LITERATURE REVIEW

Groundwater discharge by evapotranspiration from phreatophytes in arid and semiarid regions is a principal mechanism for water loss, and in some areas the sole mechanism (Nichols 1993 and Nichols 1994). Saltcedar is one of the phreatophytes that have spread throughout these regions in the United States. Several studies have been conducted to determine the water use (evapotranspiration) by this plant. The estimated rate of water use by saltcedar varies depending on method of measurement, location of study and other factors (Table 1).

Different techniques to determine evapotranspiration include: evapotranspirometers, stem-heat-balance, Bowen ratio, lysimeter, drums, well monitoring, Blaney-Criddle and Eddy covariance (Table 1). The Bowen ratio, Eddy covariance and Blaney-Criddle methods use meteorological measurements (temperature, wind speed, solar energy, daylength, CO_2 fluxes etc.) to estimate evapotranspiration. Whereas, evapotranspirometers, lysimeters, drums, and tanks utilize some type of container (which the plants are grown in) so that the amount of water that is added and the amount that remains after evapotranspiration can be measured. The difference is considered evapotranspiration loss.

Lysimeters are used to control lateral water movement through the soil (non-weighing). The weighing lysimeters can measure the weight of the soil at a determined interval. The difference between measurements is assumed to be evapotranspiration.

Table 1. Estimated annual water use by saltcedar (*Tamarix* sp.) in the Southwestern United States.

Reference	Location	Method	Water use Minimum	Water use Maximum
Meterological				
Gay and Fritschen (1979)	NM	Bowen ratio	7.2 mm/d	9.5 mm/d
Devitt, et al. (1998)	NV	Bowen ratio	75 cm/yr	145 cm/yr
King and Bawazir (2000)	NM	Eddy covariance	1193 mm/yr	1325 mm/yr
Luo (1994)	NM	Blaney-Criddle	1.4 ft/yr	4.7 ft/yr
*Bureau of Reclamation (1995)	CA	Mirco-meterological Data		2.5 ft/ yr
**Weeks et al. (1987)	NM	Energy budget	30 in/yr	42 in/yr
Lysimeter				
van Hylckama (1974)	AZ	Evapotranspirometer	92.4 cm/yr	228.7 cm/yr
Davenport, et al. (1982)	CA	Drums	2.21 mm/d	15.8 mm/d
**Bureau of Reclamation (1979)	NM	Non-weighing lysimeter	15.6 in/yr	56.4 in/yr
**Grosz (1972)	NV	Tanks	14.9 in/yr	29.2 in/yr
Gay and Fritschen (1979)	NM	Lysimeter	6.2 mm/d	9.4 mm/d
Plant Measurements				
Sala et al. (1996)	NV	Stem-heat-balance	5.9 mm/d	16.3 mm/d
Wells				
Inglis, et al. (1996)	NV	Wells	0.013 ft/d	0.034 ft/d
Watershed				
**Culler et al. (1982)	AZ	Water budget	25 in/yr	56 in/yr

Water use measurements reported as they are in the literature. *As cited in Lines and Bilhorn (1996). **As cited in Johns (1989).

The methodologies used for measuring water use have different strengths and weaknesses. One weakness is when the transpiration rates for saltcedar are expressed per unit of transpiring surface, the transpiring surface can be difficult to determine because of its small feathery foliage (Davenport et al. 1982). Devitt et al. (1998) suggested that a detailed spatial assessment of stand density and an evaluation of water availability to atmospheric water demand over time is needed to characterize the evapotranspiration of full stands of *Tamarix*. They found the Bowen method did not account for horizontal energy flow, which would need to be added to the energy balance equation. Anderson (1982) presented evidence

> indicating that the stomatal mechanism of *T. chinensis* provides a finely tuned system for preventing excessive water loss and increasing water use efficiency by responding to prevailing light and humidity conditions…It is clear that the plants are not just wicks in the ET equation. Failure to treat stomatal resistance as a variable in attempts to predict ET from meteorological data and stand characteristics may result in significant overestimates.

Evapotranspirometers also have problems as the equipment should be surrounded by a buffer zone of the same plants and all other conditions should be as similar to those in the instrument (van Hylckama 1974). If these conditions are not met then an oasis effect may result. The oasis effect can occur when plants are grown in a lysimeter without vegetation surrounding the lysimeter. The plant in the lysimeter will use more water if other plants do not surround it. This can lead to an over estimate of water use by saltcedar.

