MODELING THE HYDROLOGIC IMPACT OF *ARUNDO DONAX* ON THE

HEADWATERS OF THE NUECES RIVER USING THE SWAT MODEL

A Thesis

by

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ABSTRACT

The invasive species *Arundo donax* (hereafter *Arundo*), has invaded the riparian zones of the Rio Grande River and the rivers of the Texas Hill Country over the last two decades. *Arundo,* also known as the giant cane, is a robust herbaceous plant that can grow in many different climatic conditions. *Arundo* was first observed along the Nueces River in 1994 by the Nueces River Authority (NRA). It then spread rapidly downstream due to its high growth rate and/or stream flow and completely displaced the native vegetation, primarily *P. virgatum* (hereafter switchgrass), in the riparian zone wherever it got established. An eradication program was started in 2010 by the NRA to remove *Arundo* from the Nueces River. The objective of this research project was to (1) develop an algorithm to simulate the propagation of *Arundo,* (2) study changes in streamflow patterns during pre- and post- *Arundo* invasion periods, (3) calibrate and validate the Soil Water Assessment Tool (SWAT) for the Nueces River Headwater (HUC 12110101) watershed in central Texas, and (4) assess the effects of the invasion of *Arundo* on the watershed hydrology by comparing it to the native grass species switchgrass (*Panicum virgatum*) that used to be the dominant species in the watershed. *Arundo* parameters appropriate for the Nueces River were added to create a new crop category in the SWAT database. Calibration and validation of SWAT were based on measured streamflow data available at the USGS gage (USGS 08910000) on the Nueces River for the period 1960 to 1994.

Switchgrass, the native vegetation, was chosen as the plant to compare *Arundo* with so that the difference in hydrology could be understood. The results revealed that accumulated evapotranspiration was not statistically different between *Arundo* and switchgrass for the period of 16 years (1995-2010). There was also no difference in the water yields of *Arundo* and switchgrass. In conclusion it appears that *Arundo* in the Nueces River has not caused any changes in water uptake compared to the native grass, switchgrass, that previously dominated the headwaters.

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NOMENCLATURE

ALMANAC	Agricultural Land Management Alternative with Numerical Assessment Criteria
ET	Evapotranspiration
HRU	Hydrologic Response Unit
HUC	Hydrologic Unit Code
NRA	Nueces River Authority
PHU	Potential Heat Units
STATSGO	State Soil Survey Geographic Data
SWAT	Soil Water Assessment Tool
USDA- ARS	United States Department of Agriculture – Agricultural Research Service

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CHAPTER I

INTRODUCTION

I.1 Need for study

Invasive species "means a species that is not native to an ecosystem and whose introduction to the ecosystem causes or is likely to cause economic harm, environmental harm, or harm to human health. Humans, domestic livestock, and non-harmful exotic organisms are not invasive species"(Swinford and Hegar, 2009). Invasive woody species have been widely studied to understand their impact on the water cycle and how they must be managed (Ansley et al., 1995; Walker and Smith, 1997; Wilcox, 2002; Watts, 2009). In Texas, the species most widely studied have been woody plants Juniperus spp., mesquite (Prosopis glandulosa) and Tamarix spp. as these have invaded large proportions of the rangeland in the state. Saleh et al. (2009) used the eddy covariance technique and found a significant difference in water uptake between a plot with mesquite as against one that had been brush managed. Nagler et al. (2008) found Tamarix in the Rio Grande region to not have any difference in transpiration over the native plants. Afinowicz et al. (2005) found a significant difference in the evapotranspiration of brush in the Guadalupe region in areas with a high density of brush. Wilcox and Thurow (2006) have written about the need to study species on a watershed level so that they can be understood as an ecosystem as against looking at the species in isolation.

Non-woody invasive species such as grasses which alter the ecology have been called ‘transformer species’ (Pyšek et al., 2004) and have been known to alter ecosystems (Milton, 2004) by way of increasing/ decreasing fires, using resources such as light and water excessively, sand stabilizing, erosion pattern changing etc. However, very little work has been done in studying the relationship between invasive non-woody species and the water cycle (Watts, 2009). *Arundo* is one such species that has been termed 'transformer' by Richardson et al. (2005) in California and is known to adversely affect both the biodiversity by way of changing vegetation structure and jeopardizing bird and wildlife habitat that mainly feed on insects in California (Herrera and Dudley, 2003) and ecosystem (Quinn and Holt, 2008) by way of high competitive advantage over a large range of native species of the region it invades. This study looks at the effect of the transformer species *Arundo* on the hydrological cycle in a watershed.

I.2 *Arundo*

Arundo, also known as the giant cane, shown in Figure 1 was brought into California from the Mediterranean in the 1820s (Perdue, 1958) and has invaded the riparian zones of the Rio Grande River and the rivers of the Texas Hill Country. It was originally brought to the U.S. make thatched roofs, musical instruments and prevent soil erosion (Perdue, 1958). The species has been cultivated in Asia, Europe, North Africa and the Middle East (Bell, 1997).

Arundo is a hydrophyte (McGaugh et al., 2006) which has been known to absorb up to 1,100 mm of water annually (Bell, 1997). Gowda et al. (2011) have found the water demand of the species to be 5.2 mm/ day in the Rio Grande Basin in Texas while Watt and Moore (2011) found the demand to be as high as 9.1 mm/day in the lower Rio Grande region in Texas and Giessow et al., (2011) found it to be 41.1 mm/day in

Southern California. Leaf Area Index (LAI) for the species has been known to range from an average of 15.6 in a study by the California Invasive Plants Council (Giessow et al., 2011) to 4.5 in a study done by Watts and Moore (2011) on the lower Rio Grande River in texas. It has a growth rate of up to 5cm/ day under optimum conditions (Perdue, 1958).

Arundo is a robust plant that can grow in many different climatic conditions. Because of its high growth rate and vegetative reproduction, it invades newer areas and takes over the native species in the region (Benton et al. 2005). It forms colonies in the process that can be several acres in size and its rhizomatous root masses stabilize stream banks and alter flow regimes (Zahran and Willis, 1992). It is mainly known to propagate through flooding (Giessow et al., 2011) but other causes could include forest fires, wind and human movement of soil from one place to another. Dudley (2000) documents millions of dollars being spent on *Arundo* management and eradication which is being done using chemicals (Bell, 1997) and biological controls (Goolsby et al., 2007).

I.3 *Arundo* on the Nueces River

Arundo was first observed along the Nueces River in 1995 by the Nueces River Authority (NRA). It then spread rapidly downstream and completely displaced the native vegetation, primarily switchgrass, in the riparian zone wherever it got established. Its density was in the order of 760,000 stalks in a 3.52km2 area. An eradication program was started in 2010 by the NRA to remove this species from the Nueces River. They used chemicals such as plant amino acid blocker Imazapyr using both aerial spray and ground-level spraying techniques. Figure 2 shows a colony of *Arundo* after it was sprayed. The NRA also has a program called the "Pull, Kill, Plant" to make the residents of the region aware of *Arundo* and teach them what is to be done when they find the species. The motivation of this study was to model the impact of the invasion of *Arundo* on the hydrology of the headwaters of the Nueces River to provide a scientific backbone to the management projects being undertaken for its control and for ecological risk management.

Figure 1. *Arundo* (Ventura County Weed Management Area, 2011)

Figure 2. A colony of *Arundo* treated using Imazapyr by the Nueces River Authority in 2012

I.4 Objectives

While the overall goal of this research is to understand the effects of the invasion of *Arundo* on the hydrology of the headwaters of the Nueces River, the specific objectives and contribution of this study are:

1: develop an algorithm to simulate the propagation of *Arundo*

2: study changes in streamflow patterns during pre- and post- *Arundo* invasion periods (i.e., before and after 1994)

3: calibrate and validate SWAT for the Nueces River Headwater watershed in central Texas

4: assess the effects of the invasion of *Arundo* on the watershed hydrology when comparing it to the native grass species switchgrass that used to be the dominant species in the watershed.

The methodology followed is that a streamflow trend analysis is done for the study area following which an algorithm has been developed for the propagation of *Arundo* which is a geographical information systems analysis. The SWAT model then has been calibrated for the watershed, *Arundo* parameters have been added to the crop database of SWAT and finally its impacts on the hydrology of the watershed have been analyzed. This has been described in detail in the chapters that follow.

CHAPTER II

STREAMFLOW ANALYSIS

II.1 Introduction

The objective of this chapter is to assess if there are any changes in streamflow patterns during pre- and post-*Arundo* invasion periods (before and after 1995). Changes in streamflow patterns are an indicator of changes in the hydrology of a watershed. There are two ways of studying eco hydrology impacts: finding the effect of landuse change on hydrology or the effect of hydrology on landuse change. While this thesis explores the former question, this chapter looks at how hydrology has changed over time in the watershed based on precipitation and streamflow trends. Landuse and climate have been hypothesized to be two important factors that cause changes in streamflow on many occasions (Stohlgren et al., 2003; Zhang and Schilling, 2006;Changnon and Demissie, 1994). Wilcox and Huang (2010) looked at various watersheds, including the one in this study, in the Hill Country region in Texas to find that streamflow and baseflow followed an increasing trend over time when looking at the period 1925-2010. They suggested that the reason for this was that invading brush had helped the rangeland that had been degraded by overgrazing in the 1950s. The invasive species opened up the dry soil to encourage infiltration, thereby increasing baseflow which further increased streamflow. The motivation to study the streamflow patterns in this watershed is to verify if the invasion of the *Arundo* can be considered a causal factor for any trends observed.

II.2 Description of study area

The area chosen for this study is the watershed of the Nueces Headwaters (HUC 12110101) (U. S. Department of Interior, 2013). The counties that are included in this watershed are Edwards, Real, Uvalde and Kinney. This watershed, which is located in the “Hill Country” in Texas, lies just north of the Edward’s aquifer recharge zone, which is a karst region. It covers an area of about 2126 km^2. The outlet of the watershed is at the Laguna gage (USGS 08190000). The daily streamflow data is available for this gage from 1923 to 2013. The temperature in the watershed ranges from a maximum of 43° C during the months of August and September to -15°C in the months between December and February. The average annual rainfall over the period from 1950 to 2010 is 69 cm. The major land-use in this region is rangeland covered by brush (55%) according to the 2006 National Land Cover Dataset (NLCD). Although the Edward’s aquifer recharge zone is to the south of the area of study, the watershed area is still extremely karst and one can observe water disappearing into the ground and coming out of the stream through springs in various stretches of the river (Banta et al., 2012). The river is also geomorphologically complex in that it changes its course rapidly and underlying processes are not well understood. Figure 3 shows the location of the study watershed in Texas. An area of 3.52 km^2 in the riparian areas of an 8 km stretch of the Nueces River north of the Laguna gage in the watershed has been densely populated by *Arundo* (Figure 4).

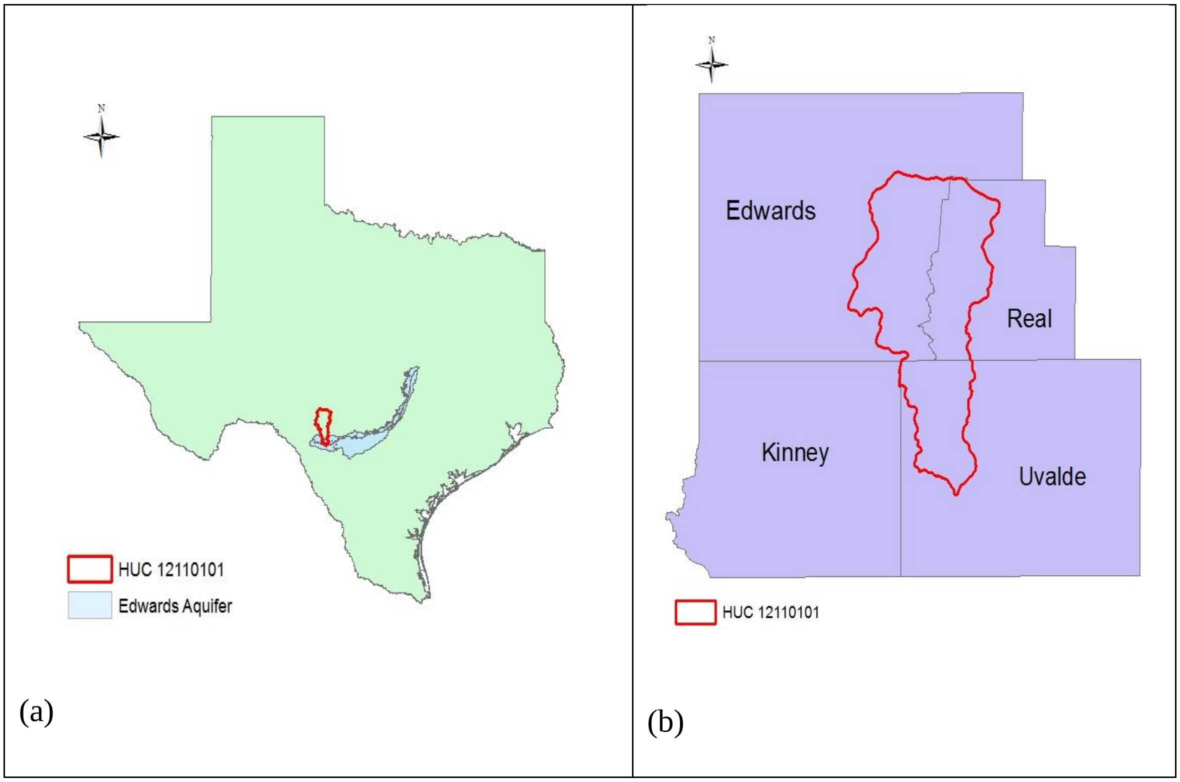


Figure 3.(a) Location of Nueces Headwaters Watershed (HUC 12110101) in Texas towards the north of the Edwards Aquifer, and (b) the boundary of HUC 12110101 with the counties

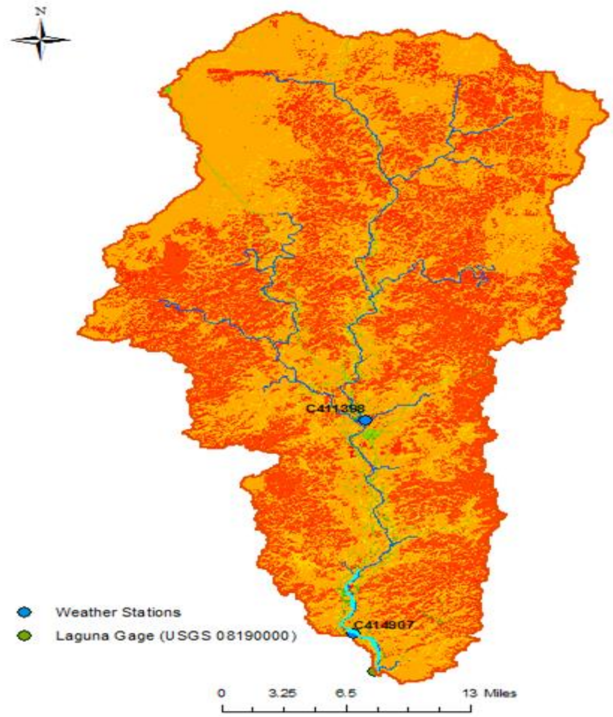


Figure 4. The small bright blue line near the watershed outlet was the area (3.52 km^2) covered by *Arundo*.

