April 2016

Assessment of Water Table and Water Quality Variations with Respect to River Flow Along the Rio Grande Between Garfield, NM and the New Mexico-Texas Border

WRRI Technical Completion Report No. 372

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New Mexico State University graduate student Benjamin Nano O Kuffour collected water samples from monitoring wells from Hatch down to Anthony, New Mexico.

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ASSESSMENT OF WATER TABLE AND WATER QUALITY VARIATIONS WITH RESPECT TO RIVER FLOW ALONG THE RIO GRANDE BETWEEN GARFIELD NM AND THE NEW MEXICO – TEXAS BORDER

By

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TECHNICAL COMPLETION REPORT NO. 372
Account Number 124453

April 2016

New Mexico Water Resources Research Institute
New Mexico State University
in cooperation with the
Department of Plant and Environmental Sciences

The research on which this report is based was financed in part by the State of New Mexico, through the New Mexico Water Resources Institute.

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ACKNOWLEDGEMENTS

We would like to thank the New Mexico Water Resources Research Institute and the State of New Mexico for partial funding that helped us perform this study. We would also like to thank the Elephant Butte Irrigation District for providing access to their observation wells and for providing some of the transportation for water sample collection.

ABSTRACTS

The interaction between the Rio Grande and the groundwater in the Lower Rio Grande Basin in New Mexico was studied for a limited time from May of 2014 to June of 2015. During this period of time, river flow was observed and shallow groundwater levels were measured at various times from 58 monitoring wells owned and operated by the Elephant Butte Irrigation District. The monitoring wells are located between Hatch, New Mexico down to the New Mexico-Texas border and situated within the shallow alluvium of the Rio Grande floodplain in the area. In addition, select water quality attributes to include electrical conductivity (EC), salts (sodium, calcium, potassium and magnesium), and sodium adsorption ratio (SAR) were measured and recorded for water samples collected from monitoring wells both during times of flow in the river and times of no-flow. The measurements further validate that there is an interaction between the Rio Grande and the shallow groundwater aquifer. However, the relationship between the low EC water flows that percolated into the aquifer from the river did not seem to have much of an impact on the shallow alluvium groundwater EC. It is believed that possible sources for the salts are excessive irrigation and other groundwater sources. Further testing is required to determine the source of the salts. Empirical equations were developed for modelling the initial flow from the Rio Grande into the groundwater aquifers in the Hatch-Rincon Valley and the Las Cruces areas. Despite the high correlation values that were determined for the equations, further study is required to validate these equations.

Keywords: water table, water quality, Rio Grande, New Mexico-Texas border, surface groundwater interactions, river flow, Elephant Butte Irrigation District, monitoring wells, flow modeling

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INTRODUCTION

The Lower Rio Grande Basin in New Mexico, particularly the Elephant Butte Irrigation District in the southernmost extent of the state, is facing a severe shortage of surface water for irrigation and the problem is getting worse with continued drought. There is a strong possibility that the drought situation is not going to improve in the near future (Deb et al. 2012). Low surface water availability for irrigation is putting increasing pressure on groundwater resources (Sharma et al. 2013). Recent measurements (Natural Resources Conservation Service (NRCS); Deb et al. 2012) indicate that the water table has dropped due to the continuous pumping for irrigation from Hatch and Anthony, NM to areas south of El Paso, TX and the concentrations of salts appear to be increasing. The U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) has recorded a drop in the water level from observation wells in the Hatch area. Some of the observation wells in the Las Cruces area that were monitored in this study were dry when measurements were taken in the May of 2014. Similar drops have been observed by measurements from this study along the Rio Grande River between Garfield, NM and the New Mexico-Texas border. Farmers in the Hatch area complain that in the middle of the irrigation season, the well water level is so low that they cannot pump enough to meet crop water demand. In the Las Cruces area, there are mixed concerns about well water. Some water users complain about dropping water levels, while others complain of increasing salt concentrations.

