METHODOLOGY

Location and Description of Study Sites

Three locations (UTM NAD83 Zone 13 and 14) were chosen for this study. The first location was on the Colorado River in Borden County Texas (3610237.537 N 290269.114 E). This location was approximately 48.28 km from the start of the Colorado River in Texas and would be covered by 3.05 meters of water if Lake J.B. Thomas were at full capacity. The study location was approximately 460 m from the river channel. The soils at this location were alluvial deposits and consisted primarily of loams and sandy clay loams. The vegetation at this site consisted of young growth saltcedar with a sparse herbaceous understory. The above ground flow of the Colorado River at this location was not continuous. The river only flowed during high runoff events and the water table was well below the soil surface.

The second location was on the Texas Parks and Wildlife Department's Gene Howe Wildlife Management Area (3973311.081 N 385514.490 E) in Hemphill County Texas. The site was immediately adjacent to the North side of the Canadian River. The soils were sandy and the water table was close to the soil surface. Saltcedar was not the dominant woody vegetation at this location and there was a dense herbaceous understory. The Canadian River did not continuously flow above ground.

The third location consisted of two sites (Sites A and B) on the East side of the Pecos River in Loving County Texas (Site A 3515606.641 N 61725.083 E, Site B 3516763.900 N 61513.762 E) just west of Mentone. Both sites were immediately adjacent to the river channel. The soil at both sites was predominately sand. At both sites, wells were located in dense old growth saltcedar along the river, and one well at each site was located away from the river's edge in native vegetation. The Pecos River flowed throughout the growing season; however, the flow changed with water releases (for irrigation) from Red Bluff Lake.

Water Level Recorder

Global Water[1] (Global Water Instrumentation, Inc. Gold River, Ca. USA) WL14X water level loggers were used to measure hourly water levels in the wells. The sensor on the WL14X is a submersible pressure transducer that is amplified and temperature and barometric pressure compensated with an accuracy of 0.2%. Loggers used in this study had an accuracy of ± 0.0091 m. The loggers were battery powered, held 6000 readings and were downloadable in the field. The loggers were calibrated prior to being placed in the wells, and the data was downloaded and the batteries changed twice per year. The loggers were set to record water levels in feet every hour. All calculations were in feet and then converted to metric units.

Location and Installation of Wells

Shallow wells were installed at each study site to provide data on the fluctuation of the groundwater table. The wells were constructed by hand auguring below the water

---

[1] Mention of brand names is provided for reference and does not imply endorsement.

table until gravel or a thick clay layer was encountered. All wells differed in depth and elevation at each location (Table 5).

Wells 3 and 4 at the Canadian location were similar in elevation because they were both located in a slough while Well 2 was located in the upland. The wells at the Colorado location were similar in elevation and depth. Wells 1 and 5 at Site A at the Pecos location were lower in elevation than Well 2 at the saltcedar edge. Wells 1 and 3 at Site B were lower in elevation than Wells 2 and 5, which were located at the saltcedar edge and the upland respectively.

Table 5. Depth of wells from the soil surface and surface elevations at each site.

Location and Well #	Depth from soil surface	Surface Elevation* (m)
Canadian 2	2.06(m)	30.48
Canadian 3	1.68 (m)	28.22
Canadian 4	1.29 (m)	28.44
Colorado 1	7.31 (m)	30.36
Colorado 2	7.73 (m)	29.84
Colorado 3	6.83 (m)	30.48
Pecos A 1	3.51 (m)	29.41
Pecos A 2	4.62 (m)	30.48
Pecos A 5	4.64 (m)	29.90
Pecos B 1	2.38 (m)	28.19
Pecos B 2	4.36 (m)	30.48
Pecos B 3	2.65 (m)	28.90
Pecos B 5	5.79 (m)	31.58

*These are not actual sea level elevations, but elevations in relation to one well designated to be 30.48 m.

