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Tamarix and the Colorado River Basin

An Interactive Qualifying Project Report
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Abstract

Human development of the Colorado River, in order to alleviate water and energy shortages in the American Southwest, has caused stress on riparian ecosystems. As a result, foreign plant species can thrive. Through literature review, this project examined the complex relationship between river development, water limitations, and invasives such as *Tamarix*. It was found that *Tamarix* may not be as high a water consumer as previously assumed, but has contributed to an ongoing pattern of declining ecosystem health.

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"You never miss the water till the well runs dry."

-Rowland Howard [*Floruit* 1876]
(qtd. in: Morley 1964)

1 Introduction

Water has been a key factor in the development of the American Southwest. A major source of that water has been the Colorado River. The human population in the Colorado River Valley region has more than doubled from 1960 to 1990 which is two and a half times the national growth rate for that same period (Grahame and Sisk 2002). Since much of the area is arid to semi-arid, the demand on the Colorado is enormous. Metropolises such as Los Angeles, Phoenix, Tucson, and Las Vegas are located in the middle of deserts and depend largely on the Colorado River as a significant water and power source (WEF - Water Education Foundation 2000).

In order to better utilize the Colorado River resources, construction projects have taken place such as dams and diversions. These alterations have affected the natural systems that have developed over millennia by interrupting or destroying the fluctuations in water flow and course. For example, minerals are prevented from flowing down the river and seasonal flooding has come to a halt. These changes can have devastating effects on ecosystems along every part of the river.

Riparian ecosystems lie on the intersection of waterways and land. It makes sense therefore that they will receive the brunt of the effects of the river projects of the past seventy-five years. Riparian areas also represent some of the most biologically diverse areas in all of the United States. In the eleven western states, a majority of all plant, mammal, reptile, bird, and amphibian species depend on the existence of healthy riparian ecosystems at some point in their lives (Grahame and Sisk 2002). In addition to local species, migratory species also frequent the riparian areas of the Colorado River.

Additional stress on the Colorado River ecosystem has arisen from invasion by foreign plant species. Since people were able to travel, they have also been moving plant and animal species either directly or unintentionally. In removing species from their natural habitat, they are also being separated from their natural enemies. In the introduced environment, this advantage can allow them to survive, reproduce rapidly, and consume the resources of native vegetation. As a result, many native plant species are wiped out, and with them food and habitat sources for countless other species.

Introduced primarily for its aesthetic appearance, *Tamarix* (also commonly known as Tamarisk and salt cedar) is one such plant genus that is thriving in the United States and is non-native to the Americas. It has been classified among the ten worst noxious weeds in the country (Mahr 2000) but has been given little attention by the U.S. Department of Agriculture because it is not an agricultural nuisance. *Tamarix* has been widely referred to as a high water user. It is commonly known that it is a phreatophyte, meaning its primary root system grows downward into the water table or its capillary fringe. As a result, it may be consuming already highly limited ground water.

This project consisted of an investigation into invasive species, specifically *Tamarix*, the amount of water it consumes through evapotranspiration, its influence in the degradation of biodiversity in riparian areas, and human construction of the Colorado River. In order to understand this complex relationship, the history of the land, its peoples, and their control over it were introduced. Next, the environmental consequences of river control projects were summarized. Discussion includes factors which may result in invasive plant species replacing native varieties, as has been observed along the Colorado River. As *Tamarix* is often mentioned as a particular concern, it is discussed most specifically.

The methodology of this project consisted of the analysis and comparison of various publications regarding water use, invasive species, and *Tamarix*, with a special focus on Glenn et al. (1998), Vandersande et al. (2001), and Horton & Clark (2001). Through case study research, the physiological advantages of *Tamarix* were reported which in part explain its recent success compared to other native species. Additionally, *Tamarix* water use was examined including the most current evapotranspiration measurement methods. Next, possible control methods were explored followed by a conclusive summary of all performed research.

2 The Colorado River Basin

The Colorado River Basin covers an enormous piece of the American West, approximately 130,000 square miles. It encompasses parts of northern Arizona, western Colorado, northwestern New Mexico, and southeastern Utah. It could only be contained within the states of Alaska, Texas, California, and Montana. The basin was originally named the 'Colorado Plateaus' by Explorer John Wesley Powell; though the 'plateau' more accurately resembles a giant basin, confined within highlands, and containing many individual plateaus (Wheeler 1990), as well as mesas, plains, and smaller basins (Grahame and Sisk 2002). Three-fourths of the land contained in the basin is federally devoted in the form of national forests, parks, and American Indian reservations (Royo 2000).

Rivers

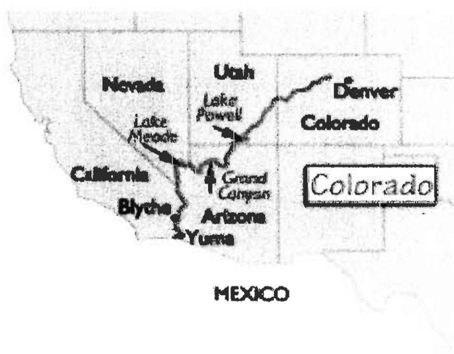

Figure 1: US Portion of Colorado River (worldatlas.com 2003)

The Colorado River is the heart of the basin.

At the same time, the river carves out magnificent canyons and supports six national parks and numerous recreational areas. It travels through two major deserts, the Sonaran on the Arizona (eastern) side and the Mojave on the California (western) side, providing life to the region (Royo

2000). The river also provides water to growing metropolises in the middle of deserts such as Los Angeles, Phoenix, Tucson, and Las Vegas (WEF 2000). These cities would likely not exist, at least in their current forms, without the Colorado River.

The Colorado River begins with the combination of snow melt from the Rocky Mountains of Colorado and glacial melt from Wyoming (Moving Waters 2001). It travels southeast for approximately 1,470 miles into Mexico where it is discharged (sometimes at the level of only a trickle) into the Gulf of California. The majority of its route, 1,360 miles, is within the United States making it the nation's fifth longest river (Royo 2000).

Several other smaller but still significant rivers and tributaries cut through the basin; the San Juan, Sevier, Little Colorado, Green, Virgin, Kanab, Paria, Escalante, Dirty Devil, Dolores, and Gunnison Rivers, as well as the Colorado have together cut out thousands of miles of canyons that exist in the basin (Wheeler 1990). The longest and most impressive of these gorges is the Grand Canyon, stretching from the mouth of the Paria to Grand Wash Stream. In southeastern Utah, at the juncture of the Green and Colorado Rivers, Canyonlands National Park is similarly magnificent (Royo 2000).

Geohistory

The Colorado River Basin region is ancient, even in terms of geographic history. This sizable piece of land mass is at least 500 million years old. According to continental drift theory, it stood alone 300 to 400 million years while the remaining land mass that today comprises North America was still part of Africa, Asia, and South America.

Standing alone, it had a significant amount of shoreline. Rising seas my have inundated a significant portion of it. The water created mounds of sediment which over time, under heat and pressure, hardened forming a mantle of sedimentary rock several miles thick. This geographical 'classic' has stood the test of time. Even when, 10 million years ago, the western United States rose to elevations reaching three miles above sea level the basin was likely anchored under its own weight while at the same time floating upon molten lava (Wheeler 1990).

Human Control of the Colorado Basin

Evidence of human occupation of the Colorado Basin has been dated back about 11,500 years through carbon dating. This period falls toward the end of the Pleistocene period. This period marks the last ice-age and it is also characterized by the presence of distinctively large animals and birds (such as the mammoth, mastadon, and sabre-toothed cats) (Waggoner, et al. 1995). Early inhabitants of the basin were big game hunters and may have contributed to the extinctions of a lot of the large animals of the area (Grahame and Sisk 2002).

About 8,000 years BP (before present), Archaic people inhabited large areas of the basin. The large animals used for food by those before them were for the most part extinct. Archaic people were mostly nomadic and likely trailed the movements of small game animals and gathered plants for sustenance (Waggoner, et al. 1995). What is particularly amazing about these people is that they survived in the region for approximately 6,000 years while having little impact on their environment, unlike the

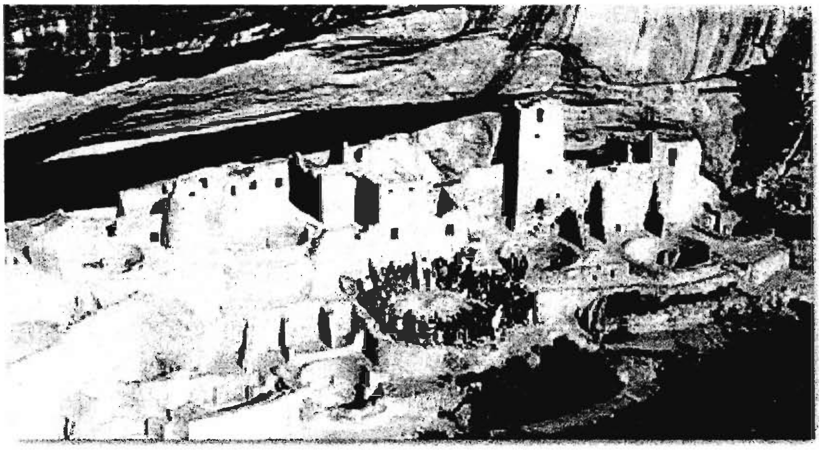

Figure 2: Anasazi Palace (Sharp 2002)

cultures who resided their previous and who reside their today (Grahame and Sisk 2002).

The next inhabitants to the area were the Anasazi people. They dropped the nomadic ways of the people before them and began cultivating the earth. While they still hunted/gathered, they did this mostly to complement the corn, beans, and squash they were cultivating (Sharp 2002). They were highly successful peoples and carved amazing palaces and homes out of the high stone walls typical of the area, many of the larger ones containing 100 to 500 rooms (Figure 2). They thrived and their populations boomed to around 1 million (comparable to today's population of the area) (Grahame and Sisk 2002).

Around the thirteenth century A.D., the golden age of the Anasazi was coming to an end and populations shifted. The reasons for this sudden dispersal are not definitively known, but it was likely water shortages caused by a combination of drought conditions (lasting for about 50 years) and other climatic cycles which caused the water table to further decline. Many migrated to areas with a more constant water source such as along the Rio Grande River (Grahame and Sisk 2002).

The next major groups to inhabit the area are Europeans. In central and northern New Mexico, roughly 100,000 American Indians lived in about 100 pueblo communities at the time of the Spanish arrival in the 1500's. Populations of American Indians declined sharply due to the arrival of European diseases and the Spanish military. Between 1776 and 1847, numerous European explorers and trappers were making contact with native peoples without though they persisted. The opening of the West to Anglo-American settlers through the Homestead Act of 1862 forced most of the American Indians off the basin or confined them to negligible plots of land. On the basin today, about a quarter of the residents are American Indian, the majority of whom are members of the late-arriving Navajo (Grahame and Sisk 2002).

Bureau of Reclamation

Today, the Colorado River is developed to serve a significant portion of the water and electrical demands of 25 million people in seven states: Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California. The residential, agricultural, and commercial water needs of these communities make the Colorado River one of the most stressed rivers in the world (Moving Waters 2001; WEF 2000). It is responsible for the irrigation of 3.5 million acres of farmland. More water is extracted from the Colorado River Basin than from any other river basin in the world (WEF 2000). As well, of its 9 1/2 million potential horsepower, a large portion of that, nearly two million has been developed (Royo 2000).