The problem with estimating water use by saltcedar for an entire site using only measurements from one part of a plant will depend on the conversion ratio. The conversion ratio can be difficult to determine and any errors can be magnified (Heikurainen 1963).

Estimating water use based on diurnal groundwater fluctuations observed in monitoring wells also has some problems. Estimates cannot be made when there are no diurnal fluctuations. For instance when the water table experiences a sharp rise associated with river levels. During this time recharge rates exceed evapotranspiration and no diurnal cycles are present.

Factors Affecting Evapotranspiration

Evapotranspiration rates for saltcedar vary based on water availability, stand density, weather conditions, soil characteristics, salinity, and depth to groundwater (Davenport et al. 1982 and Devitt et al. 1997). The majority of transpiration takes place during the daytime because sunlight and weather conditions are major components of transpiration and these will be discussed in the diurnal cycle of the groundwater table section.

Anderson (1977) stated that, "exchange of water vapor between the plant canopy and the atmosphere depends upon air and leaf temperatures, atmospheric humidity, aerodynamic or boundary layer resistance, and leaf diffusion (stomatal) resistance." He found the optimum leaf temperatures for photosynthesis in saltcedar were between 23° and 28°C, and that stomatal resistance in saltcedar increased as leaf temperatures increased between 14° and 50°C. He concluded that the increase in stomatal resistance would contribute to the decrease in net photosynthetic rate above 28°C.

Anderson (1982) found that saltcedar twigs under full sunlight at 30°C and 45 % relative humidity transpire a mass of water greater than their own fresh mass each hour. Van Hylckama (1969) using evapotranspirometers in Arizona discovered that saltcedar was temperature sensitive and it reduced water use on hot afternoons. The ecophysiological attributes (functional traits) of cottonwoods (*Populus* sp.), willows (*Salix* sp.), mesquite (*Prosopis* sp.), and saltcedar are different (Smith et al. 1998) (Table 2). Saltcedar is highly tolerant to water and salinity stress and has higher water use efficiency than mesquite, willows and cottonwoods. The peak transpiration rate (on a leaf area basis) for saltcedar and mesquite are moderate but high for cottonwoods and willows. However, on a stand basis saltcedar has the highest peak transpiration rate.

Table 2. Comparison of ecophysiological attributes of cottonwoods, willows, mesquite, and saltcedar. Adapted from (Smith et al. 1998).

Attribute	Cottonwoods/ Willows	Mesquite	Saltcedar
Stress Tolerance (water/salinity)	Low	Moderate	High
Peak Transpiration Rate (leaf area basis)	High	Moderate	Moderate
Peak Transpiration Rate (stand basis)	High	High	Very High
Water use efficiency*	Low	Moderate	High

*Water use efficiency is defined as the amount of organic matter produced by a plant divided by the amount of water used by the plant in producing it (www.co2science.org).

Depth to Water Table

Several investigators have studied the effects that depth to the water table has on plant water use. Devitt et al. (1997) found that sapflow decreased in saltcedar grown in lysimeters as the water table and soil water declined (lysimeters placed at desert edge, river edge and open stand). They found that "daily sapflow totals on a leaf area basis were higher for the plants growing along the river's edge, with midday hourly values significantly higher when a water table was present." This study also had a drydown phase that showed sapflow decreased in the river's edge and open stand lysimeters as the water table dropped.

Saltcedar grown in evapotranspirometers, in a dense thicket in Arizona, used 226. 4 cm/yr with a depth to the water table of 1.5 m and 86.5 cm/yr with a depth to the water table of 2.7 m (van Hylckama 1970) (Table 3). He concluded that given a lower water table saltcedar may thrive but use considerably less water.

Table 3. Water use by saltcedar decreased as depth to the water table increased. Modified from van Hylckama (1970).

Depth to Groundwater	Water Use cm/yr 1961	Water Use cm/yr 1962	Water Use cm/yr 1963	Average* cm/yr (STD)
1.5 meters	199.3	218.3	226.4	214.67 (13.91)
2.1 meters	141.1	137.1	159.4	145.87 (11.89)
2.7 meters	104.8	93.9	86.5	95.07 (9.21)

*Average and standard deviation was calculated for values shown using years as replications.