River wells were installed by placing a PVC pipe down the bank of the river to the bottom of the river (Fig. 3). Each well, except for river wells, consisted of a 7.62 cm hand bored opening in which a 5.08 cm diameter PVC pipe with a 1.22m long well screen attached was inserted to the bottom of the boring. The slots in the well screen were 0.01 mm. The PVC pipe extended approximately 0.9 m above the soil surface. Blasting sand was used to fill the annular space around the well casing to within 0.3 m of the soil surface. The last 0.3 m of annular space was capped with pre mix cement to prevent overland flow entering the annular space around the well casing. During the coring process, soil samples were taken for each 0.3 m interval for laboratory analysis to determine soil particle size distribution (texture) (Fig. 4).

Fig. 3. River well installed at Canadian location.

Fig. 4. Soil sample collection at Colorado location, Well 1.

Triangular placement of the wells will allow determination of the direction of groundwater movement. Water can be moving parallel to the river through the riparian zone, from the river into the surrounding landscape or from the surrounding landscape into the river or percolating downward.

The exact elevation and distance of wells in relation to each other and the river were determined with a survey transit and range pole. One well was assumed to be at an elevation of 30.48 meters at the soil surface and the other well elevations were determined from this mark. Distance to the water table from the soil surface will be used to correct groundwater levels to a local benchmark in another phase of this long-term study.

Vegetation Monitoring

Plant density, cover and composition were determined for the Colorado and Canadian River sites each September using permanent line transects. Transects, 20 m long, were measured in each cardinal direction at each well. Bare ground, rock, litter, grass, forb or woody vegetation was recorded along each transect at 1m intervals directly below the left side of the tape (from the well). The nearest live plant was identified at each 1m interval to calculate species composition. Density, number of stems, and height of woody vegetation were determined by species size class (<5, 5 to 10, >10 cm in basal diameter) on 0.001 hectare (2 m radius) circular plots located at 7 m and 14 m along the transects (Blackburn et al. 1982).

Permanent line transects that bisected each well and transversed the landscape perpendicular to the river were used on the Pecos sites. Each transect began at the rivers edge for the initial date and extended beyond the upper edge of the existing saltcedar stand. Bare ground, rock, litter, grass, forb or woody vegetation was recorded along each transect at one meter intervals directly below the left side of the tape. Woody plant canopy intercept was recorded along each transect by species to determine canopy cover for each transect at the Pecos location. At each one-meter interval, the nearest live plant was identified for determining species composition. A 1.22 m belt transect, along the same line, was used to determine woody plant density. Stem diameter and height of woody vegetation was determined by species size class (<5, 5 to 10, >10 cm in basal diameter) within the belt transect. In 2001, woody vegetation data was gathered using a 20 m circular plot around Well 5 at the Pecos Location at both Sites A and B.

Soil Characterization and Specific Yield

The soils collected from each well were analyzed for each 0.3 m increment from the soil surface. The hydrometer method of soil texture analysis was attempted but several of the samples contained gypsum. The gypsum caused the clays to flocculate and this gave erroneous results. Soil texture analysis was conducted, by the Texas A&M Soil and Crop Sciences Soil Characterization Laboratory, using the pipette method (Kilmer and Alexander 1949 and Steele and Bradfield 1934) after the gypsum was leached from the soils. Once the soil texture was determined the specific yield for each increment was determined using a specific yield triangle (Johnson 1967).

By viewing all water level data for each growing season, the water bearing zone for each well was determined. The mean of the specific yields observed in the water bearing zone during the growing season was used in water use calculations. For example, if the depth of the water in the well remained in a 1 m zone throughout the growing season the specific yield of the soils in that zone were averaged and used as the specific yield for that well.