II.3 Approach

II.3.1 Hydrograph separation to estimate baseflow component

Streamflow consists of baseflow and stormflow. Baseflow is the groundwater contribution to the streamflow which occurs even when there is no precipitation, while the main cause for stormflow is runoff during flood events. The hydrograph is separated into baseflow and other components by using one of the following three commonly used techniques (Brodie and Hostetler, 2005):

1. Manual Separation of hydrograph- In this technique, the baseflow is separated from a streamflow graph manually based on where the baseflow comes in contact with stormflow. For this, all flow is assumed to be baseflow until a flood event occurs.

2. Regression Analysis- The regression analysis focuses on the recession curve of the hydrograph and identifies patterns in periods of antecedent recession. These patterns are then used to separate the baseflow from the stormflow. Computer models such as USGS RECESS (Rutledge, 1998) and USGS PART (Rutledge, 1998) can be used in conjunction for this analysis. While RECESS develops a master recession curve, PART uses this curve to separate baseflow and stormflow.

3. Digital Filters- Digital filtering uses the method of frequency analysis to separate out low frequency signals as baseflow from a streamflow graph. There are two kinds of filters- recursive and non-recursive. While the output of a non-recursive filter is the weighted sum of a portion of the input data, recursive filters serve like feedback filters where the output of one filter goes back into another filter. Sponberg (2000) reported that the recursive filters are more efficient than the non-recursive ones.

The manual separation technique is highly subjective and Arnold et al. (1995) argue that computer based programs should be used for baseflow separation in order to get consistency. Recession analysis was not considered appropriate for this study in view of the karst nature of the underlying aquifer. Although the Recession analysis works well for areas such as Harris catchment in Southwest Australia (Wittenberg and Sivapalan, 1999), in a karst aquifer, which is characterized by sink holes, caves, underground drainage systems, springs and sinking streams, surface water moves very quickly into the subsoil and hence the normal pattern of hydrograph recession doesn't appear. The filter separation, which is a commonly used technique, comes from the field of signal processing and normally has no basis in hydrology. The Baseflow Filter Program developed by Arnold et al.(1999) and the Web GIS Based Hydrography Analysis Tool (WHAT) developed by Lim et al. (2005) are two commonly used programs to carry out the baseflow separation through recursive filtering. Another filtering technique is the USGS HYSEP (Sloto and Crouse, 1996). Of these, the WHAT program is the most user friendly and it has been tested against HYSEP and the Baseflow Filter Program. The results of all three techniques have been found to be very close (Lim et al., 2005). Out of the above options of baseflow separation, considering high variability in flow in the watershed and due to a lack of availability of better techniques to handle karst streamflows, the digital filtering technique was chosen for baseflow separation in this study. The digital filtering technique was previously used by Wilcox (2009) for the analysis of streamflow trends in some karst watersheds in Texas including Nueces, Llano, Frio and Guadalupe watersheds where an increase in streamflow and baseflow trends was found over the time. The WHAT program was selected for baseflow separation in this study.

II.3.2 Trend analysis

Trend analysis can be done in five ways using parametric, non-parametric or mixed tests (Helsel and Hirsch, 2002) combined with the verification of the presence of any associate variables. As streamflow does not come from any known probability distribution function and since it is a random phenomenon (Helsel and Hirsch, 2002), trend analysis of streamflow needs to use a non-parametric test. The Mann-Kendall test that assumes no distribution, is robust against outliers and has a high power for non-normally distributed data (Onoz and Bayazit, 2003). This test is used to check the statistical trend in data with respect to time (Helsel and Hirsch, 2002).This test has been used in various streamflow trend analysis studies (Kumar et al., 2009; Wilcox et al., 2008). The data for this test needs to be independent of serial correlation. Positive serial correlation tends to overestimate the significance of the trend while negative serial correlation underestimates it (Yue et al., 2002). To test for autocorrelation, the Durbin Watson test can be used which looks at each pair of consecutive elements in the dataset to test for correlation (Durbin and Watson, 1971). If there is autocorrelation, it can be removed using the Cochrane Orcutt procedure(Cochrane and Orcutt, 1949) which has been used to remove first order correlation in streamflow, baseflow and climate datasets in various studies (Lettenmaier, 1994; Wilcox, 2008).

II.4 Methodology

Daily streamflow data for the Laguna gage (USGS 08190000) for the period from 1979 to 2010 was obtained from the USGS website (USGS, 2014). The WHAT program was used to separate daily, monthly and annual estimates of baseflow from streamflow. The daily baseflow, streamflow and precipitation were converted to incremental percentiles annually for further analysis (Wilcox, 2008). The data was tested for normality. The null hypothesis that the data is normal was rejected for both baseflow and streamflow with p values of <.0001. Once confirmed that the data was non- normal, it was tested for serial correlation using the Durbin Watson test. If the Durbin Watson test gave a p-value less than 0.5, it implied that there was autocorrelation of the first degree which was removed by the Cochrane Orcutt procedure. No significant correlation was found for either streamflow or baseflow data. Finally, the non-parametric Kendall's tau statistic was used to analyze the values for both baseflow and streamflow. If the Kendall's tau statistic had a significant p-value, it implies there is a high probability of the presence of a trend in the data. The statistic for the measure of this trend is the Sen's slope. The Sen's slope is calculated as the median between each pair of data points. A positive Sen's slope implies a positive trend while a negative Sen's slope implies a negative trend.

II.5 Results and discussion

The null hypothesis for the Mann-Kendall test is that there is no change in the trend implying that the baseflow, streamflow and precipitation have neither decreased nor increased over time. This hypothesis was tested to verify if it could be rejected based on a significance value of 0.1. Table 1 shows the values of Sen's slope and significance values for stream flow, baseflow and precipitation over a monthly time step. Figure 5 shows the graphs of streamflow, baseflow and precipitation over a monthly time step for the two periods- 1979- 1994 and 1995- 2010. Table 2 shows the values of the Kendall's tau statistic for the annual incremental baseflow and streamflow values. The statistic could not be found for incremental percentiles of precipitation as the values for precipitation were 0 up to the 70^{th} percentile. Table 3 shows the values of Kendall's tau for annual averages for baseflow, streamflow and precipitation.

Table 1. Monthly Sen's Slope statistic and p- value for streamflow, baseflow and precipitation for *Arundo* pre-invasion (1979-1994) and post-invasion (1995- 2010) time periods.

	1979-1994	1995-2010
Streamflow		
Sen's slope	0.16334	-0.2158
p-value	0.046661	0.029053
Baseflow		
Sen's slope	0.113477	-0.39251
p-value	0.071406	6.01E-07
Precipitation		
Sen's slope	-0.00998	0.059955
p-value	0.811771	0.183846

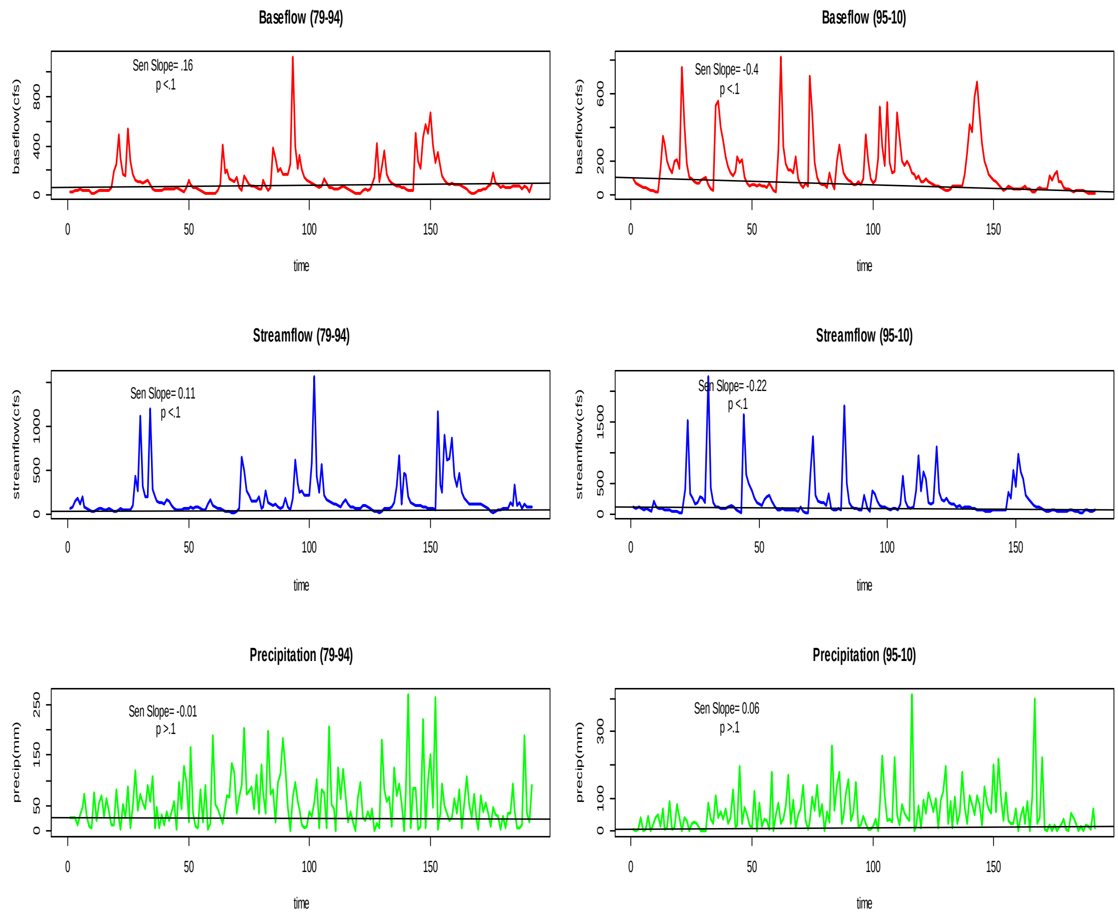


Figure 5. Trends for baseflow, streamflow and precipitation for the two periods 1979-1994 and 1995-2010.

Table 2. Daily percentile Kendall's tau statistic and p- value for streamflow and baseflow for *Arundo* pre-invasion (1979-1994) and post-invasion (1995- 2010) time periods.

	Streamflow (1995-2010)		Streamflow (1995-2010)	
percentile	Kendall's tau	p-value	Kendall's tau	p-value
10	1.045455	0.278435	-5.56E-02	0.928033
20	1.733333	0.392314	-8.85E-01	0.685329
30	1.675	0.392314	-1.23E+00	0.588633
40	1.2875	0.52807	-1.94E+00	0.52807

Table 2. continued.

	Streamflow (1995-2010)		Streamflow (1995-2010)	
percentile	Kendall's tau	p-value	Kendall's tau	p-value
50	1	0.821892	-8.71E-01	0.684723
60	1.468376	0.752642	-1.49E+00	0.752642
70	1.922222	0.588633	-1.67E+00	0.892558
80	3.342857	0.52807	-6.54E+00	0.344418
90	5.094444	0.499461	-8.56E+00	0.392314
100	43.833333	0.620425	-1.27E+03	0.010279
	Baseflow (1979-1994)		Baseflow (1995-2010)	
	Kendall's tau	p-value	Kendall's tau	p-value
10	0.821375	0.224134	-0.1075524	0.964089
20	1.469683	0.260351	-0.8385833	0.685329
30	1.435083	0.558351	-1.065	0.558351
40	1.015545	0.444044	-1.5906667	0.444044
50	1.034222	0.821892	-0.9228333	0.620425
60	1.26579	0.620425	-1.289035	0.821892
70	1.3486	0.558351	-0.7596923	0.821892
80	2.914951	0.499461	-5.1977143	0.344418
90	3.7144	0.620425	-10.242191	0.344418
100	2.903846	0.752642	-165.795	0.006026

Table 3. Annual Kendall's tau statistic and p- value for streamflow, baseflow and precipitation for *Arundo* pre-invasion (1979-1994) and post-invasion (1995- 2010) time periods.

	1979-1994		1995-2010	
Streamflow				
	Kendall tau	p-value	Kendall tau	p-value
Mean	0.183	0.34442	-0.333	0.07910
Baseflow				
	Kendall tau	p-value	Kendall tau	p-value
Mean	0.0251	0.92818	-0.25	0.19167
Precipitation				
	Kendall tau	p-value	Kendall tau	p-value
Sum	0.05	0.82189	-0.133	0.49946

The annual and daily incremental percentile values showed no trends with any significance for baseflow, streamflow and precipitation because the number of sample points was only 16 for each dataset which is not a large enough dataset to get a reliable result. For monthly values on the other hand, there were 192 points in each dataset and it was found that while there was no significant trend in precipitation, there was a positive trend found in streamflow and baseflow for the period 1979-1994 and a negative trend for the period 1995-2010. The null hypothesis of no trend in flow could be rejected at a significance value of 0.1. The changing of the Sen value from 0.1633 to -0.215 for streamflow and 0.113 to -.39 implies a significant change in trends.

The limitations of all the above methods include the inability to take into consideration spatial distribution of subsurface flow and precipitation. They all assume a sheet flow scenario and the region in the Nueces headwaters is karst. Hence flow is variable. Due to lack of methods available to deal with karst regions, the available software had to be used to separate the hydrograph. Another limitation was a lack of availability of enough precipitation data for such a large watershed. There were only two weather stations in the watershed that had complete precipitation records for the study period. When the rainfall distribution (from two weather stations) in the watershed was plotted against the streamflow, some hydrograph peaks and rainfall events didn't match indicating that the available precipitation data was not representative for the watershed.