Gary (1963) studied root distribution in saltcedar and found their roots could adapt themselves to favorable soil moisture conditions. He found that in areas where the water table was deep, saltcedar produced long taproots and the branch roots where vertical in nature. The branch roots occupied the areas immediately above the groundwater table and were in the capillary fringe. He also found that when the water table was high, saltcedar developed a taproot and secondary roots that occupied all zones of the soil profile above the water table.

Carman and Brotherson (1982) found that the highest stand densities of saltcedar occurred where water tables were close to the surface. In a stable isotope study of saltcedar and associated vegetation in Arizona, Busch et al. (1992) found that saltcedar not only gets water from the water table but is capable of getting it from unsaturated alluvial soils. This evidently gives saltcedar a competitive advantage over native phreatophytes that are not able to survive when water levels are low or non-existent.

Salinity Effects

Van Hylckama (1970) showed that salinity levels affected water use by saltcedar. He compared flushed evapotranspirometers to non-flushed (those that did not have salt removed by flushing the system with fresh water) evapotranspirometers and showed that saltcedar in the flushed system used 229 cm of water compared to the non-flushed system, which used 115 cm of water. Cumulative water use from the evapotranspirometers showed that with an electrical conductivity of 10 (mmho cm $^{-1}$ at

25° C) saltcedar water use averaged approximately 300 cm/yr and with an electrical conductivity of 40 saltcedar water use averaged approximately 50 cm/yr.

Carman and Brotherson (1982) comparing sites infested and not infested with saltcedar and Russian olive found that saltcedar occurred on sites with soluble salt concentrations ranging from 700-15000 ppm and Russian olive occurred on sites with soluble salt concentrations ranging from 100-3500 ppm.

Saltcedar has shown resistance to salinity changes in excess of 30 dS m^{-1}, while other woody shrubs (i.e., *salix*) succumbed to the change (Smith et al. 1998). Tomanek and Ziegler (1962) found that transplanted saltcedar seedlings can withstand salt contents up to 4000 ppm but at 2500 ppm the seedlings are stressed. Busch and Smith (1995) found that saltcedar was likely to be tolerant to a relatively high degree of salinity and water stress and these adaptations benefited the plant in these environments.

Stand Characteristics

Davenport et al. (1982) found that evapotranspiration by saltcedar varied based on stand density (Fig. 1). Water use ranged from approximately 2.0 mm/day by a sparse stand of saltcedar to almost 16 mm/day for a dense stand.

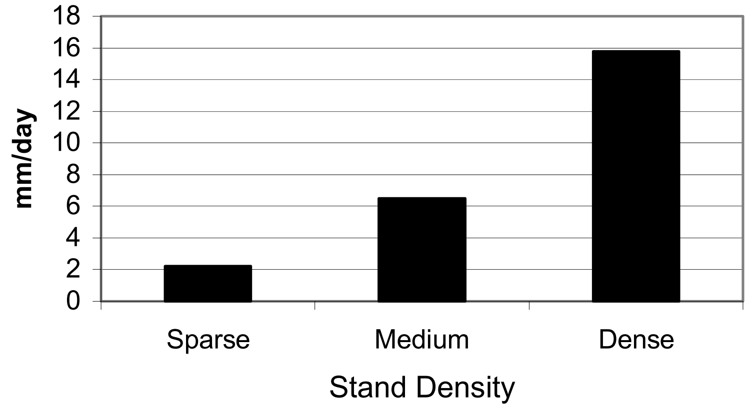

Fig. 1. Comparison of water use by saltcedar (mm/day) grown in drums located in different stand densities when local PET was 7 mm/day. Adapted from (Davenport et al. 1982).

Sala et al. (1996) found the key factors controlling water use by *Tamarix ramosissima, Pluchea sericea, Prosopis pubescens, and Salix exigua,* using the stem-heat-balance method, under moderate to high water tables (depths not given) include leaf area index (LAI) and stand density. They concluded that feedback mechanisms could reduce transpiration rates:

> under ample water availability, transpiration rates of *Tamarix ramosissima* measured on either leaf-area or dry-mass bases were no greater than those of sympatric native phreatophytes. Dense *Tamarix* stands can lose very high amounts of water under high evaporative demands, and this water loss tends to increase as individual leaf area increases. Such high rates of water loss in dense *Tamarix* stands may trigger feedback mechanisms due to the creation of a surface boundary layer that decreases vapor pressure deficit at the leaf level, resulting in reduced peak transpiration rates. However, strong advective conditions combined with high LAI [leaf area index] would tend to compensate for this boundary layer effect, resulting in stand ET

> [evapotranspiration] rates that can be almost twice as high as PET [potential evapotranspiration] during certain times of the year.