Study Objectives

1) Measure the fluctuations of the water table on a monthly basis throughout the year along the Rio Grande south of Garfield, NM and develop a model that describes the influence of the river and canal systems on the aquifers.
2) Monitor the fluctuations in groundwater quality parameters (salinity and sodicity) by collecting water samples from over 50 observation wells and river water from Garfield, NM down to the New Mexico-Texas border.
3) Develop a preliminary water budget for the experimental area and identify the influence of surface-groundwater interaction on select water quality parameters.

Impacts on New Mexico

The interaction between surface water and groundwater is dynamic and complex (Frenzel, 1992; Wilson et al. 1981). Past research indicates that there is a close interaction between the Rio Grande discharge and groundwater aquifers in the areas south of Hatch (Deb et al. 2012). For example, it has been irrefutably proven that pumping water from wells near the river, depletes water in the river (Witcher et al. 2004; Frenzel and Kaehler, 1992; Wilson et al. 1981). Accordingly, the rate at which water travels from the river to the groundwater aquifers needs to be understood. This work should help researchers and water users better understand the surface groundwater interaction and provide a model/relationship that will help to manage the water efficiently.

In addition, there appears to be an increase in salts in the shallower aquifers in this area. The river water has a low salt concentration and could potentially improve shallow alluvium groundwater quality. However, there are claims that this is not happening (Sheng et al. 2010). The data being collected appear to support the concerns regarding salt concentrations for portions of the aquifers.

LITERATURE REVIEW

Groundwater depth is a spatio-temporary dynamic variable (Dinka 2010; Hecker et al. 1998). Comparably, shallow groundwater levels generally fluctuate more frequently than deeper levels of groundwater (Helmuth et al. 1997) and this either occurs on daily, monthly, seasonally or over several years depending on the prevailing rainfall conditions and certain anthropogenic activities (irrigation pumping) (Hecker et al. 2010). Thus changes in water-table depth relate the groundwater system to external factors (Jinglong et al. 2008).

Aslan and Gundogdu (2007) stated that frequent monitoring of the spatio-temporal variations in groundwater depth, especially in irrigation areas, are essential for effective management of groundwater resources. Observing and evaluating groundwater depths in agricultural areas helps water managers assess the effect of irrigation and precipitation on the changes to groundwater depth. This helps to improve irrigation planning and precautionary measures can be taken for the use of groundwater resources. Also, concurrent studies of time and spatial changes in groundwater depth provide insight to the dynamics of aquifer systems (Kumar and Ahmed 2003). Furthermore, continuous and periodic measurement of groundwater levels, provide the most reliable source of information on the effect of hydrologic stresses on groundwater systems (Alley and Taylor 2001).

Related Research

Groundwater levels worldwide have declined over the past decades (Cay and Uyan 2009). In southern New Mexico, there has been a reported decline in groundwater levels (Sharma et al. 2013). Weeden and Maddock (1999) mentioned that pioneer investigations of water quality and depth to water table in the Mesilla and Rincon valleys, southern New Mexico were done by Slichter (1905) and Lee (1907). In 1954, Conover generated groundwater contour maps to show that the Rio Grande alternates between a gaining and losing stream in the Mesilla and Rincon valleys. The Rio Grande is a gaining stream from Leasburg Dam to about 6 miles south and is predominantly a losing stream as it flows down in the Mesilla Basin. Overall, the river replenishes the groundwater system (Weeden and Maddock 1999). Wilson et al. (1981) reported that the "water table in Mesilla Valley is typically 10 to 25 feet below land surface and has a southward declining gradient of 4.5 feet per mile (Weeden and Maddock 1999). Since Conover's studies from 1954, subsequent seepage investigations in the Rio Grande between Radium Springs, New Mexico and El Paso, Texas show that during the irrigation season the river is a gaining stream to about five miles north of Mesilla Dam where it changes to a losing stream. This condition occurs predominantly during low-flow events (Water Resources Data, New Mexico, Water Year 1997; Nickerson, 1994; Weeden and Maddock, 1999). Weeden and Maddock (1999) stated that the water table in the Rincon and Mesilla valleys fluctuates about two feet during the irrigation season and rises as the aquifer gets recharged by irrigation water. Sheng and others (2010) analyzed the river flow, total dissolved solids (TDS) and salt loading at selected segments of the Rio Grande reach and associated underlying aquifers from Caballo Reservoir in NM, continuing through the urbanized areas of Las Cruces, NM and El-Paso, TX to Fort Quitman, TX. They found that salt concentrations increase downstream up to an average of 3,200 mg/L during the irrigation season, and identified patterns of salt exchange between the river and underlying aquifers.