II.6 Conclusions

There was a positive trend in streamflow and baseflow for the pre-invasion of *Arundo* period while there was a negative trend in the same in the post-invasion period. Since there was no significant change in precipitation trends during the pre- and post-invasion periods, *Arundo* invasion appears to have reduced streamflow and baseflow in the study watershed. However, this needs to be further tested using more robust statistical techniques that are suitable for karst aquifers. In addition, hydrologic models such as the Soil and Water Assessment Tool (SWAT) could provide more insights into hydrological processes occurring in the watershed and enable us to better understand the effects of *Arundo* invasion on hydrology. The SWAT model application for the study watershed is described in subsequent chapters.

CHAPTER III

ARUNDO PROPAGATION

III.1 Introduction

In the previous chapter, it was discussed about how streamflow and baseflow in the watershed have changed over time. It was hypothesized that the invasion of *Arundo* might be the cause of the observed changes in streamflow and baseflow trends. As part of studying the invasion of *Arundo,* its propagation has been modeled in this chapter.

The propagation of an invasive species is a complex phenomenon that requires modeling to take into account space and time (Dragic´evic, 2010). Movement of seeds through wind dispersal (Horn et al., 2012; Greene and Johnson, 1989) and by humans (Wichmann et at.,2008) has been modeled but no known dispersal models have been validated with independent datasets (Pitt et al, 2011). Processes governing dispersal of seeds through water have been studied by Merritt and Wohl (2002) but these have not been modeled to simulate propagation of a species. Cellular-automaton is a frequently used technique to model species propagation. This technique relies on a set of rules where whether a species is born or dies in a particular cell is dependent on the state of its surrounding cells. It has been used to model rhizominous species (Pirchio, 2007) such as *Thalassia testudinum* and monotypic species such as *Changium Smyrnioides*(Xu et al., 2011). The downside of cellular automaton is that the complexity of natural phenomenon cannot be modeled using a universal set of simple rules (Rohde, 2005). While there has been a lot of work done on ecological modeling, there is little information available about the propagation of an invasive species such as the *Arundo* that propagates in the riparian region mainly through floods.

Arundo invaded the riparian zone of the Nueces headwaters in central Texas rapidly between the years 1995 and 2010. Very little is known about how this species propagates over space and time. In order to understand the hydrologic effects of this species, it was necessary to model propagation of this species with time. A California Invasive Plant Council Report (Giessow et al., 2011) suggested that one of the ways *Arundo* spreads is through flood events. The growth of *Arundo* is rhizominous and the nodes falling on the ground can become responsible for the start of new colonies. On close examination in the study area, it is found that *Arundo* is also present in water and hence the carrier of the nodes appears to be water. Other means of *Arundo* propagation could include i) movement of nodes by wind, ii) movement of nodes by human factors such as digging of mud from one region and its placement in an another location, and iii) falling of nodes on the ground due to fires and their development into colonies. Keeping the above information in mind, the propagation of *Arundo* was modeled in a GIS system using a combination of Python (Guzdial and Ericson, 2009), R (Hornik, 2014) and the Geospatial Modeling Environment (Hawthorne, 2012).

Arundo propagation was modeled based on the following two assumptions:

1. *Arundo* propagates downstream due to flooding events. This was corroborated by the fact that all the colonies of *Arundo* were in the downstream of the first plant observed by the Nueces River Authority in 1995.

2. Propagation of *Arundo* colonies follows an exponential growth pattern.

This assumption was based on the data (*Arundo* swaths and number of stalks) available from the measurements made by the Nueces River Authority.

III.2 Methodology

Data relating to number of stalks and diameter of *Arundo* colony are reproduced in Table 4, were obtained from the Nueces River Authority. A set of 36 data points was used to find the correlation between the diameter of a colony and the number of stalks (Figure 6). The curve was tested for a polynomial and linear fit but an exponential curve was found to be the best-fit curve for this data with R^2= 0.8381. Hence the assumption that growth of *Arundo* colonies proceeds exponentially was valid.

Table 4. Data showing diameter of colonies versus the number of stalks which was obtained from the Nueces River Authority

Measurement No.	No. of Stalks	Diameter (m)	Measurement No.	No. of Stalks	Diameter (m)
1	17	0.9144	19	100	4.8768
2	150	5.4864	20	2500	15.24
3	77	4.572	21	1300	7.62
4	32	1.8288	22	10	0.6096
5	19	0.6096	23	1000	10.668
6	28	0.4572	24	14	0.762
7	150	4.572	25	5000	22.2504

Table 4. continued

Measurement No.	No. of Stalks	Diameter (m)	Measurement No.	No. of Stalks	Diameter (m)
8	75	4.2672	26	200	4.572
9	58	3.048	27	50	1.524
10	400	6.7056	28	20	1.2192
11	1000	14.3256	29	150	3.6576
12	100	3.6576	30	250	6.096
13	100	4.2672	31	5000	22.86
14	35	1.2192	32	50	2.4384
15	400	7.0104	33	150	4.2672
16	1300	9.4488	34	400	6.096
17	50	1.8288	35	300	7.62
18	90	3.6576	36	70	3.6576

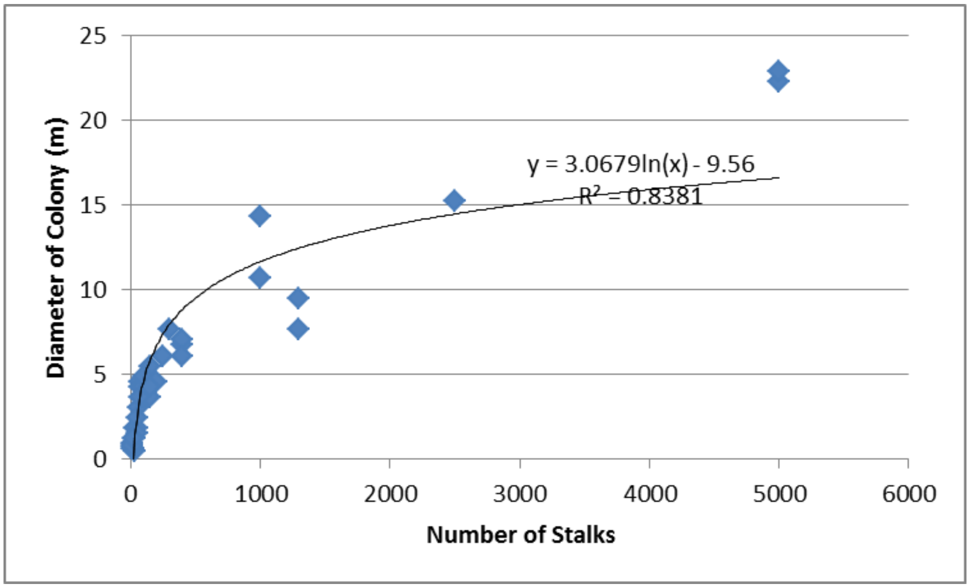


Figure 6. Colony formation follows an exponential distribution.

The colonization curve (Figure 6) also closely follows a logistic regression curve described by Equation 1 and Figure 7 below.

Equation 1. from Law et al., 2003

$$G=rN[(K-N)/K]$$

where

G = population growth

r = intrinsic growth rate

N = number of individuals in the population

K = carrying capacity, maximum population size that an environment can sustain.

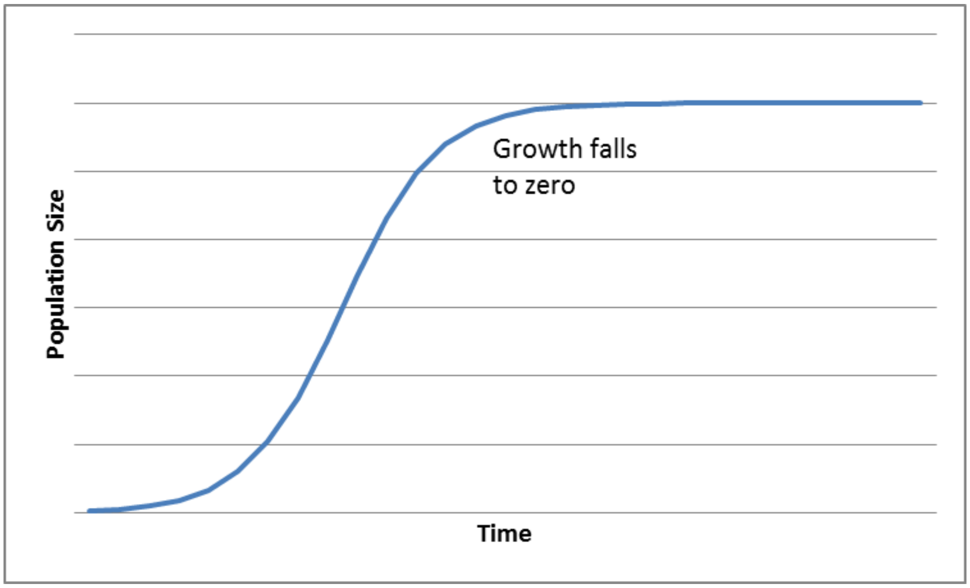


Figure 7. Density dependence- growth rate is a function of population size.

From the curve in Figure 6, the value of K was taken as 5000 stalks. The value of N was taken as the number of plants present in the swath at a given time step. The intrinsic growth rate was taken as 2 per older stalk. Equation 1 was used for each swath separately. The value of G obtained at each iteration determined the population in each iteration.

Data from aerial photography taken in 2010, available from the Nueces River Authority, showed formation of colonies with clumps of *Arundo* plants in the riparian reaches of the river in the 3.53 km^2 study area (Figure 8). A k-means analysis was run on this data to isolate clusters of colonies (Figure 9).

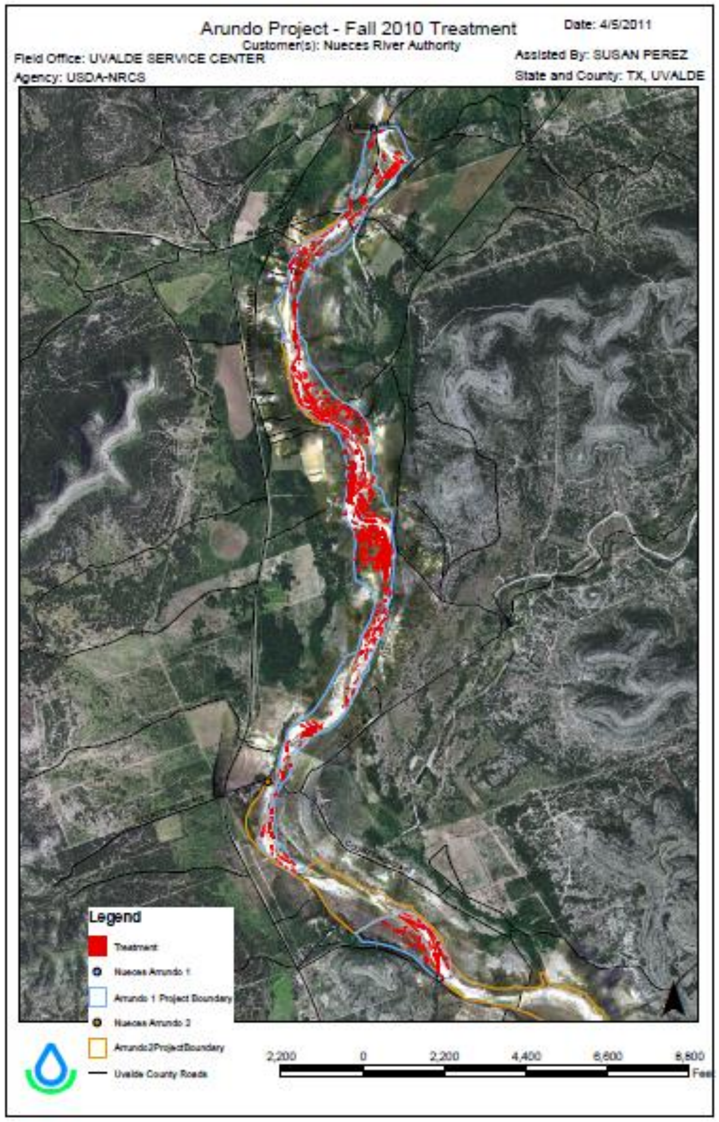


Figure 8. Swaths of *Arundo* that were treated by the Nueces River Authority in 2010.

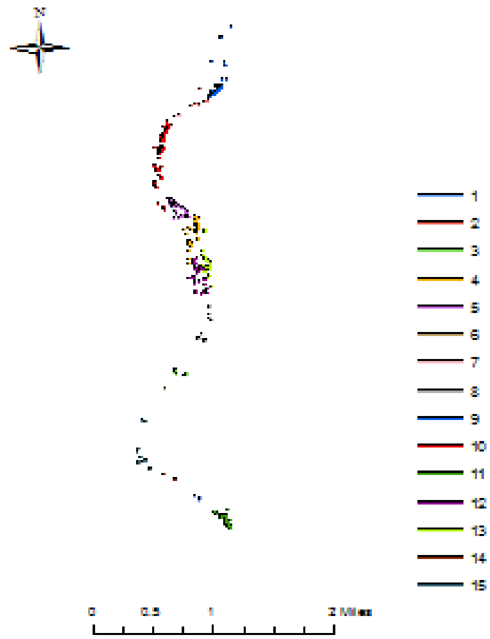


Figure 9. Cluster analysis using K-means created 15 clusters in the study area.

Following the assumption that the plant propagates downstream through flooding, data on flood events in the watershed was downloaded from the National Oceanic and Atmospheric Administration (NOAA) website where a flood event for the region is defined by the river stage being over 3.048 m. There were five flood events during the time period from 1995 to 2010 (Table 5). On the basis of this observation, a Poisson distribution was used with a lambda of (5/168 = .03) to generate random flood events in the period of growth. The distribution was used in place of the actual events so that the frequency of the events could be simulated for a more general scenario where the simulation needs to be run for the future when the dates of flood events are not known. It was assumed that whenever there was a flood event, *Arundo* would propagate downstream.

Table 5. Flood events in the Nueces Headwaters Watershed based on crests in the historical hydrograph for the Laguna Gage (USGS 08190000).