In the late 19th Century, some small forms of river development were taking place along the river in the form of small dammings or pondings, by the Mormons in Utah for example. As a prominent engineer in the U.S. Geological Survey, Arthur Powell Davis was one of the earliest advocates of large scale development of the Colorado River. He possessed the skills and connections to draw up a plan for "the gradual comprehensive development of the Colorado River by a series of large storage reservoirs" with which he could gain public backing. What resulted was the United States Bureau of Reclamation in 1902 with which Davis became an engineer (Hundley 1996).

Few major developments occurred in the years to follow, although the seeds of growth had been sown. Congressman William Kettner introduced a bill in 1917 under pressure from his farmer constituents that would allow for the creation of a canal. The canal was intended to relieve the farmers' dependence on water from Mexico. This bill got Davis's attention who argued the plight of the Imperial Valley farmer was "inseparably linked with the problem of water storage in the Colorado Basin as a whole." as the canal would still be at the mercy of natural water flows (Hundley 1996).

Davis's position seemed well received in Washington. Another party to take notice was officials in the city of Los Angeles. The city's chief of the Bureau of Water Works and Supply and the head of the Bureau of Power and Light had dedicated their lives to providing adequate water and electricity to the city. At the same time, they had seen the population of the city grow 600% in just 20 years. They turned to a form of Davis's solution for support and approached city council who took to the plan quite favorably (Hundley 1996).

In order to gain water and power from the Colorado River, diversion dams, generators, an aqueduct, and pumping stations would all be required. This project was not within the budget of the city and turned to backing from local communities. What ultimately resulted from this was the creation of the Metropolitan Water District of Southern California (MWD) in 1924, which was able to get support from the state of California. Davis, the Imperial Valley residents, Los Angeles, and the twenty-six other member communities of the MWD were now fierce in their eagerness to develop the Colorado River. Many in the other basin states watched with skepticism as members of the federal government, and the state that contributed the least amount of runoff to the river, planned for its future. Still, others were planning their own reclamation projects (Hundley 1996).

Heightening concern throughout the upper basin was a series of events that seemed to be favoring faster growing states such as California. One such milestone was the passing of the doctrine of prior appropriations which entitled only those who were first settled to water rights. The upper basin states continued to appose Reclamation projects until their interests were safeguarded. The leader in devising such a protective strategy was Delph Carpenter of Colorado. At a meeting of the League of the

Southwest, Carpenter called for a compact that would focus on the issues surrounding the Colorado River. After approval by the League, the legislatures of all the basin states, and Congress, the Colorado River Commission was formed. Delegations began in January of 1922 with Secretary of Commerce, Herbert Hoover, presiding (Hundley 1996).

Carpenter once again took steps to aid in compromising between states. He distributed a draft proposal before a November 1922 meeting of the Colorado River Commission suggesting that the upper and lower basins should equally share appropriations of the river's waters. The mid-point of the river, as defined in his proposition, was Lee's Ferry, an old river-crossing station in northern Arizona near the Utah border. Thus his proposal mainly defined the upper basin as Wyoming, Colorado, Utah and New Mexico and the lower basin as Arizona, Nevada, and California. It was approved with each basin receiving 7.5 million acre-feet per year (one acre-foot equal 326,000 gallons) based on the Reclamation Bureaus's calculation that the flow of the Colorado River at Lee's Ferry was 16.4 million acre-feet annually and that at least half of the water deposited into the river is done so in the upper basin. While the method used for these calculations was likely understood to be not perfect, it was lightly discussed (Hundley 1996).

Mexico was allocated very little and American Indian tribes of the Colorado River Basin fared no better. This was particularly concerning to Mexico because just across from California's Imperial Valley is Mexicali, also very rich agricultural land. After 15 days of bargaining, on November 24 1922, the formal signing took place. Arizona was concerned however and refused to ratify the compact because of fears that they would have none of the river remaining for themselves when their state contributes a significant contribution of runoff and because the first major project planned for the Reclamation Bureau, the Boulder Canyon legislation would likely not benefit them.

The Boulder Canyon Bill, or Swing-Johnson Bill, apportioned 0.3 million acre-feet to Nevada, 4.4 million acre-feet to California, and 2.8 million acre-feet to Arizona (Hundley 1996). The bill also authorized construction of the Boulder (now Hoover) Dam (Royo 2000). Congress effectively warned California to not take more than its share and on June 25, 1929, it was declared effective by President Herbert Hoover (Hundley 1996). The Reclamation Bureaus first major project, the Hoover Dam, began in 1931 (WEF 2000). Construction was slowed by the onslaught of the Great Depression of the 1930s, but the Hoover Dam was completed in 1935 and one year later hydroelectric power was reaching southern California communities (Hundley 1996). This is the first time the concept of a multipurpose dam was implemented (Royo 2000). They started to receive water from the river, as did farmers in the Imperial Valley. Los Angeles, reaping from the benefits of the Colorado, grew to three million (Hundley 1996).

Arizona argued that California was taking water that rightfully belonged to them and turned to the US Supreme Court. They asked that the Boulder Canyon Act be deemed unconstitutional though the courts disagreed. Differences between California and Arizona intensified with other court cases and culminated in 1933 when Arizona sent their National Guard to prevent the construction of diversion works planned by California's MWD, though they were only able to hold them back temporarily. With increasing populations in both states, electricity and water were becoming more and more valuable. Arizona, in suffering electricity shortages, agreed to tapping in to the electricity supply of the Hoover Dam in 1939. On February 24, 1944, after twenty-two years of opposition, the Arizona legislature unconditionally ratified the Colorado River Compact and almost immediately began working with the Bureau for a reclamation project of their own (Hundley 1996).

Shortly after the success of the Hoover Dam, planning began almost immediately for the Parker Dam, which was to be located just downstream the Hoover Dam. From Havasu Lake, the reservoir behind the dam, water is transported to supply water to Los Angeles and San Diego. The Davis, Imperial, Laguna, and Morelos dams were all to follow in the lower basin (Royo 2000). In the upper basin, Reconstruction projects were taking place as well. The most controversial was the Glen Canyon Dam in Utah. Opposition to its construction was large though construction was completed in the mid-1960's. The controversy over the creation of this Dam helped contribute to the rise of water management and environmental protection legislation (Royo 2000).

Controversy still existed between the states regarding allocation of water until a 1963 U.S. Supreme Court decision which explicitly defined the amount of water apportioned to the states as well as the amounts allocated to American Indian reservations and federal public land. In the wake of this decision Arizona was able to gain a project of their own, the Central Arizona Project. Completed in the 1980s, the project gave Arizona the means needed to transport water from Lake Havasu to the cities of Phoenix and Tucson (Royo 2000).

Today, more than 20 dams have been constructed on the Colorado River and its tributaries (Royo 2000) as well as 20 hydroelectric plants and 80 diversion channels (Moving Waters 2001). The River's waters are diverted to supply water to many local communities including Cheyenne, Wyoming; over the Continental Divide to the city of Denver; communities in the Salt Lake Valley in Utah and the Rio Grande Basin in New Mexico (WEF 2000). Nationally, the Bureau of Reclamation operates more than 457 dams and 348 reservoirs (BoR). The sum of court decisions, compacts, treaties, and laws that govern the distribution of these resources are collectively known as the Law of the River.

Many argue that these current technologies are necessary in order to provide the area with inexpensive, and relatively environmentally clean, power, drinking and irrigation water, and protection from possibly destructive floods. Others however, including many in the scientific community, have realized that these projects can have devastating effects on the local environment including fish, wildlife, and four endangered fish species known to be in the river. Nothing along the Colorado River is easy and policy regarding the basin is always tied up in litigation and controversy. Conflicts over the river's valuable resources continue to this day between states over water rights and between those in the environmental and political communities (WEF 2000). As Jackson et al. (2001) contend, water rights are important because they lie at the interface of science, politics, society, and the environment. Today, environmental effects of all river projects must be assessed before construction may begin (Royo 2000).

Environmental Consequences

One of the major effects of the construction by the Bureau of Reclamation on the Colorado River has been the stabilization of natural river flow. The natural timing and quantity of river flow has drastically altered the normal environmental conditions that the plants and animals of the basin have come to depend on. As a result of this stress, local fish and wildlife suffer. Dams and diversions destroy, or at least alter, natural aquatic habitat.

The quantity of water in the river has been drastically reduced by Reclamation projects. Populations in many southwest cities have been booming requiring increased water needs. Nearly every drop of the river's water is pumped out. If the water is returned, such as when the top soil of agricultural land is flushed, it returns contaminated with salts, pesticides, and sediment.

Ground water levels are further stressed by cities. Water is pumped out more rapidly than it can be replaced. Further, cities cause the ground to become 'impervious.' As the ground is covered with buildings, roads, and parking lots, it loses its ability to absorb groundwater. Instead, the water is drained into a local stream or river with high oil and waste content.

Riparian Areas

Riparian areas are those that border streams and rivers; they represent the interface between dry and wet ecosystems. In the eleven western states, riparian areas total only one-percent or less of the total area of public land space, but a large quantity of the local wildlife frequent these areas: 80% of all mammals, 72% of all reptiles, 90% of all bird species, and 77% of all amphibian species. These animals use the riparian areas primarily as a water and food source, as a source of cover, and as migration routes. Many animals, such as 30% of the regions bird species, reside solely in wetlands and riparian areas. The degradation of riparian habitats not only spells doom for the large number of local species which depend on them; riparian areas of the Colorado Basin also support many migratory species and other continental species with already declining populations (Grahame and Sisk 2002). Of course, there are many plant species which depend on the water sources that riparian areas provide, some of which will be discussed throughout this paper.

Humans have had a long history of altering environments along the Colorado River. In the 19th Century fur trappers nearly eliminated the region's beaver population. Beavers are an important member of riparian biospheres. The dams they build help support many area mammal populations, fish populations, and some bats and birds (Grahame and Sisk 2002).

While beaver dams are necessary, human damming has been detrimental. Dams, diversions, channelization, and irrigation have had devastating effects on riparian ecosystems; they have quelled natural hydrologic systems when some species depend on their unpredictability. Human consumption of the natural water ways have reduced them to a mere trickle and have caused water tables to decline. Cottonwood and willow (native competitors of the exotic *Tamarix*) in particular thrive in areas where flooding and channel shifting occurs, which now occurs very infrequently. The loss of riparian vegetation, in turn, causes sediment to be washed down river, thus stream beds become shallower and wider and water temperatures increase degrading fish and aquatic invertebrate habitat (Grahame and Sisk 2002).

Other human behaviors that have altered the natural ecosystem of the Colorado Basin include building, logging, construction and other development. Agriculture has caused a drastic increase in the amount of fertilizers, salts, and nutrients in rivers and streams. Sewage treatment facilities have also contributed to the declining water quality and increased eutrophication. Moreover, domestic livestock have overgrazed much of the area hitting willows and cottonwoods especially hard (Grahame and Sisk 2002).

Riparian areas in particular have been negatively affected by development in the Colorado River Basin. This is of concern because many area plant and animal species depend on riparian areas at some point in their lives; the health of these areas ripples outwardly to affect other ecosystems. Logging, mining, agriculture, grazing, and urbanization all affect both the quality and quantity of water entering the rivers (AR - American Rivers).

