk does begin to climb back up after beetle activity stops. A more accurate estimation of water saved would account for the differences in ETg rate across the entire year, not just the differences over the summer. However, the method used in this study is calibrated to work on mid-summer scenes (Beamer et al., 2013), and if I used the method on colder scenes I would introduce error into the ETg calculations.

Limitations on Available Data

The methods used in this study require the total precipitation for a full water year, so this method cannot be run on Landsat scenes from the current year. In addition, because the scene used had to be free of clouds and not have preceding precipitation events, not all of the scenes used for each year occurred at the same time. In addition, after 2011, the Thematic Mapper on the Landsat 5 Satellite ceased function, so we did not have access to Landsat 5 data for the year 2012.

Future Directions

The conclusions reached by this study on the impacts of tamarisk defoliation on groundwater reserves are somewhat incomplete. The only estimation obtained for defoliation was for the year of 2011, which is when the northern tamarisk beetle population was established, but before it reached equilibrium with the tamarisk population. Reaching that equilibrium takes multiple years and continuing observation through this method on future years would bring more accurate conclusions.

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