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The Response of Shallow Groundwater Levels to Fuels Reduction in the Middle Rio Grande Bosque

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The Response of Shallow Groundwater Levels to Fuels Reduction in the Middle Rio Grande Bosque

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Committee Approval

The Master of Water Resources Professional Project Report of **Lynda Price** entitled **The Response of Shallow Groundwater Levels to Fuels Reduction in the Middle Rio Grande Bosque,** is approved by the committee:

Chair	Date

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Abstract

Throughout the southwest, exotic and non-native plant species such as saltcedar (*Tamarix ramosissima*) and Russian olive (*Elaeagnus angustifolia*) have transformed the environment by competing for groundwater and dominating ecosystems formally occupied by native cottonwoods (Populus deltoids ssp.) and willow (Salix sp.). Saltcedar was introduced to the Middle Rio Grande riparian forest (bosque) to control flooding and to decrease soil erosion rates due to its deep root system and prolific growth rate. This transformation, along with channelization and commensurate reduction in over bank flooding, has not only changed the ecology, structure, and composition of riparian vegetative communities, but also greatly increased the severity and frequency of wildfires. Saltcedar and Russian olive both have the tendency to produce large masses of dead dry branches or stems because of high stem mortality rates. This downed wood is the fuel that creates the swift moving wildfires in the Middle Rio Grande bosque. These fires present a major threat to structures and communities living near the bosque and causes substantial damage to the bosque environment.

A study to evaluate the effects of the removal of exotic fuels was initiated in 1999 by the Rocky Mountain Research Station of the USFS in collaboration with other local organizations. Saltcedar and other exotic fuels were removed in several sections in the Middle Rio Grande bosque using three different methods to limit re-growth. In addition to determining the effects of fire propagation, the fuel reduction study included a component to investigate the impact of fuel removal on shallow groundwater resources. To determine the impacts to shallow groundwater from the fuel reduction treatment, a series of 24 shallow monitoring wells were installed and instrumented with data loggers to measure water levels. These wells were located in three different blocks, stretching from Albuquerque to the Bosque del Apache National Wildlife Refuge. Diurnal groundwater fluctuations were analyzed from years 2003 and 2005 during summer and winter periods, and the variations at control sites (no fuel reduction) were compared with treatment sites where exotic vegetation was removed and treated with herbicide. The diurnal data showed variations between the study plots as well as seasonal variability. Overall, the average fluctuations from the summer control sites (-10.81 mm and 6.69 mm) were of greater magnitude or similar to the fluctuations from the treatment sites (-9.98 mm and 7.58 mm). During the winter dormant season, the treatment sites (-2.89 mm and 2.58 mm) held higher average fluctuations when compared to the control sites (-1.20 mm and 0.79 mm). The results indicated there was a low impact on shallow groundwater from the removal of exotic species because of only slight differences in diurnal fluctuations between the control and treatment sites.

1.0 Introduction

1.1 Study Area

The Rio Grande is the third longest river in the United States, approximately 3220 km in length with a basin area of 470,000 km² (Figure 1). The headwaters begin in the San Juan Mountains of southern Colorado and the river flows through a widely diverse landscape of mountains, forests and desert through New Mexico and Texas into the Gulf of Mexico. For approximately two thirds of its course, the river also serves as the border between the U.S and Mexico (Crawford et al. 1993).

The Middle Rio Grande is the reach of the Rio Grande bounded on the north by Cochiti Dam and to the south by San Marcial, New Mexico (Crawford et al. 2003). It flows 260 km through semi-arid central New Mexico encompassing parts of Santa Fe, Sandoval, Bernalillo, Valencia, Socorro, Torrance, and Cibola counties (Scurlock 1998). The Middle Rio Grande is vegetated by great basin grassland, semi desert grassland, and Chihuahua desert scrub (Crawford et al. 1993). The riparian forest (or bosque) consists of native species of cottonwood (Populus deltoids ssp.) and willow (Salix sp.), as well as introduced exotic species, mainly Russian olive (Elaeaganus angustifolia) and tamarisk or salt cedar (Tamarix pentandra and Tamarix chinesis) (Bartolino and Cole 2002). The floodplain varies in width from 1.5 to 10 km in width. The Middle Rio Grande has several key tributaries that contribute to its annual flow; the largest being the Rio Puerco and Rio Salado.

In common with most southwestern rivers, the vegetation, hydrology, and geomorphology of the Rio Grande have been altered from their past condition. Historically, flooding along the Rio Grande was a severe issue and began to increase in

the 1870's due to an aggrading riverbed and rapid runoff from the upper watersheds (Scurlock 1998). It would typically flood during late spring and early summer when the snow in the upper watershed had melted. These floods would wash away dead and downed wood while distributing the new seeds of native species. The increased runoff can be attributed to the over grazing of livestock and logging in the upper reaches of the watershed (Scurlock 1998). To protect roads, communities, agricultural fields, and other infrastructure, flood control projects (dams, levees, and jetty jacks) were built. Salt cedar and Russian olive were also introduced to the area in the early 1900's because of their deep root systems that simultaneously slowed erosion rates and stabilized the banks of the Rio Grande. Human intervention of the river, however, has not allowed the dead and downed wood to be pushed out with the yearly floods and in turn reduced the amount native species re-growth from the lack of seed spreading (Scurlock 1998).

Currently, the main consumptive use of water in the Middle Rio Grande Basin is irrigation in the inner valley of the Rio Grande (Bartolino and Cole 2002; Papadopulos 2000). The other consumptive uses of water are by reservoir evaporation, recharge to the groundwater, and evapotranspiration by riparian vegetation (Bartolino and Cole 2002). Non- consumptive uses include recreation, aesthetics, and ceremonial use by Native Americans (Bartolino and Cole 2002). The Albuquerque area has grown significantly since World War II. This increase has caused groundwater to be withdrawn faster than it was being replenished by natural recharge. Municipal wells were pumped dry decades ago from this overdraft of groundwater. Since then, efforts to conserve water have been established by the city of Albuquerque (Bartolino and Cole 2002). The city has also encouraged a mix of surface water coming from the San Juan Chama Project and

groundwater to be diverted in the Rio Grande upstream of the city for direct use so less groundwater is being used overall (Brown et al. 1996, Bartonlino and Cole 2002).

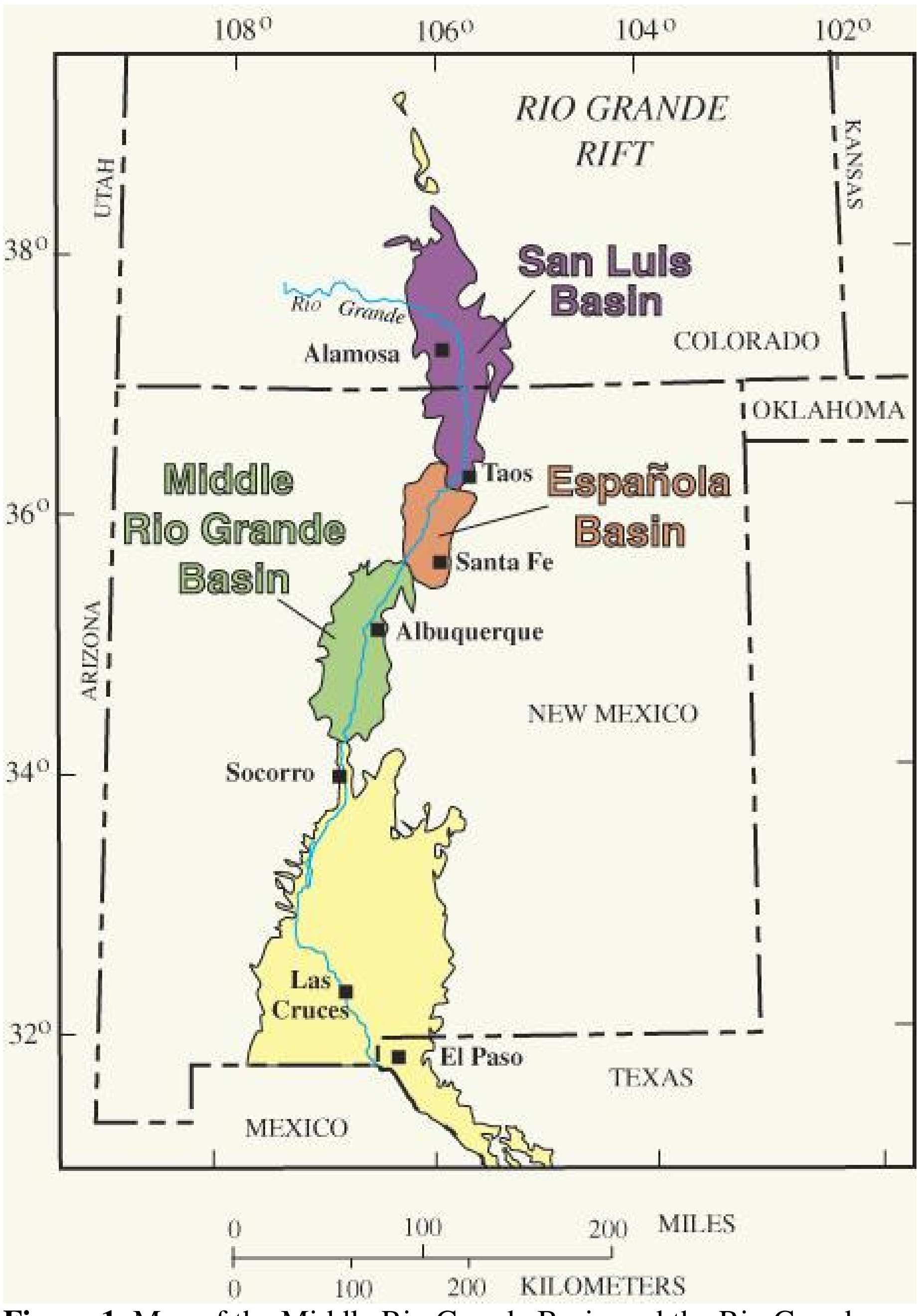


Figure 1. Map of the Middle Rio Grande Basin and the Rio Grande. (http://anquetil.colorado.edu/~arlowry/RGR/basin.jpg)

1.2 Invasive Vegetation as a Fuel

Throughout the southwest, riparian ecosystems have been transformed by human development including flood control and protection measures, agricultural activities, and municipal and industrial development. Dams and other structures have altered the flow frequency, duration or intensity of floods; floodplain water tables have been lowered; and introduced of invasive species such as salt cedar (Tamarix ramosissima) and Russian olive (*Elaeagnus angustifolia*) now dominate areas formerly filled with native cottonwoods (*Populus deltoids* ssp. *wislizeni*) and willows (*Salix gooddingii*) (Busch and Smith 1995). In addition, the spread of saltcedar is closely related to river regulation (Harms and Hiebert 2006). Altered hydrologic cycles, including reduced flooding, stream bank stabilization, and lowered flood plain water tables, are likely the primary cause of declining native vegetation and subsequent saltcedar colonization (Busch and Smith 1995; Stromberg 1998; Howe and Knopf 1991). Saltcedar, a woody, perennial, Eurasian native species, has proliferated along rivers of the southwest since the early 1900's while native cottonwood and willow forests have been on the decline (Stromberg 1998). Riparian forests are important centers of biodiversity for many areas, offering refuge and habitat for a variety of organisms. However, because of saltcedar's rapid and dense growth, saltcedar has added to a reduction in biodiversity and dramatically altered this environment (Naiman et al. 1993). Saltcedar is known to be highly reproductive, to have high water use with a deep root system, to be tolerant of drought and flooding, to increase soil salinity, and to reduce the available forage and access to water for wildlife and livestock (DeLoach et al. 2000; Everitt 1980; Busch and Smith 1995). Thus, these factors may give saltcedar a competitive advantage over cottonwood forests.

Historically, saltcedar was introduced to the Middle Rio Grande to control flooding and stabilize the banks of the Rio Grande (de Gouvenain 1996). Over time, these invasive species have not only altered the structure and composition of riparian vegetative communities but also greatly increased the frequency and severity of wildfire. Dead and downed wood and dense growth of exotic saltcedar and Russian olive provide fuels that increase fire risks in the bosque and increase the intensity and magnitude of fires that do occur. Its adaptation to saline conditions also allows it to thrive in the elevated soil salinities that fires often produce (Busch and Smith 1993). In addition, the plant can quickly resprout from below ground after its above-ground vegetation has completely burned away. Saltcedar's high flammability places native bosque flora and fauna at increased risk of mortality by fire. Native tree species inhabiting the Middle Rio Grande, such as the Rio Grande cottonwood and Gooding's willow, are not adapted to environments in which frequent fires occur and thus cannot resist fire damage or respond with regenerative resilience to fires (Busch 1995). When fires rage through the bosque, most native species are killed and stands of dead cottonwoods and are soon overgrown with new shoots of saltcedar. This cycle decreases the biodiversity of native species in the bosque and increases the dense thickets of non- native species, encouraging wildfires to regenerate again.