Dams in particular devastate riparian areas. They flood upstream zones and prevent variable flow of water and sediment distribution down stream. Diversions and withdrawals for municipal, mining, or irrigation uses also harm the riparian zone as well as groundwater removal (AR).

Invasive Species

One of the effects of these stresses on riparian areas is that native species become disadvantaged and replaced by species that would otherwise be uncommon in that area.

Invasive species (also called exotics, alien, non-native, nonindigenous, foreign, or introduced species) are organisms that have extended beyond their native habitat or have been intentionally or unintentionally moved from one part of the world to another (Grahame and Sisk 2002). In doing so, the species often is separated from all of its natural enemies. Thus, if it can naturalize itself in its new environment, it has a distinct advantage over native species.

Invasive species travel in a variety of ways and can have devastating effects on the environment which they inhabit. They can travel attached to a boat or plane, they can make their way into export bags of seed, they can even be moved purposely, as is the case for pets, food, or ornamental shrubs. Because they are being separated from their natural enemies, they can replace native species. This reduces biodiversity and can produce monocultures, which are always detrimental to the environment. Other problems invasive species can bring with them are disruptions of nutrient and fire cycles, and changes in plant succession (Hart 1999). Invasive species have likely infested every ecosystem on this planet. Currently, there are thousands of invasives in the U.S. introduced both intentionally and unintentionally. Some common plant species which are actually exotics include: wild barley, Mediterranean grass, tumbleweed, fountain grass, red brome, wild oats, wild mustards, buffel grass, and lonegrass (Hart 1999).

Tamarix

Of all the invasive plant species in North America, the genus *Tamarix* has been one of the most successful (Hart 1999). *Tamarix* (often referred to as Tamarisk or Saltcedar; see Taxonomy) is now a dominant riparian plant in the Colorado River Basin, particularly at elevations below 6,000 (Grahame and Sisk 2002; Stevens, *Exotic*) or bellow 2,000 feet as reported by Graf (1978). In particular, it is one of the most dominant species in riparian habitats throughout the American Southwest and Australia (Stevens, *Exotic*; *Scourge*). *Tamarix* currently occupies more than one million acres of riparian area. (Stevens, *Scourge*).

Figure 3: Tamarix (Hart 1999)

Taxonomy

Currently, the taxonomy of *Tamarix* is in a state of confusion. The genus *Tamarix* is a member of the *Tamaricaceae* family. Because members of the genus have few consistent differentiating features, and because taxonomists have disagreed over which are most important, the species within the genus have been difficult to classify (WA-NWCB - WA state Noxious Weed Control Board 2002). Baum (1978) reports 54 species in the genus *Tamarix*, while Hart (1999) reports 90. Much more study will likely be required before we have a complete understanding of the classification of *Tamarix*.

There is a greater level of agreement on the number of species that have been introduced to the United States. Most reports claim eight species of *Tamarix* have invaded the United States (Grahame and Sisk 2002; Hart 1999; WA-NWCB 2002). However, the U.S. Department of Agriculture (2003) lists nine (http://plants.usda.gov, see Table 1). Some authors distinguish between species, others do not. As an example of the confusion that has surrounded the taxonomy of this genus, it has been reported that *Tamarix* pentandra has been used for *Tamarix* ramosissima (Munz and Keck 1973) but *Tamarix* pentandra may actually be a synonym for *Tamarix* chinesis (Kartesz and Kartesz 1980). Russo et al. (1988) also reports that *Tamarix* ramosissima and *Tamarix* chinesis are often confused with each other. In general, the genus name, *Tamarix*, is used throughout this report to minimize confusion, but specific species names are used when it is relevant.

Tamarix is native to a zone stretching from north Africa through the Middle East to southern Europe to south Asia to China and Japan (WA-NWCB 2002). It does not appear to pose an ecological threat in its native habitat because of ecological balances that are maintained. For example, in Eurasia, *Tamarix* is consumed by more than 250 different species of invertebrates, including livestock and camels. In North America, zero invertebrate species use *Tamarix* as a significant food source (Stevens, *Scourge*).

Table 1: Species of the genus *Tamarix*
as reported by US Dept. of Agriculture (2003)

Genus specie	Common Name
Tamarix africana Poir.	African tamarisk
Tamarix aralensis Bunge	Russian tamarisk
Tamarix canariensis Willd.	Canary Island tamarisk
Tamarix chinensis Lour.	Fivestamen tamarisk
Tamarix gallica L.	French tamarisk
Tamarix parviflora DC.	Smallflower tamarisk
Tamarix ramosissima Ledeb.	Saltcedar
Tamarix tetragyna C. Ehrenb.	
Tamarix aphylla (L.) Karst.	Athel tamarisk

Tamarix was most likely introduced into this country in the early 19th Century (Hart 1999; Muzika 1999; Stevens, *Scourge*). All eight or nine species of *Tamarix* residing in North America were introduced to set up wind breaks, for stream bed stabilizing, as ornamental shrubs, or for creating shade (DeLoach 1997; Grahame and Sisk 2002; Russo et al. 1988; Stevens, *Exotic*). Nurseries along the east coast were likely stocked with the plants by 1823 (Frasier and Johnsen 1991); at least three different species were sold from a nursery in 1854 (Stevens, *Exotic*).

Tamarix likely migrated west through sales between nurseries. Its ability to withstand the desert conditions, along with its beauty and shade, made it a popular ornamental (Frasier and Johnsen 1991). During the 1870's *Tamarix* was widely available in nurseries in the west (Stevens, *Scourge*). During this same period, it was for the first time reported to have escaped cultivation (DiTomaso 1998; Frasier and Johnsen 1991). By the 1920's, *Tamarix* was spreading rapidly through the riparian zones of the southwest (Frasier and Johnsen 1991). The greatest degree of *Tamarix* invasion occurred between 1935 and 1955 (Christensen 1962). Between 1922 and 1938 it first appeared in the Grand Canyon (Stevens, *Scourge*). By the 1950's *Tamarix* was a major problem causing damage to riparian areas from northern Mexico to Montana, from the Pacific to the Great Plains (DeLoach 1997). It has been of greatest concern however in southwestern states such as Texas, Arizona, New Mexico, Nevada, California, Utah, and Colorado (Figure 4).

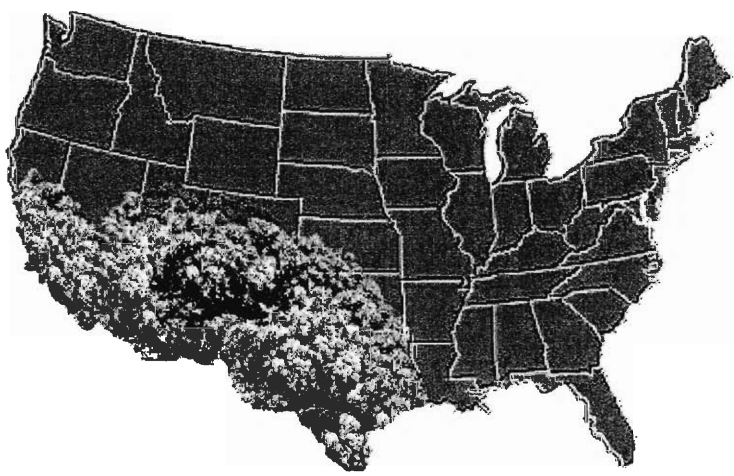

Figure 4: Area of primary Tamarix Invasion (Hart 1999)

Based on a broad view of all the literature collected for this report, it appears as though the three *Tamarix* species which currently pose the greatest threat to the largest area of land are, in descending order: *Tamarix ramosissima*, *Tamarix chinesis*, and *Tamarix parviflora*. These three species in total have habituated themselves in nearly every lower-elevation streambed from southern Canada to northern Mexico (Grahame and Sisk 2002). On the opposite end of the spectrum, *Tamarix aphylla*, a type of evergreen tree, is not easily capable of sexual reproduction in our North American climate and therefore poses no significant threat (WA-NWCB 2002). Most other species in the genus, the shrubby, deciduous varieties, are of more serious concern but are less widespread. The difference between the two most common *Tamarix* varieties, *Tamarix ramosissima* and *Tamarix chinesis*, is flower morphology and habitat. *Tamarix ramosissima* is found invading areas of higher salinity and in areas with standing water such as oases, marshes, and salty lakes, riverbanks, and steppes. *Tamarix chinesis* establishes in areas of lower salinity and along major river drainages (Russo et al. 1988).

Reproduction

The deciduous members of the *Tamarix* genus are shrubs or small trees that generally grow 12-15 feet in height but can reach heights of up to 35 feet (Stevens, *Scourge*). They often occur in dense thickets (Muzika 1999). The branchlets are slender, with 0.5-3.5 mm long appressed scaly leaves which are gradually tapered to sharply pointed (Figure 5). The scale-like leaves are often encrusted with salt secretions, which is from where the common name ‘salt cedar’ developed (Russo et al. 1988).

Tamarix stem tissue, including root crown material, will sprout vigorously when in contact with warm moist soil forming a new plant. In a greenhouse experiment, nearly all fresh stem cuttings from a variety of locations of the plant and in all sizes formed roots (Russo et al. 1988).

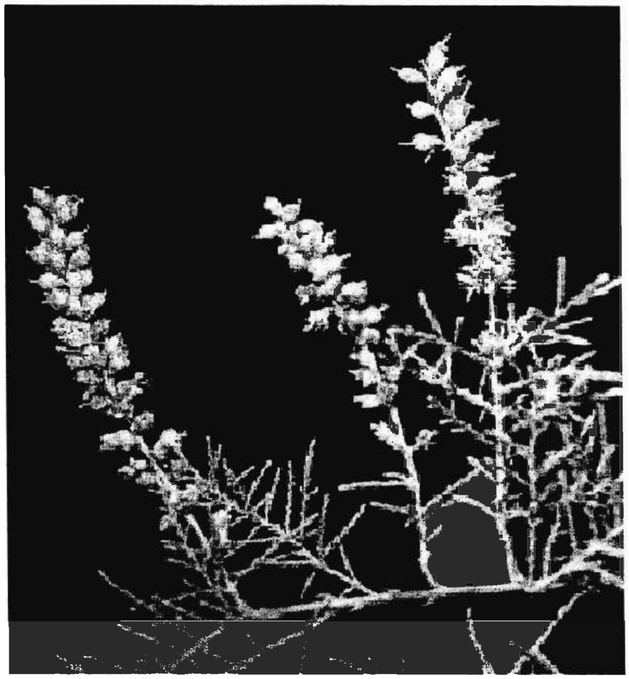

Figure 5: *Tamarix* (deciduous variety) Leaves and Flowers (Lym 2003)

More commonly however, *Tamarix* regenerates from seeds. *Tamarix* is not self-compatible; it is almost wholly dependent upon insect-pollination (Stevens, *Scourge*). *Tamarix* seedlings produce flowers quite quickly, often by the end of their first year (Neill, 1983). *Tamarix* flowers are white to pink in color and produce tiny seeds, each only 450 μm in length, 170 μm in diameter, and weighing 10 μg (Lym 2003; Wilgus and Hamilton 1962). Each seed has a 2 mm long, unicellular hair (Wilgus and Hamilton 1962). These pappus hairs not only assist in dispersing the seeds by wind, but they form a column when moistened helping to anchor the seed in the soil.