Date	Stage (m)
10/28/1996	7.8
06/22/1997	7.74
08/22/1998	6.11
11/17/2004	4.92
06/16/1997	3.56

III.3 Algorithm

Figure 10 shows a flow chart of an algorithm for the code written using Python Scripting to create a model that would propagate the growth of *Arundo*. After the K-means analysis was run (as described above), the data was split into 15 clusters using the "Split" function in the geoprocessing toolkit. The "convexHull" function was then used to create polygons based on the split cluster points. These were then sorted from North to South (upstream to downstream) direction. Later, the "Create Random Points" function was used to generate random points in the most upstream polygon. After that, an iterative loop was run based on G, the population growth that was calculated at each step. For colonization, "Generate Conditional Random Points" function was used from the Geospatial Modelling Environment package. This function generates random points based on a normal distribution for each random point that was already present in the polygon, hence enabling the modeling of exponential growth. The number of conditional random points was therefore given by G. Based on a Poisson distribution, it was verified whether or not there was a flood event. If there was a flood event, random points were generated in polygons downstream. If there wasn't a flood, then no propagation was simulated downstream, but only colonization of already existing stalks was simulated. *Arundo* propagation simulation was run on a monthly time step over 14 years.

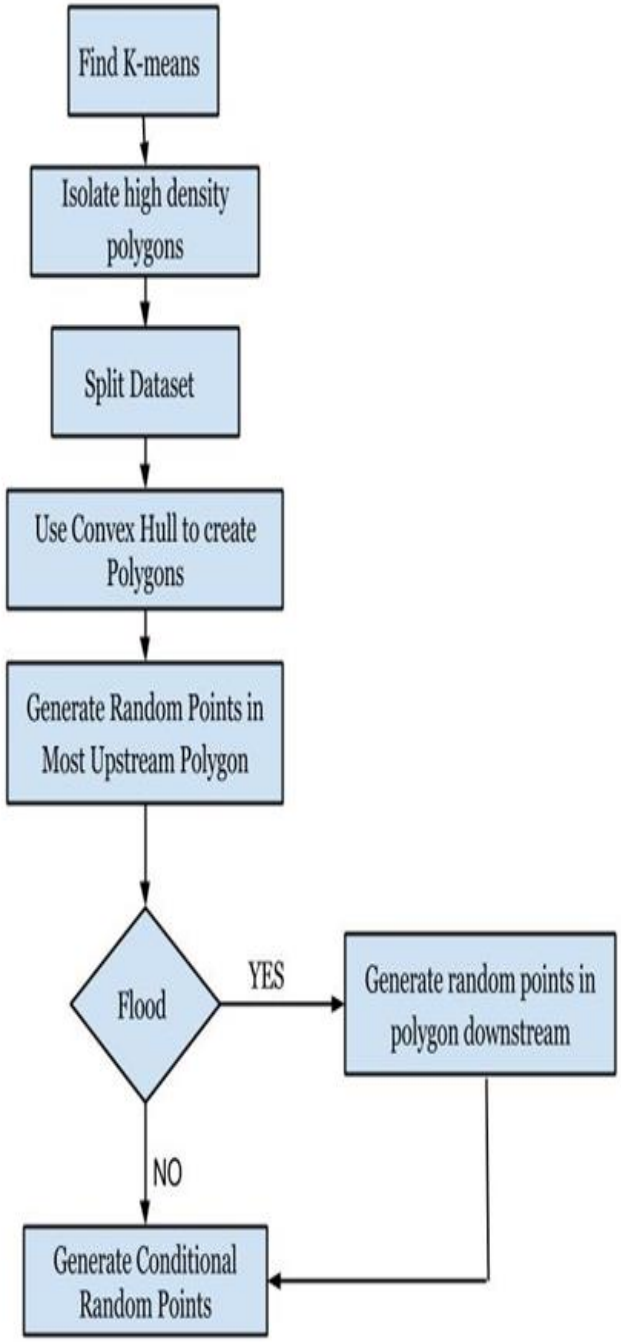
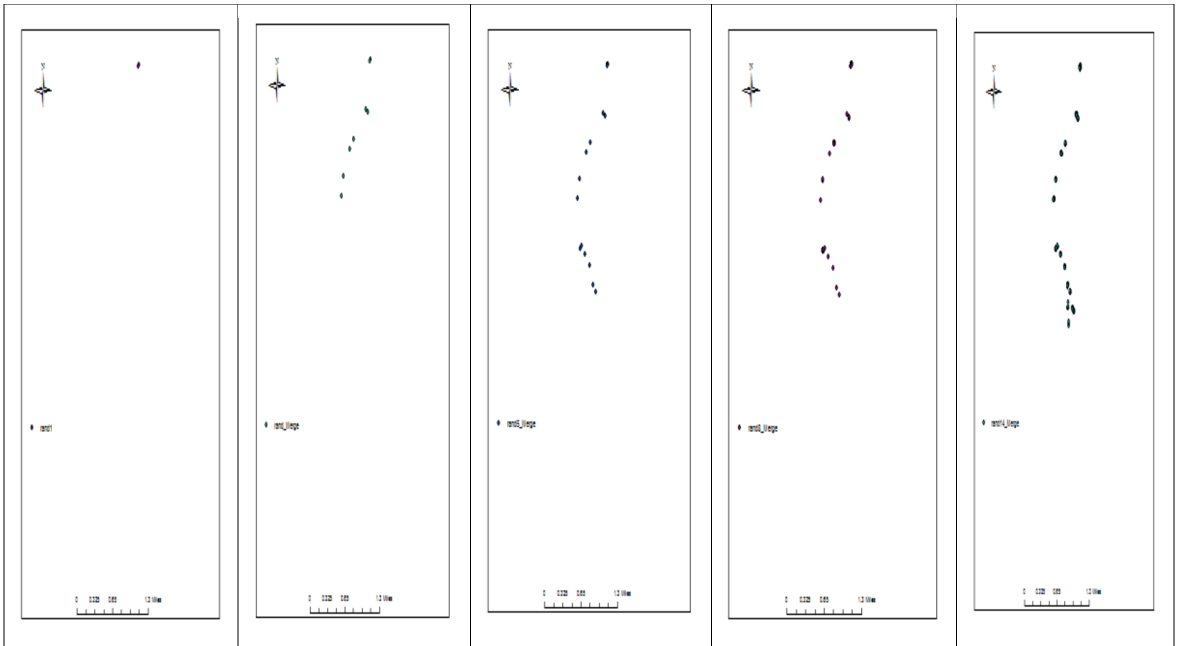


Figure 10. Algorithm for the simulation of *Arundo* propagation

III.4 Results and discussion

Before analyzing the results, it was made sure that both criteria of generating clusters downstream based on floods and colonization based on exponential growth were satisfied. Figure 11 shows *Arundo* propagation downstream with time. It may be noticed that in years 5 and 8, there was no propagation of *Arundo* downstream. This was because there was no flood event between years 5 and 8. However, zooming in to these two figures indicates that the density of the colonies in year 8 was much higher than that in year 5. The colonization is illustrated in Figure 12, which depicts the modeled exponential growth of *Arundo* over time by zooming into one out of the 15 polygons formed during the k-means analysis.

When the simulated output was compared with the observed data on *Arundo* Colonies, a general matching pattern was seen. However, the spread of the random points was not simulated well. The reason for this is that the other factors affecting *Arundo* propagation could not be incorporated into the developed algorithm due to a lack of availability of relevant data. Also, there was no data showing snapshots of the propagation over time such that distance between the colonies as time progressed could not be assessed.



Year 1	*Year 4*	*Year 5*	*Year 8*	*Year 13*

Figure 11. Propagation of *Arundo* downstream with flood events.

In this preliminary simulation, a time step of one month was used. Minimum distance between two generated conditional random points also needs to be incorporated in this approach so that the propagation density is not restricted to a very small radius around the transplanted *Arundo* stalks during flood events.

Factors such as transport of stalks due to wind or humans were also not incorporated into this algorithm at this stage. The developed algorithm forms a framework that can be further improved to model the propagation of various species. The conditions that could not be used due to lack of available data such as what wind speeds cause migration and in which direction, how often humans are responsible for movement of stalks through fires or soil digging and what kind of turbulence in flow conditions causes migration of stalks in the water. These can be added to the algorithm using simple logical conditions. Real time wind movement and precipitation data can also be incorporated to make better predictions. These developments were beyond the scope of this study, however.

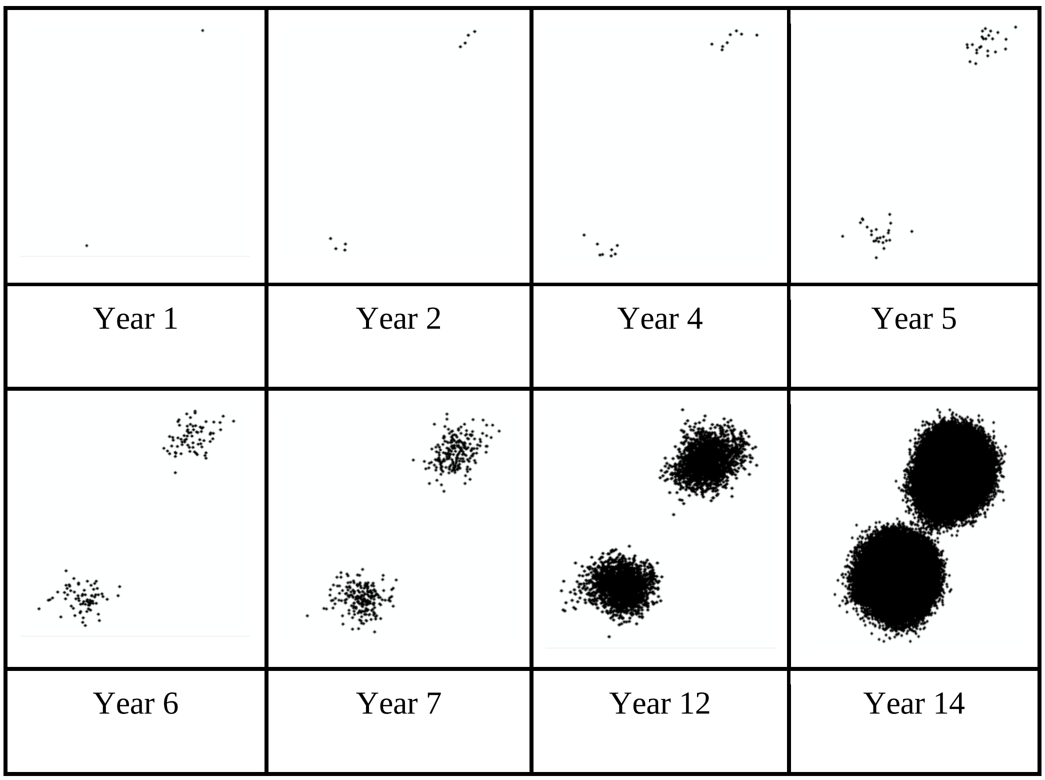


Figure 12. Growth of *Arundo* colonies based on an exponential distribution within one polygon.

The model could not be calibrated statistically due to a lack of sufficient observed information. Aerial photography was not available before 2010 and hence the output of the algorithm at different time steps could not be compared with observed data.

The propagation of *Arundo* involving its increase in density over time as well as its movement from one location to another was modeled. The next question to be addressed was how the species affects the hydrology of the watershed. For this purpose, the SWAT model was chosen. The output from *Arundo* propagation algorithm could not be directly used in the SWAT simulations as the above algorithm simulates the increase in density of the species over time and one cannot alter the density of a crop in the SWAT model. The heart of the SWAT model is hydrologic response units (HRUs) which are explained in Chapter IV and these are defined by a combination of landuse, soil type and slope. Within a landuse, one cannot create a mixture of crops or simulate clusters, which is what is done by the above algorithm. This algorithm was still added to this thesis as it is a contribution to understanding the propagation of the species.

The subsequent chapters will talk about modeling the study watershed using the SWAT model to understand the hydrologic impacts of *Arundo*.

CHAPTER IV

SWAT CALIBRATION AND VALIDATION AND ASSESSING IMPACTS OF *ARUNDO* ON THE HYDROLOGY OF THE WATERSHED

IV.1 Introduction

In previous chapters, an algorithm to propagate *Arundo* was developed (Chapter 3) and an analysis of streamflow trends for the headwaters of the Nueces River (Chapter 2) was carried out. Analysis of streamflow trends revealed a positive trend in streamflow before *Arundo* invasion and a negative trend after invasion. This chapter will discuss the modeling of the watershed using the Soil Water Assessment Tool (SWAT) and further an analysis of how the invasion of *Arundo* has impacted the area of the watershed it was found in.

The effect of an invasive plant species on hydrology can be studied at two both the field scale and the watershed scale. At the field level, techniques such as eddy-covariance for assessing evapotranspiration (Snyder et al., 2012; Dzikiti et al.,2012; Sonnentag et al.,2011) , rainfall simulators (Porter, 2005) for assessing water budget at a plot scale, and bulk density measurements fitted to models such as Van Dechten or Durner to assess root water uptake capability (Tokumoto, 2013) are used. While several studies have been undertaken at a field scale, Wilcox et al.(2006) argue that it is important to understand how vegetation changes are affecting the water cycle at a watershed scale. Process based watershed scale models used for such studies include SWAT (Arnold et al.,1993, 1998), Hydrological Simulation Program- FORTRAN (HSPF)(Bicknell et al.,1997), Soil and Water Integrated Model (SWIM) (Krysanova et al., 1998) and Dynamic Watershed Simulation Model (DWSM) (Borah and Bera, 2004) . In a comparison of these models, Borah and Bera (2003) show that while HSPF is useful for mixed agricultural and urban watersheds, SWAT is a more appropriate model for continuous simulations in agricultural watersheds. DWSM is a single rain event model and would not be appropriate for this study. SWIM is a modification of SWAT. SWAT was thus the most appropriate model for this study. It has also been used in studying the hydrological impacts of invasive species in the works of Afinowicz et al. (2005) and Arnold et al. (2003). The SWAT model is a hydro- dynamic and physically- based semi-distributed model (Arnold et al., 2012), which has been widely used in the field of ecohydrology. It simulates the water cycle at a basin scale. It is based on five linear reservoirs; vegetation, surface, snow accumulation and melting, underground and surface runoff (Simic et al., 2009). This study tries to understand how a change in the vegetation reservoir affects the other reservoirs. The heart of the SWAT model is the Hydrologic Response Unit (HRU), which is a combination of a landuse type, a soil type and slope. The HRU responds to weather inputs such as, rainfall and temperature, based on equations for processes in the hydrological cycle such as evapotranspiration, infiltration, and runoff.