1.3 Relationship between Shallow Groundwater and Riparian Vegetation

Understanding the basics of groundwater hydrology and its relationship to the surrounding environment allows water scientists and land managers to make better choices when faced with water resource challenges. In the Middle Rio Grande, the Rio Grande is the primary source of surface water and groundwater recharge for the bosque

and most municipal, industrial and agricultural development within the Middle Rio Grande basin. Contact with this source is vital to many riparian plant species for the beginning stages of growth and for growth throughout their lives. When rapid changes in the groundwater depth occur, newly established plants easily die.

In the southwest, evapotranspiration from a flood plain can result in a reduction in the quantity of water sent to downstream users (Culler et al. 1982). Phreatophytes, deep-rooted plants, obtain most of their water from the saturated zone, or shallow groundwater, and capillary fringe. A large part of the water lost to downstream users is from the water used during the process of transpiration from phreatophytes (Culler et al. 1982). Phreatophytes are plant species that are adapted to fluctuating water tables and their roots typically extend downward to the saturated soil layers at or near the water table (La Maitre et al 1999). Vegetation found in riparian forests is closely tied and dependent on shallow groundwater systems, particularly where precipitation is seasonal. Shallow, local scale systems will exhibit seasonal variability in flow rate, and may be greatly impacted by land use or climate changes in the short term (Smerdon and Redding 2007). Arid environments, as found in the Middle Rio Grande Valley, are impacted because surface and groundwater are in high demand for agriculture and also exert a strong influence on abundance and composition of riparian vegetation (Richter 1993).

Many riparian communities in the arid southwest are faced with declining water resources and increasing forest fires due to extended drought. These riparian areas are dominated by phreatophytes, specifically saltcedar, and are capable of consuming large quantities of water via transpiration, thus increasing evapotranspiration losses in the water budget (Molles et al. 1998; Dahm et al. 2002). Water lost to the atmosphere

through riparian evapotranspiration is believed to rank in the top third of water budget depletions (Cleverly et al. 2006). In these riparian areas, water loss to the atmosphere dominates basin water budgets and are estimated to be greater than 90 % of the Middle Rio Grande depletions from open water evaporation, soil evaporation, transpiration, and irrigated agriculture (Cleverly et al. 2002; Dahm et al. 2002). Using the method of eddy covariance to measure evapotranspiration, Dahm et al. 2002 reports that estimates of evapotranspiration for 320 km reach of the Middle Rio Grande are about 150-250 x 10^6 m^3/year. This is about 20-33% of total estimated depletions along the Middle Rio Grande. They also discovered that a dense stand of saltcedar and a mature cottonwood stand with a diverse understory of salt cedar and Russian olive had the highest rates of evapotranspiration, approximately 123 cm in 2000. A mature cottonwood stand with a closed canopy had intermediate rates of evapotranspiration, approximately 98 cm in 2000, and a less dense saltcedar stand had the lowest rates at approximately 74 cm in 1999 and 76 cm in 2000.

The relationship between riparian vegetation and groundwater is complex. Interactions between vegetation and groundwater occur at two stages in the water cycle: interference in the processes by which precipitation reaches the groundwater and the extraction of groundwater either through deep roots or by being situated in groundwater discharge areas (La Maitre et al. 1999). Plants may tap water stored in river banks or in shallow aquifers, which may be dependant on periodic flooding for their recharge; or they may tap groundwater that is discharging to streams (Le Maitre et al. 1999). Vegetation also directly extracts groundwater from saturated strata and reduces the proportion of rainfall that is eventually recharged by interfering with the passage of precipitation from

the atmosphere to the water table in recharge areas (La Maitre et al. 1999). In addition, evapotranspiration losses are large when riparian areas are filled with dense thickets of vegetation. Vegetation composition and cover largely determine the proportion of rainfall that reaches the soil and may also influence infiltration rates, drainage, evapotranspiration losses, and storage capacity.

The groundwater demand by riparian vegetation is very competitive, particularly between native and non-native species (Sala et al. 1996). As mentioned before, saltcedar has an advantage over native riparian species in drought situations. When the water table is low, saltcedar's deep root system taps into the shallow groundwater, or vadose zone, and contributes to evapotranspiration losses while shorter rooted native species tend to die off.

1.4 Fuels Reduction Study

Fuels reduction in a riparian forest (bosque) is achieved by the removal of woody species, treatment of the stumps and stems with herbicide to prevent regrowth, and removing the dead and downed wood to reduce wildfire hazard. The Middle Rio Grande Fuels Reduction Study was initiated in 1999 by a sector of the USDA Forest Service, Rocky Mountain Research Station, under a Memorandum of Agreement among several partners including the Bosque del Apache National Wildlife Refuge, Middle Rio Grande Conservancy District, City of Albuquerque Open Space, Bureau of Land Management, New Mexico Department of Environment, and NRCS Plant Materials Center, Los Lunas, NM (Finch et al 2001). This project monitored and evaluated the responses of not only groundwater to the fuels reduction treatments, but also soils, vegetation, and bird, bat, reptile, and amphibian populations. Pre-treatment data were collected from 2000-2002.

Data were collected continuously at all sites during 2003-2004 and at all treatment stages. Post-treatment data were collected from 2005-2007.

Non-native and exotic woody species, such as saltcedar and Russian olive, were removed in three randomized blocks in the Middle Rio Grande bosque spanning from Albuquerque down to the Bosque del Apache Wildlife Refuge, approximately a 145 kilometer (90 mile) stretch along the Rio Grande (Figure 2). The objectives of the overall fuel reduction project were to 1) identify the most effective way to reduce bosque fuels and exotic species while limiting the damages to cottonwoods and other native shrubs; 2) limit the damage to the surrounding natural environment; 3) have minimal impact on native wildlife; and 4) reduce the risk for catastrophic fires in the bosque (Finch et al 2003).

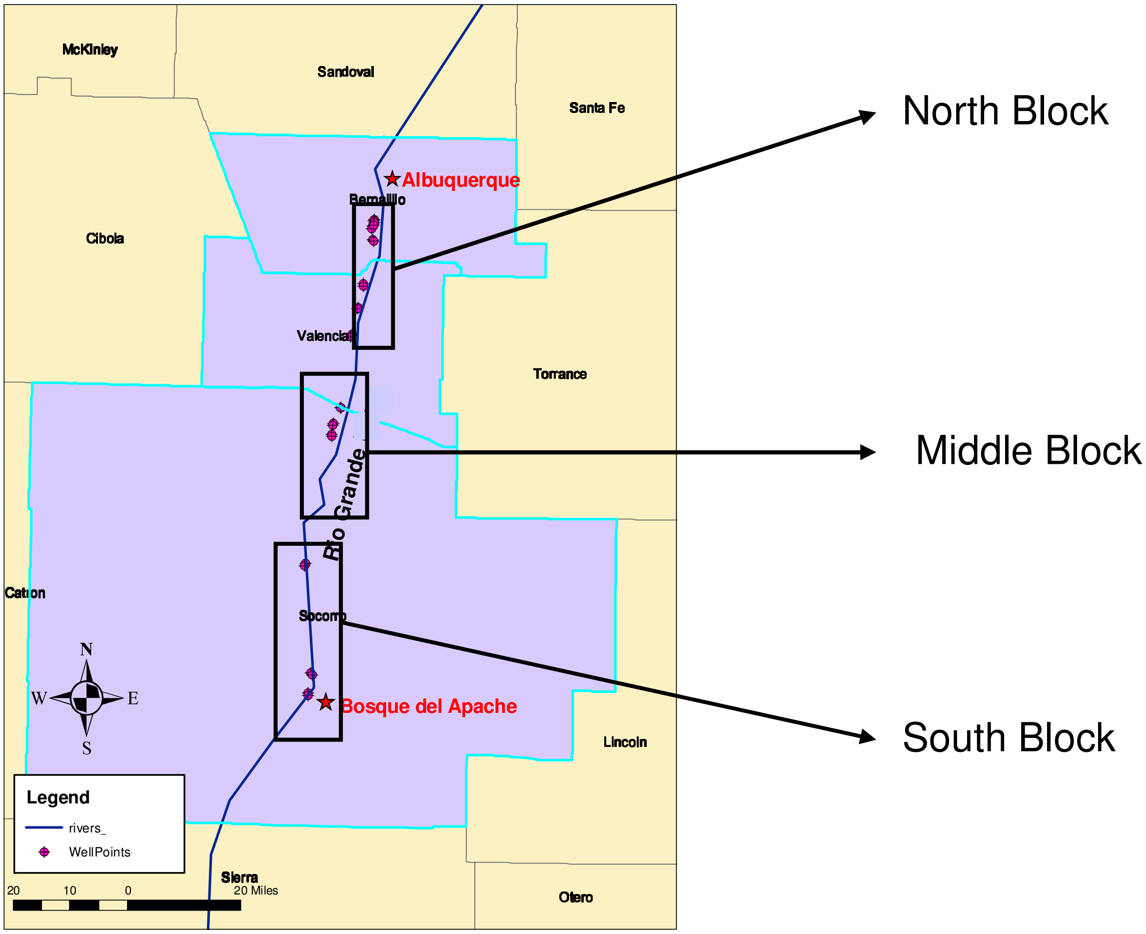


Figure 2. Map of study area.

1.5 Objectives of Study

The overall objective of this research was to evaluate the impacts of a fuels reduction treatment on shallow groundwater levels. Diurnal trends were analyzed between summer and winter dates during two different years of treatment for changes as a result of treatments in the Middle Rio Grande bosque. The other objectives for this study were to evaluate how groundwater levels differed between pre/post treatment application and to determine if fuels reduction is a viable method to reduce catastrophic fires in the Middle Rio Grande bosque without negatively impacting groundwater levels.

2.0 Methods

2.1 Study Design and Well Locations

A total of 24 groundwater monitoring wells, located in the Middle Rio Grande bosque from Albuquerque to the Bosque del Apache Wildlife Refuge were installed by the Rocky Mountain Research Station between 2000 and 2001, two years prior to treatment. The wells were installed in three blocks, Albuquerque block (North), Los Lunas- Bernardo block (Middle) and Lemitar- Bosque del Apache Wildlife Refuge block (South). Each block encompassed a control site and three treatments sites which were divided in accordance with a randomized block design to control and reduce experimental error. Two wells (replicates) were installed at each control and treatment site producing 8 wells per block (Figure 3). The sites were also determined by the following criteria: 1) visibly- high fuel loads as identified by landowners and the NM Environmental Department, 2) relatively homogenous vegetation at least 20 hectares in size, 3) cottonwood overstory with an exotic woody plant understory, 4) accessible by road, 5) access to site and block design treatments were permitted by landowner, and 6) relatively undisturbed by grazing, vehicles, and other uses (Finch et al. 2001). Wells were hand augured in 2000-2001 to depths between three and four meters. The well screens were 1.3 to 1.7 meters in length with a mesh size of 0.020 mm. In-situ miniTROLL pressure transducers with built in data recorders were installed approximately 0.5 meters above the bottom of each well. The data loggers record depth to groundwater below the soil surface and temperature at fifteen minute intervals. Temperature was recorded in one of the two wells at each site.

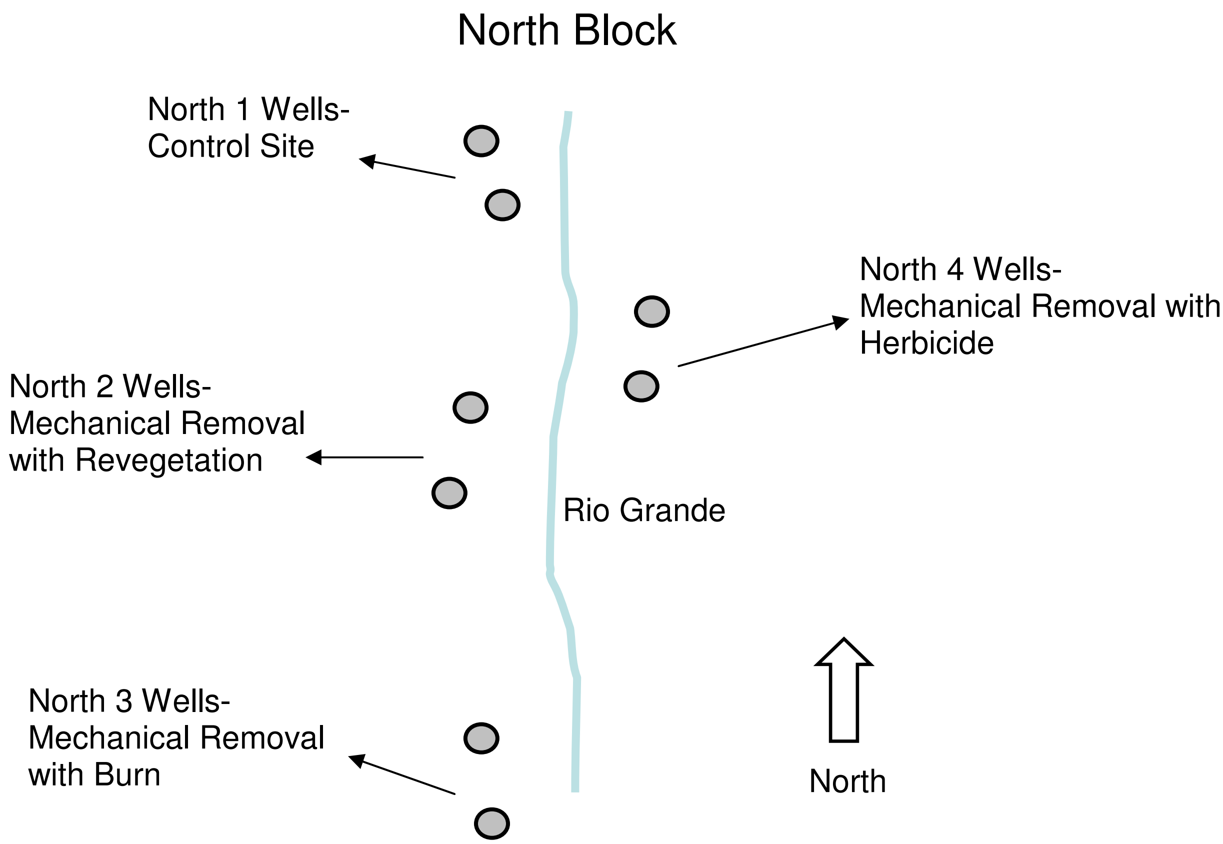


Figure 3. Example of the design of the North block with control and treatments. Size and distance not to scale.