METHODOLOGY

Study Area

The study area (Figure 1) follows the Rio Grande and includes Garfield, Hatch-Rincon, Radium Springs, Leasburg, Las Cruces, La Mesa, and Anthony located in south-central New Mexico down to the New Mexico–Texas border (Figure 1). The Rio Grande flows for 1,900 miles from southern Colorado through New Mexico to the Gulf of Mexico. In southern New Mexico, the river flows through Doña Ana County, which includes the New Mexico part of the study area. The fertile valley, formed by historical repeated heavy spring floods along the river extends from Hatch, at the northern corner of Doña Ana County, to the west side of El Paso, Texas (Kammerer 2008).

The Rio Grande streamflow serves as the primary source of recharge to the aquifer system in the Mesilla Valley. The largest amount of recharge to the aquifer system is due to seepage in the losing reaches of the stream, infiltration of applied irrigation water, seepage from irrigation canals, and recharge from precipitation and interbasin groundwater inflows (Nickerson and Myers 1993). While portions of the Rio Grande within the Mesilla Valley are a losing stream, there do exist slight river gains from Leasburg Dam to 6 miles north of Las Cruces (Wilson et al. 1981; Nickerson and Myers 1993), and at the immediate upstream of El-Paso, Texas to the southern end of the basin.

Topography

The topographical elevations on the study region range from approximately 3,700 to 3,900 feet on the Rio Grande Valley to about 5,000 feet on the upland plains (Bullock et al. 1980).

Climate

Low precipitation, low humidity, and large diurnal temperature fluctuations characterize the climate of the study area. Close to 50 percent of annual rainfall occurs in the “monsoon” season from July to September. During this period, precipitation events are due to convection and result in brief heavy rainfall (Wilson et al. 1981; Weeden and Maddock 1999). Average annual rainfall is 9.41 inches and evaporation is 93 inches per year. Annual snowfall experienced in the region ranges from 2.5 inches to 3.6 inches (Period of Record of Monthly Climate Summary; State

University, New Mexico). Temperatures exceed 100°F at elevations below 5,000 feet during summer; but the average monthly maximum temperatures are in July, the warmest month, range from slightly above 90°F at the lower elevations to upper 70s at high elevations (New Mexico Climate Center, 15 January 2008).

Hydrogeology

In the Mesilla Basin quality of groundwater and surface water deteriorates significantly on the eastern margins from Las Cruces southward adjacent to Interstate 10 (Frenzel and Kaehler 1992, see section by Anderholm 1993; and Wilson et al. 1981). Water quality is lower in the far western and northwestern margins of the basin, and a zone of poor quality overlies good quality water in the shallow aquifer system beneath the Mesilla Valley floodplain (Wilson et al. 1981). Salinity increases in the shallow aquifers and in the Rio Grande basin outlet south of Anthony (Witcher et al. 2004).

The aquifer transmissivity in the central portion of the Mesilla Valley is generally estimated to range from 10,000 to 40,000 square feet per day. The central part of the valley consists of Santa Fe Group and Rio Grande Valley deposits (Witcher et al. 2004). The upper 1,200 feet of saturated fill of the aquifer has an estimated transmissivity of 50,000 square feet per day at few localities within the Mesilla Valley (Wilson et al. 1981; Witcher et al. 2004). The horizontal hydraulic conductivities in the upper 600 feet of saturated basin fill of the valley range from 22 to 70 feet per day. However, below 600 to 1,800 feet of tested-aquifer zones have a median conductivity value of about five feet per day (Frenzel and Kaehler 1992; Kernodle 1992). The vertical hydraulic conductivities values for the entire thickness of the confining layer at aquifer test sites within the basin range from 0.2 to 3.0 feet per day (Kernodle 1992).