Procedures for Removing Logger Error

In order to estimate water use by saltcedar and associated vegetation from the hourly changes in water level (diurnal groundwater fluctuations), the daily high and low water level associated with each well had to be determined. However, several of the instruments had “error/fluctuations” that could not be explained. These instrument “error/fluctuations” varied among wells (loggers). These erratic readings were considered errors due to the instrument when the following hourly reading returned to a value “matching” the trend from the previous hourly reading. Preliminary analysis showed many of these erratic lows and highs would be used to calculate water use. This would result in higher water use estimates. In order to “smooth” these erratic readings a three-hour running average of the data was used. For example, if the water level for 10:00 was 5.9898, 11:00 was 5.7888, and 12:00 was 5.9444 the corrected water level reading for 11:00 would be 5.9077. To insure that thi “smoothing” procedure did not influence results between wells, all data was “smoothed” by taking the running average of three recordings as shown in the above example. The overall trend was maintained (Fig. 5). All data sets were “smoothed”, even when loggers were functioning properly.

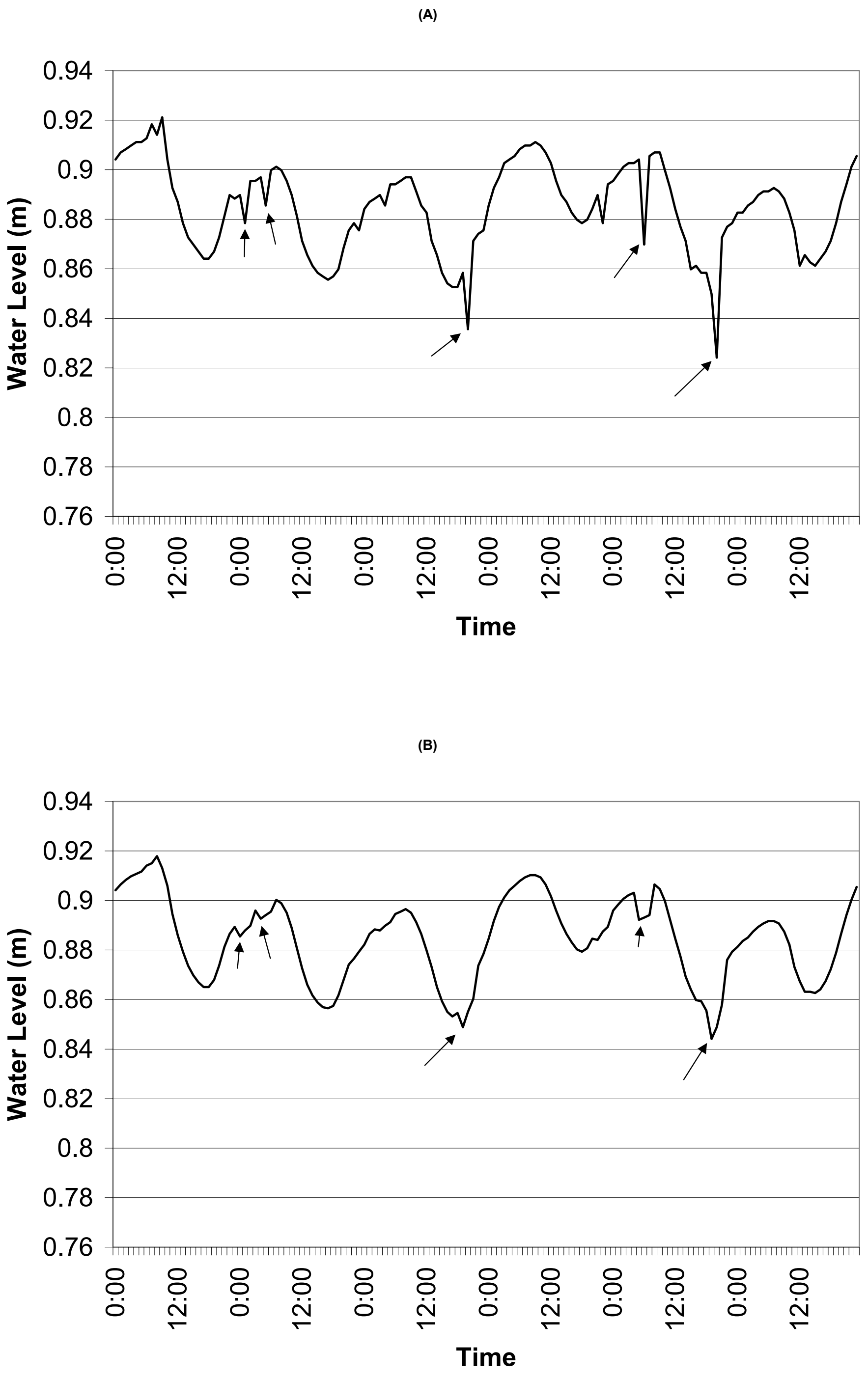

Fig. 5. Example raw data from Canadian Well 4 for June 18-23, 2001 showing erratic readings, indicated by ↑, believed due to logger error (A). The "smoothed" data removed the extreme values (B) by using a 3-hour running average.

Procedures for Estimating Water Use

Three basic methods were identified in the literature for estimating water use from hourly diurnal groundwater table fluctuations (White 1932, Troxell 1936, and Dulohery et al. 2000). White (1932) developed a formula for calculating evapotranspiration based on hourly fluctuations. He explained his theory for the formula as follows:

> During the day the capillary fringe is depleted by the plants, and the movement of groundwater by capillary action to meet the depletion is more rapid than recharge by hydrostatic or artesian pressure. Therefore the water table declines and the head increases. During the night transpiration and evaporation losses are small, the water table moves upward, and the pressure head declines.
>