In the fall of 2002, three treatment types were designed and in the beginning stages of implementation with the goal of creating sites where the risk of catastrophic fire would be reduced by removing the mass of fuel (Table 1). Each treatment was designed and chosen because they reached fuel-loading levels estimated to reduce catastrophic fire risk. The exotic fuel removal treatments implemented in this study were: 1) mechanical removal of dead and downed wood and exotic shrubs / trees followed by spot herbicide application, 2) partial mechanical removal of dead, down, and exotics followed by spot herbicide and light, prescribed fire, 3) mechanical removal of dead, downed, and exotics followed by spot herbicide and revegetation with native plants, and 4) control, no

treatment (Finch et al. 2003). The spot herbicide application was Garlon 4, sprayed on the stump within 10-15 minutes of being cut. Ultimately, these treatments were designed to determine which method is most efficient at reducing fire risk while simultaneously leaving a small impact on the ecology of the environment.

Table 1. Summary of Treatments

Block	Site	Area (ha)	Groundwater Sampling Started	Treatment Type	Dates of Treatments Performed	Treatments Completed as of 2005
NORTH	North 1	16.07	5/1/2000	Control Site	None	None
NORTH	North 2	18.33	5/1/2000	Re-vegetation with Native Vegetation	2002-Nov./2003-Nov.	Cut, Chip, Herbicide
NORTH	North 3	17.03	5/1/2000	Mechanical Removal, Chipping, and Herbicide	2003-Apr./2004-Apr.	Cut, Chip, Herbicide, Firewood
NORTH	North 4	23.43	5/1/2000	Controlled Burn	2002-Nov./2003-Apr.	Cut, Pile, Herbicide, Firewood
MIDDLE	Middle 1	19.41	5/1/2000	Mechanical Removal, Chipping, and Herbicide	2002-Nov./2004-Mar.	Cut, Chip, Herbicide, Firewood
MIDDLE	Middle 2	29.17	5/1/2000	Controlled Burn	2004-Oct./2004-Dec.	Cut, Chip, Herbicide, Firewood
MIDDLE	Middle 3	13.21	5/1/2000	Re-vegetation with Native Vegetation	2004-Apr.	Cut, Chip, Herbicide, Firewood
MIDDLE	Middle 7	35.00	5/1/2000	Control Site	None	None
SOUTH	South 1	28.87	5/1/2000	Control Site	None	None
SOUTH	South 2	15.54	5/1/2000	Re-vegetation with Native Vegetation	2003-Feb./2003-Apr.	Cut, Pile, Herbicide, Firewood
SOUTH	South 3	26.71	5/1/2000	Controlled Burn	2002-Nov./2003-Feb.	Cut, Pile, Firewood, Herbicide
SOUTH	South 4	15.45	5/1/2000	Mechanical Removal, Chipping, and Herbicide	2002-Nov./2003-Feb.	Cut, Chip, Herbicide, Firewood
						Updated: March 2006

2.2 Site Descriptions

The north control and treatment sites are located in the Albuquerque South Valley. Both sites possess substantial leaf litter on the bosque floor and thick canopy cover in the summer season (Figure 4). The control site has an extensive amount of downed wood or fuel. The treatment site encompasses a thick growth of annuals in the summer, cottonwood trunk resprouts, elm seedlings, piles of cut wood, and a larger open forest floor compared to the control site.

Figure 4. Pictures of North control site on left, treatment site on right. Taken May 4, 2007.

The middle sites are located in the Los Lunas vicinity. The control site possesses many new shoots of salt cedar, mature cottonwoods and a thick layer of leaf litter. The treatment site has a clear understory, many tall annuals growing in the summer, and a lot of downed wood (Figure 5).

Figure 5. Pictures of the Middle control site on left, treatment on right. Taken September 2, 2007.

The south control site is located near Bernardo, NM and consists of leaf litter on the surface, very sandy soil, adolescent cottonwood, and young saltcedar with saltcedar litter on the ground. The treatment site is located in the Bosque del Apache National

Wildlife Refuge and encompasses many New Mexican Olive, mature cottonwoods, moderate downed wood, some grass, and woody plants sprouting vigorously (Figure 6).

Figure 6. Pictures of South control site on left, treatment on right. Taken March 19,2007 for the control site and May 16, 2007 for the treatment site.

The pictures below represent the sites in the winter with dormant vegetation. Sites in the winter tend to have large amounts of leaf litter, a canopy that is more open on the treatment sites, and higher fuel loads in the control sites.

Figure 7. Example of the winter season. Pictures from North control site on left, treatment on right. Taken February 19, 2007.

2.3 Data Collection

Groundwater levels and temperature were collected from 24 monitoring wells on 12 sites along the Middle Rio Grande. The monitoring wells were visited every other month and the data were downloaded from the Insitu miniTROLL pressure transducer into a handheld computer in the field (Figure 8). The data were then loaded into a PC database that allowed for specific date and time ranges to be selected from particular wells and post processing to be applied.

Figure 8. Downloading data from the data logger located inside the well.

Wildfires and vandalism were problems that occasionally threatened the monitoring wells in the Middle Rio Grande bosque. In the summer of 2006, a fire burned through Isleta just west of I-25 and burned the North 3 site. The lock on the well cap was melted shut and the cable, which was attached to the logger inside the steel well, was

burned and destroyed from the fire. Mechanical failures from the loggers were also common, therefore, the chance for loss of data increased from these types of incidents.

2.4 Data Analysis

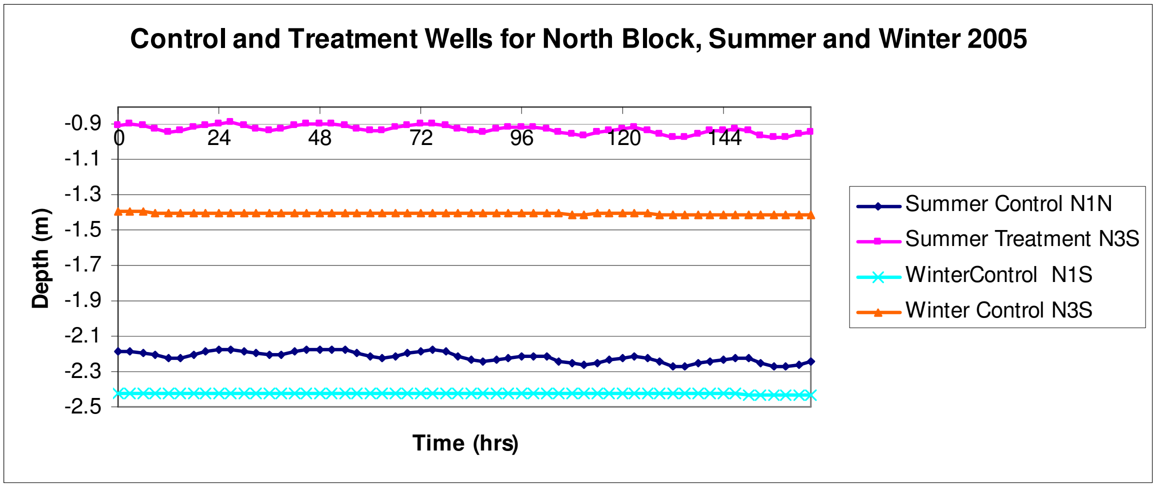
Water level data were downloaded to a database that was created for this project. Twelve, fifteen minute measurements were averaged to arrive at a representative value for the three hour time periods. The averaging reduced the bulk of the data and eliminated the noise or random fluctuations of the data. These averaged data were then used to investigate the diurnal fluctuations for summer and winter seasons during two different years of treatments. Initially, pre and post treatment data were to be analyzed. Pre treatment data would have provided a baseline to compare the post treatment data with. However, because of a lack of sufficient pre treatment data prior to thinning activities, that was not feasible. Specific time periods were selected from this study. Periods with at least 5 days of minimal change in discharge in the Rio Grande were selected from USGS 0833000 Rio Grande at Albuquerque Stream Gage record. The USGS website was used to find these periods for the summer and winter of years 2003 and 2005. These periods provided data that were not influenced by rapidly varying river water level elevations resulting from runoff events. The years were chosen based on their proximity to the start date of the treatments. The dates selected were July 9-15, 2003; January 31- February 6, 2004; June 4-10, 2005; and November 21-27, 2005.

The date specific data were then organized in a Microsoft Excel spreadsheet and analyzed with the statistical analysis tools from the software. Dr. Tim Ward, P.E. a surface water hydrologist and a professor of Civil Engineering at UNM, provided assistance with the analyses. A simple difference (value at period i is subtracted from

period i + 1) was calculated to remove any trends from the data and arrive at a stationary series of constant mean and variance (Table 2). The differencing method has the effect of approximating the first derivative of the curve representing water depth plotted against time. Thus, a positive value represents a positive slope of the curve and a negative value represents a negative slope of the curve (Figure 9).

Table 2. Example of calculating a simple difference for well N1N.

N1N			
Time (hrs)	Depth (m)		Difference (m)
0	-2.77323		
3	-2.77278	-2.77323	0.000448
6	-2.77231	-2.77278	0.000468
9	-2.7716	-2.77231	0.000717
12	-2.77109	-2.7716	0.000512
15	-2.77079	-2.77109	0.000291
18	-2.77051	-2.77079	0.000283
21	-2.77026	-2.77051	0.000256
24	-2.76993	-2.77026	0.000328



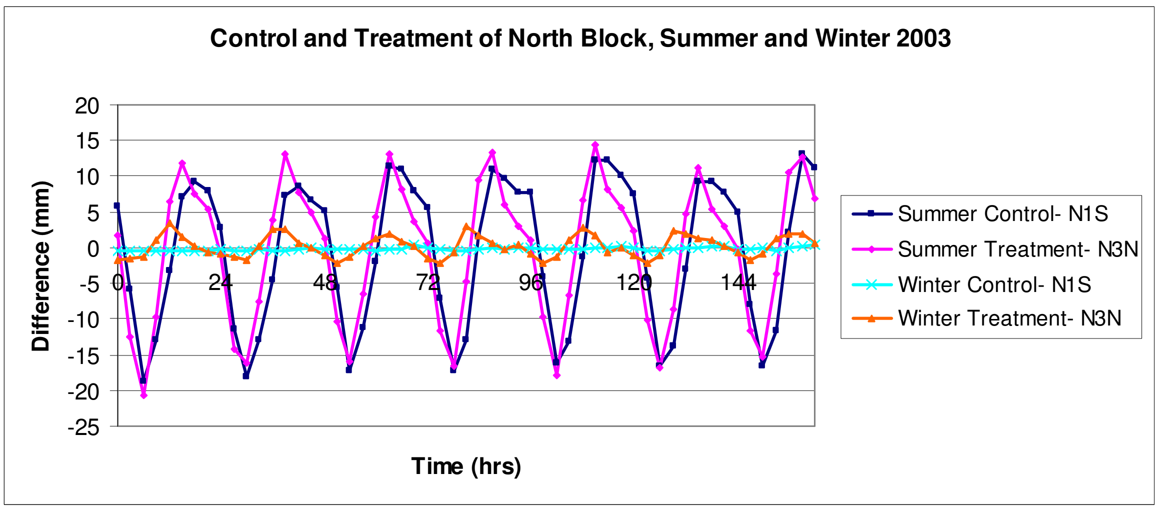


Figure 9. Example of how the actual depths (above) differ from the calculated simple difference (below). See Appendix C for more depth to water graphs.