The specific yield within the Mesilla Valley is estimated to vary from 0.1 to 0.2 under unconfined aquifer conditions. Specific storage in confined parts of the basin-fill aquifer system range from 0.00001 to 0.000001 feet (Frenzel and Kaehler 1992; Kernodle 1992). The estimated storage coefficients range from 0.002 to 0.00003 (Wilson et al. 1981).

The direction of groundwater flow in the Rincon Basin is northeast, from the mountains into the valley, and then toward the south and east down the Rio Grande. Naturally, groundwater discharge from the basin in the shallow alluvial sediments is approximately equal to recharge (Wilson et al. 1981). Groundwater in New Mexico and Texas parts of the Mesilla Basin generally flow from its flanking highlands and the upstream (Seldon Canyon) Rio Grande Valley segment toward and sub-parallel to the Mesilla Valley (Witcher et al. 2004).

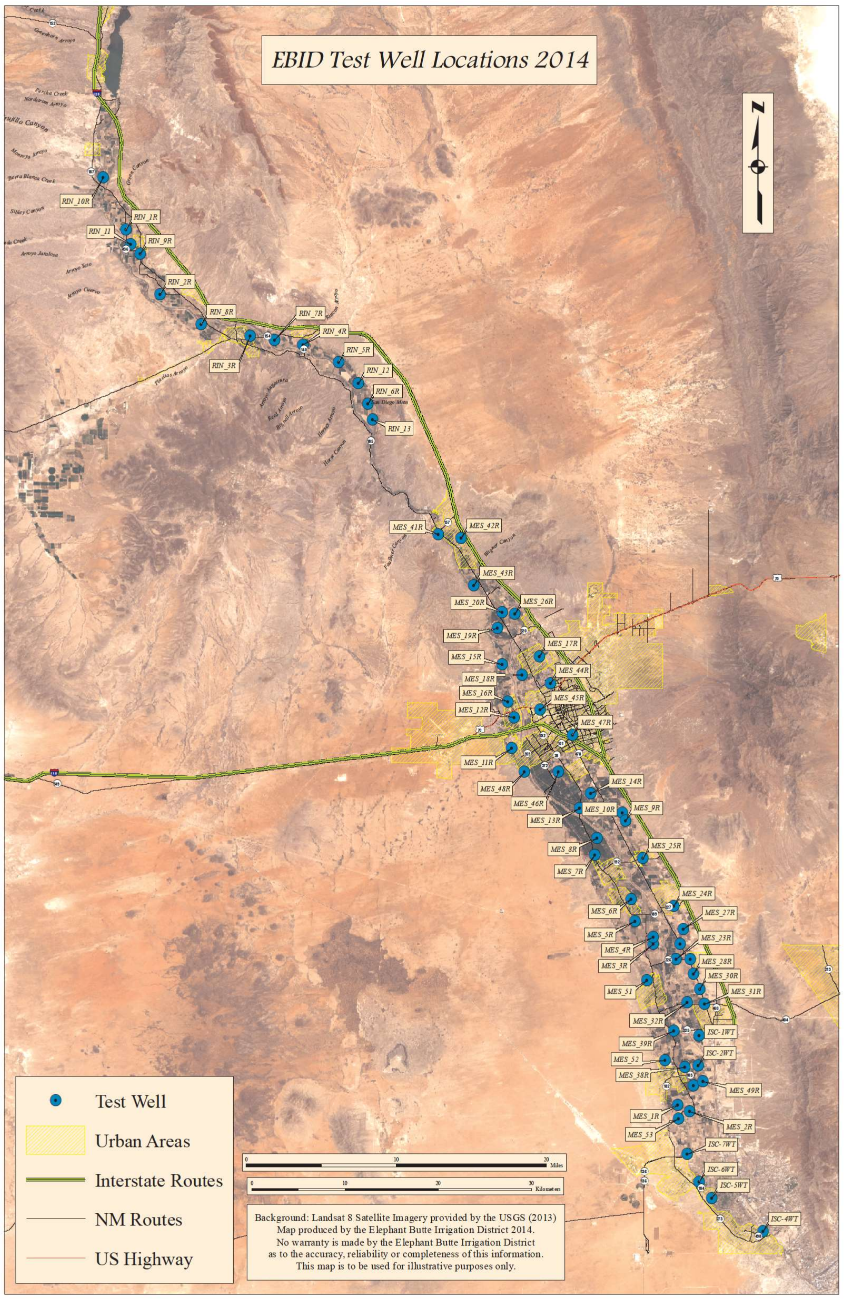

Figure 1. Map showing sampling sites on the Rio Grande and groundwater sampling sites (monitoring wells) within the area of study from Garfield to Canutillo, New Mexico.