> From about 6 to 10 in the evening and again from about 6 to 10 in the morning recharge approximately balances discharge, and for a few hours the water table is nearly at a stand still. This state of equilibrium would be reached earlier both in the evening and in the morning if it were not for lag in some operations. At or soon after sunset the rate of transpiration and evaporation declines to a small fraction of the rate that prevails during the day, but for a time the plants continue to draw some water to fill their circulatory systems, which have become somewhat depleted. (Nearly all plants become slightly wilted during the day, particularly on hot days, and tend to have a drooping appearance at night, quite in contrast with their fresh, turgid appearance in the morning.) Moreover, during the day the recharge of the capillary fringe from the zone of saturation lags somewhat behind the discharge by the plant action. By midnight, or slightly before, the veins of the plants have become filled with water. Meanwhile capillary equilibrium had been nearly established in the capillary fringe, and during the hours from midnight to morning there is little movement of water to the fringe from the zone of saturation.
>
> Between midnight and 4 a.m. the water table is approximately at a mean elevation for the 24-hour period, and therefore the head is

> also approximately at a mean, provided there is no gain or loss in water-table elevation during the 24-hour period. If the water table has a net fall during the 24 hours, the head in the early morning hours mentioned is slightly above the noon mean; and if it has a net rise, the head is slightly below the mean but the difference is generally not great. The velocity of water moving through a rock or soil varies approximately as the hydraulic gradient. Therefore if the slight losses by transpiration and evaporation between midnight and 4 a.m. are neglected, as well as the slight difference between the hydraulic head at this time and the true mean for the day, the hourly rate of recharge from midnight to 4 a.m. may be accepted as the average rate for the 24-hour period. The total quantity of groundwater withdrawn by transpiration and evaporation during the 24-hour period can then be determined by the formula $q=y(24r \pm s)$, in which q is the depth of water withdrawn, in inches, y is the specific yield of the soil in which the daily fluctuation of the water table takes place, r is the hourly rate of rise of the water table from midnight to 4 a.m., in inches, and s is the net fall or rise of the water table during the 24-hour period, in inches. In field experiments the quantities on the right hand side of the formula except specific yield can be readily determined from the automatic records of water-table fluctuation.