A correlation analysis was performed on the difference series to determine if there was a relationship between the two replicate wells at each site. Correlation measures the direction and strength of the linear relationship between two quantitative variables (Moore 2004). One well (set of water levels) from each site was selected as a representative to reduce using replicated data based on its correlation value. In addition to the simple differencing scheme, a trend line was fit to those data series where a trend was

apparent and then the relationship was used to remove the trend. However, the simple difference scheme provided a more stable series than using the trend line relationship. Therefore, the simple differenced data series were used in further analyses.

The sites with treatment by mechanical removal with herbicide showed the most variability in daily difference fluctuations when compared to the other treatments. This signal of large daily differences for the herbicide treatment wells was easier to quantify and interpret therefore, only the well data in the plots with herbicide treatment were analyzed and compared to those in the control plots. In contrast, the burn and revegetation treatments were much less variable so they were not used in this study.

3.0 Results

There were two replicate wells located on each control and treatment site. Correlations betweens the two wells on each site were calculated to determine if there was a relationship between them (1.0 being the value of strongest correlation), showing that using data from one of the two wells would be sufficient. One of the two wells was chosen to represent the control and treatment sites based on one of three factors: 1) the data had a high correlation value (close to 1.0) so one well was chosen with no bias, 2) due to failure of the data logger there was only one data set available from one well so that was used and 3) there was poor correlation between the two wells so the better of the two was chosen.

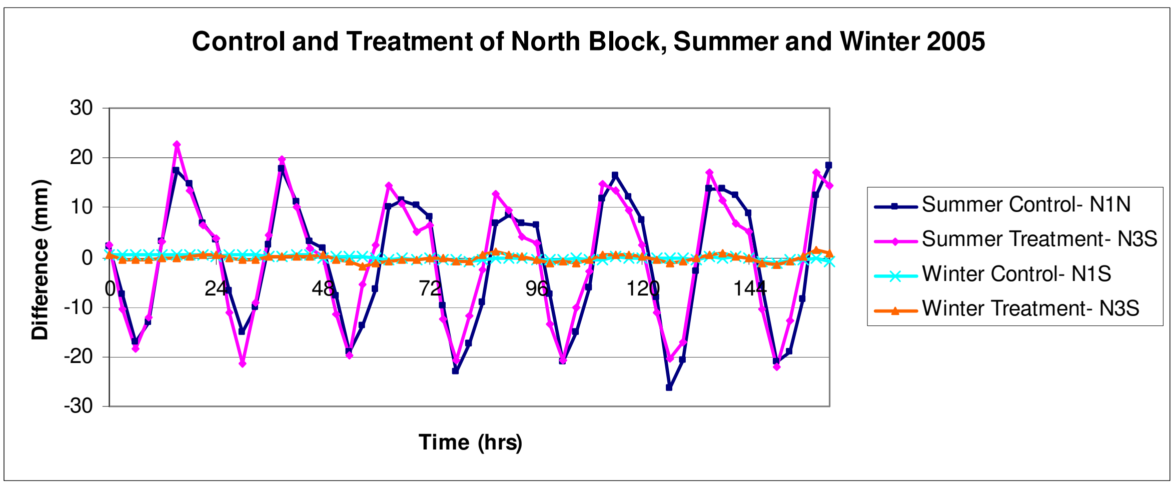
Table 3. Correlation values from each control and mechanical treatment site. These values were used to determine which of the two wells per site to use.

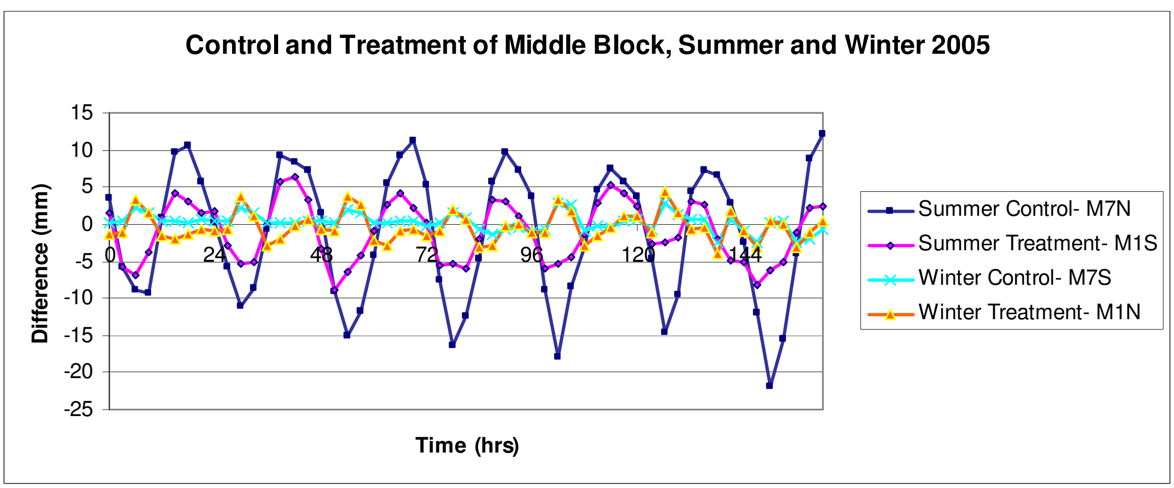
	Correlation Factors for the Replicate Control and Treatment Wells					
Date	**N1**	**N3**	**M1**	**M7**	**S1**	**S4**
Summer 2003	n/a	0.98	0.89	0.91	0.41	0.17
Winter 2003	n/a	n/a	n/a	0.86	n/a	0.89
Summer 2005	0.6	0.93	0.98	0.85	0.24	0.88
Winter 2005	0.79	0.67	0.63	0.89	0.46	n/a
	Control	Treatment	Treatment	Control	Control	Treatment

Note: N= North Block, M= Middle Block, S= South Block.

The 2005 summer and winter data showed that overall the fluctuations for the of the treatment sites in the winter (with an average amplitude of -2.82 mm and 2.58 mm for all the wells) were larger than those of the control (with an average amplitude of -1.20 mm and 0.79 mm) (Figure 10 and Table 4). The winter also does not exhibit a large diurnal pattern (smaller daily fluctuations) which is consistent with the fact that most vegetation in the bosque is dormant, therefore evapotranspiration effects are reduced. The summer, however, illustrated that the fluctuations for the control (average amplitude

of - 20.35 mm and 12.6 mm) and the treatments (average amplitude of -20.49 mm and 13.3 mm) were of similar magnitude on the North block. The control (-9.96 mm and 7.46 mm) had slightly larger fluctuations than the treatment (-7.54 mm and 6.74 mm) on the South block and the control (-15.2 mm and 9.68 mm) had considerably higher fluctuations than the treatment (-6.27 mm and 4.13 mm) on the Middle block. The summer shows a strong diurnal trend with fluctuations increasing during the day and decreasing at night. Figure 11 shows more detail on the South block fluctuations for the summer and winter of 2005.





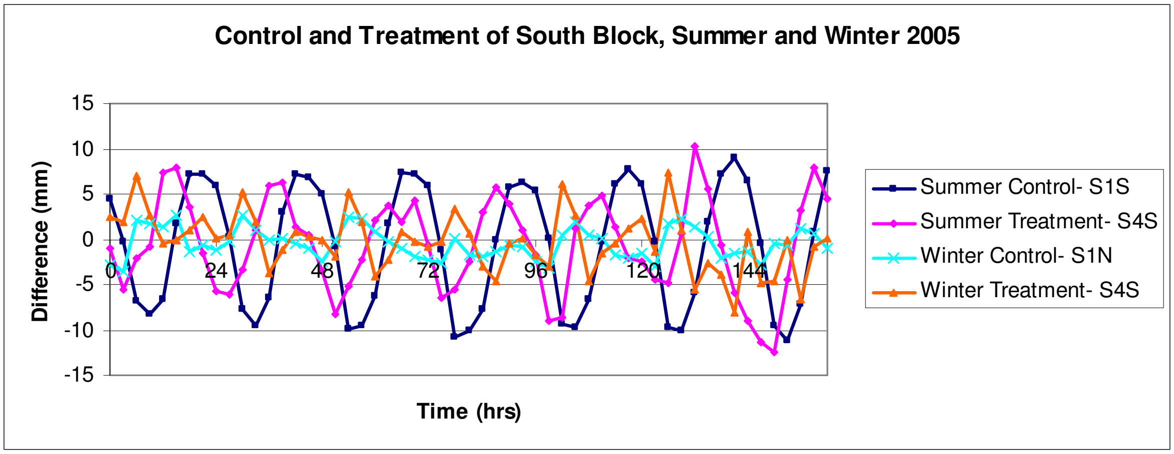
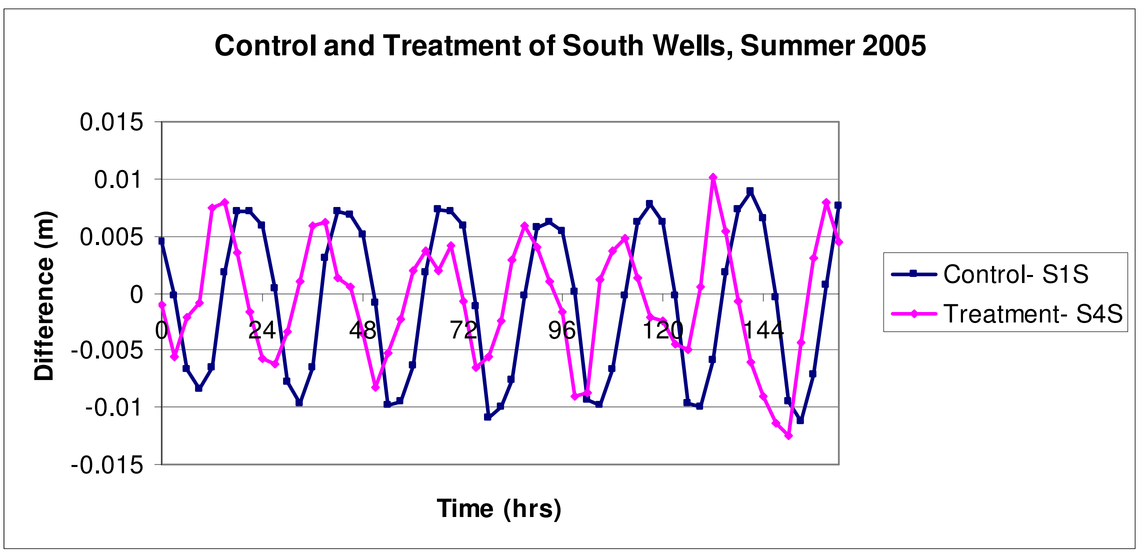


Figure 10. Simple differences of the Control and Treatments wells for the North, Middle and South Blocks, Summer and Winter 2005.



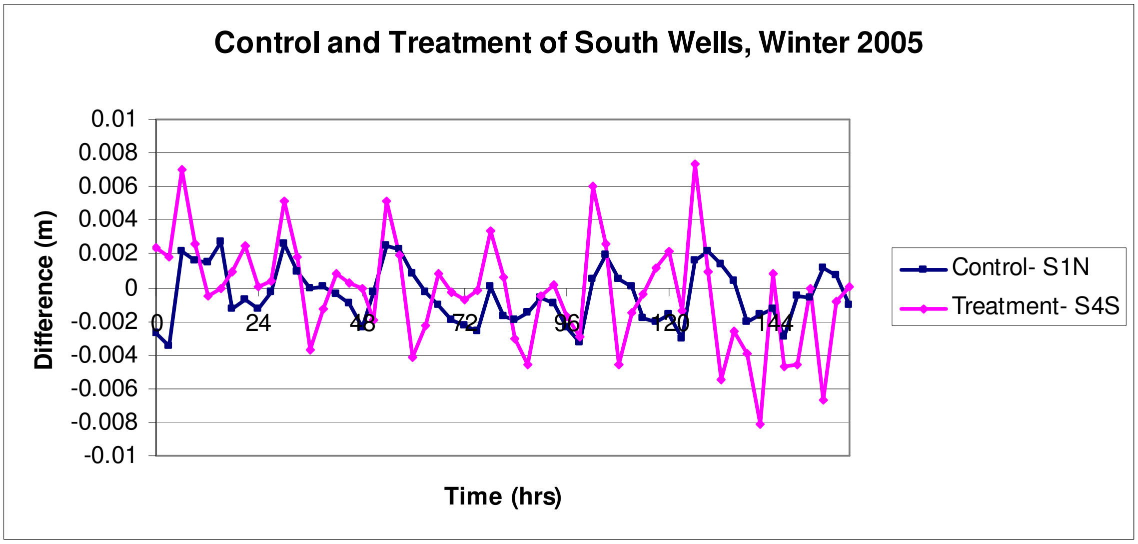


Figure 11. More detailed look at the Control and Treatment of South Wells from Summer and Winter 2005.