Depth to Groundwater Table Measurement

Groundwater-table depths (the distance from the ground surface to the water surface in the well) of 58 observation wells located along the Rio Grande from Garfield to Canutillo, New Mexico were measured. The depths to groundwater table of the wells were measured on a monthly basis for the study period by using a Solinst Model 101 P7 Probe Water Level Meter.

Water Sampling and Laboratory Analysis

Groundwater samples were collected from the 58 observation wells belonging to the Hydrology Department of the Elephant Butte Irrigation District (EBID) in New Mexico. Sampling was done monthly from June, 2014 through to May, 2015. To ensure that samples represent the chemical characteristics of the groundwater, samples were collected below the water table by using a submersible Teflon tube that cannot alter the chemical composition of the water. Surface water (river water) samples were collected from selected sites along the Rio Grande reach within the study area from south Garfield to Canutillo, New Mexico. River water samples were collected on a monthly basis from June, 2014 to May, 2015. All samples were collected in clean plastic bottles and were rinsed with either groundwater or river water where appropriate prior to collecting a sample. Per availability of water, the bottles were filled completely to attain zero headspace. Samples were labeled and kept cool, and were stored in a refrigerator upon return from field. The specific locations of all river water sampling sites and observation wells were recorded with a Garmin global positioning system (Garmin GPSMAP 78 Series).

All water samples were allowed to thaw completely, and then filtered before analyzing for constituents in the Soil Science Laboratory in the Department of Plant and Environmental Sciences, New Mexico State University (NMSU). The filtered water samples were analyzed for the elemental constituents (magnesium, calcium, and sodium) using Perkin Elmer Optima 4300 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES).

Electrical Conductivity (EC) Measurement

Electrical Conductivity measurement on each sample was performed using an Oakton PC 300 pH/Conductivity/TDS with built-in temperature meter. Prior to the measurement of the EC, the instrument was calibrated with 1412.4 µS/cm conductivity standard. The probe was rinsed at least twice with distilled water before using and also rinsed properly between each measurement.

Sodium Adsorption Ratio (SAR) Determination

The elemental (magnesium, calcium, and sodium) analysis results obtained from the inductively coupled plasma optical emission spectrometer were used to determine the SAR for each of the samples. The calculations were computed using the formula:

$$SAR = \frac{(Na^{+})}{\sqrt{\frac{1}{2}(Ca^{2+} + M^{2+})}} \quad (1)$$

Where (Na^{+}), $(Ca2^{+})$, and $(Mg2^{+})$ represent the concentrations of sodium, calcium and magnesium, respectively, in milli-equivalent per liter.

CURRENT EXPERIMENTAL RESULTS

Spatial and Seasonal Variability in Groundwater and River Water Characteristics

Monthly fluctuations in the following parameters: groundwater levels, electrical conductivity (EC), and Sodium Adsorption Ratio (SAR), calculated from ion concentrations (Mg^{2+}, Ca^{2+}, and Na^{+}) were measured and calculated for all well locations across the study area from June 2014 to May 2015.

All the wells experienced monthly small to large fluctuations in groundwater levels (depth to groundwater table) throughout the periods of river flow and no-flow, and changes occurred irrespective of well distance relative to the river. However, the river flow is not the only factor that was likely influencing these fluctuations. A large number of groundwater wells in the area were being pumped throughout the irrigation season. This likely had an influence on the fluctuations as well.