Mature *Tamarix* plants are capable of producing many, many seeds. Estimates of annual yields range from thousands per growing season (Wilgus and Hamilton 1962) to hundreds of thousands (Sudbrock 1993) to 250 million (Stevens, *Exotic*; *Scourge*). *Tamarix* seeds are viable for a few weeks (Horton et al. 1960) to about 2 months

(Stevens, *Exotic*) and germinate in less than 24 hours in warm, moist, preferably sandy soil (Stevens, *Scourge*; WA-NWCB 2002). In areas where these conditions are available, 'green lawns' of *Tamarix* seedlings can result. Seedling densities of 15,000 per square yard have been reported in riparian areas along the Green and the upper Colorado Rivers (Stevens, *Scourge*).

Tamarix's Success

Its ability to produce seeds in such amazing numbers does not alone explain *Tamarix*'s success. As we have already mentioned, being removed from their natural enemies gives invasive species a distinct advantage. Unlike the native species with which *Tamarix* competes, "only one native North American insect species slightly damages it" (DeLoach 1997) while more than 200 predators were easily identified in China and the Soviet Union (Mahr 2000). *Tamarix* has several other survival mechanisms in place that aid in its ability to out-compete native species. *Tamarix* has gained so much success that "[h]istorically, the area and the density of plant growth have increased wherever the species has become established. This effect may be expected to continue wherever new areas become established" (Robinson 1965 qtd. in Russo et al. 1988).

Tamarix is extremely drought tolerant which greatly increases its chances for survival in the arid southwest. Once seedlings become established, they can endure severe drought conditions (Schopmeyer 1974). *Tamarix* grows most successfully along stream and lake edges (Brock 1994). It is not dependent upon surface water for survival however as it is a phreatophyte; meaning it grows a 'tap root' which heads straight down into the soil in hopes of making contact with the water table or its capillary fringe. The tap root is very dense and woody and may extend 100 feet or more below the ground (Stevens, *Scourge*). It is also capable of developing lateral roots of about 150 feet in length when no ground water is present making it well equipped for a variety of water conditions (Hart 1999; Stevens, *Scourge*).

In addition, once *Tamarix* seedlings are established, the plant is very tolerant of flooding conditions. It's hard, dense wood makes it resilient to the thrashing water. *Tamarix* species may be better equipped to survive flooding than any of the native woody riparian species with which it rivals. A few *Tamarix* plants have been reported to survive for more than two years of root-crown inundation in the cold, fierce Colorado River waters from 1983 to 1986 (Stevens, *Exotic*; *Scourge*).

Tamarix has been known to be more salt tolerant than most of its native competitors. This property has been quite advantageous as human occupation of the Colorado River Valley (esp. due to agriculture and water management projects) has resulted in increased levels of soil salinity. Campbell and Strong (1964) report that *Tamarix* species force pressurized salt mixtures out of pores. These pores are part of highly turgid salt glands that "are primarily desalting organs capable of reducing salt in the mesophyll cells of the leaves" (qtd. in Russo et al. 1988). *Tamarix* has been observed growing in areas with high salt concentrations, about 700-15,000 ppm (parts per million or mg/kg), whereas low to medium concentrations lie in the 100-3500 ppm range (Neill

1983). *Tamarix* has even been found growing in Death Valley, CA, where the groundwater contains up to 5 percent (50,000 ppm) dissolved solids (Robinson 1965).

Human projects along the Colorado River have put unnecessary stress on the local environment. Water management programs, such as the construction of dams and reservoirs, river diversions, flow regulations, and irrigation projects affect the natural flow of water (Hart 1999). Often, these disruptions create soil conditions unsuitable for the survival and regeneration of native riparian species such as willows and cottonwoods. These programs usually create declining water tables and an increase in soil salinity, unfavorable conditions for native species but fit for *Tamarix* habitation (DiTomaso 1998). As well, agriculture, through clearing, plowing, and overgrazing, seem to create conditions less than desirable for native species but optimal for salt cedar infestation (Hart 1999).

Tamarix thrives best in the moist sandy soil found along riverbeds (Russo et al. 1988). It is in conditions like this, along river drainages, and at lower elevations, that *Tamarix* first became naturalized (Schopmeyer 1974). Today, however, its habitat includes irrigation ditches, streambanks, moist lowlands, and pastures (Russo et al. 1988). *Tamarix* occupied and continues to occupy pre-dam terraces and riparian zones along the Colorado River's tributaries. Also, *Tamarix* was the first species to spread throughout the newly stabilized post-dam riparian zone in the Grand Canyon and along new high water zones (Turner and Karpiscak 1980; Stevens, *Scourge*).

David Thompson, a hydrologist with the U.S. Geological Survey, was working on issues related to surface and ground water hydrology in the Mojave River area in the 1910's and 20's. In doing so, he photographed areas such as the upper and lower narrows near Victorville, the reach upstream of Helendale, the areas of Barstow and Yermo (not shown), and the reach between Camp Cady Ranch and Afton Canyon (Figure 6). Native species evident in the pictures include: cottonwood (*Populus fremontii*), goodding or black willow (*Salix gooddingii*), mesquite (*Prosopis glandulosa* and minor amounts of *Prosopis pubescens*). Smaller-stature species that were also captured in some of the photographs include coyote willow (*Salix exigua*) and seep willow (*Baccharis glutinosa*). Non-native species include *Tamarix* and giant reed (*Arundo donax*), which appeared in the lower Narrows photographs (Webb et al. 2001).

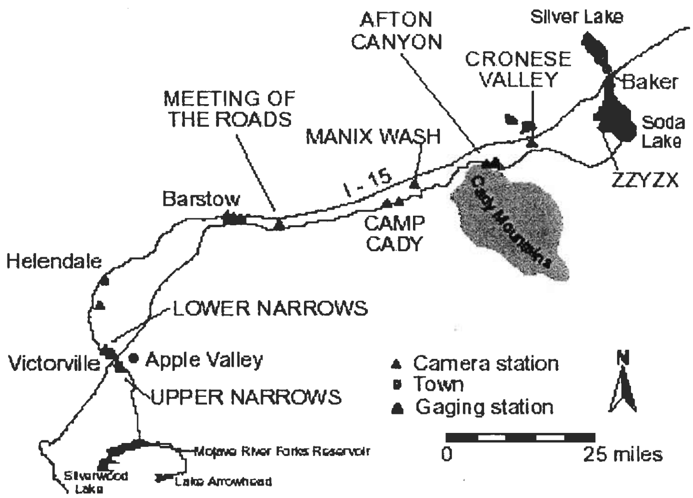

Figure 6: Map of Mojave River basin, CA.

(Webb et al. 2001)

Webb et al. (2001) compared these pictures with modern pictures taken of the same areas. They also noted that ground-water levels in the Mojave River basin have been steadily declining in the latter part of the 20th Century, probably due to local ground-water pumping. They observed that when there was a change in vegetation, the changes were highly variable: populations boomed in some areas and were nearly completely eliminated in other areas, for example. The largest increase in vegetation they observed was at what is now the Mojave Narrows Regional Park, upstream of the upper narrows and between Victorville and Apple Valley. This area was largely dominated by goodding willows in 1917, and now cottonwood prevails. In other areas, native vegetation, including mesquite, cottonwood and goodding willow, dwindled over time, likely due to the decrease in the ground water supply. At Barstow, native riparian vegetation, which was largely mesquite, has been replaced by thickets of *Tamarix*.

A rapid infestation rate by *Tamarix* was observed in other studies. Prior to 1912, no records or reports of the presence of *Tamarix* exist in the Lake McMillan area on the Pecos River in New Mexico. By 1915, *Tamarix* thickets covered approximately 600 acres of delta land. By 1925, *Tamarix* had seized 12,300 acres. Vegetative surveys of the Bernardo Bridge-San Marcial Reach in 1947 and 1955 showed that cover densities of *Tamarix* increased more than 100 percent while the volume of the foliage increased over 75 percent during this short period (Robinson 1965).

Infestations were also observed and recorded in central Utah and along the Rio Grande and Pecos river valleys in Texas and New Mexico (Neill 1983). In 1920, the estimated acreage of land dominated by *Tamarix* in the western U.S. was 10,000 (Robinson 1965). By 1960, that area had increased to between 90,000 (Robinson 1965) and 900,000 (Neill 1983) acres. Stevens (*Scourge*) estimates that by 1970 *Tamarix* occupied more than one million acres (app. 1500 sq. mi.) of riparian habitat in the American west.

Other invasive Plants

Another plant exotic to the American southwest that has been thriving is the russian olive. This tree was also imported from Eurasia and has been replacing native species (such as cottonwood) throughout the west but especially in riparian woodlands (VNPS - Virginia Native Plant Society 2003). Cheatgrass is another invasive that poses a problem in the southwest. Cheatgrass germinates earlier than most native grasses and therefore evapotranspires much of the surface water before the competition even has a chance. Cheatgrass dies early in the season, by the end of July, and causes increased wildfires during the summer months (Grahame and Sisk 2002). Other noxious invasive plants to the Colorado Basin include: knapweed (diffuse, russian, and spotted), toadflax (dalmation and yellow), leafy spurge, and camelthorn (Grahame and Sisk 2002).

3 Methodology

This project is concerned with water consumption in the Colorado River Basin by invasive species. The extent to which invasive species consume Colorado River water or lower the water table in the surrounding arid environment was examined. Invasive species and their effects on the environment were researched, especially in relation to water use in the Colorado River Valley. At the heart of the conversation regarding invasives is *biodiversity* as it is being threatened by exotic species.

Biodiversity

Biodiversity is a measure of the number of different species per unit area. A healthy, diverse ecosystem supports many different kinds of plants, insects, and animals. A healthy ecosystem signifies a clean water source, an abundance of soil nutrients, and low pollution. Diversity is healthier for both local life and broader ecosystems. When people alter natural ecosystems, indigenous species may become extinct from the increased stress.

In general, people disrupt ecosystems in various ways including logging, suburbanization, soil contamination, water depletion, and road building. Natural disruptions like these often can have rippling effects. Problems can be caused when only initially small changes to the environment can impact a broader range of natural systems. For example, in Nigerian ecosystems, a simple road built for loggers then provides access to the outside world which effects native life and is driving the chimpanzee species to extinction.

A significant portion of the Colorado River Basin has never been developed. Steadily, this land is decreasing as the amount of road planning and construction has risen. In particular, the Bureau of Reclamation has played a large role in this kind of development; by damming the Colorado River, many access roads were created that were previously unavailable. Changes such as these impact the quality of life of native animal and plant populations.

Likewise, humans have altered the plant make-up of the Colorado River Basin by introducing foreign species into the area either directly or indirectly and through putting stress on native species. People have imported exotic plants for ornamental purposes that afterwards naturalize into the new open ecosystem. It is possible in these cases that the invasive plant life can contribute to the stress of native plants replacing them. Humans have drastically changed the hydrology of the Colorado River as well as decreased water table levels in the arid Colorado River Valley. Overall, this project will investigate what influence invasive species have on the already stressed water situation in the Colorado River Basin.

Evapotranspiration

Two processes contribute to the loss of ground water to the atmosphere: evaporation and plant transpiration. Together, these processes are referred to as evapotranspiration. Because the water is not returned to the soil, evapotranspired water is consumed water.

Evaporated water is lost from everywhere: from ponds, pavements, and soil to name a few. Energy is needed for this process to take place and that energy comes from direct solar radiation and the ambient temperature of the air, specifically 540 calories of latent heat are needed to evaporate one gram of water. Drier air can more easily transfer water vapor to the atmosphere and wind helps to carry away the humid air on the surface replacing it with drier air. Solar radiation, air temperature, air humidity, and wind speed are therefore critical in determining evaporation rates (Allen et al. 1998).