The area of study is the headwaters of the Nueces River (HUC 12110101) which is a karst region towards the north of the Edward’s Aquifer recharge zone in Texas Hill Country (see Chapter 2.2). SWAT has been used to model karst regions in the previous studies by Baffaut and Benson (2009), Amatya et al. (2011) and Echegaray (2009). Baffaut and Benson (2009) suggest treating sink holes as ponds with high soil hydraulic conductivity and increasing transmission losses to account for losing streams. Echegary (2009) further suggests that SWAT HRUs be modified for karst regions by altering the baseflow recession constant and groundwater delay parameters such that in regions by altering the baseflow recession constant to as high as one, and adjusting groundwater delay parameters in such a way that the delay time to recharge the aquifers is made as low as one day in the regions of sinkholes. Springs, according to Baffaut and Benson (2009), were considered to be point sources. Since data about the quantity of water flowing out of the springs could not be obtained, this modification could not be incorporated in the SWAT model developed for this study. The guidelines laid out for working with sinkholes were followed in this study, however.

IV.2 Statistical analysis

The statistical analysis for the evaluation of the goodness of fit of the SWAT model was done based on the guidelines provided by Moriasi et al. (2007). The indicator statistics used for assessing the model performance include: percentage bias (PBIAS), Nash Sutcliffe efficiency (NSE), Root Mean Square Error (RMSE) and standard deviation ratio (RSR). The PBIAS statistic is a measure of how far the average tendency of the simulated values is from that of the observed values. A positive PBIAS means overestimation of observed value while negative PBIAS means its underestimation. The optimal PBIAS value is zero. The NSE is a measure of the residual variance of the simulated data as against the variance of the observed data. Its value ranges between negative infinity and one where the higher value indicates better fit. The RMSE is an indicator of error in the simulated values as against the observed values and the RSR is the RMSE normalized by the standard deviation of the observed values. The best value for the RSR is zero. PBIAS, NSE, RMSE and RSR were used to evaluate the fit of the SWAT model after its calibration and validation.

IV.3 *Arundo*

Arundo did not exist as a crop in the SWAT crop database. This is because it has newly been established to be an invasive species and there have been very few studies about its parameters. To add a new crop to the SWAT database, 35 parameters for crop growth need to be inputted. The details for these parameters are laid out in Appendix A of the SWAT Input/Output File Documentation (2012). This Appendix is included at the end of this Thesis for ready reference. Literature was reviewed for identifying appropriate parameters for *Arundo* as this species was not present in the crop database. For a parameter such as Leaf Area Index (LAI), there were a wide range of values found. A study by the Giessow et al. (2011) found an average LAI of 15.6 over 14 surveyed sites in Southern California while Watts and Moore (2011) measured the LAI for the species in the Lower Rio Grande region in Texas and found it to be 4.5. Maximum canopy height and rooting depth values varied from 9.9 m and 1 m respectively in Southern California (Giessow et al., 2011) to 6 m (Rieger and Kreager, 1990) in Southern California near San Diego and 5 m in California (Frandsen, 1997). Details such as fertilizer uptake and harvest index for optimal growth conditions could not be found for *Arundo* in the literature. After consultation with Dr. Moore (Ecosystem Science and Management Department), who has done substantial work on *Arundo* on the Rio Grande River, and Dr. Kiniry, Research Agronomist at the United States Department of

Agriculture – Agricultural Research Service (USDA-ARS) Laboratory at Temple, TX, *S. officinarum* (sugarcane) was recommended as a substitute for *Arundo* for modeling purposes. After further examination, the SWAT model used a value of 25 (kg/ha)(MJ/m^2) for sugarcane for the radiation use efficiency while a value of 54 (kg/ha)(MJ/m^2) was found for *Arundo* by Ceotto (2013). Hence sugarcane could not be used as a direct substitute and new crop parameters had to be developed for *Arundo.*

Agricultural Land Management Alternative with Numerical Assessment Criteria (ALMANAC) has been used to find the parameters for the crops in the SWAT crop database. ALMANAC is a crop model developed at the USDA- ARS (Kiniry et al., 1992) and it simulates crop growth based on nutrient uptake, water use, water stress, temperature stress, and nutrient stress. This model operates at a one square meter plot scale from which the biomass of the plant is taken and analyzed. The model has been used to find crop growth parameters as a model such as SWAT is a watershed scale model and needs input from a model such as the ALMANAC to simulate plant growth. ALMANAC has been used to find plant parameters for all the plants in the SWAT crop database. The plant growth is based on potential heat units (PHUs) that are accumulated when the average temperature in a day is higher than the base temperature required for that plant. For crop parameters of *Arundo*, the initial crop parameters were taken to be sugarcane, and then modified in the ALMANAC model to produce the values for *Arundo.*

Switchgrass was the native species in the riparian region of the watershed that was replaced by *Arundo.* Maximum LAI of the switchgrass has been found to be between 4.9 in Nebraska (Mitchell et al., 1998) and 12 in Texas (Kiniry et al.,1996). It is known to have a water uptake capacity of up to 670 mm annually in Iowa and 656 mm annually in Texas (Kiniry et al., 2008). The parameters for switchgrass were already present in the crop database for SWAT.

The objective for this section is to calibrate and validate the SWAT model for the headwaters of the Nueces River and use the calibrated model for assessing the impacts of the invasion of *Arundo* on the watershed hydrology (or water balances).

IV.4 Approach

IV.4.1 SWAT model calibration and validation

IV.4.1.1 Datasets used

The geospatial and temporal datasets for the SWAT modeling were obtained from various sources. The Digital Elevation Model (DEM) (USGS, 2010) of the study area was downloaded from the National Hydrography Dataset (subbasin "d" in region 12). The DEM resolution was 30 m X 30 m. The land cover/land use data for the watershed was obtained from the National Land Cover Dataset (NLCD) (Fry et al., 2011) and the National Agricultural Statistics Service (NASS) (Han et al., 2012) resources. The soil information was obtained from the Natural Resource Conservancy State Soil Survey Geographic Data (NRCS STATSGO) database that comes with SWAT. Weather data was taken from the USDA- ARS Temple website. Two weather stations, C41198 and C414907, located as shown in Figure 4,were found to be in the watershed when the latitudes and longitudes of the available weather stations from the afore mentioned website were mapped to the watershed. The data for daily precipitation and temperature (minimum and maximum) for these two stations was thus downloaded. The weather data was available from January 1, 1950, to December 31, 2010.

IV.4.1.2 Model set up

The DEM was used to delineate the watershed using ArcSWAT 2012 with geographical information systems software ArcGIS 10.1 which was developed by Environmental Systems Research Institute (ESRI) in 2012. The watershed boundary was constructed based on the points of highest elevation in the topography of the region after placing the outlet at the Laguna gage (USGS 08190000). The flow lines which were to be used for the routing of water in the watershed were created by ArcSWAT on the principle that water flows from a higher elevation to a lower elevation. Hence a flow direction grid was created. A threshold was defined such that only cells accumulating more water than the threshold number of cells were used to create the flow network. Since the DEM resolution was 30m * 30m and the watershed covered an area of 2126 km^2, the threshold was set at 22,000 cells, which translated to a minimum draining area of 20 km^2. A total of 29 subbasins were isolated within this watershed. Hydrologic response units (HRUs) were defined based on a unique combination of soils, slopes and landuse. The slopes were classified into five categories based on the natural breaks in the histogram of the slopes obtained from the DEM. The threshold for the area to be covered by the soil and slope class for HRU definition was set to be 10% while that for landuse was set at 0% since *Arundo* needed to be simulated and it occupies a very small area of

$3.52 km^2$. A total of 1224 HRUs were created, out of which *Arundo* had invaded in 7 HRUs after 1995. A summary of the slopes, soils and landuse is shown in Table 6 below.

Table 6. Summary of landuse, slopes and soil types for HRU definitions and % area covered by each of these.

		Area [ha]	% Watershed Area
LANDUSE:			
	Water → WATR*	155.79	0.08
	Residential-Low Density → URLD	2,285.37	1.20
	Residential-High Density → URHD	231.84	0.12
	Commercial → UCOM	58.50	0.03
	Wetlands-Mixed → WETL	11.88	0.01
	Southwestern US (Arid) Range →SWRN	85.95	0.05

Table 6. continued

		Area [ha]	% Watershed Area
	Forest-Deciduous → FRSD	17475.03	9.16
	Forest-Evergreen → FRSE	55504.35	29.08
	Forest-Mixed → FRST	16.83	0.01
	Range-Brush → RNGB	104808.9	54.91
	Range-Grasses → RNGE	9351.9	4.9
	Hay → HAY	15.12	0.01
	Agricultural Land-Row Crops → AGRR	43.2	0.02
	Wetlands-Forested → WETF	472.77	0.25
	Sugarcane → SUGC	0.27	0
	Alamo switchgrass → SWCH	352.62	0.18
SOILS:			
	TX155**	110,018.30	57.64

Table 6. continued

		Area [ha]	% Watershed Area
	TX157	804.87	0.42
	TX159	893.61	0.47
	TX253	2549.61	1.34
	TX467	34033.05	17.83
	TX544	27446.85	14.38
	TX546	6183.27	3.24
	TX581	8940.69	4.68
SLOPE:			
	0-2.13%	18,809.64	9.85
	10.688-22%	43903.17	23.00
	2.13-5%	32518.35	17.04
	22-9999%	54540.18	28.57
	5-10.688%	41098.95	21.53

* SWAT landuse name.

** Soil classification from the STATSGO database in SWAT

Once the HRUs were defined, the weather files were input into the SWAT model. The SWAT model was then run on a daily time step while the output was read on a monthly time step.

IV.4.1.3 Calibration and validation

The simulations were run for the period from 1950 to-1994 on a daily time step with a monthly time step output and the first 10 years were considered as warm up period. The warm up period helps the model set basic flow conditions and bring the hydrologic processes to an equilibrium condition. The period for calibration was chosen to be 1960-1977 and the validation period was chosen to be 1978-1994. These time periods were selected so that the hydrology of the watershed could be simulated correctly before the invasion of *Arundo* that was first observed in 1995.

The most sensitive parameters during calibration were found to be curve number (CN2), soil available water capacity (sol_awc), baseflow recession constant (alpha_bf), groundwater delay (GW_DELAY), soil evaporation compensation factor (ESCO), transmission losses (ch_k2), threshold water level in shallow aquifer for base flow (GWQMN), saturated hydraulic conductivity of the first layer of the soil (SOL_K) and aquifer percolation constant (RCHRG_DP). CN2 affects the runoff and decreasing CN2 decreases runoff. SOL_ AWC is used in percolation calculations and an increase in available water capacity increases percolation. An increase in Alpha_bf results in a shorter receding limb of the hydrograph and indicates a rapid response to recharge. GW_DELAY is a measure of the delay time for an aquifer to recharge. In the case of this karst watershed, there are certain regions with very rapid groundwater recharge. These regions have a GW_DELAY of as low as one day while there are other regions where the response is slow enough that the value for GW_DELAY is of the order of 218 days. The baseflow filter (Arnold et al., 1999) was run to partition the hydrograph into baseflow and streamflow components. From this, an alpha_bf value of 0.015 and GW_DELAY value of 218 days were obtained. SOL_K is also used in percolations calculations and an increase in SOL_K results in more percolation. ESCO is a measure of the fraction of soil water that evaporates and an increase in ESCO means higher evapotranspiration and lower flows out of the system. CH_K2 is a factor considered in arid and semi-arid watersheds where there are ephemeral streams and there are losses of water as the flood wave travels downstream. An increase in transmission losses reduces the flow output of the model. GWQMN which is a measure of the water required in the aquifer before baseflow occurs should be increased if there is capacity in the aquifer to store water before it moves towards the streams as baseflow. RCHRG_DP is a fraction of the water that percolates into the deep aquifer from the shallow aquifer. An increase in RCHRG_DP reduces the amount of water that goes to the stream and hence reduces flow volume.

The above mentioned parameters were not uniformly changed over the subbasins because of the karst nature of the study area, which included some regions without flow and some regions with springs. No flow reaches are reaches where the water from the stream disappears into karst limestone. Based on a gain loss study by Lambert et al. (2012), the subbasins with springs and those where no flow was observed were isolated. The coordinates of the sinkholes and springs were marked through GIS on the delineated watershed six subbasins were found to contain the areas of no flow and two were found to contain springs. There was no information available for the other subbasins. Figure 13 shows the subbasins containing sinkholes and those containing springs.

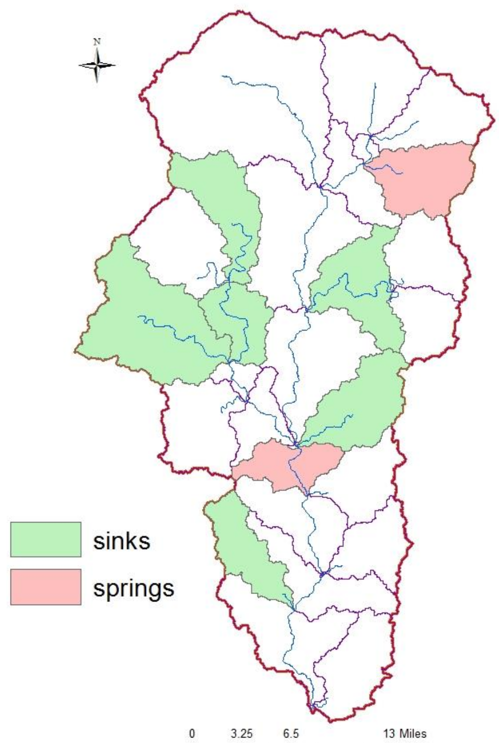


Figure 13. Subbasins with springs and subbasins with no flow reaches underlain by karst limestone.

For the subbasins with no streamflow, the fraction of recharge to a deep aquifer and the transmission losses were increased. The soil saturated hydraulic conductivity was increased, baseflow recession constant was increased and groundwater delay was decreased based on studies by Baffaut and Benson (2009) and Echegaray (2009). The ranges of adjustment for these parameters are shown in Table 7. For the subbasins where springs were found they could not be treated as point sources due to lack of information about flow from these springs. However, the groundwater delay in these subbasins was increased and transmission losses were decreased.