In a study conducted on saltcedar grown in evapotranspirometers it was noted that when 50% of the transpiring surface of the saltcedar was removed there was only a 10% to 15% decrease in the amount of water used (van Hylckama 1970).

Diurnal Cycle of the Groundwater Table

Maidment (1993) stated:

> water levels in piezometers fluctuate on time scales ranging from a few minutes to hundreds of years, depending upon the nature of the processes that initiate the fluid pressure variations. Short-term fluctuations in confined aquifers can be caused by changes in barometric pressure of the atmosphere, earth tides, and seismic events. Earth tides can lead to water-level changes of 1 or 2 cm; atmospheric pressure changes may cause fluctuations of several tens of centimeters, depending upon elastic properties of the aquifer and the magnitude of change in atmospheric pressure. These types of water-level changes are damped in unconfined aquifers. However, fluctuations can occur in response to time-varying rates in consumptive use of water by plants whose roots penetrate to the water table.

The difference between confined and unconfined aquifers is that confined aquifers are separated from the soil surface by a confining layer. This could be rock or a thick clay layer. The unconfined aquifer does not have this confining layer and water is able to move into the aquifer from the soil surface or river or lake.

Tromble (1977) explained the various components of the groundwater hydrograph. Groundwater fluctuations reflect varying rates of water use (evapotranspiration) and water movement through the soil. He pointed out there are several inflection points in the diurnal fluctuations (Fig. 2).

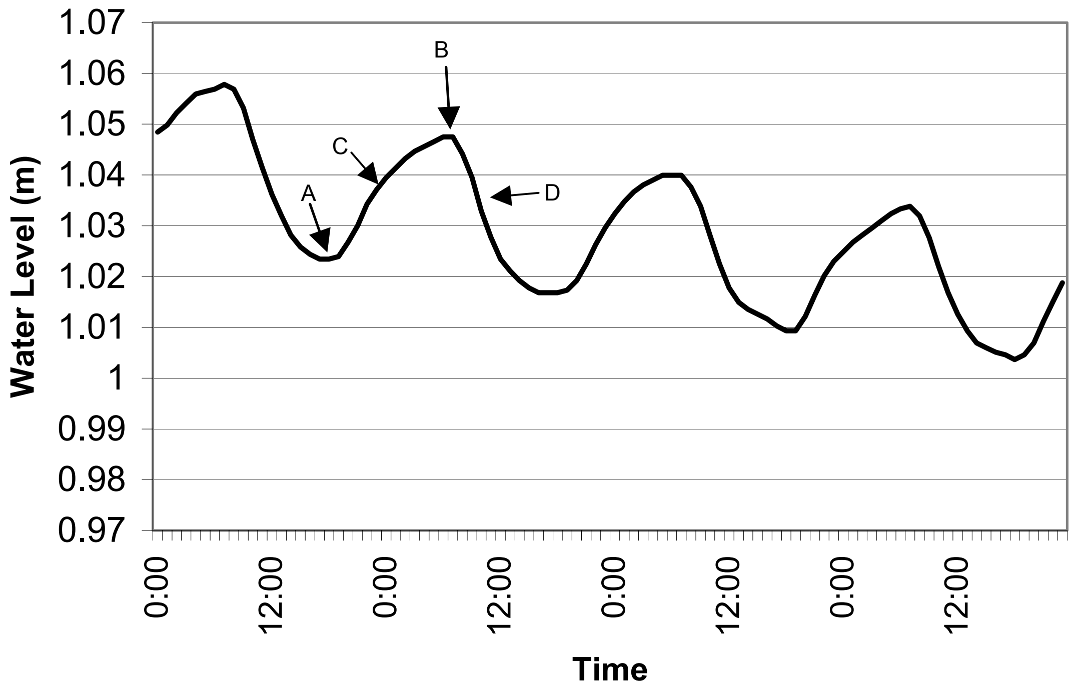

Fig. 2. Diurnal fluctuations of groundwater table with inflection points (Tromble 1977). At point (A) the inflow and outflow are about the same, at point (B) recharge and transpiration are at a minimum, at point (C) inflow is greater than outflow and at point (D) outflow is greater than inflow.