Transpired water is lost to the atmosphere through stomata, small cellular voids on the plants surface that can open to allow gases and vapor to pass aiding in the photosynthesis process. Water, along with some nutrients, are taken up through the roots and distributed within the plant. Water vaporization occurs predominately within the intercellular spaces of the leaf where it is also discharged to the atmosphere. Most water transpired by plants is consumed in this manner and only a tiny fraction is utilized by the plant. Radiation, air temperature, humidity, and wind also affect transpiration rates as do water content, capillarity, and salinity of the soil and CO_2 rates in the air (Allen et al. 1998).

Evapotranspiration is highly variable and when measurements are made, it is difficult to separate evaporated water from transpired water. This project is primarily concerned with whether or not invasive species transpire enough water for there to be significant concern. Ground water is primarily transpired by phreatophytic vegetation though long tap roots, as is the case with *Tamarix*. It has been estimated that phreatophytes consume 2 acre-feet of water per acre annually (Blackburn et al. 1982).

Research Process

In researching invasive species in the Colorado River Basin, *Tamarix* appeared in a lot of the literature. *Tamarix* is a phreatophytic plant, it is presumed to be a very high water consumer, and its prominence is growing. Therefore, it was examined more closely to determine if it is an environmental problem and contributing to local water shortages.

In order to do this, journal articles and web-sites were examined. Studies regarding transpiration of the plants were analyzed and similarities and differences amongst their findings were discussed. Through a comparison of the research, the risk posed by *Tamarix* was assessed. Control options are discussed as well.

4 Results/Findings

In this chapter, the effects that *Tamarix* has on the environment are reported on. This chapter also closely examines the most recent studies regarding *Tamarix*'s transpiration rates. As well, we will closely examine physiological differences between *Tamarix* and the native species with which it is replacing. Such characteristics are important to an understanding of why *Tamarix* has become so prominent; specifically, drought, flood, and salinity tolerance will be examined.

Environmental Effects

This research indicates that many physiological qualities of *Tamarix* give it a distinct advantage over other native plant species in the Colorado River Basin. As well, *Tamarix* actively changes its environmental surrounding, often in such a way as to further disadvantage native growth. The most frequently discussed environmental effects of *Tamarix* are increased soil salinity, increased wild fire frequency, water consumption, it displaces native plant species and animal habitat, and it chokes streambeds.

Increased Salinity

Tamarix is not only highly tolerant to saline soils, it actively alters the salinity in the top-soil around it. Stems and leaves of mature *Tamarix* plants draw from the soil and secrete salt in the form of a solution out pores which either falls to the ground immediately, or dries up and drops with the leaf. This salt then forms a crust above and just below the ground inhibiting the growth of other plant species (Sudbrock 1993). Saline levels have been shown to increase by the mere presence of *Tamarix* thickets. Most native plant species are not as tolerant to high salinity as *Tamarix* is and are unable to grow, furthering the ability of *Tamarix* to spread. For example, two native plants whose niche is now regularly taken up by *Tamarix*, willow and cottonwood can tolerate up to 1,500 ppm salt salinity, while *Tamarix* has been shown to tolerate 36,000 ppm (Hart 1999).

Increased Wildfire Frequency

Tamarix plants mature early and die early compared to most native plant species in the Colorado River Valley. They die and dry in late summer when temperatures can be sweltering. The result is that *Tamarix* introduces fires to riparian woodlands which researchers believe would otherwise be highly uncommon (Grahame and Sisk 2002). For example, in the lower Colorado River floodplain it has been estimated that between 1981 and 1992, fires burned 85% of *Tamarix*-dominated land area. During that same period, fires burned only 2% of land occupied by native plant species. *Tamarix* is also a very fire adapted species and can quickly exploit land recently struck by fire (Hart 1999). Thus, as in the case with soil salinity, *Tamarix* actively alters the land in such a way as to disadvantage native species while creating environmental conditions with which it itself is highly suited.

Water Consumption

There are wide discrepancies in the literature regarding the exact amount of water *Tamarix* transpires, though it is likely significant. Evapotranspiration quantities will vary with water availability, humidity and other weather conditions, stand density, and calculation method. One report stated that at 80ºF, *Tamarix* transpires the weight of its foliage every hour (Stevens, *Scourge*). It has also been reported that a single large plant can absorb 200 gallons of water per day (Hoddenbach 1987). Others report that transpiration rates of salt cedar may be higher than any other evaluated phreatophyte in southwestern North America. Annual water consumption totals may reach as high as 2.1 cubic meters per square meter (Carmen and Brotherson 1982).

Displaces Native Plant Communities, Wildlife Habitat

In creating these environmental changes, *Tamarix* displaces native vegetative communities. It aggressively ousts native shrubs and trees in several ways (Neill 1983). By taking up the area "that native plants might otherwise occupy," *Tamarix* prohibits their growth and proliferation (Stevens, *Scourge*). *Tamarix* replaces various native species, but specifically fremont cottonwood, willows (sandbar or coyote and Goodding's) and arrowweed (Stevens, *Exotic*). In areas where *Tamarix* and the willow cohabitate, the *Tamarix* prefers the sandy areas while the willows are usually found in the muddier parts (Christensen 1962).

In displacing plant communities, *Tamarix* also affects local wildlife by replacing the plants that used to provide it shelter and food. *Tamarix* shares a symbiotic relationship with very few North American species. In fact, "frugivores, granivores, insectivores, and cavity dwellers are uncommon or absent in saltcedar thickets" (DeLoach 1997). *Tamarix* is unable to provide an adequate food source to native North American wildlife, as it produces only tiny fruits and seeds. As well, its foliage is unpalatable. In displacing native plant communities, *Tamarix* damages valuable wildlife habitat in an area where animal species are otherwise diverse and plentiful. *Tamarix* robs habitat from not only a huge number of North American species, but also migratory animals and birds that use southwestern riparian areas during their travels. As an example, Anderson and Ohart (1976) found that on average, the number of bird species is fewer in *Tamarix* occupied areas than in native cottonwood-willow communities during the same time period.

Streambed Narrowing

One of the reasons *Tamarix* was distributed in the United States was because of its ability to control and tame streambeds. When settled along rivers and streams, its root growth is outward laterally, anchoring it in stream sediment. This quality has helped it thrive along most of the Colorado River and its tributaries. In occupying these areas, *Tamarix* roots can clog streams reducing the stream velocity. This in turn reduces the streams ability to carry sediment. Additional stream sedimentation increases the clogging effects. By deepening and increasing the velocity of the flows, channelization makes it harder for the land surrounding the river to absorb floodwaters (AR). Large thickets can create damming and ponding effects and can increase the frequency and intensity of flooding (Blackburn et al. 1982). Hart (1999) has also reported a correlation between *Tamarix* thickets and flooding. For example, Blackburn et al. (1982) documented *Tamarix* effects on the Brazos River in Texas. Between 1941 and 1979 the river's width decreased from 515 ft. to 220 ft while sediment decreased the water depth at the same time.

When established, *Tamarix* negatively effects the environment by increasing soil salinity, evapotranspirating large quantities of ground water (when surface water is not available), increasing the frequency of wildfires, and narrowing streambeds. It is a highly tolerant species that can thrive in a variety of environmental conditions. *Tamarix* displaces native plant communities and thus wildlife food and habitats causing species to become threatened and endangered. As well, *Tamarix* occupies land which could be valuable to humans recreationally, agriculturally, or otherwise (DeLoach 1997).

Positive Effects

Tamarix has also demonstrated some usefulness to humans and to the environment. *Tamarix* plants can create effective wind breaks and erosion control (with the possible, and likely, consequence of spreading to other areas). Beekeepers value it as a capable of producing a large turnout of honey (Russo et al. 1988); however, the honey is invaluable to the consumer market because it is dark and overly aromatic. The honey is mostly used to feed overwintering hives of bees (Stevens, *Scourge*). Along the Colorado River in the Grand Canyon, some native bird species and many Neotropical migrant birds nest preferentially in *Tamarix* (Stevens, *Scourge*). *Tamarix* thickets make are often used by white-winged doves as nesting habitat for example (Russo et al. 1988).

Case Study 1

In a study by Glenn et al. (1998), six species were compared. *Tamarix ramosissima* was compared to five native plant species (Table 2).

Table 2: Summary of Glenn et al. (1998)

Genus specie	Common Name	U.S. nativity	Salinity Tolerated (g/l)	RGR slopes	Water Loss ($g\ g^{-1}\ day^{-1}, hr^{-1}$)
Allenrolfea occidentalis	pickleweed	native	32	non-linear	3.99 , 0.33
Tamarix ramosissima	salt cedar	invasive	32	2%	12.86 , 1.07
Pluchea sericea	arrowweed	native	16	5%	9.39, 0.78
Baccharis salicifolia	seepwillow	native	8	6%	8.25, 0.69
Populus fremontii	cottonwood	native	8	9.5%	13.05, 1.09
Salix gooddingii	willow	native	8	11%	10.55, 0.88

Species seedlings were tested for salt tolerance and water use characteristics including transpiration rates and water use efficiency. To set up the experiment, seedlings were planted in pots and covered with plastic to minimize evaporation and covered with foam to prevent solar heating of the soil. Solutions were prepared using various concentrations of NaCl with municipal water. NaCl was used as it is the salt most likely to accumulate in riparian areas in the lower Colorado River Basin (Ohmart et al. 1988). Each species was subjected to each salinity treatment. In order to calculate transpiration rates, the quantity of water added to the pot was carefully measured as well as the amount of water that drained from each pot.

After harvest, salt tolerance (% growth reduction per g NaCl) was calculated from each species relative growth rates (RGR, based on mass, $g\ g^{-1}\ day^{-1}$). Individual RGR values were converted to % RGR relative to the fastest observed growth in that species. Salt tolerance is then the slope of the growth response to salinity determined using linear regression analysis

Evapotranspiration (plant^{-1}) was calculated by simply subtracting drained water from added water. Transpiration (plant^{-1} day^{-1}) was calculated by subtracting expected evaporation (based on evapotranspiration rates of empty pots) from cumulative evapotranspiration then dividing by days of growth. Water-use efficiency was calculated by dividing dry production by its cumulative transpiration.

What was demonstrated was that *Tamarix* and *Allenrolfea* were highly salt tolerant (continued to transpire at salinity 32 g/l, highest concentration tested) while *Baccharis*, *Populus*, and *Salix* were intolerant (ceased to transpire at 8 g/l) and *Pluchea* was intermediate. They also demonstrated that in general transpiration decreases with increasing salinity (*Allenrolfea* was the exception and with a peak in growth at 8 g/l). In 1974 Kleinkopf & Wallace had concluded that salinity hinders plant growth because the plant needs to divert more energy towards increased respiration and salt pumping. What Glenn et al. (1998) also did was to calculate the salt tolerance of *Tamarix* and five native riparian plant species. The decline in transpiration was much more pronounced for *Salix* and *Populus* (11% and 9.5%) than with *Tamarix* (2%) and *Allenrolfea*.