The changes in groundwater levels obtained from some well measurements during river flow were significantly higher compared to the periods of no river flow ($p \leq 0.05$). These changes or fluctuations followed the trend of reduction in river water levels. Thus, as the river water level dropped gradually from June through to September (month in which river flow was last witnessed in the year 2014), the depth in the groundwater table observed in those wells increased (Figures 2, 3 and 4).

In the areas south of Garfield in the Hatch-Rincon Valley, there is a short initial increase in groundwater depth observed for the majority of the wells during river flow. After the initial period, continued increases in groundwater depth were observed in 30 percent of the wells (Figure 2). These wells were found within 1600 to 4900 feet from the river. However, two wells within the 1600 foot range and one beyond 4900 foot from the river exhibited a decline in the groundwater depth when the river was flowing compared to periods of no-flow. Generally the mean estimates of the well depths indicate a decline in the groundwater table during periods of river flow, June to September, 2014 (Table 1).

Table 1. The Mean River Water Level, Depth to Groundwater Table, EC, and SAR estimated in groundwater wells and the river during June to September 2014 when the river was flowing and during October 2014 to May 2015 when the river was not flowing, in Hatch-Rincon, south of Garfield, NM.

Well Number	Well Distance from River (ft)	Groundwater table depth (ft)	Groundwater table depth (ft)	Groundwater EC (µS/cm)	Groundwater EC (µS/cm)	SAR	SAR
		River flow	No River flow	River flow	No River flow	River flow	No River flow
RIN_5R	0 to 1600	19.5 (16.8-22.7)	*16.9 (15.5-21.1)	1757 (1029-2700)	2161 (2020-2420)	3.2 (2.9-3.7)	2.8 (2.6-3.0)
RIN_8R		17.9 (16.7-20.6)	17.7 (17.2-18.8)	1355 (1130-1618)	1370 (1229-1565)	2.0 (1.8-2.2)	2.0 (1.8-2.4)
RIN_1R	>1600 to 3200	23.8 (21.9-28.4)	22.8 (21.4-25.1)	2607 (2290-2890)	2210 (2070-2330)	3.6 (3.3-4.0)	3.6 (3.1-3.9)
RIN_2R		21.7 (19.7-23.9)	*20.2 (19.2-20.6)	1530 (1322-1898)	1867 (1214-2080)	3.8 (3.5-4.0)	3.6 (3.1-3.9)
RIN_4R		23.8 (22.7-25.9)	*22.2 (21.6-23.9)	1262 (976-1724)	1200 (1083-1331)	2.4 (2.0-2.8)	2.6 (2.0-3.1)
RIN_7R		27.7 (24.5-31.1)	23.7 (19.9-29.2)	2352 (2030-2660)	1924 (1726-2490)	1.9 (1.7-2.0)	2.1 (1.8-2.4)
RIN_10R		**16.7 (15.5-18.1)	17.7 (17.5-17.9)	2687 (2600-2800)	2547 (2390-2710)	4.5 (4.4-4.8)	4.7 (4.2-5.4)
RIN_12R		22.5 (22.0-23.0)	21.5 (21-22.3)	4822 (4650-4940)	4722 (4510-5050)	6.3 (5.9-6.5)	6.5 (6.1-6.9)
RIN_13R		9.4 (8.5-10.5)	9.4 (9.2-9.8)	3466 (2680-4290)	3292 (3190-3470)	5.5 (4.5-6.2)	5.1 (4.8-5.3)
RIN_3R	>3200 to 4900	20.1 (19.0-21.9)	*18.8 (18.2-19.6)	946 (758-1255)	867 (788-1032)	3.9 (3.8-4.0)	5.8 (4.1-6.8)
RIN_6R		10.9 (10.4-12.1)	11.4 (10.7-13.3)	4292 (3770-5270)	4357 (4280-4470)	6.9 (6.6-7.6)	7.2 (6.7-7.8)
RIN_11R		23.7 (22.5-24.8)	22.5 (21.4-24.3)	2742 (2670-2810)	2768 (2710-2830)	3.6 (3.4-4.0)	3.7 (3.3-4.0)
RIN_9R	>4900 to 6500	26.6 (26.2-26.9)	*25.3 (24.2-26.1)	4142 (4030-4280)	3840 (3580-4030)	6.5 (6.3-6.9)	6.0 (5.8-6.6)
RIVER		5.5 (3.0-7.5)	0.0	683 (229-878)	0.0	1.7 (0.5-2.9)	0.0

The mean depths to groundwater table (GWT) with * indicates the mean rise in GWT observed in a well during no river flow period was significant ($p \leq 0.05$): The mean depths to GWT with ** indicates the mean rise in GWT observed in a well during river flow is significant ($p \leq 0.05$).