Inglis et al. (1996) in studying water use by saltcedar used White’s (1932) formula. They believed for "improved estimates of water consumption, adjustments should be made to account for background fluctuation in stream flow. The relationship between stream stage and water levels in wells without the influence of vegetation and evaporation would need to be determined. Without accounting for stream stage fluctuation, calculated water consumption would likely decrease from wells adjacent to the stream channel." They did not show a correction for stream stage fluctuation in their paper.

Others have questioned the accuracy of White's (1932) formula. Troxell (1936) believed the formula is subject to a certain error. He believed the error was based on the assumption the rate of recharge (r) continued as a constant throughout the 24-hour period. He explained that as the water level dropped the rate of recharge increased and then slowed down when transpiration demands were lower.

Gatewood et al. (1950) used White's method in a study that compared calculated water use from well level fluctuations to actual transpiration loss from tank experiments. They found significant transpiration loss at night. Thus they computed a 1.25 correction factor for saltcedar water use based on twelve determinations (i.e. the calculated water use would be multiplied by this correction factor).

Nichols (1993) believed that White's formula underestimates the discharge of groundwater because "the volume of water moving laterally and vertically through the aquifer in response to increased groundwater gradients was not considered." He used energy budget micrometeorological measurements to determine water use.

Seven procedures for calculating water use (Q) from groundwater well data were compared in this study (Table 6). All of the calculations included multiplying the answer times the specific yield (sy) of the soil. (1) Method 1 involved calculating water use by using the current days maximum water level (H_1) minus the average of the two adjacent days low water levels (L_1,L_2) (Dulohery et al 2000). (2) Method 2 involved calculating water use by using the current days maximum (H_1) minus the current day minimum (L_1) minus the change in maximum water level from the current day (H_1) to the next day (H_2). (3) Method 3 involved calculating water use by using the current day maximum (H_1) minus the current day minimum (L_1) plus the change in maximum water level from the current day (H_1) to the next day (H_2). (4) Method 4 involved selecting the first high water level (H_1) for the day, then selecting the first low level (L_1) for the day and then the first high water level for the following day (H_2). These levels and the amount of time that passed between the highs and lows (T_1 and T_2) were used to calculate water use when transpiration exceeded recharge. (5) Method 5 is the same as method 4 except the net fall or rise of the water table (H_1-H_2) during the 24-hour period was added to the equation. For Methods 4 and 5, the data was divided into nighttime and daytime. Nighttime was considered to be from 9:00 pm to 8:00 am and daytime was from 9:00 am to 8:00 pm. (6) Method 6 was the method developed by Walter N. White (1932). A 24 hour recharge rate was estimated from the average rate of change in the water table from midnight to 4:00 am. This number was then multiplied by 24 and added to the change in maximum water level from one day to the next. (7) Method 7 is the same as the one developed and described by White (1932). The only difference was the 24 hour recharge rate was estimated between midnight and 2:00 am (Table 6).

Once the water use was calculated for each day of the growing season, the results were inspected and any day that had a negative water use was not included in the results. Additionally, days that showed extremely high water use were checked with the water level data and excluded if it was determined that there was an extreme increase or decrease in the water level due to river fluctuations that would cause the calculation method to over estimate the daily water use. The daily average water use was determined for each month from the remaining data (negative and extremely high water use results not included) and then multiplied by the number of days in the month to determine monthly water use. These were totaled for the growing season.

Table 6. Formulas evaluated for calculating water use.