Table 7. Values for parameters changed during calibration of the SWAT model.

Parameter	Range of Default Values	Range of Values After
	Subbasins with No Flow	
Alpha_bf	0.048	0.9 - 1
GW_DELAY	31 days	1 day
SOL_K	Default	+15%
CH_K2	0	250 mm/hr
RCHRG_DP	Default	+.2
GWQMN	0	5mm
	Subbasins with Springs	
Alpha_bf	0.048	.015
GW_DELAY	31 days	218 days
SOL_K	Default	-30%

Table 7. continued

Parameter	Range of Default Values	Range of Values After
Subbasins with Neither Springs nor Sinkholes		
Alpha_bf	.048	.015
GW_DELAY	31	218 days
SOL_K	Default	-20%
CH_K2	0	50mm/hr
Parameter	Range of Default Values	Range of Values After
All Subbasins		
CN2	Default	-15%
ESCO	Default	-0.1
SOL_AWC	Default	+0.1

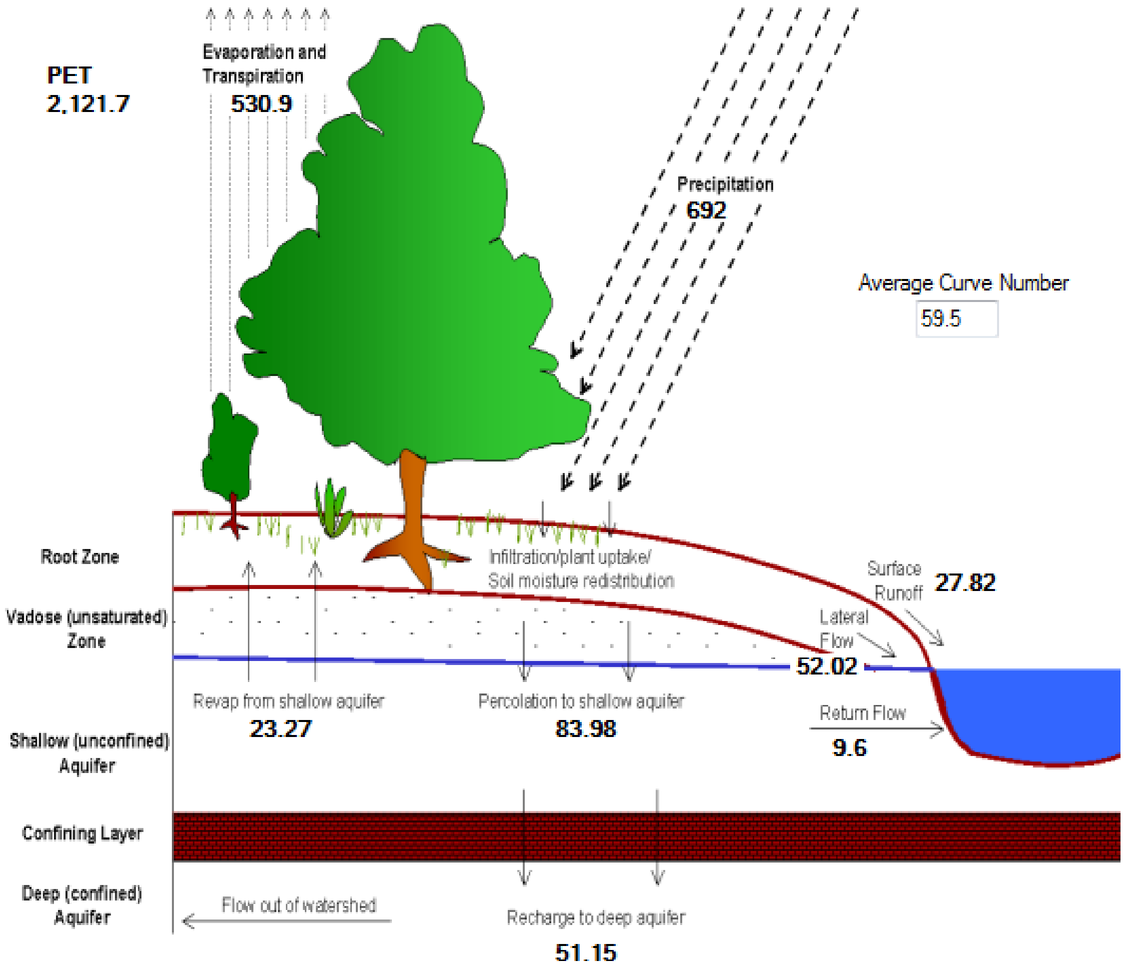


Figure 14. The average annual water balance for the headwaters of the Nueces River watershed for the period 1950 to- 1994. All the values in the figure above are in units of mm. Average values of values infiltration, evapotranspiration, lateral flow, runoff, recharge to deep and shallow aquifers and return flow for the watershed are shown above. Approximately 77% of the precipitation (692 mm) is lost to evapotranspiration (531 mm), about 12% percolates (84 mm), 7% goes to recharge (51 mm) the deep aquifer and 13% contributes to the streamflow (90 mm). Baseflow (62 mm) contributes to 70% of the flow in the river while surface runoff (28 mm) contributes 30%.

After making the adjustments in the parameters stated in Table 7, a hydrograph was plotted to compare the flow values obtained from the SWAT simulation as against flow values observed at the Laguna Gage. Figure 14 shows the average annual water balance for the watershed for the period 1950 to- 1994. Figure 15 and Figure 16 show the hydrographs. As can be visually observed, most observed and simulated peaks match As can be visually observed, most observed and simulated peaks matched. The simulated values even out some of the peaks seen in the observed values. Also, majority of the precipitation events and the peaks of the simulated values matched while some of the observed value peaks did not match with precipitation. A reason for this was that data was available for only two weather stations for a 2,146 km^2 watershed. Not only this, the weather stations were closely situated in the Southern region of the watershed and there were no representative weather stations for the entire Northern region. SWAT used triangulation method to distribute the data from these two weather stations to all the subbasins in the watershed. Rain events that might have occurred in regions that did not have weather stations could not be accounted for.

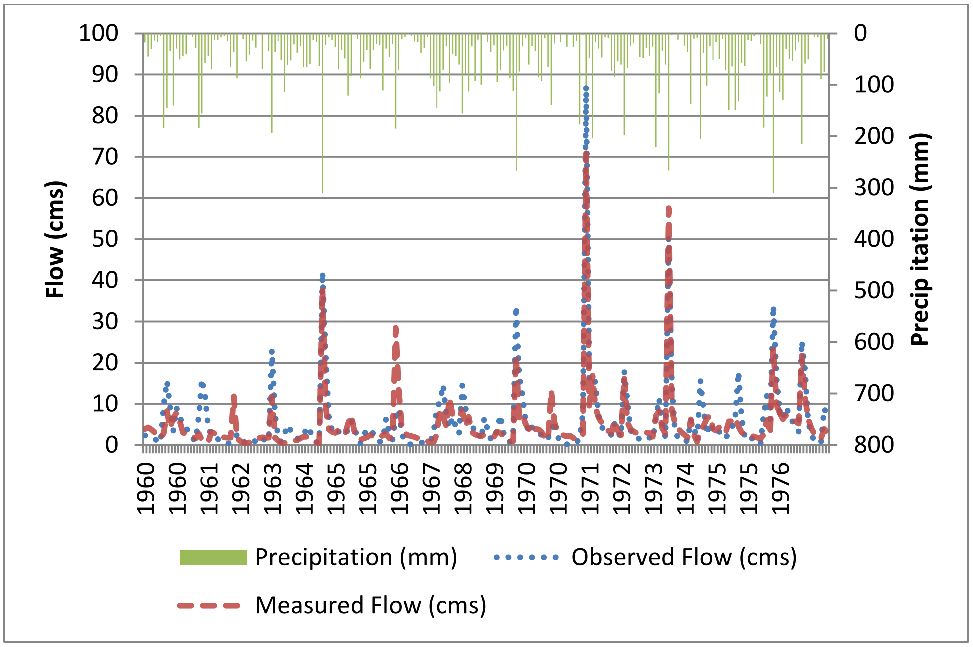


Figure 15. Measured and simulated monthly flow rates in the Nueces River during the calibration period along with monthly precipitation (1960-1977).

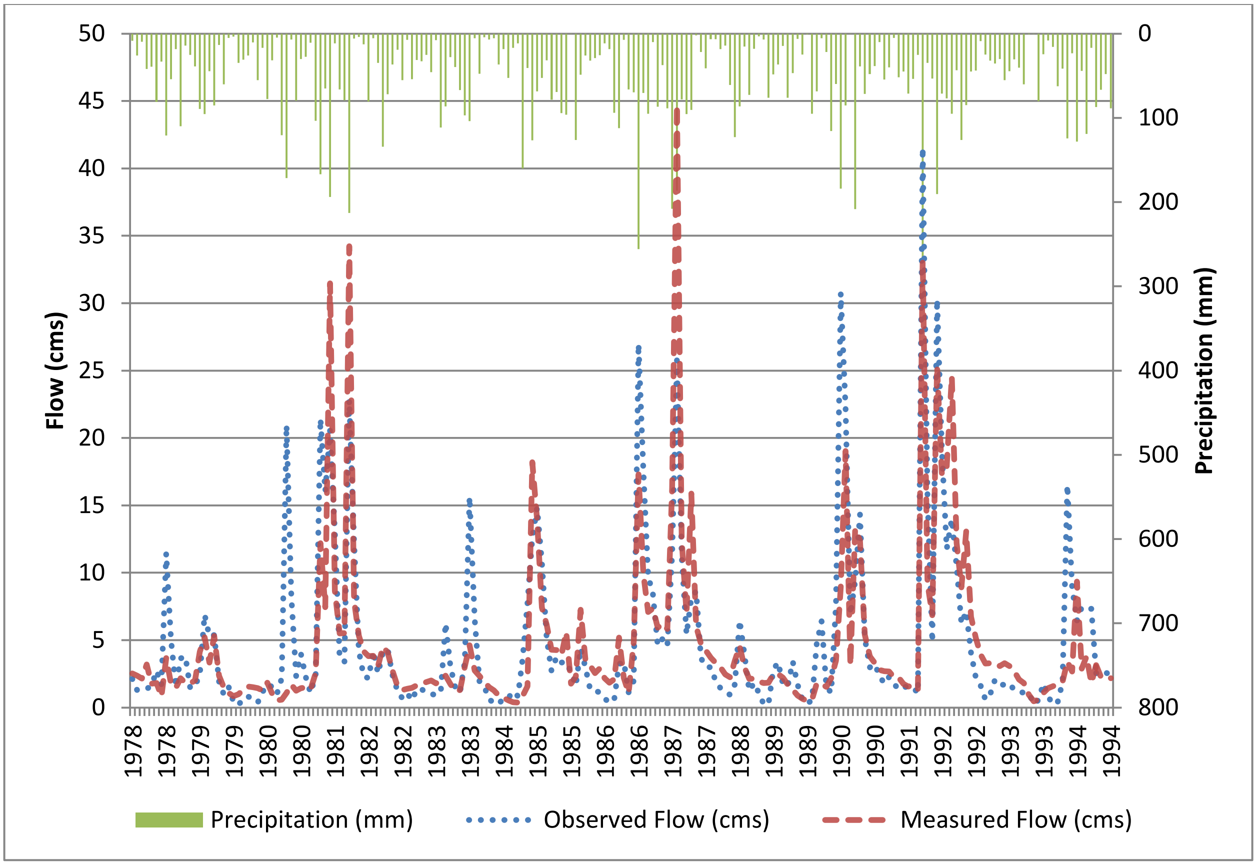


Figure 16. Measured and simulated monthly flow rates in the Nueces River during the validation period along with monthly precipitation (1978-1994).

IV.4.1.4 Statistics

A Nash-Sutcliffe (NSE) of 0.79, a P-Bias of 15.5 % and an R-square value of 0.76 were achieved for the calibration time period. For the validation time period, a Nash-Sutcliffe of 0.736, a P-Bias of 4.3 % and an R-square value of 0.64 were achieved. Table 8 shows the interpretation of these statistics based on Moriasi et al. (2007). For calibration period, the NSE fell in the range of very good, the PBIAS was satisfactory and the RSR was very good. For the validation period, the NSE was good, PBIAS was very good and RSR was good. Afinowicz et al. (2005) used SWAT to simulate a karst watershed in the Edward's aquifer region in Texas and got a value of 0.29 and 0.5 for NSE for monthly calibration and validation. Spruill et al. (2000) modeled a karst region in central Kentucky and got a month NSE of 0.89 and 0.58 for calibration and validation respectively. Considering the karst region modeled in this study, the achieved NSE of 0.79 and 0.736 for calibration and validation periods can be considered as good.

Table 8. Model performance statistics for SWAT calibration and validation periods in comparison to the guidelines of Moriasi et al. (2007).

Statistical	Period	Value	Range	Evaluation (Moriasi et al.,
Nash-Sutcliffe	Calibration	.79	0.75 < NSE <	Very Good
	Validation	.736	0.65 < NSE <	Good
PBIAS	Calibration	15.48%	±15 < PBIAS <	Satisfactory
	Validation	4.3%	PBIAS < ±10	Very Good
R-square	Calibration	.7647	0 to 1	Higher- better
	Validation	.6414	0 to 1	Higher- better
RSR	Calibration	.4537	0.00 < RSR <	Very Good
	Validation	.513	0.50 < RSR <	Good

IV.4.1.5 Conclusion

The SWAT model was set up for the study watershed, and calibrated and validated against observed data to ensure that the simulated hydrology of the watershed was close to the real system before the impacts of *Arundo* were simulated. The calibration and validation durations covered a period of 34 years.

Arundo was first observed in the watershed in 1995. In the next section the approach to adding the *Arundo* to the SWAT database and studying its impact on the watershed hydrology using SWAT will be discussed.

IV.4.2 Hydrologic changes due to Arundo *displacing switchgrass*

IV.4.2.1 Use of ALMANAC to establish crop parameters for *Arundo*

The ALMANAC model was run to establish the parameters for the crop growth of *Arundo* with the help of Dr. Kiniry at USDA- ARS. Sugarcane was the base crop that was taken for this simulation. Table 9 shows the parameters that were started with and the parameters that were found for *Arundo.* While the LAI for sugarcane in the SWAT crop database is 6 that for *Arundo* was found to be twelve. The radiation use efficiency was increased from 25 (kg/ha)(MJ/km ^{2}) to 45(kg/ha)(MJ/km ^{2}). Other major changes were increasing the harvest index from 0.5 to 0.9 since *Arundo* is not harvested unlike *Sugarcane* which is harvested since it is grown as an agricultural crop.