The water characteristics of *Allenrolfea* made it far more efficient than any other species. It had the lowest transpiration rate as was measured the day before harvest. In those 24 hours, the water loss of *Allenrolfea* was 3.99 (g water transpired/g fresh weight day^{-1}) and 12.86 and 13.05 for *Tamarix* and *Populus* respectively. When water use efficiency rates were calculated, *Allenrolfea* was significantly more efficient than any other species who all did comparably well.

As with all greenhouse experiments, the conditions are oversimplified and may not accurately represent natural conditions. In comparing their results with studies not conducted in a greenhouse by in the very ecosystems with which we have been discussing, Glenn et al. (1998) found their conclusions to be similar. Sala et al. (1996) measured transpiration rates for *Tamarix*, *Prosopis juliflora* (mesquite), and *Salix* using the stem heat balance method on plants of similar sizes to those in Glenn et al. (1998). Their results, expressed as water loss per fresh weight of leaves, ranged from 2.1-2.3 g g^{-1} hr^{-1} among species. If it is assumed that transpiration takes place over a twelve hour period, the rates for *Tamarix*, *Populus*, and *Salix* in Glenn et al. (1998) convert to 0.8-1.1 g g^{-1} hr^{-1}. And, if it is assumed that leaves make up 50% of shoots, the results are quite similar to each other. Anderson (1982) conducted field measurements on *Tamarix* and *Populus* using the 'leaf chamber method', a method of measurement of transpiration by stomatal conductance, and found somewhat lower rates, 1.1 and 1.2 g g^{-1} hr^{-1}. Other studies, including Busch & Smith (1995) who used a variation Anderson's method (1982), make up the most current measurements on water use of *Tamarix* available today and all demonstrate a similar pattern: that *Tamarix* may not in fact be as high a water consumer as it is widely assumed.

Also in agreement between studies is that *Populus*, *Salix*, and *Baccharis* are not able to complete with *Tamarix* and *Pluchea* in areas of high salinity, above 4 g/l NaCl. The lower Colorado River contains roughly 0.8 g/l of salts. Thus, evapoconcentration can concentrate the salts in the riverbank soil as much as 5-times before significant damage to native species takes place.

Another disadvantage to this study is that the results only document behavior of the species' for the first few months of their existence only. It is quite possible that any of the characteristics described in this study may change as the plants develop.

Case Study 2

In this study by Vandersande et al. (2001), the performance of *Tamarix* ramosissima was compared to those of four of the native species used in Case Study 1, Populus, Salix, Baccharis, and Pluchea. Performance in drought and inundated conditions were measured. In the drought experiment, seedlings of each species were planted and covered as tightly as possible with plastic, foam, and perlite to prevent evaporation. Each pot was watered only once with 3 l of water containing 0.5, 1, 2, and 4 g l^{-1} NaCl. Evapotranspiration was calculated by subtracting the mean water loss of control pots from the water loss by the pots containing plants. In the flood experiment, seedlings were covered with water to a level of approximately 5 cm above soil level until the plants failed to grow any longer.

At the 0.5 g l^{-1} level, all species evapotranspired the same amount of water. *Tamarix* and *Pluchea* performed the best in saline conditions, showing only a minor decrease in transpiration with increased salinity. Water use efficiency remained fairly constant for each species at each salinity level with *Tamarix* consistently having the lowest efficiency level.

While the inundation experiment was supposed to continue until each plant was lifeless, every species was still thriving at day 58 except for the *Tamarix* seedlings which were entirely lodged. No other species even showed signs of stress.

Again, the research suggests that *Tamarix* possesses a sharp advantage in highly saline soils. This study also demonstrated that *Tamarix* seedlings are not drought tolerant unlike many native riparian plant species. Vandersande et al. (2001) took note that *Tamarix* was the only species not to develop a prolific root system. An adventitious root system is necessary to surviving anoxic conditions, as has been shown in other studies (e.g. Bloom et al. 1994; Krasny et al. 1998). This suggests that the regulation of the Colorado River, in storing all flood waters behind dams, may have had a large influence on the success of *Tamarix*. This study also suggests that as a possible management practice seasonal floods could be mimicked at dams along the Colorado River which could possibly desalinate the topsoil surrounding the river while lodging many seedlings through inundation.

Case Study 3

This study by Horton & Clark (2001) compared *Tamarix chinesis* seedlings with *Salix* seedlings. It was conducted in a quest to understand why, in the Sonoran Desert, located in the southern-most part of California and Mexico, that riparian forests previously dominated by *Populus* and *Salix* are quickly being replaced by *Tamarix*.

Four 'rhizopods' were constructed each containing 15 tubes, 7 with *Salix* plants, 7 with *Tamarix* plants, and 1 to measure volumetric water content. Each rhizopod also had a central reservoir with which the volume of water in all of the tubes could be varied simultaneously. Rates of water decline, as based on field observations, were 0, 1, 2, and 4 cm/day. Data on seedling height and survivorship were usually collected twice weekly. This data was analyzed at both the mid-point (21st day) and the end (42nd day) by which point the reservoirs of both the 2 and 4 cm/day treatments were empty. Total root length, root-to-shoot ratios, biomass, and leaf area were measured and compared after harvest.

Survivorship of *Tamarix* seedlings nearly remained constant across all treatment levels. (midpoint: 86-92%, harvest: 80-88%). The survivorship for the native *Salix* however varied widely with treatment levels (midpoint: 82-100%, harvest: 18-94%). Regardless of treatment, *Tamarix* seedlings were almost always taller than *Salix* seedlings. Conversely, *Salix* seedlings weighed more than *Tamarix* seedlings in all cases. *Salix* root growth was always lateral making root vertical length measurements futile. The more interesting root measurements are from the *Tamarix* plants - root length did not necessarily decrease with a declining water supply. Surprisingly, the root length was actually lowest in the control rhizopod where there was no decline in the water level.

The roots in the 1 cm/day treatment were nearly three times those of the control with the 2 and 4 cm/day treatments seeing an increase in root growth of 71 and 45%.

Tamarix seedlings are highly adaptive to a variety of water conditions. *Salix*, along with other native riparian plant species, likely evolved in conditions where there was a regular water source and where seasonal flooding is common. Thus the seedlings emphasize lateral growth as anchoring themselves is important to survival.

Measuring Evapotranspiration

In a greenhouse setting, evapotranspiration is fairly easy to measure. In the field, it's a lot more difficult as there are a lot more factors at play.

Presently, a common method of calculating evapotranspiration is using the modified Blaney Criddle crop coefficient model:

$$u = \sum_{i=1}^{12} k \frac{\overline{T_i}}{\overline{p_i}}$$

where u is water consumed, i is the month of the year, k is the empirical coefficient of the plant, $\overline{T}$ is the monthly temperature, and $\overline{p}$ is the mean monthly proportion of daylight hours. Methods such as these work fairly well over crops, but the variability that exists along the Colorado River's riparian is rarely included in coefficient estimates. Riparian ecosystems in semi-arid and arid regions experience greater environmental variability than any other ecosystem. Further doubt is cast upon this method as the sources of the coefficients are questionable (Cleverly et al. 2002).

Further, data between studies rarely correlates. Previous studies have shown that evapotranspiration of *Tamarix* is highly variable across time, space, and conditions. Just a few variables include: temperature, humidity, water availability, salinity, and irradiance. This variability makes year long consumptive water loss measurements necessary for characterizing natural behavior. Technological and scientific developments have lead to more accurate evapotranspiration measuring techniques. While few in number, studies performed over an entire growing season can best be compared with other evapotranspiration studies (Cleverly et al. 2002).

One such method of doing so is through 3-dimensional eddy covariance. Eddy covariance directly measures all four of the vertical energy fluxes (latent heat flux, sensible heat flux, soil heat flux, and net radiation) without any prior assumptions. Other evapotranspiration models assume a balance that does not exist during the monsoon season and in hot, arid aridlands for example. The materials for such a project include a 3-dimensional sonic anemometer, a hygrometer, a thermometer, a net radiometer, and soil heat flux plates (Cleverly et al. 2002).

Data from various plants at multiple sites will be invaluable in understanding growth patterns. Such information is key to the success or failure of regional water resource planning, to restoring native riparian species, and for explaining plant invasions (Cleverly et al. 2002).

Control

There are four primary control methods used in vegetative management: fire, mechanical, chemical, and biological (Brock 1994).

Fire, Fire/Chem Treatment

Since *Tamarix* plants can spread quickly across fire razed plains, it would likely not make an effective control method. Howard et al. (1983) studied the survival rates of *Tamarix* plants in response to fire and herbicide combinations. 2,4-D (2,4-Dichlorophenoxyacetic Acid), the third most widely used herbicide in the United States and Canada and the most widely used worldwide, was used. They applied fire and fire-herbicide treatments to *Tamarix* thickets during the months of July, September, and October and came to the following conclusions: (1) fire and fire-herbicide treatments had not effect on survival rates when applied in September and October, (2) fire in late July produced a 64% mortality rate the year following the burn, and (3) applying herbicide one month after the July burning increased mortality to 99%.

Mechanical, Mechanical/Chem Treatment

Mechanical treatment of *Tamarix* has been researched and practiced, with moderate success. Mechanical treatment has proven to be a difficult process because of the habitat of the plant. *Tamarix* has a relatively large form and grows along waterways, both of which make mechanical treatment slow and difficult and provide optimal conditions for root resprouting (Brock 1994).

As well, *Tamarix* is known to resprout easily from buried root and stem tissue. It is therefore necessary to prepare the earth following *Tamarix* removal by means of auguring, root ripping, or chemical treatment in order to minimize the renaturalization of *Tamarix* and have significant regrowth of native species. For example, in a study done by Anderson and Ohmart (1976), an area of *Tamarix chinesis* was cleared using bulldozers in the spring of 1978. By the following autumn, in October of 1979, there was a regrowth rate of 59 trees per ha. Bill Neill, a *Tamarix* specialist with the CA Desert Protective Council, has explained that in his experience the most effective means of *Tamarix* control is to use a combination cut stump-herbicide method. Individuals are paired in groups while one person cuts the tree as close to the ground as possible and the other applies the herbicide to the stump immediately, usually with Tordon (active ing.: 2,4-D) (Russo et al. 1988).

Figure 7: Clearing of *Tamarix* (Lym)

Since *Tamarix* is usually located in marshy areas or near bodies of water, chemical treatments may not be possible. In cases such as these, *Tamarix* will have a shallow, lateral root system which may be able to be removed with a backhoe or tractor and chain. Control methods such as these have been successful near Darwin Dry Lake and Chukwalla Well, both located in California. This type of control treatment is best carried out during the months of April and May when the plants are blossoming and therefore more detectable (Russo et al. 1988).

It has been shown that following mowing treatments, evapotranspiration by *Tamarix* thickets can be reduced by roughly 50%, if not for only a temporary period. In central Arizona, mowings are necessary during the months of May, July, and September to keep foliage at a reasonable height and succulent for area cattle. *Tamarix* has shown to be suppressed on reservoir deltas and flood-plains by frequent foliage removal such as by mowings. Mortality rates using such treatment varied wildly between time and space. Thickets were rarely killed by one season of mowing alone, but mortality rates were significant when plants were entirely defoliated at frequent intervals (Campbell 1966).

Chemical Treatment

Chemical treatment has been shown to produce the greatest *Tamarix* mortality rates of all control methods currently being practiced. Systemic herbicides (e.g. those applied to the base and absorbed by the plant) are recommended in particular. Systemic herbicides can be applied as foliar sprays, aerial sprays basal bark treatments, and cut-stump treatments (Muzika 1999).