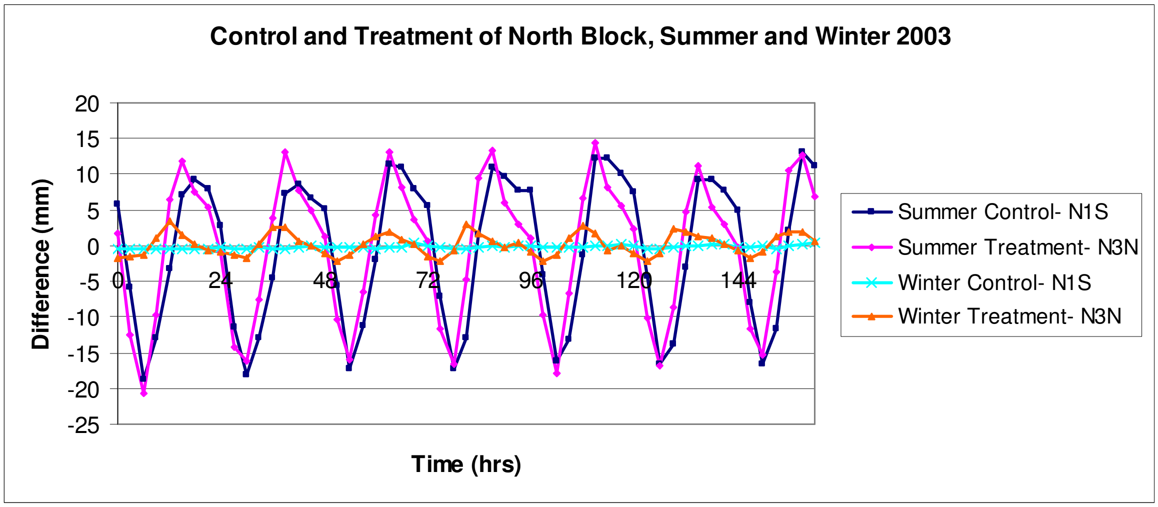
Table 4. Average low and high amplitudes (mm) from the difference plots for each control and treatment site.

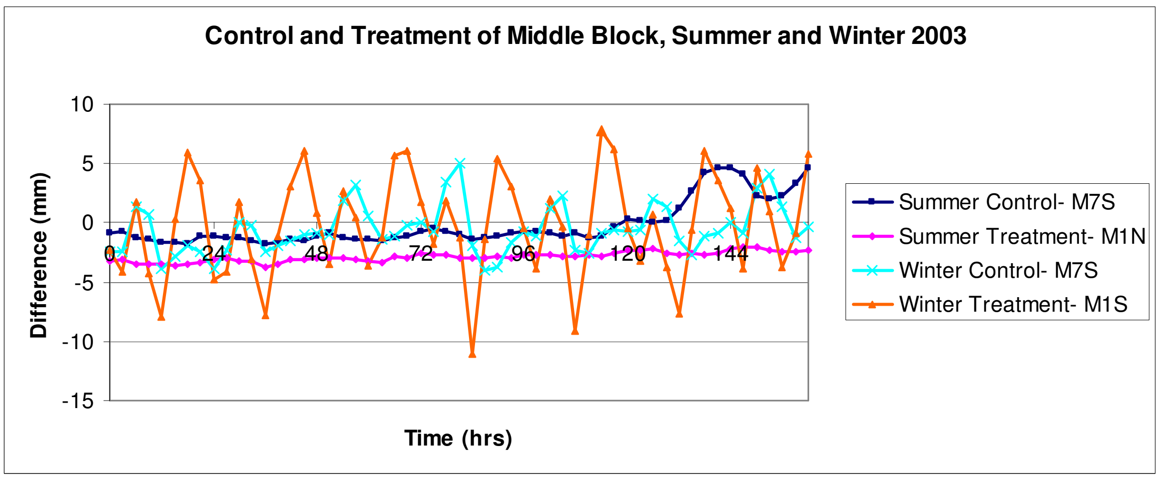
				Average Amplitude (mm)	
Well ID	**Control/Treatment**	**Season**	**Year**	**Low**	**High**
N1S	Control	Summer	2003	-17.2	10.7
M7S	Control	Summer	2003	-0.35	0.35
S1S	Control	Summer	2003	-1.78	0.97
N1N	Control	Summer	2005	-20.35	12.6
M7N	Control	Summer	2005	-15.2	9.68
S1S	Control	Summer	2005	-9.96	7.46
			Average	**-10.81**	**6.96**
N3N	Treatment	Summer	2003	-17	12.8
M1N	Treatment	Summer	2003	-3.19	2.54
S4N	Treatment	Summer	2003	-5.38	5.94
N3S	Treatment	Summer	2005	-20.49	13.3
M1S	Treatment	Summer	2005	-6.27	4.13
S4S	Treatment	Summer	2005	-7.54	6.74
			Average	**-9.98**	**7.58**
N1S	Control	Winter	2003	-0.32	0.097
M7S	Control	Winter	2003	-2.49	1.6
S1S	Control	Winter	2003	-1.4	0.68
N1S	Control	Winter	2005	-0.2	0.13
M7S	Control	Winter	2005	-0.74	1.13
S1N	Control	Winter	2005	-2.06	1.11
			Average	**-1.20**	**0.79**

N3N	Treatment	Winter	2003	-2.01	2.6
M1S	Treatment	Winter	2003	-5.57	4.06
S4S	Treatment	Winter	2003	-2.95	3.65
N3S	Treatment	Winter	2005	-0.93	0.45
M1N	Treatment	Winter	2005	-2.3	1.95
S4S	Treatment	Winter	2005	-3.18	2.76
			Average	**-2.82**	**2.58**

Note: Site ID's are read as N1S= North Block, Site 1, South well; M7N= Middle Block, Site 7, North well; S4S= South Block, Site 4, South well.

The 2003 data had several interesting features (Figure 12 and Table 4). The North block shows similar diurnal fluctuations between the control (average amplitude of -17.2 mm and 10.7 mm) and treatment (average amplitude of -17.0 mm and 12.8 mm) for the summer. The winter showed a small variation between the control (-0.32 mm and 0.097 mm) and the treatment (-2.01 mm and 2.6 mm) with the treatment showing a slightly higher amplitude. The Middle block had minimal fluctuations in the summer for both the control (-0.35 mm and 0.35 mm) and treatment (-3.19 mm and 2.54 mm) but the control had an unexpected upward trend towards hour 130 (Figure 12). The South block showed higher fluctuations for the treatment (-5.38 mm and 5.94 mm) than the control (-1.78 mm and 0.97 mm) in the summer which is not what was anticipated due to more expected vegetation and evapotranspiration losses on the control site. The treatment site (-2.95 mm and 3.65 mm) showed higher fluctuations than the control site (-1.4 mm and 0.66 mm) in the winter as well.





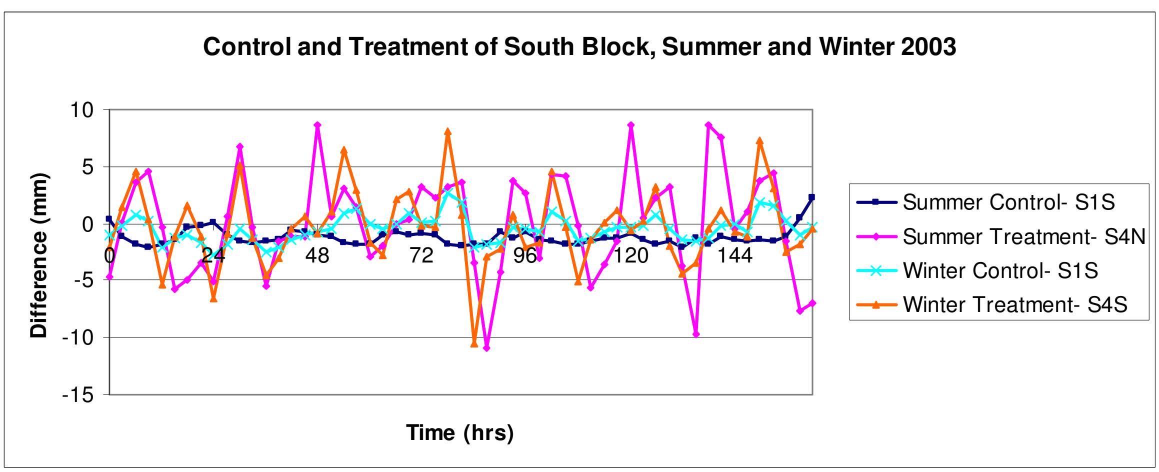


Figure 12. Simple difference of the Control and Treatment wells for the South Block, Summer and Winter 2003.

The amplitudes from the differences were measured from the control and treatment graphs and averaged for each well to develop a quantifiable value (Table 4).

The table is divided up into seasons, the top half is summer and the lower half is winter. Overall, the amplitude values were much greater in the summer versus the winter which was to be expected because of evapotranspiration losses during the day. However, there are several anomalies within the table. For the ‘summer control’ plots of M7S and S1S in 2003, their average amplitude values were less than 1 mm in the positive direction and less than 1.8 mm in the negative direction; extremely low compared to the overall average of 10.81 mm in the negative direction and almost 7 mm in the positive direction. The north sites for the ‘summer treatment’ in 2003 and 2005 both had extremely high average amplitude; 17 mm in the negative direction and 12.8 mm in the positive direction for 2003 and respectively -20.49 mm and 13.3 mm for 2005. One would expect the treatment sites to have lower fluctuations because vegetation was removed. The amplitude averages from the “winter control’ and ‘winter treatment’ plots were normal with no anomalies. However, the control sites had lower total average amplitudes than the treatment sites. This may be caused by a variety of phenomenon that is discussed in the next section.

4.0 Discussion

The control and treatment sites portrayed more variation than expected with several treatment sites exhibiting larger fluctuations than the control sites for winter for both years. The wells from the Middle block from summer 2003 have smaller fluctuations in the summer than the winter. There are several possible explanations for these observations: 1) the vegetation buffer zone located between the river and treatment sites could be influencing the groundwater fluctuations 2) there might be a stronger connection to the river's diurnal fluctuations (due to open water evaporation) and shallow groundwater levels because of the proximity of a well to the river at one site versus another, 3) sites might differ between soil types and porosity causing evapotranspiration to occur more readily 4) the cottonwood stands on the treatment sites might be affecting the groundwater levels more than anticipated and 5) precipitation could be altering groundwater levels at one site and not another and 6) an open canopy in the winter could allow more radiation to hit the ground surface for soil water evaporation, causing the higher winter treatment fluctuations.

4.1 Relationship between Surface water and Groundwater

Although there have been many linkages between surface water and groundwater, water managers have long looked at the two as separate entities (Fleckenstein et al. 2004). With increasing development of land and water resources, the understanding that the development of either of these resources will affect the quantity and quality of the other has gained great importance (Winter et al 1999). Groundwater discharge to streams, or baseflow, often makes up the major source of streamflow during dry periods. During these periods, groundwater use is usually highest and minimum flow requirements can be

violated if base flows are reduced (Fleckstein 2004). Intensive pumping by irrigation wells from alluvial aquifers reduces the recharge to streams and rivers and may, at times, reverse the hydraulic gradient so that stream depletions occur. Therefore, over-pumping for irrigation purposes in the Middle Rio Grande could be affecting the groundwater fluctuations. In riparian areas, the hydraulic connection between groundwater and the river increases closer to the river. This connection is the reason why vegetation in riparian areas is so dependent on groundwater and flooding.

Most riparian vegetation is dependent on shallow groundwater for survival. In the summer when plant species are transpiring water during the day and dormant at night, the water table lowers and rises, respectively. This same diurnal pattern can be seen in the river, levels rising and lowering during a 24 hour period because of open water evaporation and transpiration losses caused by nearby vegetation. Because there is a strong connection between the river and groundwater, open water evaporation could be a possibility as to why there is unexplained variability in the summer treatment sites.

The river discharge was plotted to compare how it varies between seasons for the two years being investigated (Figure 13 and Figure 14). There was just as much variation in discharge for the summer as there was for the winter discharge rates for 2003 (Figure 13). One would expect to see higher fluctuations in the summer discharge values than in winter because of daily open water evaporation. Figure 14 illustrates the trend of more variability in the summer and less in the winter. However, since day to day fluctuations are seen in the summer discharge for years 2003 and 2005, this could affect groundwater fluctuations in the treatment sites. In addition, the winter discharge fluctuation in 2003 could cause the larger fluctuations seen in the Middle block from the treatment well M1S.