Table 9. Comparison of *Arundo* parameters determined using ALMANAC model with parameters of sugarcane present in the crop database in SWAT. The description of the parameters is in Appendix A.

	Sugarcane	*Arundo*	Units
BIO_E (RUE)	25	45	(kg/ha)/(MJ/m2)
WAVP	10	10	
BIOEHI	33	52	
CO2HI	660	660.29	µL CO2/L air
BLAI	6	12	
FRGRW1	0.15	0.1	

Table 9. continued

	Sugarcane	*Arundo*	Units
LAIMX1	0.01	0.2	
FRGRW2	0.5	0.5	
LAIMX2	0.95	0.95	
DLAI	0.9	0.95	
CHTMX	3	3.6	m
RDMX	2	2	m
T_OPT	25	25	°C
T_base	11	10	° C
PLTNFR1	0.01	0.01	kg N/kg biomass
PLTNFR2	0.004	0.004	kg N/kg biomass
PLTNFR3	0.0025	0.0025	kg N/kg biomass
PLTPFR1	0.0075	0.0075	kg P/kg biomass
PLTPFR2	0.003	0.003	kg P/kg biomass
PLTPFR3	0.0019	0.0019	kg P/kg biomass
HVSTI	0.5	0.9	
WSYF	0.01	0.15	(kg/ha)/(kg/ha)
CNYLD	0	0.0069	kg N/kg yield
CPYLD	0	0.0017	kg P/kg yield
USLE_C	0.001	0.001	
GSI	0.0055	0.007	m/s
VPDFR	4	4	kPa
FRGMAX	0.75	0.75	
RSDCO_PL	0.05	0.05	
ALAI_MIN	0.75	0.75	
BIO_LEAF	NA	NA	
MAT_YRS	NA	NA	
BMX_TREES	NA	NA	metric tons/ha
EXT_COEF	-	0.65	

IV.4.2.2 Model simulations

The calibrated SWAT model was run for the period 1950 to 2010 wherein a landuse change was made for the period 1995 to 2010. The landuse change was the substitution of the switchgrass by *Arundo*. The 3.52 km^2 of the watershed that was covered by *Arundo* (Figure 4) in the riparian region of the Nueces River was represented by 7 HRUs in the SWAT model. Since the area covered by *Arundo* was a miniscule proportion of the watershed (0.16%), the growth of *Arundo* over time downstream of where it was initially found was not simulated. switchgrass which was the native species in the region before the invasion of *Arundo*, was completely substituted for *Arundo* in the 7 HRUs. The model was then run for two scenarios, (1) with switchgrass for the period 1950 to 2010, and (2) with switchgrass in the HRUs for 1950 to 1994 and *Arundo* substituting switchgrass for the period 1995 to 2010. The reason for this was that *Arundo* started growing in 1995. Then, for the period between 1995 and 2010, a comparison was made for the 7 HRUs between the evapotranspiration and water yield from the two model scenarios.

A comparison between the crop parameters of the invasive *Arundo* and the native switchgrass is made in Table 10. The parameters for switchgrass were already present in the SWAT crop database and were not modified. The maximum potential LAI for *Arundo* was taken to be 12 as compaired to 6 for switchgrass.The radiation use efficiency of the two crops was similar. The maximum canopy height for the invasive species was 3.6 m as compared to the native species while its maximum rooting depth was 2 m as compared to 2.2 m. The maximum stomatal conductance for *Arundo* was determined to be 0.007 m/s as compared to 0.0055 m/s for the switchgrass implying that transpiration for *Arundo* should be higher than that for switchgrass . The nitrogen uptake for *Arundo* was less while the phosphorus uptake was higher. Plant growth in SWAT depends on Potential Heat Units (PHUs) where the growth of a plant depends on the number of heat units accumulated. The number of heat units is proportional to the difference in temperature between the ambient and the optimum temperature required for plant growth. The PHUs for switchgrass were taken to be 2,300 (Kiniry et al.1996) while that for the *Arundo* were taken to be 3000 which was determined from the ALMANAC model.

Table 10. Comparison of plant growth parameters used for *Arundo* and switchgrass. The descriptions of the parameters is in Appendix A.

Parameter	switchgrass	*Arundo*	Units
BIO_E (RUE)	47	45	(kg/ha)/(MJ/m^2)
WAVP	8.5	10	
BIOEHI	54	52	
CO2HI	660	660.29	µL CO_2/L air
BLAI	6	12	
FRGRW1	0.1	0.1	
LAIMX1	0.2	0.2	
FRGRW2	0.2	0.5	
LAIMX2	0.95	0.95	
DLAI	0.8	0.95	
CHTMX	2.5	3.6	m
RDMX	2.2	2	m
T_OPT	25	25	°C
T_base	12	10	° C
PLTNFR1	0.035	0.01	kg N/kg
PLTNFR2	0.015	0.004	kg N/kg
PLTNFR3	0.0038	0.0025	kg N/kg

Table 10. continued

PLTPFR1	0.0014	0.0075	kg P/kg
PLTPFR2	0.001	0.003	kg P/kg
Parameter	switchgrass	*Arundo*	Units
PLTPFR3	0.007	0.0019	kg P/kg
HVSTI	0.9	0.9	
WSYF	0.9	0.15	(kg/ha)/(kg/ha)
CNYLD	0.016	0.0069	kg N/kg yield
CPYLD	0.0022	0.0017	kg P/kg yield
USLE_C	0.003	0.001	
GSI	0.0055	0.007	m/s
VPDFR	4	4	kPa
FRGMAX	0.75	0.75	
RSDCO_PL	0.75	0.05	
ALAI_MIN	0.75	0.75	
BIO_LEAF	NA	NA	
MAT_YRS	NA	NA	
BMX_TREES	NA	NA	metric tons/ha
EXT_COEF	-	0.65	

Plant growth curves for the two plants were simulated using LAIs obtained from SWAT runs. These growth curves are a function of PHUs and LAI. The PHUs determine the period for which the plant will be active and LAI starts to decline when 70% of the heat units have been reached (Kiniry et al., 1996). Figure 17 shows the plant growth curves for *Arundo* and switchgrass for a sample year. As can be seen, since the PHUs for the switchgrass accumulate earlier, its LAI starts declining before that of *Arundo*. Although the potential LAIs for *Arundo* and switchgrass are 12 and 6, respectively, neither of the plants attained their peak LAIs due to water and nutrient stress.

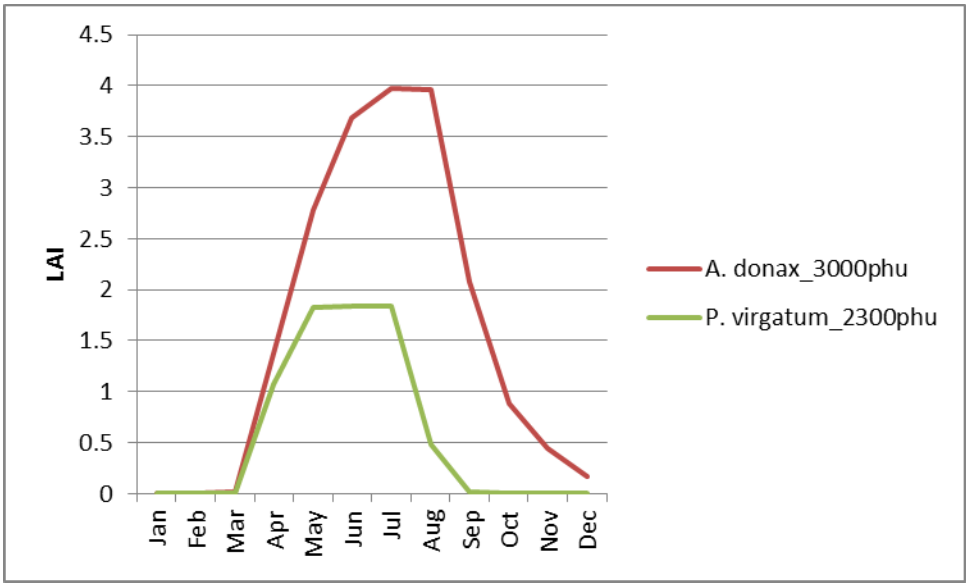


Figure 17. Plant growth curves for *Arundo* and switchgrass for an average year based on SWAT simulations of the two crops.

The highest LAI changed every year based on the climatic conditions in that year. This can be observed in Figure 18 which compares the plant growth curve of *Arundo* over two different years- one with rainfall of 312 mm and one with a rainfall of 980 mm. From the graphs, it can be seen that the plants are water stressed. *Arundo* is able to have a longer duration and higher extent of activity based on its LAI for a year when there is more rainfall.

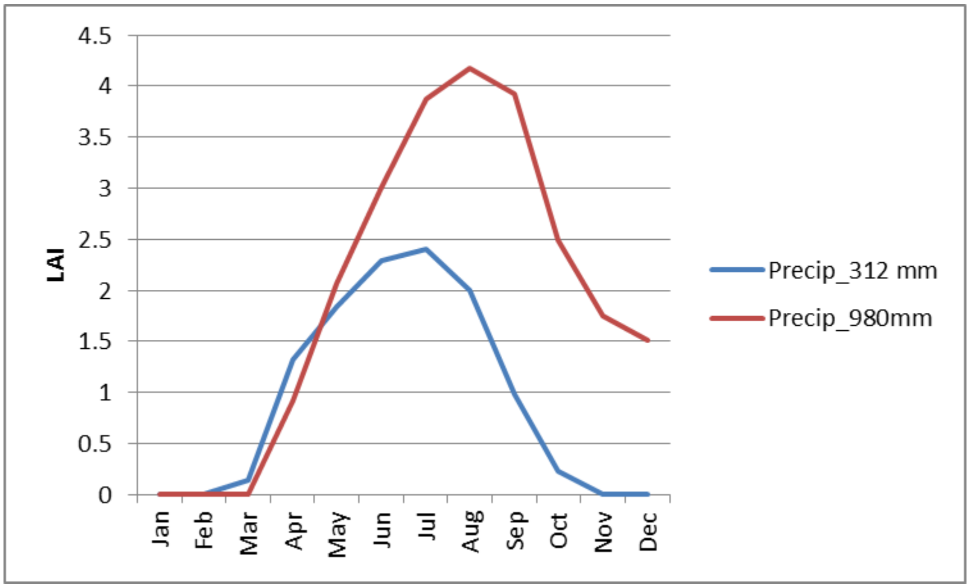


Figure 18. Growth curves for *Arundo* over two years with different amounts of rain, 312 mm and 980 mm.

IV.4.2.3 Analysis

Once the plant growth curves were found to be reasonable, the model was run for two scenarios- with native switchgrass and with *Arundo* during the 1995-2010 period. The water balance can be defined by the following equation (SWAT Manual, 2009 p.9):

Equation 2

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{sweep} - Q_{gw})$$

where

SW_t = Final soil water content (mm H_2O)

SW_o= Initial Soil Water Contect on day 'i' (mm H_2O)

t = the day for which the simulation is run

R_{day} = Amount of Precipitation on day 'i' (mm H_2O)

Q_{surf}= Surface Runoff on day 'i' (mm H_2O)

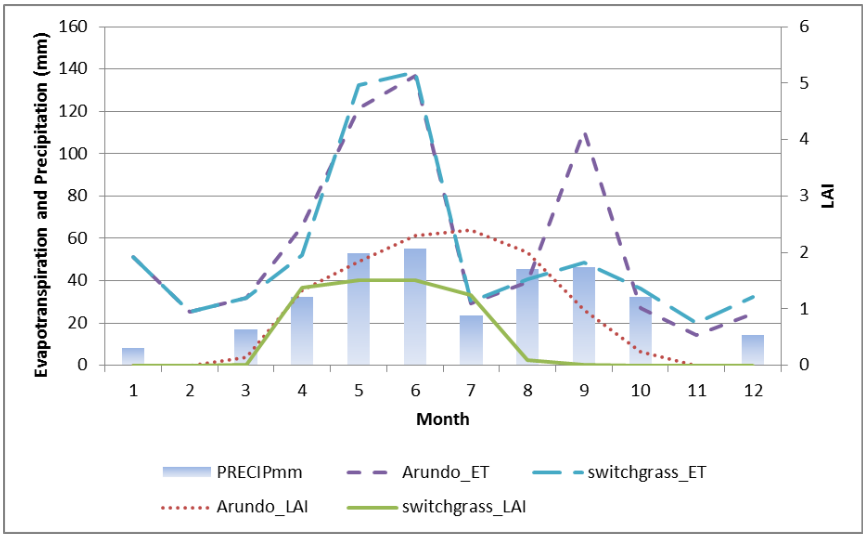
E_a= Evapotranspiration on day 'i' (mm H_2O)

w_{sweep}= Amount of water entering the vadose zone on day 'i' (mm H_2O)

Q_{gw}= Return flow on day 'i' (mm H_2O)

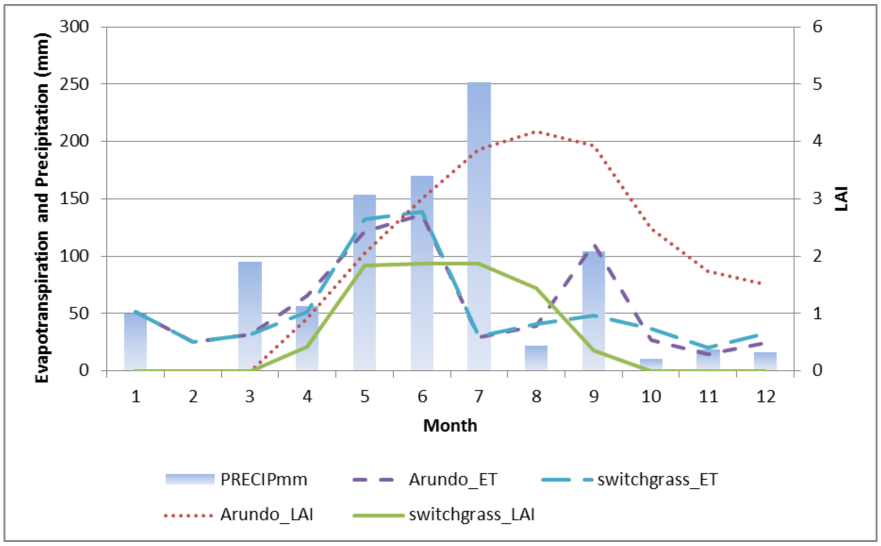
In Equation 2, the factor that would change due to a change of plant type would be evapotranspiration, which in turn would affect the soil water content, amount of water entering the vadose zone and return flows.