While Tordon has been shown to be a highly effective herbicide, it is prohibited for use on federal lands. In addition to Tordon, triclopyr (ester and amine) and Imazapyr have been tested for their effectiveness against *Tamarix*. Triclopyr amine proved ineffective against *Tamarix* while triclopy ester ([(3,5,6-trichloro-2-pyridinyl)oxyl] acetic acid) has been effective when applied as a basal and stump treatment. A high concentration of triclopyr is necessary in the solution however making it quite expensive.

Biocontrol

Tamarix has very few predators in the United States. It can sometimes be grazed by local insects and wildlife, but rarely to a large degree. Only two insects can be found regularly on *Tamarix* in the American southwest; both are host-specific insects from Eurasia. One is an "eighth-inch green, brown tipped cicadellid leafhopper, *Opsius Statagallus*" and occur on the plant in such great numbers that they are visible on the plant in summer months with little difficulty (Stevens, *Scourge*). Russo et al. (1988) reports that natural field populations of this species has had a significant influence in controlling new *Tamarix* growth. The hot, water stressed conditions of the lower basin where *Tamarix* often resides may not be capable of supporting leafhoppers however thus making it ineffective in such areas (Stevens, *Scourge*). The other is a "sixteenth-inch, white disapidid scale, *Chinoaspis etrusca*" (Stevens, *Scourge*), which also may be a significant, though more limited, threat.

Other species found grazing *Tamarix* include: red-naped sapsuckers in winter, shoshone grasshopper (native), wood-boring beetle, beaver, deer, and bighorn sheep. None find *Tamarix* pallatable or edible enough to be significantly damaging (Stevens, *Scourge*). While biocontrol is not actively being practiced against *Tamarix*, it is being researched (Hart 1999). Fifteen insects are currently being investigated as possible biocontrol options. Eight of these are being studied abroad and an additional five are subject to testing here in the United States. The remaining two, a leaf beetle and a mealybug, have preliminary approval for release (Muzika 1999).

Various insect species have been identified that are known to be capable of destroying fruiting bodies, causing moderate and long-range damage, as well as being highly damaging to *Tamarix* (Gerling and Rugler 1976). Russo et al. (1988) report that *Tamarix* is perhaps the ecological weed most suited for investigation of biocontrol. The reasons to adopt a biocontrol strategy against *Tamarix* are plentiful: *Tamarix* is not a native species and it contributes little while taking a lot from the ecosystems it inhabits. As well, it may be a high water consumer and possible biocontrol agents are known. Since *Tamarix* has had little effect on agriculture, the USDA has been unenthusiastic about donating its resources and it will likely be through intense lobbying that they will commit.

Exotic insects are not the only species that can put up a fight with *Tamarix*. When planted strategically at *Tamarix* dominated sites, native plants such as cottonwood achieve survival rates of 90%. Especially where water tables are high and soil salinity low, cottonwoods and willows may fare quite well. Areas where water tables are now high enough to support competition include the lower Colorado River Valley near Yuma (agricultural irrigation has helped raise water table levels in such areas) and in the Grand Canyon (DeLoach 1997).

Flooding

Historically, spring flooding was common along the Colorado River and its tributaries in response to spring melting. Diminishment of these floods has resulted in reduced decomposition (Molles et al. 1995) and historic natural systems (Molles et al. 1998). Hydrologic modification also determines the growth and survivorship of native species often conceding to invasives (Auble et al. 1994).

A return to annual flow variations, via natural or unnatural means, may slow degradation or even improve riparian health. Flooding rinses topsoil of salts that would otherwise favor *Tamarix*. Rinsing of salts would be the primary reason for purposely flooding the River and such restoration plans have already been drafted (Briggs 1996). In order for any flow regime to be successful, an understanding is necessary of seed production, root growth, inundation and scour, and tolerance of drought characteristics for each species that would be affected (Horton et al. 1960).

Control Comparison - Is Erradication Possible?

Tamarix is highly stress tolerant and therefore difficult to eradicate. In some areas where control is practiced, for years seedlings may continue to sprout. During this period hand pulling can be an effective method of control as it is the recommended control method when the stem diameter is less than 3 cm (Russo et al. 1988).

Control can also be quite costly. One report claims that saltcedar clearing, through a combination of herbicide, burning, and mechanical techniques, would cost from $750 to

$1300/ha. (Taylor and McDaniel 1998). In most areas of the southwest, it is probably not economically feasible to control the invasion of *Tamarix*. Treatment is expensive and almost always retreatment is necessary (Russo et al. 1988).

On a more positive note, numerous control projects have demonstrated that upon the removal of *Tamarix*, native vegetation returns quickly, streams flow again, and water and habitat is returned to local wildlife. While some areas are likely going to be dominated by *Tamarix* for quite some time due to high salinity levels, many other areas are suitable for revegetation by willows and cottonwoods or mesquite, quailbrush and other native plants (DeLoach 1997).

The repercussions of introducing entirely new exotic species must be thoroughly examined first. Of the 49 endangered or threatened species that live in *Tamarix* infested habitat, (34 fish, 5 birds, 3 plants, 2 amphibians, 2 mammals, 2 reptiles, and one anthropod), most would be benefited by biological control of *Tamarix*. Only the southwestern sub-species the willow flycatcher uses *Tamarix* to a significant degree. The birds use *Tamarix* preferentially for nesting habitat but it lacks critical food which the birds need. Biological control is expected to operate slowly. During this period, native willows will slowly return providing new homes for the willow flycatcher. Further, as demonstrated in other successful weed control projects, 15 to 25% of *Tamarix* will exist perpetually if the flycatcher needs it (DeLoach 1997).

If any control methods are practiced, detailed documentation is important. Biological monitoring will help determine the effectiveness of these projects. Following up on sites that have already gone through control methods is an effective way of learning which methods are most efficient (Russo et al. 1988).

5 Concluding Discussion

Development of the Colorado River for power and water, as well as other human effects such as grazing, logging, mining, industrial pollution, road-building, and suburbanization, has had devastating effects on the environment in the Southwest and especially on the fragile riparian ecosystem. The crisis is so severe that many scientists and land managers view the situation as an 'ecological crisis' (Grahame and Sisk 2002).

In the Colorado River Basin, water remains a rare but integral commodity to both human civilization in the region as well as the surrounding ecosystem. These riparian areas are crucial to maintaining biodiversity and are the source of ecological health in the basin. Vegetation in these natural areas relies on a significant portion of the water from the Colorado River. However, human developments such as dams have changed the natural hydrological systems and adversely affected the native habitat. Due in part to the stress caused by the human-induced changes to the river, native plant species are being replaced by invasive species such as the genus *Tamarix*.

Tamarix was introduced into the United States from nurseries for several purposes, including home and city beautification, shade, wind break, and controlling stream flow. However, *Tamarix* is a very stress tolerant species and quickly escaped the original intended purposes. In addition, the taming of the Colorado River put additional stress on native species and created conditions in which *Tamarix* could thrive and overtake the area. The very same qualities that once made *Tamarix* appealing (ability to survive in semi-arid cities, stream bank control, etc.) now have turned the plant into an environmental nightmare.

Once established, *Tamarix* plants are highly stress tolerant. They are highly adaptive to a variety of water conditions; they can grow primarily lateral roots or they can grow a long tap root in order to gain access to low water tables. Nearly steady survivorship has been demonstrated in *Tamarix* across a variety of water conditions. Their hard wood protects them from flooded conditions. They are fire tolerant, and they can grow in highly saline soil conditions as they are able to excrete the salt from glands on its leaves and stems. It can quickly sprout from moistened stem or root tissue. Many plants native to the riparian areas of the Colorado River are not so adept. *Tamarix* plants further disadvantage native species by taking surface and ground water early in the season, increasing soil salinity, and causing an increase in wildfire instances.

The amount of water the plant consumes is highly variable and therefore not well understood. The case studies suggest that, at least in the early part of the plants life, and in a greenhouse setting, and under low to average salinity levels, water use is similar for *Tamarix* and the four native plants *Salix*, *Populus*, *Baccharis*, and *Pluchea*; water use was only slightly higher with *Tamarix*. A*llenrolfea*, a native often found alongside *Tamarix*, had significantly lower water use than any other plants tested.

Field testing of evapotranspiration with adult plants in the field is less understood. The most common method for calculating evapotranspiration is principally applied to agricultural plants and likely can not be applied directly to plants in riparian areas where conditions are highly variable. Methods of field measurement are available however. The quantity of field measured data is not currently extensive and because evapotranspiration is so variable along time and space, direct comparison of the data has been difficult. Most field measurements that do exist, even when gathered by highly varied methods, thus far suggest that *Tamarix* is not as high a water consumer as has been previously thought. In order to more clearly understand evapotranspiration activity in riparian habitats field measurements completed over an entire growing season would be most helpful which modern methods are capable of gathering.

Research seems to suggest that the physiological advantages that have made *Tamarix* such a successful invader are its tolerance to salts and its phreatophytic nature. Greenhouse research has shown that *Tamarix*, *Allenrolfea*, and *Pluchea* seedlings are more salt tolerant than other plants living in the Colorado River basin. It is these plants that are more often found in the lower basin while less salt tolerant plants including *Salix*, *Populus*, and *Baccharis* are found in the upper basin. The lower basin has been measured to be more saline than the upper basin, largely due to runoff from agricultural land. Thus it can be concluded to a high degree of certainty that salinity plays a major role in the makeup of riparian habitats.

Current hydrological conditions along the Colorado River also seem to favor *Tamarix* over other native riparian plants. Before damming, water levels fluctuated throughout the year; studies suggest that *Tamarix* seedlings would be disadvantaged during times of peak runoff. Native species have evolved to live in areas of constant flooding by stressing adventitious root develop to anchor themselves. Conditions have flipped which makes the genetic script of native species a disadvantage.

Research suggests that human development of the Colorado River has created conditions which put stress on native plant species and favored invaders such as *Tamarix*. The rate with which it evapotranspires water does not seem as high as once believed. The greater threat that *Tamarix* poses is to biodiversity. The strain it has put on native plant species ripples outward by taking away food and habitat for animals, for example.

Control is difficult because *Tamarix* is stress tolerant. Mechanical and fire methods alone are ineffective as *Tamarix* can resprout from root tissue protected underground. Chemical means in combination with one of these methods has proven effective; however, because *Tamarix* often lives near water, chemical treatment must be done carefully and in accordance with all environmental protection laws. Biocontrol seems to be a promising option and studies are under way. Flooding the river in such a way as to mimic a more natural rate of flow may combat *Tamarix* and increase overall riparian health, though much planning and many more studies regarding the physiology of various plant species along the river would need to be conducted.

References

Allen, Richard G. et al. "Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements." Food and Agricultural Organization of the United Nations - Irrigation and Drainage Paper No. 56. 1998. <http://www.fao.org/docrep/X0490E/X0490E00.htm> (20 Apr. 2003).

AR - American Rivers. "The Importance of Instream Flow." <http://www.amrivers.org/aboutrivers/instreamflow.htm> (20 Apr. 2003).

Anderson, B.W. and R.D. Ohmart. "A Vegetation Management Study for the Enhancement of Wildlife along the Lower Colorado River, annual report." In Fulfillment of Bureau of Reclamation Contract #7-07-30-V0D09. Arizona State University, Tempe, AZ. 1976.