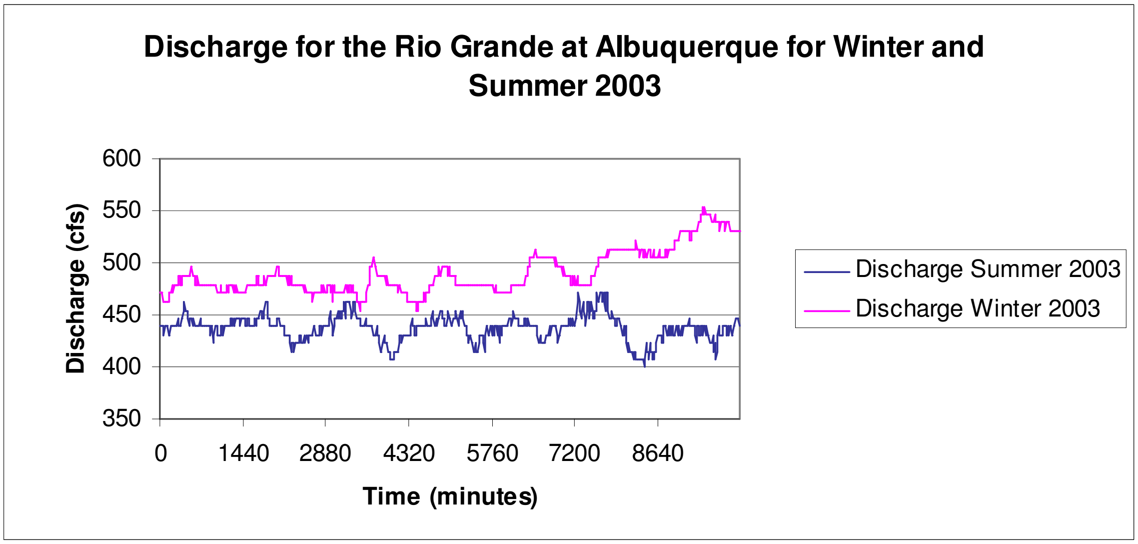


Figure 13. Discharge for the Rio Grande at Albuquerque (USGS 0833000) for winter and summer 2003. July 9-15, 2003 and January 31- February 6, 2004.
Note: Data was not available for the river gages just north of Los Lunas for the given dates. The Rio Grande at Albuquerque was the closest river gage located up stream from the Middle block.

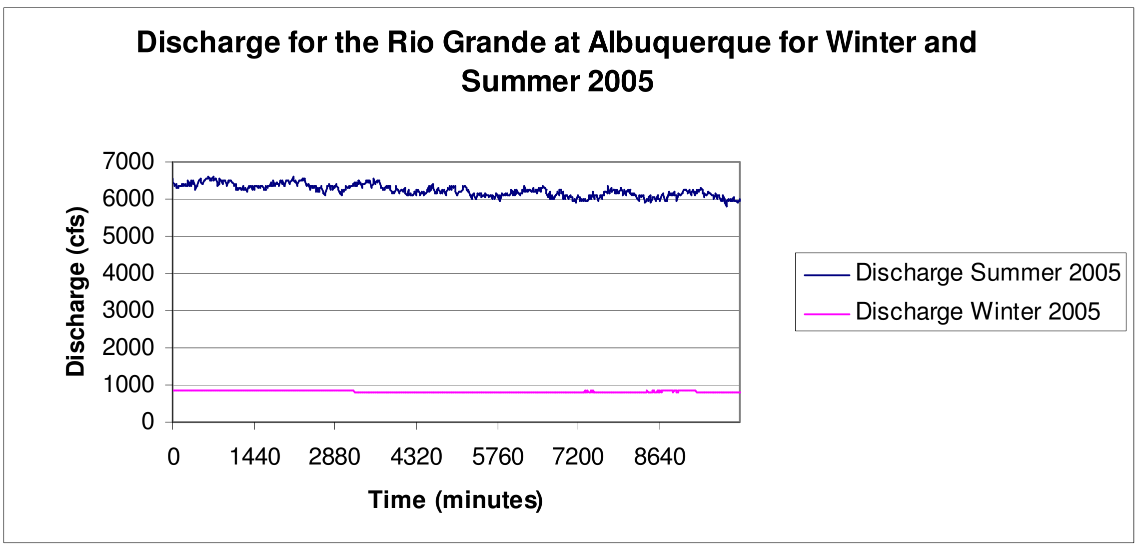


Figure 14. Discharge for the Rio Grande at Albuquerque (USGS 0833000) for winter and summer 2005. June 4-10, 2005 and November 21-27, 2005.
Note: Data was not available for the river gages just north of Los Lunas for the given dates. The Rio Grande at Albuquerque was the closest river gage located up stream of the Middle block.

The distance from the river to each well was measured using the coordinates of the wells and a map created in GIS to determine if certain wells were located closer to the river than others. The groundwater elevations closest to the river might be more strongly

influenced by the river stage than those that are further away, therefore, creating strong groundwater fluctuations when they are not to be expected.

Table 5. Distance from the wells to the river.

		Well ID	Distance from River (m)
North Block	Control	N1N	140.00
		N1S	34.44
	Treatment	N3N	46.33
		N3S	115.42
Middle Block	Control	M7N	67.61
		M7S	210.59
	Treatment	M1N	157.71
		M1S	71.88
South Block	Control	S1N	107.29
		S1S	174.49
	Treatment	S4N	n/a
		S4S	n/a

There were two sites with significant differences between their distances to the river; the middle block from winter 2003 and the north block from winter 2005. The north wells from 2005, N1S and N3S, have distances 34.44 m and 115.42 m respectively. However, their fluctuations do not differ considerably (-0.2 mm and 0.13 for N1S and -0.93 mm and 0.45 mm for N3S) thus distance is not effecting their fluctuations. The middle wells from winter 2003, M7S and M1S, have distances 210.59 m and 71.88 m respectively. M1S, the treatment, has higher average amplitudes of -5.57 m and 4.06 m compared to the control site, M7S, with average amplitudes of -2.49 m and 1.6 m. The higher amplitude values are found in treatment site which is approximately 139 m closer to the river than the control site. These higher fluctuations could be caused by the stronger connection M1S has to the Rio Grande than M7S possesses, giving the treatment

site a valid reason to have higher fluctuations than the control site in the winter. In addition, the varying river stage as seen in Figure 13 could be adding to this fluctuation.

The south sites have a unique situation in that the wells found in S4 are located in the Bosque del Apache National Wildlife Refuge. These wells are located between a wetland that gets drained and filled seasonally and the Rio Grande. The groundwater from these wells is more likely influenced by the wetland and the river giving it more variability than the other sites.

4.2 Vegetation

As discussed previously, there is a strong connection between riparian vegetation and shallow groundwater. The fuels reduction treatment for this study included complete clearing of non-native and invasive species and treating one of the three treatment sites with herbicide so that only cottonwood and other native species remained inside the test plot. However, outside the plot between the river and the treatment plot stands a 20-50 meter buffer zone of vegetation with both native and non-native species. This vegetation buffer zone could be one of the factors influencing the summer and winter fluctuations in the treatment plots but it is difficult to determine without proper vegetation density measurements.

Cottonwood stands flourish in floodplains with shallow water tables and few flooding events (Stromberg et al. 1998). Vegetation left intact in the treatment sites consist primarily of cottonwoods which are known to transpire a large amount of water during the summer months. The cottonwood stands located on the treatment sites also hold the possibility of influencing the groundwater fluctuations more than were expected. And once again, vegetation density measurements would be needed to calculate if the

cottonwood stands were denser on one site versus another, influencing the groundwater fluctuations. In addition, the fuels reduction opened the cottonwood canopy when the treatments were implemented. In the winter when cottonwoods drop their leaves, the canopy is open and the ground is vulnerable to direct radiation from the sun. This could allow for soil water evaporation to occur causing the winter treatment sites to have higher fluctuations than the control sites as seen in the results. However, the site photos and descriptions from the treatment sites indicate that there is leaf litter on the ground surface therefore allowing little, if any, soil evaporation to take place.

The control and treatment wells in the north and middle blocks are located in close proximity to each other within their designated block. The wells in the south block, on the other hand, are not within close proximity. The control site is located near Bernardo, NM and the treatment site is located in the Bosque del Apache National Wildlife Refuge, approximately 40 miles away.

Soil types were identified by the USDA Forest Service, Southwestern Region while conducting an Ecological Site Description before treatments were established in each block. Each control and treatment has a different soil type which could explain the variation in diurnal groundwater levels. Soil types have different porosity and permeability levels, levels in which water can infiltrate through. For example, clays have higher porosities (~0.50) but relatively low permeability and sands have lower porosities (~0.35) but high permeability (Ingebritsen and Sanford 1998). Therefore, soil type could affect the connectivity rates of the river to groundwater and the rates at which precipitation infiltrates, adding to the different fluctuation values between the control to treatment sites.

Table 6. Types of soil texture at the surface and 1 meter below ground. (Finch et al. 2004)

Site ID	Soil Texture at Surface and at 1 m
North 1 - Control	Silt clay loam
	Silt clay
North 3- Treatment	Silt loam
	Sand
Middle 1 -Treatment	Fine sandy loam
	Loamy sand
Middle 7- Control	n/a
South 1- Control	Very fine sandy loam
	Silt loam
South 4- Treatment	Silt clay
	Silt clay loam

4.3 Precipitation

Precipitation in the southwest is limited. Average annual precipitation ranges from less than 25.4 cm (10 inches) over much of the southern desert and Rio Grande and San Juan Valleys to more than 50.8 cm (20 inches) in the higher elevations (Western Regional Climate Center 2007). Summer rains fall almost entirely during brief, but intense thunderstorms. The intense summer rains were thought to possibly be influencing some of the more variable summer treatment plots. However, according to Table 7 less than two centimeters of precipitation fell at each weather station, except the Albuquerque Valley during February 2004 with 3.12 cm, during the months listed below. The weather stations are located throughout the reach from the north of the study area to the south. Less than two centimeters of precipitation per month is not enough rain to directly affect the daily fluctuations of groundwater levels in the monitoring wells.

Table 7. Monthly precipitation values (cm) for cities near the study sites. The months were chosen based on the time periods used in this study (month and year). (Western Regional Climate Center 2007)

Date	Albuquerque Valley	Los Lunas	Bernardo	Bosque del Apache
July 2003	1.88	0.64	0.79	0.89
Feb 2004	3.12	1.57	1.17	0.51
June 2005	0.53	0.00	1.78	1.30
Nov 2005	0.00	0.00	0.00	0.00

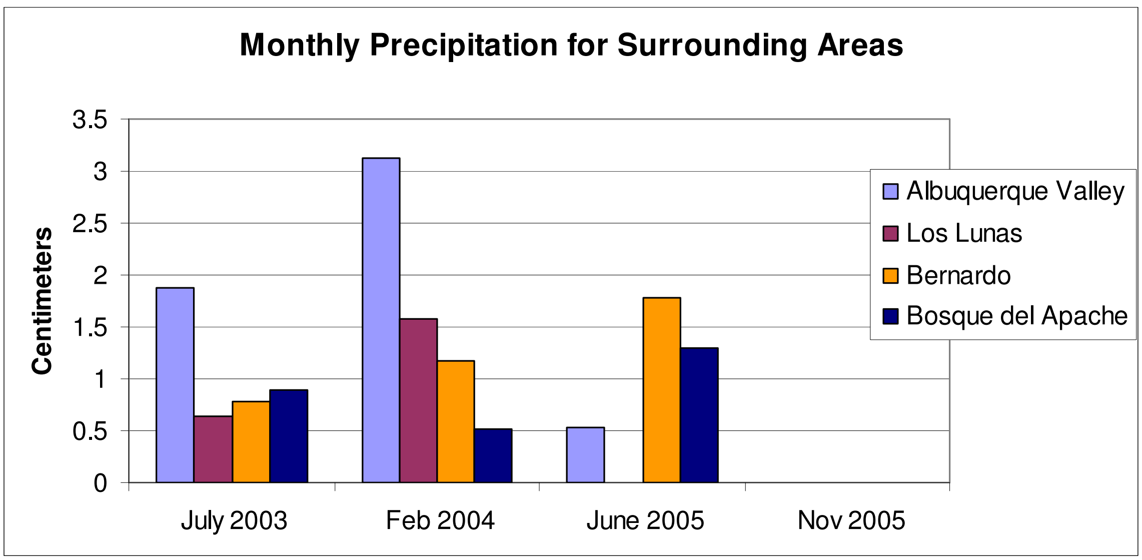


Figure 15. Graph of monthly precipitation for cities surrounding the study sites. (Western Regional Climate Center)

5.0 Conclusions and Recommendations

Groundwater levels from three control sites (no fuel load reduction) and three treated sites (woody fuels mechanically removed and spot treated with herbicide) in the Middle Rio Grande bosque have been recorded at 15 minute intervals since 2001. Shallow groundwater level fluctuations from the control sites were compared to those of the treated sites to determine if there were impacts or changes to groundwater levels from removing fuels (invasive species) from the bosque. Invasive species like saltcedar and Russian olive often compete with native riparian vegetation for groundwater in the bosque, later on dominating these areas because of the competitive advantage they hold over native species; high reproduction rates, high water use with deep root systems, tolerance of drought and flooding, and tolerance for high salinity levels. Saltcedar's high rate of stem mortality causes large masses of dead and downed wood, in turn creating dry fuel for catastrophic wildfires and threatening communities and structures near the bosque as well as destroying the native bosque environment.