An insignificant difference was found in the water yield and evapotranspiration when accumulated over the 16 year simulation period. The evapotranspiration was found to be higher for *Arundo* by 10. 35 mm over the period of 16 years. The difference in water yield was found to be higher for switchgrass by 0.676 mm over the period of 16 years. Over 16 years, switchgrass had 1347 (23%) water stressed days while *Arundo* had 2203 (37%) such days. Since water stress was faced by these plants which can be seen in the number of water stress days and the fact that they were unable to attain their maximum LAI, three instances of observing plant growth curves, evapotranspiration difference and precipitation have been shown in Figure 19 below, (a) a year with minimum precipitation, (b) a year with maximum precipitation, and (c) a year with medium precipitation. These instances were picked such that scenarios of extreme stress, medium stress and heavy rainfall for the region could be explained. There is a similar pattern that can be seen in all the three cases. There are positive differences as well as negative differences in evapotranspiration which can be explained by looking at the growth curves. The LAI of *Arundo* increases rapidly in the initial part of the year and hence it evapotranspires more than switchgrass. Then there is a period where the difference in evapotranspiration is negative. This is because *Arundo* has absorbed all of the soil moisture while there is still water available in the soil for the switchgrass. This has been explained through Figure 20 for the year 1995 which is a year of medium rainfall since all the years follow a similar pattern. In this figure the soil moisture at the end of the month of April is more for switchgrass which translates to higher evapotranspiration of switchgrass in May as compared to *Arundo.* This difference in evapotranspiration can be seen both in Figure 19(c) and Figure 20. By the time September begins, the leaves of switchgrass stop transpiring. The leaves of *Arundo* are still transpiring. The soil moisture is now taken up by the *Arundo* and there is still moisture in the soil for switchgrass. There is an evaporation component of the evapotranspiration which takes over as the year starts ending and the leaves senesce. This is the evaporation of water from the soil which is dependent on the amount of soil moisture and shading. Since there is still soil moisture in the soil for switchgrass, it has higher evaporation than the *Arundo* which has taken up all the moisture and so there is none to evaporate. Since the canopy height and LAI of the switchgrass are lower than that of *Arundo*, it provides less shade than *Arundo*. This is the reason there is a slight negative difference in the evapotranspiration between *Arundo* and switchgrass in the later part of the year. If there is a rain event in September, switchgrass has zero LAI while *Arundo* is still transpiring and *Arundo* evapotranspiration goes above that of the switchgrass's and there is a visible positive difference. If there is no precipitation event, the difference in evapotranspiration becomes slightly negative and evens out to zero.

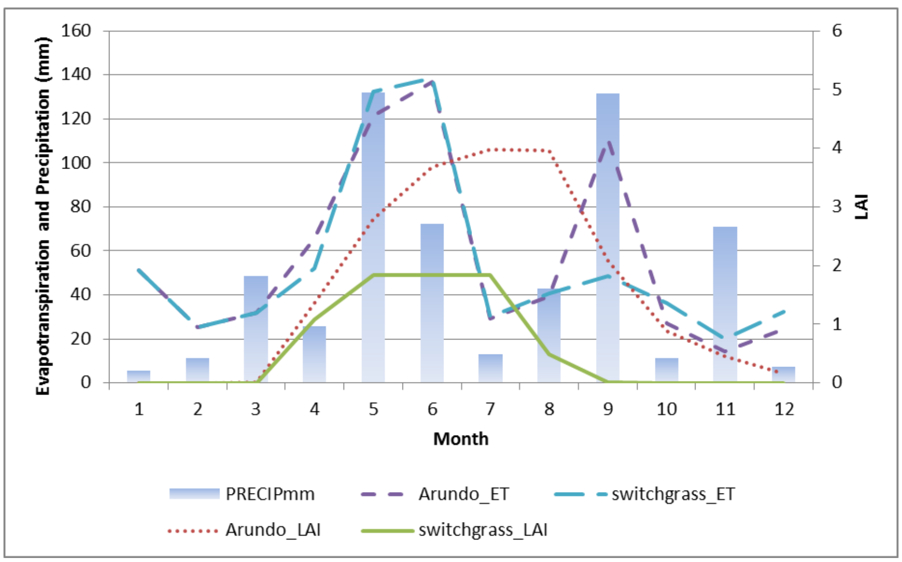


(a)

Figure 19. These graphs show plant growth curves for *Arundo* and switchgrass through their LAIs, monthly cumulative evapotranspiration for both plants and monthly precipitation in the HRUs where(a) The year (2006) had minimum precipitation (b) Year (2007) had maximum precipitation (c) Year (1995) had medium precipitation. In all three instances the evapotranspiration shows a combination of positive and negative differences based on the plant growth curve and the available soil moisture.



(b)



(c)

Figure 19. continued

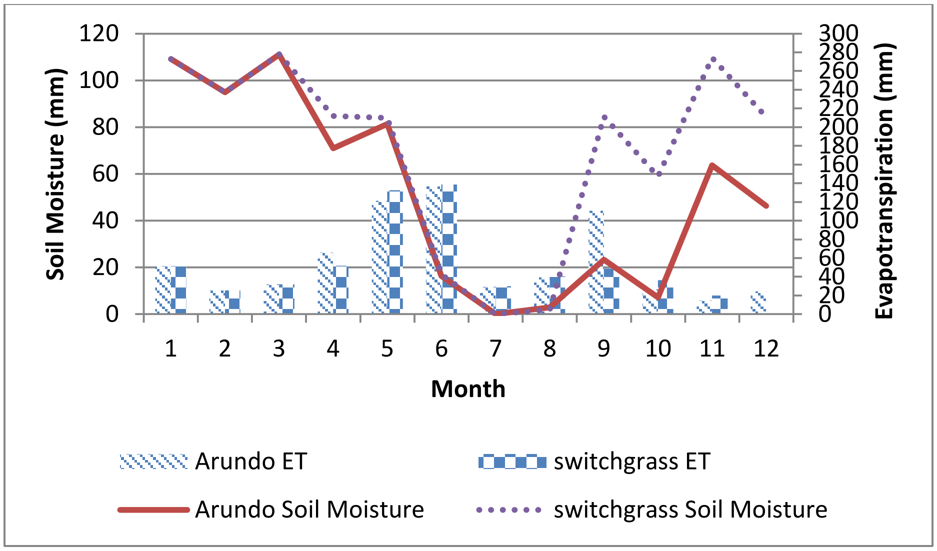


Figure 20. A plot comparing evapotranspiration (ET) by *Arundo* and switchgrass with soil moisture conditions for both types of vegetation for the year 1995.

The limitations of the study were that the SWAT model could not incorporate the density of *Arundo* and a combination of mixed vegetation in the riparian region as is actually seen in the watershed. The model simulated a large number of water stressed days. *Arundo* which can be seen growing within the river would have access to water at all times but it could not be simulated in SWAT. This *Arundo* which is in water affects its geomorphology by changing the routes of water flow and causing sedimentation which could not be accounted for. *Arundo* has invaded only the riparian region of the watershed and was found in an area that covered only 0.16% of the entire watershed analyzed in this study. If it were like invasive species such as *Tamarix* and *J. ashei* which have covered upto 80% of some of the basins in Texas, the hydrology might have been better simulated since a larger area covered would translate to a higher contribution to the water cycle in terms of leaves evapotranspiring and roots helping infiltration. The findings in this study support the study by Nagler et al. (2008) who found that there was no difference in evapotranspiration between the *Tamarix* and the native species on the Lower Colorado River.

IV.4.2.4 Conclusions and future work

The hydrologic impacts of *Arundo* were studied as against the switchgrass which was the native species in the headwaters of the Nueces Headwaters using the SWAT model. It was found that there was no significant difference in water yield or evapotranspiration due to the invasion of Arundo. This is due to the fact that the area is water stressed for a long proportion of the year and although the plants have the potential to take up water, there is none in the soil to be absorbed. The SWAT model could not account for *Arundo* that is found within the water and should not face any water stress.

Future work would include running the SWAT simulations using autoirrigation for *Arundo* so that the model can draw water from the river and make sure there is no water stress for the plant. This would help better understand how *Arundo* is competing with the native vegetation when water is abundant.

CHAPTER V

CONCLUSIONS AND FUTURE RECOMMENDATIONS

The overall goal of this research was to study the impacts of the *Arundo* invasion on the headwaters of the Nueces River watershed. The study was divided into three parts – Streamflow Analysis, *Arundo* Propagation and SWAT Modeling. The streamflow analysis of data from the Laguna gage (USGS 08190000) showed a positive trend for the period before *Arundo* invasion and a negative trend for the period after. The limitations of this analysis were the presence of one one gage with longterm streamflow data, the absence of a methodology to separate baseflow from streamflow for a karst region and only two stations with precipitation data ranging the period of this study. As no specific trend for precipitation was found for the study period, it was hypothesised that the reason for this could be land use change, namely the invasion of *Arundo*. However, this hypothesis could not be proved by the SWAT model simulations of *Arundo invasion* in the watershed.

The SWAT model successfully simulated the karst watershed and the calibrated and validated model was evaluated by a set of statistical parameters with good results. Therefore the hydrology of the watershed was well simulated by the model as indicated by good statstical performance measures. Parameters of *Arundo* were established by running the ALMANAC model. *Arundo* was added as a new crop to the SWAT database. Although the plant growth curves between the *Arundo* and the native *P.virgatum* showed a significant difference, there was an insignificant difference in the cumulative simulated evapotranspiration among two plant types over a period of 16 years. This was explained by the fact that the *Arundo* absorbs water faster than the *P.virgatum* in the initial parts of the year but the moisture in the soil is depleted in April. Due to lesser rates of evapotranspiration *P.virgatum* absorbs soil moisture through a longer period of time. As the growing seasoncomes to an end, leaves of both plants senesce and transpiration reduces. Evaporation takes over and *P.virgatum* aids more evaporation than *Arundo* because of it giving less shade. Finally the difference in evapotranspiration zeros out. The presence of *Arundo* within the waters of the river and its effect on changes in the geomorphology could not be simulated well by the SWAT model. If this could be incorporated, there would not be a lesser proportion of water stress days for the species since the roots would have direct access to the water in the reach. In addition, changes in the geomorphology in the Nueces River could not be simulated by SWAT. Also the area occupied by the *Arundo* was only 0.16% of the entire watershed.

As part of this study, a propagation algorithm was developed for the *Arundo* which can be used to study the propagation of various invasive species that might propagate due to flooding. A preliminary simulation was run that used a time step of 1 month. The assumptions that the *Arundo* spreads exponentially where its stalk falls and downstream during flood events were successfully simulated. Factors such as transport of stalks due to wind or humans were not incorporated at this stagedue to lack in data and can be added to the algorithm using simple conditionals in the form of (if..then..else..). Real time wind movement and precipitation data can be incorporated to make a more accurate modek. Minimum distance between two generated points also needs to be incorporated so that the density is not restricted to a very small radius around the transplanted stalks in flood events. These were beyond the scope of the study due to limitations in data in *Arundo* growth and propagation. Models like LANDIS II (Scheller et al., 2007) could be integrated with the present algorithm to add the factors that could not be incorporated due to lack of data about the propagation of *Arundo*.

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APPENDIX A

Table 11. Crop growth parameters.

	Parameter	Description
BIOMASS PRODUCTION	BIO_E (RUE)	Radiation-use efficiency or biomass-energy ratio
	WAVP	Rate of decline in radiation use efficiency per unit increase in vapor pressure deficit
	BIOEHI	Biomass-energy ratio corresponding to the 2nd point on the radiation use efficiency curve
	CO2HI	Elevated CO_2 atmospheric concentration (μL CO_2/L air) corresponding the 2nd point on the radiation use efficiency curve
LEAF AREA DEVELOPMENT	BLAI	Maximum potential leaf area index
	FRGRW1	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve
	LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve
	FRGRW2	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve
	LAIMX2	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve
	DLAI	Fraction of growing season when leaf area begins to decline
	CHTMX	Maximum canopy height
	RDMX	Maximum root depth
TEMPERATURE	T_OPT	Optimal temperature for plant growth
	T_base	Minimum (base) temperature for plant growth
NUTRIENTS	PLTNFR1	Nitrogen uptake parameter #1: normal fraction of nitrogen in plant biomass at emergence
	PLTNFR2	Nitrogen uptake parameter #2: normal fraction of nitrogen in plant biomass at 50% maturity

Table 11. continued

	Parameter	Description
	PLTNFR3	Nitrogen uptake parameter #3: normal fraction of nitrogen in plant biomass at maturity
	PLTPFR1	Phosphorus uptake parameter #1: normal fraction of phosphorus in plant biomass at emergence
	PLTPFR2	Phosphorus uptake parameter #2: normal fraction of phosphorus in plant biomass at 50% maturity
	PLTPFR3	Phosphorus uptake parameter #3: normal fraction of phosphorus in plant biomass at maturity
HARVEST	HVSTI	Harvest index for optimal growing conditions
	WSYF	Lower limit of harvest index
	CNYLD	Normal fraction of nitrogen in yield
	CPYLD	Normal fraction of phosphorus in yield
	USLE_C	Minimum value of USLE C factor for water erosion applicable to the land cover/plant
	GSI	Maximum stomatal conductance at high solar radiation and low vapor pressure deficit
	VPDFR	Vapor pressure deficit (kPa) corresponding to the second point on the stomatal conductance curve
	FRGMAX	Fraction of maximum stomatal conductance corresponding to the second point on the stomatal conductance curve
	RSDCO_PL	Plant residue decomposition coefficient
	ALAI_MIN	Minimum leaf area index for plant during dormant period
	BIO_LEAF	Fraction of tree biomass accumulated each year that is converted to residue during dormancy
	MAT_YRS	Number of years required for tree species to reach full development (years)
	BMX_TREES	Maximum biomass for a forest
	EXT_COEF	Light extinction coefficient