Table 1 presents the ranges and the estimated means for the groundwater table depths for each observation well in the Hatch-Rincon Valley. These depths are for periods of river flow and when no-flow is observed in the river. The estimated means and ranges of EC and SAR for river water and groundwater, river water level, and the distance of well positions from the river are also presented in the table.

The peak depth to the groundwater table (highest elevation) during river flow was 8.5 feet, at site RIN_13R, which was observed in a well found within 1600 to 3200 feet from the river south of Hatch (depths were measured from the top of the observation wells). The deepest water table depth was 31.1 feet, at site RIN_7R. This was observed from site RIN_7R in the Village of Hatch. This well was located within 4900 to 6500 feet from the river. The average depth to the groundwater table in the area during the period of river flow was 20.3 feet. During periods of no-flow in the river, the shallowest depth to the groundwater table was 9.2 feet south of Hatch. The greatest depth was 29.2 feet in a well (RIN_7R) sited in Hatch with a distance from the river similar to above. Wells observed an average of 19.2 feet depth to water during no-flow periods for the areas south of Garfield to south of Hatch along the Rio Grande.

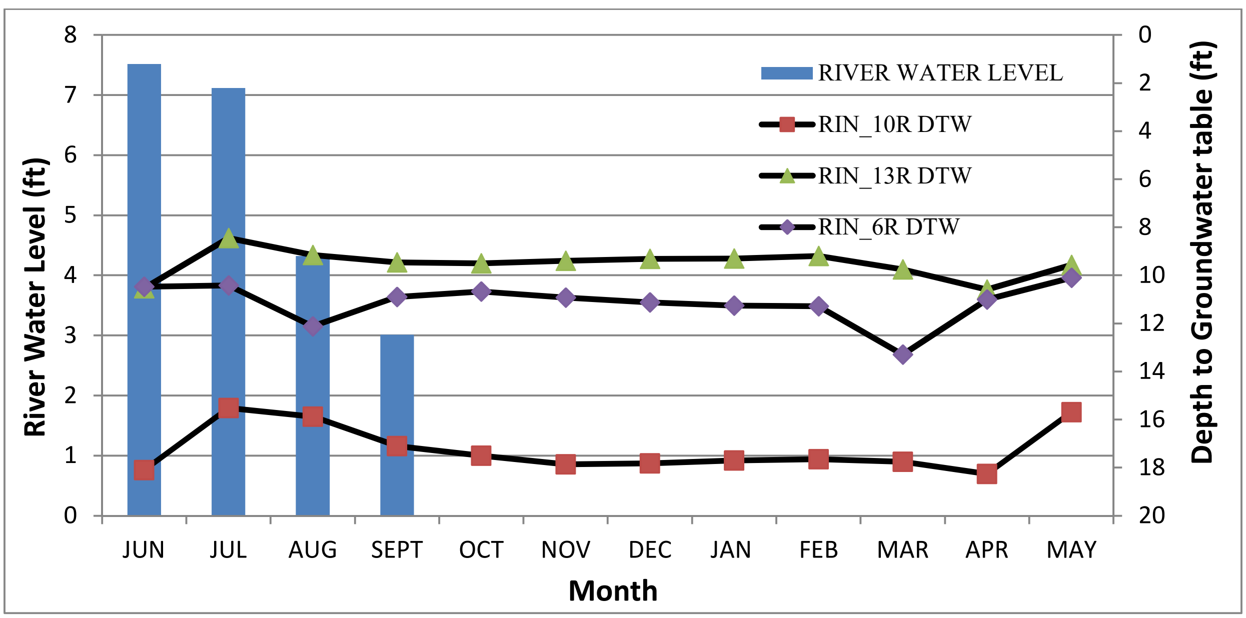

Figure 2. Monthly average river water level during periods of river flow (June to September, 2014) and average depth to groundwater table (DTW) during periods of river flow and no-flow (June to May) of selected wells in the areas of Hatch-Rincon Valley.