The control and treatment sites revealed several treatment sites held stronger fluctuations than the control sites for winter of both years and the middle bock wells from summer 2003 had smaller fluctuations in the summer versus the winter. These groundwater fluctuation differences were investigated and hypothesized to be tied to several factors: vegetation, soil type, river stage, and well location. Most of these factors are difficult to measure and it is difficult to determine their true impact on groundwater levels. However, these variables are known to impact groundwater so they should be examined further. The effect of fuel reduction on shallow groundwater levels is minimal; other factors appear to have at least as important and possibly a greater influence. In

particular, the vegetation remaining after thinning is quite important. The results are confounded by the fact that up to a 50 meter buffer of native and exotic vegetation was left along each river bank. This, often very dense vegetation, is believed to have a significant influence on shallow groundwater levels, particularly during summer months when evapotranspiration rates are greatest.

Overall, there was not much of a difference in groundwater fluctuations between the control and treatment sites in the summer and winter seasons. The ground water amplitudes from the control and treatment sites (respectively -10.81 mm/6.96mm and -9.98mm/7.58mm for the summer and -1.20mm /0.79mm and -2.89mm/2.58mm for the winter) were similar. Therefore, the results from this study show there are minimal impacts to shallow groundwater when removing fuel loads.

The USDA Forest Service project would be further enhanced with the following investigations for future work. The elevation of the well heads is not currently known. Surveying the elevation of the well heads is needed to determine the association of actual water depth and fuel removal in the bosque. This will allow for a deeper exploration into the relationship between the river, irrigation channels and the groundwater in the bosque. In addition, examining and calculating the density of vegetation in the treatment and control plots using remote sensing maps would also help determine the effect vegetation density has on groundwater fluctuation and to what extent. Lastly, contacting and sharing information with the USDA Forest Service researchers whom investigated how vegetation was impacted by fuels reduction would be beneficial to this study (and theirs) because of the many connections and relationships that occur between vegetation and groundwater.

Literature Cited

Bartolino, James R. and James C. Cole. 2002. Groundwater resources of the Middle Rio Grande Basin, New Mexico. United States Geologic Survey Series Circular 1222.

Brown, F.L., S.C. Nunn, J.W. Shoemaker, and Gary Woodward. 1996. The value of water: A report to the City of Albuquerque in response to RFP95-010-SV, January 15, 1996. pp 144.

Busch, D.E. 1995. Effects of fire on southwestern riparian plant community structure. The Southwestern Naturalist 40(3):259-267.

.

Busch, D.E., and S.D. Smith. 1993. Effects of fire on water and salinity relations of riparian woody taxa. Oecologia 94:186-194.

Busch, D. E., and S.D. Smith. 1995. Mechanisms Associated with Decline of Woody Species in Riparian Ecosystems of the Southwestern U.S. Ecological Monographs. 65(3): 347-370.

Cleverly, James R., Clifford N. Dahm, James R. Thibault, David J. Gilroy, and Julie E. Allred Coonrod. 2002. Seasonal estimates of actual evapotranspiration and Tamarix ramosissima stands using three- dimensional eddy covariance. Journal of Arid Environments. 52: 181-197.

Crawford, C. S., A. C. Cully, R. Leutheuser, M. S. Sifuentes, L. H. White, and J. P. Wilber. 1993. Middle Rio Grande ecosystem: bosque biological management plan. Middle Rio Grande Biological Interagency Team, U.S. Fish and Wildlife Service, Albuquerque, N. Mex. 291 pp. + maps.

Culler, R. C., R.L. Hanson, R.M. Myrick, R.M. Turner, and F.P. Kipple. 1982. Evapotranspiration Before and After Clearing Phreatophytes, Gila River Flood Plain, Graham County, Arizona. United States Geological Survey Professional Paper. 655-P.

Dahm, Clifford N., James R. Cleverly, Julia E. Allred, Coonrod, James R. Thibault, Dianne E. McDonnell, and David J. Gilroy. 2002. Evapotranspiration at the land/water interface in a semi-arid drainage basin. Freshwater Biology. 47: 831-843.

de Gouvenain, Roland C. 1996. Origin, History, and Current Range of Saltcedar in the U.S. Webpage: http://www.invasivespeciesinfo.gov/docs/news/workshopJun96/Paper1.html Assessed on July 2007.

DeLoach, C. J., and J. L. Tracy. 1997. Effects of Biological Control of Saltcedar (*Tamarix ramosissima*) on Endangered Species. Draft Biological Assessment. Temple, TX: USDA-ARS. 524 p.

Everitt, B.L., 1980. Ecology of saltcedar: a plea for research. Environmental Geology. (3)77-84.

Finch, D., A. Chung-MacCoubrey, J. Kelly, R. Jemison, B. Pendleton, R. Pendleton. 2001. Effects of Fuels Reductions and Exotic Plant Removal on Vertebrates, Vegetaions, and Water Resources in Southwestern Riparian Ecosystems. Proposal to Joint Fire Science Program: RFP 2001-1. USDA Forest Service, Rocky Mountain Research Station, Albuquerque, New Mexico.

Finch, D., R. Jemison, A. Chung-MacCoubrey, J. Galloway, M. Means, D. Hawksworth. 2003. Progress Report for the Middle Rio Grande Fuels Reduction Study 2000-2002, USDA Forest Service, Rocky Mountain Research Station, Albuquerque, New Mexico.

Finch, D., R. Jemison, A. Chung-MacCoubrey, J. Galloway, M. Means, H. Bateman, D. Hawksworth. 2004. Middle Rio Grande Fuels Reduction Study 2004 Annual Report. USDA Forest Service, Rocky Mountain Research Station, Albuquerque, New Mexico.

Fleckenstein, Jan, Michael Anderson, Graham Fogg, and Jeffrey Mount. 2004. Managing Surface Water- Groundwater to Restore Fall Flows in the Consumnes River. Journal of Water Resource Planning and Management. 130(4): 301-310.

Harms, Rebecca S., and Ron D. Hiebert. 2006. Vegetation Response Following Invasive Tamarisk (Tamarix spp.) Removal and Implications for Riparian Restoration. Restoration Ecology. 14 (3): 461-472.

Horton, J. S. 1977. The development and perpetuation of the permanent saltcedar type in the phreatophyte zone of the Southwest. *In* R. R. Johnson and D. A. Jones, tech. coords. Importance, Preservation, and Management of Riparian Habitat. USDA-FS GTR RM-43. Fort Collins, CO: USDA Forest Service. Pp. 123–127.

Howe, W. H., and F. L. Knof. 1991. On the imminent decline of Rio Grande cottonwoods in central New Mexico. The Southwestern Naturalist. 36: 218-224.

Ingebritsen, Steven E., and Ward E. Sanford. 1998. Groundwater in Geologic Processes. Cambridge University Press, Cambridge, United Kingdom.

Le Maitre, David C., David F. Scott, and C. Colvin. 1999. A review of information on interactions between vegetation and groundwater. Water South Africa. 25(2): 137-152.

Molles, M.C., C.S Crawford Jr., L.M. Ellis, H.M. Valett, and C.N. Dahm. 1998. Managed flooding for riparian ecosystem restoration. Bioscience. 48: 749-756.

Moore , Daniel S. 2004. The Basic Practice of Statistics. W.H. Freeman and Company. Pp. 88-93.

Naiman, R.J., H. Decamps, and M Pollock. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications. 3: 209-212.

Papadopulos, S.S. and Associates, Inc. 2000. Middle Rio Grande Water Supply. 1877 Broadway, Suite 703, Boulder, Colorado.

Richter, H.E. 1993. Delvelopment of a conceptual model for floodplain restoration in a desert riparian system. Arid Lands Newsletter. 32: 13-17.

Sala, Anna, Stanley D. Smith, and Dale. A Devitt. 1996. Water Use by Tamarix Ramosissima and Associated Phreatophytes in a Mojave Desert Floodplain. Ecological Applications. 6(3): 888-898.

Scurlock, D. 1998. From the Rio to the Sierra: An environmental history of the Middle Rio Grande Basin. USDA Forest Service Rocky Mountain Research Station, General Technical Report RMRS-GTR-5. 444 pp.

Smerdon, Brian, and Todd Redding. 2007. Groundwater: More than Water Below the Ground! Streamline: Watershed Management Bulletin. 10(2): 1-6.

Stromberg, J. 1998. Dynamics of Fremont cottonwood (Populus fremontii) and saltcedar (Tamarix chinensis) populations along the San Pedro River, Arizona. Journal of Arid Environments. (40)133-155.

Western Regional Climate Center. 2007. Can be found at http://www.wrcc.dri.edu Assessed August 2007.

Winter, T.C., J.W. Harvey, O.L. Franke, and W. M. Alley. 1999. Groundwater and surface water: A single resource. Circular 1139, U.S. Geological Survey, Washington D.C.

Appendix A. Additional Photos

The following photos represent how the canopy and ground are seen in the summer and the winter. The north site was used for all the photos because each site encloses the same trend of a full canopy in the summer and sparse in the winter. All sites contain extensive leaf litter. Photos were taken May 14, 2007 for summer photos and February 19, 2007 for winter photos.

Figure 16. Photos of the canopy from the north control site (N1) in summer (left) and winter (right).

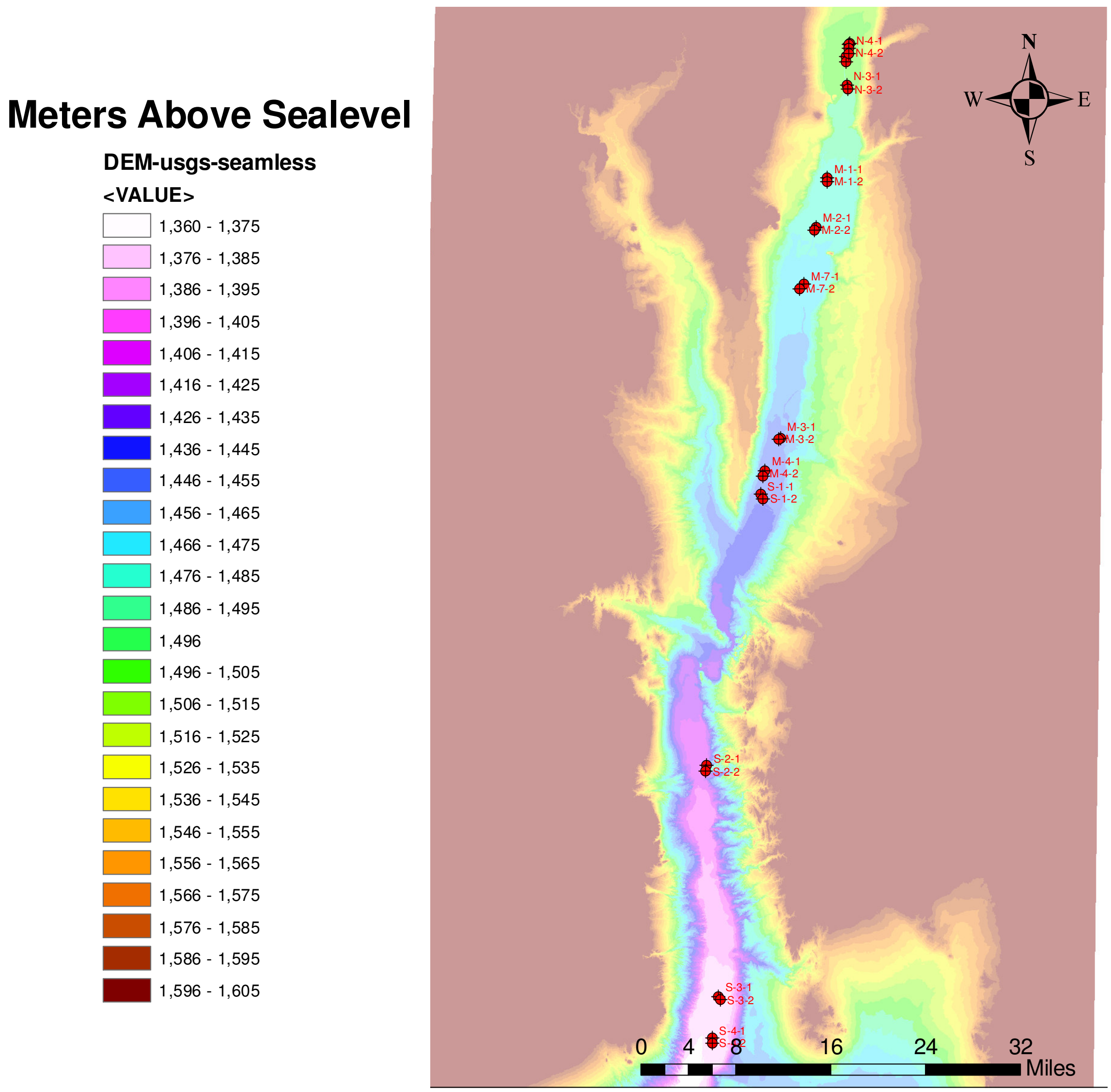
Figure 17. Photos of the canopy from the north treatment site (N3) in summer (left) and winter (right).


Figure 18. Photos of the ground for the north control site (N1) in summer (left) and winter (right).