Anderson, J. "Factors Controlling Transpiration and Photosynthesis in *Tamarix chinesis* Lour." Ecology 63: 48-56. 1982.

Auble, G.T., J.M. Friedman, and M.L. Scott. "Relating Riparian Vegetation to Present and Future Streamflow." Ecological Applications 4: 544-54. 1994.

Baum, B.R. The Genus Tamarix. Israel Acad. Sciences and Humanities, Jerusalem. 1978.

Blackburn, W., R.W. Knight, and J.L. Schuster. "Saltcedar Influence of Sedimentation in the Brazos River." Journal of Soil and Water Conservation 37(5):298-301. 1982.

Blom, C. et al. "Physiological Ecology of Riverside Species: Adaptive Responses of Plants to Submergence." Annals of Botony 74: 253-63. 1994.

BoR. "Bureau of Reclamation mission statement". Orientation to the U.S. Department of the Interior. <http://www.doiu.nbc.gov/orientation/bor2.cfm> (20 Apr. 2003).

Brock, J.H. "Tamarix spp. (Salt Cedar), an Invasive Exotic Woody Plant in Arid and Semi-Arid Riparian Habitats of Western USA." Pages 27-44 *in* L.C. de Waal, L.E. Child, P.M. Wade, and J.H. Brock, editors. Ecology and Management of Invasive Riverside Plants. Wiley & Sons, New York, USA. 1994.

Briggs, M. "Riparian Ecosystems Recovery in Arid Lands, Strategies and References." University of Arizona Press, Tucson, AZ. 1996.

Busch, D. and S. Smith. "Mechanisms Associated with Decline of Woody Species in Riparian Ecosystems of the Southwestern U.S." Ecological Monograhs 65: 347-70. 1995.

Campbell, C.J. "Periodic Mowings Suppress Tamarisk Growth, Increase Forage for Browsing." U.S. Fores Service Research Note. RM 76. 1966.

-----, and J.E. Strong. "Salt Gland Anatomy in *Tamarix pentandra* (Tamaricaceae)." Southwestern Naturalist 9(4):232-238. 1964.

Carmen, J.G. and J.D. Brotherson. "Comparisons of Sites Infested and Not Infested with Salt Cedar (*Tamarix pentandra*) and Russian Olive (*Elaeagnus angustifolia*)." Weed Science 30:360-364. 1982.

Christensen, E.M. "The Rate of Naturalization of *Tamarix* in Utah." The American Midland Naturalist 68(1):51-55. 1962.

Cleverly et al. "Seasonal Estimates of Actual Evapo-transpiration from *Tamarix ramosissima* Stands Using Three-dimensional Eddy Covariance." Journal of Arid Environments 52: 181-97. 2002.

DeLoach, Jack. “Saltcedar: Ecological Interactions and Potential Effects of Biological Control.” 1997. <http://www.colostate.edu/Depts/CoopExt/PLANTS/delo-2.html> (11 Dec. 2002).

DiTomaso, J.M. “Impact, Biology, and Ecology of Saltcedar (Tamarix spp.) in the Southwest United States." Weed Technology 12:326-336. 1998.

Frasier, G.W. and T.N. Johnsen, Jr. "Saltcedar (Tamarisk): Classification, distribution, ecology, and control." James, L.F., J.O. Evans, M.H. Ralphs, and R.D. Child, eds. Noxious range weeds, pp 377-386. Westview Press, Boulder, CO. 1991.

Gary, H.L. and J.S. Horton. “Some Sprouting Characteristics of Five Stamen Tamarisk.” U.S. Forest Service Research Note RM 39. 1965.

Gerling, D. and J. Rugler. “Natural Enemies and the Prospects of Biological Control of *Tamarix* sp.” Proceedings of the IV International Sumposium on Biological Control of Weeds. 1976.

Glenn, Edward et al. "Growth Rates, Salt Tolerance and Water Use Characteristics of Native and Invasive Riparian Plants from the Delta of the Colorado River, Mexico." Journal of Arid Environments 40: 281-94. 1998.

Graf, W.F. “Fluvial adjustment to the spread of tamarisk in the Colorado Plateau region.” Geological Society of America Bulletin 89:1491-1501. 1978.

Grahame, John D. and Thomas D. Sisk, editors. “Canyons, cultures and environmental change: An introduction to the land-use history of the Colorado Plateau.” 2002. <http://www.cpluhna.nau.edu/> (20 Apr. 2003).

Hart, Jason. “Invasive Species in the Southwest: *Tamarix* sp. (Salt Cedar).” 2 May 1999. <http://www.earlham.edu/~biol/desert/invasive.htm> (20 Apr. 2003).

Hoddenbach, G. "Tamarisk Control in Southwestern United States." Cooperative National Park Resources Studies Unit, Special Report No. 9:116-25. Tucson, AZ. 2-3 Sep. 1987.

Horton, Jonathan L. and Janelle L. Clark. "Water Table Decline Alters Growth and Survival of *Salix gooddingii* and *Tamarix chinesis* Seedlings." Forest Ecology and Management 140: 239-47. 2001.

Horton, J.S., F.C. Mounts, and J.M.Kraft. “Seedy Germination and Seedling Establishment of Phreatophyte Species.” U.S. Forest Service Research paper #48. Rocky Mtn. Forest and Range Experiment Station. 1960.

Howard, S.W., A.E. Dirar, J.O. Evans, and F.D. Porenza. “The Use of Herbicides and/or Fire to Control Salt Cedar (*Tamarix*).” Proceedings of the Western Society of Weed Science 36:65-72. 1983.

Hundley, Norris Jr. "The West Against Itself: The Colorado River-An Institutional History." Chapter 2 of New Courses for the Colorado. University of New Mexico Press, 1996.

Jackson, R.B. et al. "Water in a Changing World." Ecological Applications 11: 1027-45. 2001.

Krasny et al. "Adventitious Rootins of Four Salicaceae species in Response to a Flooding Event." Canadian Journal of Botony 66: 2597-98. 1998.

Kartesz, J.T. and R. Kartesz. A Synonymized Checklist of the Vascular Flora of the United States... Chapel Hill: Univ. of North Carolina Press, Vol. 2. of Biota of North America. 2 vols. 1980.

Lym, Rodney G. "Saltcedar (Tamarix spp.): Identification and Control." Feb. 2003 ed. <http://www.ext.nodak.edu/extpubs/plantsci/weeds/w1223.pdf> (20 Apr. 2003).

Mahr, Susan E. Rice, ed. "Natural Enemies of Tamarisk." Biological Control News vol. VII no. 9. May 2000.

Molles, M.C. et al. "Effects of an Experimental Flood on Litter Dynamics in the Middle Rio Grande Ecosystem." Regulated Rivers: Research & Management 11: 257-81. 1995.

-----. "Managed Flooding for Riparian Ecosystem Restoration." Bioscience 48: 749-56. 1998.

Morley, Christopher, ed. The Shorter Bartlett's Familiar Quotations, 16th printing. New York: Pocket Books, Inc., 1964.

Moving Waters (the Colorado River & the West). 2001. <http://www.movingwaters.org/about.html> (20 Apr. 2003).

Munz, P.A. and D.D. Keck. A California Flora: And Supplement. Univ. Calif. Press, Berkeley, Jun. 1973.

Muzika, Rose-Marie and Jil M. Swearingen. National Park Service, Plant Conservation Alliance, Alien Plant Working Group *Saltcedar Fact Sheet.* 7 July 1999 ed. <http://www.nps.gov/plants/alien/fact/tama1.htm> (20 Apr. 2003).

Neill, W. "The Tamarisk Invasion of Desert Riparian Areas." Education Bulletin #83-84. Education Foundation of the Desert Protective Council, Spring Valley , CA . 1983.

Ohmart, R. et al. "Ecology of the lower Colorado Rvier from Davis Dam to the Mexico-United States Boundary: a Community Profile." National Technical Information Service, Springfield, VA. 1988.

Robinson, T.W. "Introduction, Spread and Areal Extent of Saltcedar (*Tamarix*) in the Western States." Geological Survey Professional Paper 491-A. U.S. Government Printing Office, Washington D.C. 1965.

Royo, A.R. "The Colorado River: Colorado River Basin." Jun. 2000. <http://www.desertusa.com/colorado/coloriv/du_coloriv.html> (20 Apr. 2003).

Russo, Mary J. et al. "*Tamarix Ramosissima*; *Tamarix Chinesis...*" 5 Dec. 1988. <http://usgssrv1.usgs.nau.edu/swepic/factsheets/Tamarix_spp.pdf> (20 Apr. 2003).

Sala, A., S. Smith, and D. Devitt. "Water Use by *Tamarix ramosissima* and Associated Phreatophytes in a Mojave Desert Floodplain." Ecological Applications 6: 888-89. 1996.

Schopmeyer, C.S. Agricultural Handbook No. 450. USFS-USDA, Washington, D.C. ed. 1974.

Sharp, Jay W. "The Anasazi." Feb. 2002. <http://www.desertusa.com/ind1/ind_new/ind10.html> (20 Apr. 2003).

Stevens, Larry E. "Exotic Tamarisk on the Colorado Plateau." <http://www.cpluhna.nau.edu/Biota/tamarisk.htm> (20 Apr. 2003).

-----. "Scourge of the West: The Natural History of Tamarisk in the Grand Canyon." <http://www.gcrg.org/bqr/6-2/scourge.htm> (20 Apr. 2003).

Sudbrock, A. "Tamarisk Control 1: Fighting Back: An Overview of the Invasion, and a Low-Impact Way of Fighting It." Restoration and Management Notes 11:31-34. 1993.

Taylor, J.P. and K.C. McDaniel. "Restoration of Saltcedar (Tamarix sp.)–Infested Floodplains on the Bosque del Apache National Wildlife Refuge." Weed Technology 12:345-352. 1998.

Turner, R.M. and Karpiscak, M.M. "Recent Vegetation Changes along the Colorado River between Glen Canyon Dam and Lake Mead, Arizona." U.S. Geological Survey Professional Paper No. 1132. USGS, Washington, D.C. 1980.

Vandersande, Matthew W. et al. "Tolerance of Five Riparian Plants from the Lower Colorado River to Salinity Drought and Inundation." Journal of Arid Environments 49: 147-59. 2001.

VNPS – Virginia Native Plant Society. "Autumn Olive, Russian Olive." 2003. <http://www.vnps.org/invasive/inveleag.htm> (20 Apr. 2003).

Waggoner, Ben, et al. "The Pleistocene." 1995. <http://www.ucmp.berkeley.edu/quaternary/ple.html> (20 Apr. 2003).

WA-NWCB – WA state Noxious Weed Control Board. 9 Sep. 2002. <http://www.nwcb.wa.gov/weed_info/saltcedar.html> (20 Apr. 2003).

Webb, Robert H., et al. "Changes in Riparian Vegetation in the Southwestern United States: Historical Changes along the Mojave River, California." 2001. <http://water.usgs.gov/pubs/of/ofr01-245/> (20 Apr. 2003).

WEF - Water Education Foundation. "Colorado River Project." 2000. <http://www.water-ed.org/coloradoriver.asp> (20 Apr. 2003).

Wheeler, Ray. "The Colorado Plateau Region." 1990. <http://www.cpluhna.nau.edu/Places/places.htm> (20 Apr. 2003).

Wilgus, F. and K.L. Hamilton. "Germination of Salt Cedar Seed." Weeds 10(4):332-333. 1962.