Methods of Calculation	Formula
1	$Q=(H_1-(L_1+L_2/2))(sy)$
2	$Q=((H_1-L_1)-(H_1-H_2))(sy)$
3	$Q=((H_1-L_1)+(H_1-H_2))(sy)$
4	$Q=((H_1-L_1)+((H_2-L_1/T_1)xT_2))(sy)$
5	$Q=(((H_1-L_1)+((H_2-L_1/T_1)xT_2))+(H_1-H_2))(sy)$
6	$Q=sy(24r_1+s)$
7	$Q=sy(24r_2+s)$

Q = water use (meters)
sy = specific yield of the soil (percent)
H_1 = first high (meters)
H_2 = second high (meters)
L_1 = first low (meters)
L_2 = previous low (meters)
T_1 = number of hours between second high and first low
T_2 = number of hours between first high and first low
r_1 = the hourly rate of rise of the water table from 12:00 a.m. to 4:00 a.m. for formula 6
r_2 = the hourly rate of rise of the water table from 12:00 a.m. to 2:00 a.m. for formula 7
s = the net fall or rise of the water table during the 24 hour period (H_1-H_2)

Determining Length of Growing Season

The length of the growing season for each location was determined by observing when diurnal fluctuations began in the spring and ended in the fall (Fig. 6). The diurnal fluctuations at the study sites started at the end of April when daytime temperatures reached into the 20°C range and ceased after the first frost in the fall. White (1932) had observed these groundwater fluctuations occurred with leaf emergence and ceased when freezes caused defoliation.