In Figure 2, at the lowest point (A) on the curve, the inflow and outflow of water are about the same; both high, and at the highest point on the curve (B) recharge and transpiration are at a minimum. When outflow is greater than inflow (D) transpiration is high and when inflow is greater than outflow (C) transpiration rates are lower for the day. The recharge stopped at point (B) because the water level had reached the static head. The nighttime peak (B) and the daytime low (A) decrease over time due to water loss from evapotranspiration from the shallow water table or flow from the system.

Numerous researchers (White 1932, Croft 1948, Kittredge 1948, Gatewood et al. 1950, Heikurainen 1963, van Hylckama 1974, Tromble 1977, Anderson 1982, Gerla 1992, Sala et al. 1996, Rosenberry and Winter 1997, Caldwell et al.1998, Dulohery et al. 2000, and King and Bawazir 2000) have noted the diurnal trends in groundwater levels. Of these White (1932), Kittredge (1948), Gatewood et al. (1950), Heikurainen (1963), van Hylckama (1974), Tromble (1977), Rosenberry and Winter (1997), and Dulohery et al. (2000) investigated these fluctuations as a way to measure plant water use. Goodrich et al. (2000) noted in their study of riparian evapotranspiration that stream flow exhibits a distinct diurnal fluctuation prior to the first hard freeze and that this pattern dissipates after the freeze. They attribute this fluctuation to air temperature and riparian evapotranspiration.

Laczniak et al. (1999) reported observing diurnal groundwater fluctuations in wells and attributed it primarily to local evapotranspiration. They noted that the "magnitude and timing of the fluctuation differs with well depth, vegetation and soil conditions, climate, and distance from a surface water source." Rosenberry and Winter (1997) in their investigations of groundwater fluctuations in prairie wetlands observed diurnal head fluctuations in groundwater monitoring wells and attributed it to daily evapotranspiration.

White (1932) noted that diurnal groundwater fluctuations, in an alfalfa field, began in the spring when plants put on leaves and ceased in the fall after killing frosts. He also found that "generally the daily fluctuations vary directly with the temperature, wind movement, and intensity of sunlight and inversely with the humidity, and they follow more or less closely the daily fluctuations in evapotranspiration from a free water source." He also found that the stage and vigor of plant growth influenced the amount of the daily groundwater fluctuation.

Soils/Specific Yield

White (1932) noted that the fluctuations in groundwater monitoring wells varied in amplitude with the amount of water discharged from the zone of saturation by evapotranspiration. He also noted

> that the amount of the daily rise and fall is a function of the texture of the material in the belt of fluctuation, which controls the capacity of the material to give up water under the pull of gravity after being saturated. This capacity is the specific yield of the soil. The specific yield of a rock or soil with respect to water is the ratio of 1) the volume of water which after being saturated it will yield by gravity to 2) its own volume. It is the measure of the volume of pore space alternately emptied and filled during the daily fall and rise of the water table, or it may be defined as the depth of water that drains out of the soil as the water table declined or enters the soil as the water table rises, expressed as a percentage of the depth of soil alternately drained or resaturated. For example, if the removal of a quantity of water representing a depth of 0.1 inch on a given area causes the water table to decline 1 inch under the area, the specific yield of the soil in which the decline takes place is 10 [percent].

Specific yield is directly related to soil texture. Johnson (1967) developed a specific yield triangle to determine specific yields based on soil texture. The specific yield of the soil increases as the percent of sand in the soil increases, and the more clay in the soil the lower the specific yield.

Comparison of Water Use Among Species

Saltcedar is not the only plant species present at the three study locations for this project. Different woody species are present as well as grasses and forbs. These plants also use water. The reported water use in the literature for the woody plants found at the study locations vary among species (Table 4).

Table 4. Representative examples of water use from the literature for important species found at the study locations.

Reference	Location	Species	**Growing Season Water Use
Robinson (1970) *	Nevada	Willow (*Salix*)	0.92 meters
Gatewood et al. (1950)	Arizona	Cottonwood (*Populus*)	1.52 – 2.35 meters
Gatewood et al. (1950)	Arizona	Mesquite (*Prosopis*)	1.02 meters
Luo (1994)	New Mexico	Russian Olive (*Elaegnus*)	0.46 - 2.90 meters

*As cited by Johns (1989). **Growing seasons may vary.