Figure 19. Photos of the ground for the north treatment site (N3) in the summer (left) and winter (right).

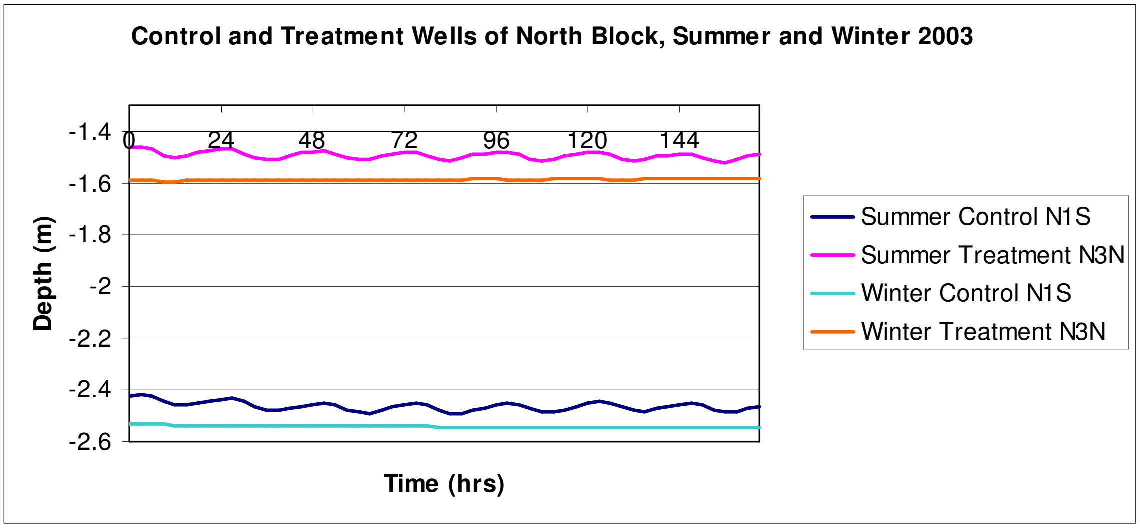
Appendix B. Elevation of Wells

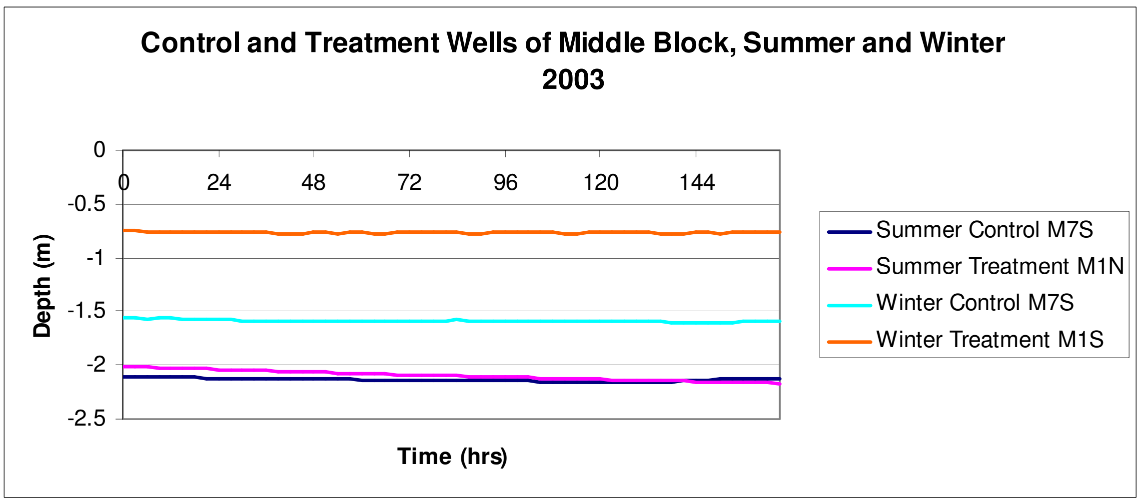
The elevations of the wells have been approximated by using Digital Elevation Models (DEMs),7.5 minute, downloaded from http://seamless.usgs.gov/ and created in GIS.

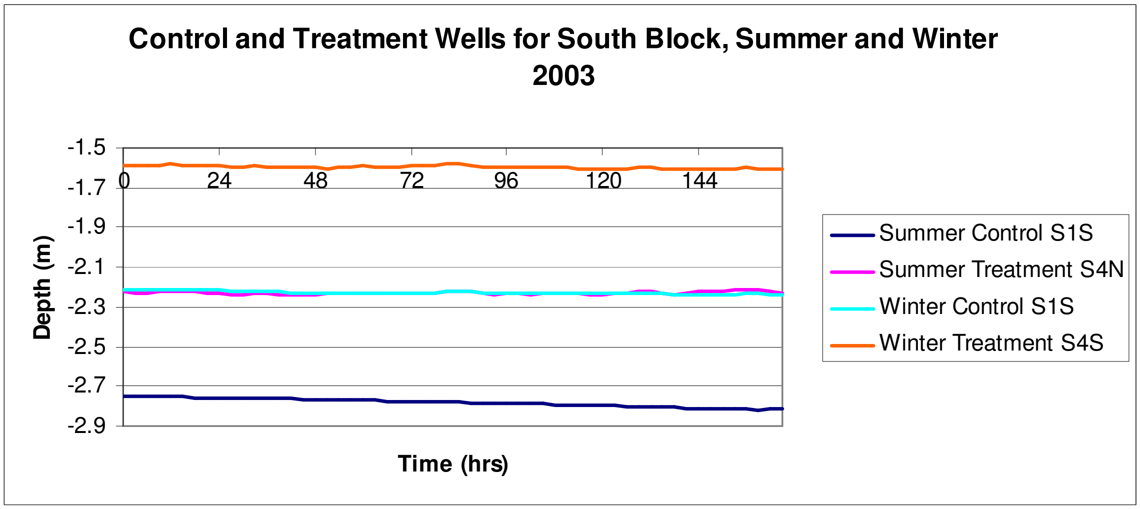


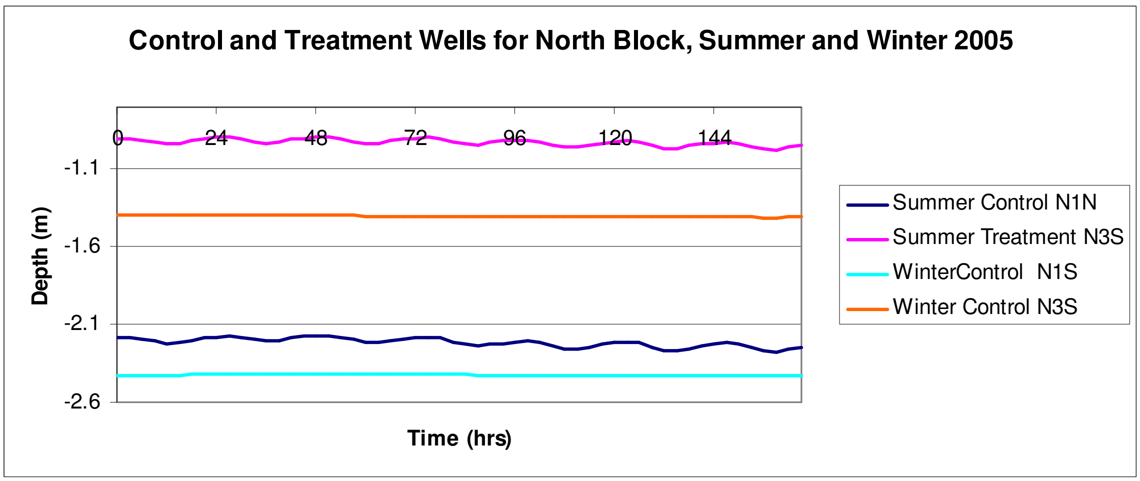
Appendix C. Depth to Water Graphs

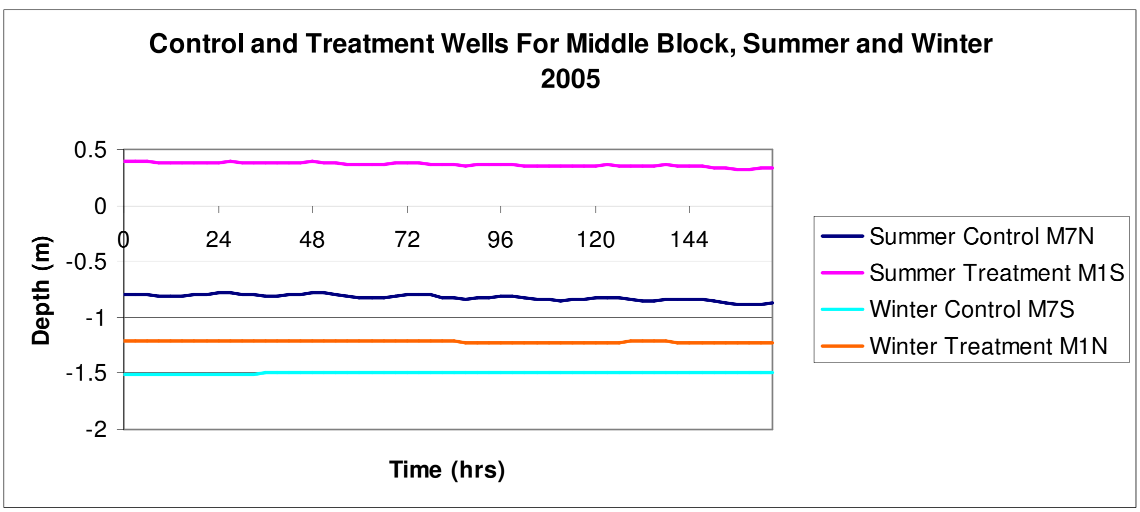
The graphs below represent the depth to groundwater found at each well location. The wells have not been surveyed so elevation has not been factored into the depths.

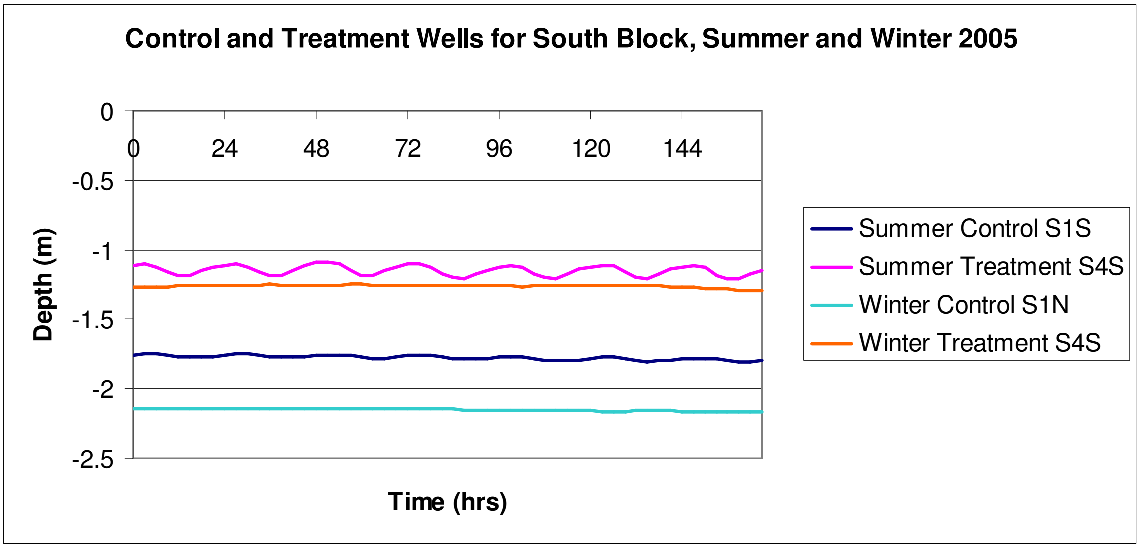





Control and Treatment Wells for South Block, Summer and Winter 2003
Depth (m)
-1.5
-1.7
-1.9
-2.1
-2.3
-2.5
-2.7
-2.9
0
24
48
72
96
120
144
Time (hrs)
Summer Control S1S
Summer Treatment S4N
Winter Control S1S
Winter Treatment S4S


Control and Treatment Wells for North Block, Summer and Winter 2005
Depth (m)
-1.1
-1.6
-2.1
-2.6
0
24
48
72
96
120
144
Time (hrs)
Summer Control N1N
Summer Treatment N3S
WinterControl N1S
Winter Control N3S


Control and Treatment Wells For Middle Block, Summer and Winter 2005
Depth (m)
0.5
0
-0.5
-1
-1.5
-2
0
24
48
72
96
120
144
Time (hrs)
Summer Control M7N
Summer Treatment M1S
Winter Control M7S
Winter Treatment M1N


Control and Treatment Wells for South Block, Summer and Winter 2005
0
-0.5
-1
-1.5
-2
-2.5
Depth (m)
0
24
48
72
96
120
144
Time (hrs)
Summer Control S1S
Summer Treatment S4S
Winter Control S1N
Winter Treatment S4S