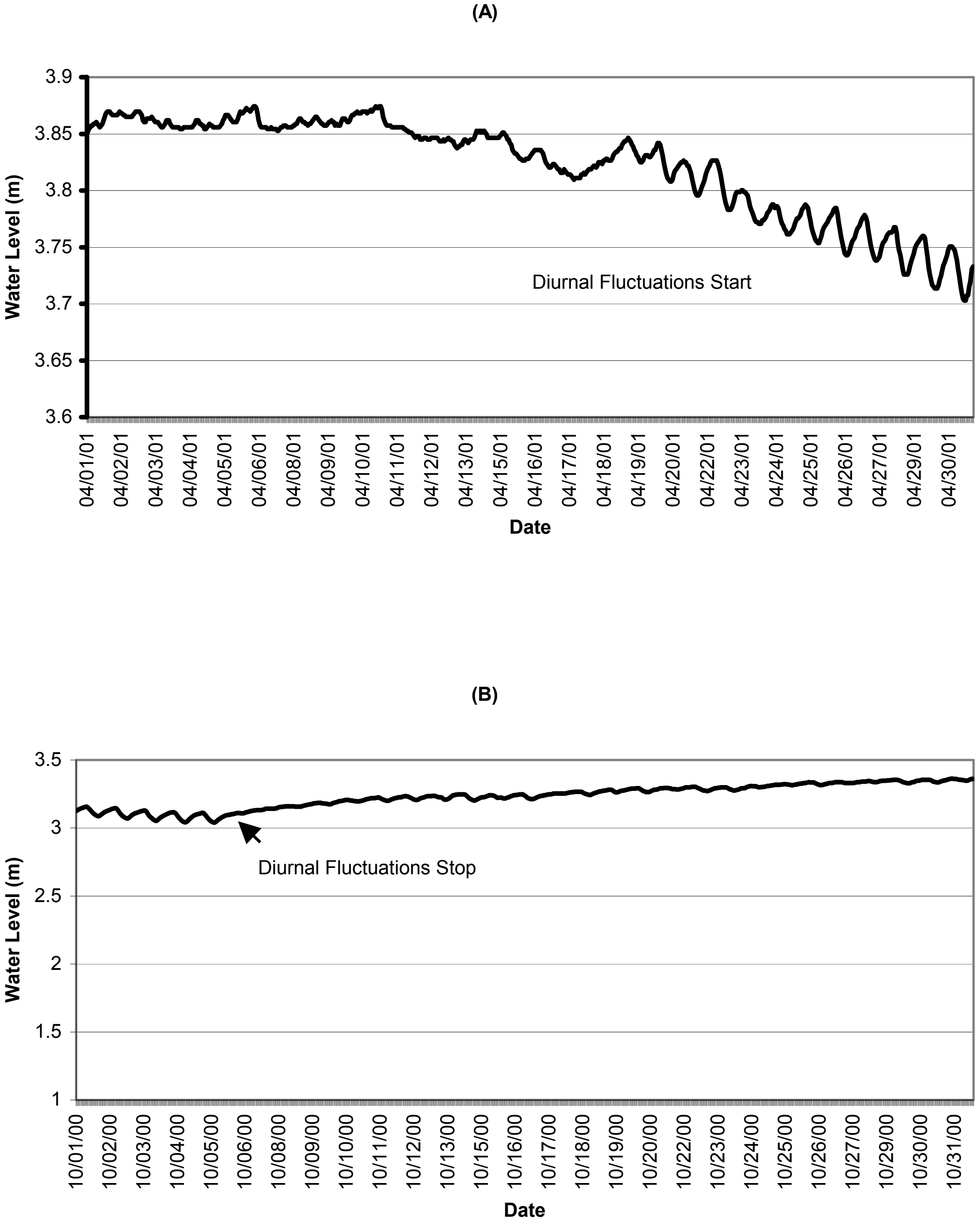

Fig. 6. Example of the beginning and ending of daily diurnal fluctuations in water level that were used to determine the length of the growing season at each location. (A) shows daily diurnal fluctuations began on 4/21/01 for Well 2 at the Colorado location and (B) stopped on 10/5/00 for Well 2 at the Colorado location.

Weather Characteristics

Several factors affect plant evapotranspiration (water use). These include relative humidity, barometric pressure, temperature, precipitation, wind, water quality, and depth to groundwater (Gatewood et al. 1950). Potential evapotranspiration (PET) data from the nearest weather station (Sweetwater, TX. 80 km from location) to the Colorado location was downloaded, from the Texas Cooperative Extension Biological and Agricultural Engineering Departments website (texaset.tamu.edu), for the 2001 growing season. Regression analysis was used to compare potential evapotranspiration (PET) on a daily basis throughout the 2001 growing season to results for estimated water use for Well 2. This was done to determine if PET could be used to estimate water use by saltcedar for this location. PET data was not available for the other study locations.

Statistical Analysis

Averages and standard deviations were used to determine if there were differences between each well at each site. If the averages fell within two standard deviations ($p<0.05$) then it was determined that there was no statistical difference between wells. Regression analysis was used for the paired plot analysis (EPA 1993) and the PET analysis for the Colorado location.

The water level loggers were set to record in feet. All of the water use calculations were calculated in feet and then converted to meters. The loggers also recorded to the eighth decimal place. When the data were sorted, they were rounded to the fourth decimal place to coincide with the accuracy of the loggers.

Paired Plot Analysis

A paired plot analysis was used for the Colorado location (EPA 1993). The procedure involved having paired plots (wells) that were calibrated prior to a treatment being initiated on one of the plots (wells). Well 1 and Well 2 served as the paired plots in this study. Both wells were monitored for one growing season prior to the area around Well 1 being treated with herbicide on August 21, 2000 (Fig. 7 and Fig. 8). The area around Well 2 was not treated with herbicide. The growing season calibration period provided information on how the water level in each well responded under the same conditions.

Fig. 7. Colorado location showing well location and herbicide treated area (shaded).

Fig. 8. Herbicide was applied to Well 1 at the Colorado location on August 21, 2000. A 49 % mortality of saltcedar was observed in September 2001.

A regression analysis for hourly water level fluctuations during the 2000 growing season was used to develop a regression equation. This equation was used with 2001 hourly water level values for Well 2 to predict what the water level should be for Well 1. The actual hourly water levels for Well 1 were subtracted from the predicted to determine any differences. Results were reported as the average difference in water table level. The "best" method for estimating water use was used to determine predicted verse actual water use for the 2001 growing season. Any difference between these values was believed to be due to treatment effects.