Figure 2 shows that an average one-foot decline in the groundwater table was observed in some of the wells during periods of no flow from October to early May. Most wells that saw this drop in groundwater table depth were sited within 1600 to 3200 feet from the river. In general, the depths to groundwater table in this portion of the study area during periods of river flow were between 8.4 to 31 feet and vary with well distance from river (Table 1). During no-flow periods, depths to the groundwater table in the wells ranged between 9.2 to 30 feet.

During river flow periods, the majority of wells exhibited a short initial increase in water level. The average increase (rise) in water level was determined for these wells and this value was subject to regression analysis, rendering the following predictive equation:

$$GDI = 0.1043 + 78.0177 \times \frac{days}{distance} \qquad (2)$$

Where *GDI* = groundwater depth increase (feet), days = number of days that the river is flowing, distance = the distance from the river (feet). This is an empirical equation and only models the initial increase in groundwater. The R^2 value for this equation was 0.93.

During the river flow period in the Hatch-Rincon Valley, the lowest EC recorded in groundwater was 758 µS/cm and this was for wells within 3200 to 4900 feet from the river in Village of Hatch. The highest EC of 5270µS/cm was measured in a well (RIN_6R) south of Hatch between 1600 to 3200 feet from the river. However, the lowest and highest groundwater EC for no-flow periods were 788µS/cm (well RIN_3R in Hatch Village) and 5050 µS/cm (well RIN_12R just south of Hatch) respectively, with wells located within 3200 to 4900 feet and 1600 to 3200 feet from the river in that order (Table 1). Moreover, the average EC estimated during river flow and no-flow periods were 2612µS/cm, and 2548µS/cm respectively. Generally, the EC of river water was found to be lower than that of groundwater in that stretch of the study area (see Table 1).

When water was flowing in the Rio Grande, the least SAR of 1.7 was calculated for a groundwater well RIN_7R in Hatch and within 3200 to 4900 feet from the river. The highest SAR of 7.6 was determined for well RIN_6R south of Hatch within 3200 to 4900 feet from river.

The average SAR for groundwater during river flow in the area was found to be 4.16. On the other hand, the least and highest SAR for groundwater at no-flow periods were 1.8 north of Hatch within 1600 feet from river and 7.8 south of Hatch within 4900 feet from river, respectively. The area average was 4.28. For over 84 percent of the wells, the SAR was higher than the river water.

For Radium Springs, Leasburg, Las Cruces (LC) to Mesquite in the Mesilla Basin, about 50 percent of the wells in the area witnessed a significant rise in groundwater table when the river was flowing ($p \leq 0.05$). During river flow periods, the majority of wells located between 0 to 4900 feet from the river exhibited a short initial increase in water level. The average increase in water level was determined for these wells and this value was subject to regression analysis using the following predictive equation:

$$GDI = 0.7674 + 88.8818 \times \frac{days}{distance} \quad (3)$$

Where *GDI* = groundwater depth increase (feet), days = number of days that the river is flowing, distance = the distance from the river (feet). This is an empirical equation and only models the initial increase in groundwater. The R^2 value for this equation was 0.9991.

As mentioned earlier approximately 50% of the wells saw a significant increase in water level. About 17 percent of the wells were within 1600 feet from the river, 33 percent were located between 1600 to 3200 feet from the river, 8 percent were positioned within 3200 to 4900 feet and the rest of the wells were beyond 4900 feet from the river. About 24% of the wells within 1600 to 3200 feet from the river, in addition to about 25 percent found beyond 4900 feet from the river in Las Cruces and Mesquite recorded a decline in estimated mean depth in groundwater table during periods of river flow (June to September) compared to the periods when the river was not flowing (October to May) (see Table 2 below). Most of these wells were located within 3200 to 4900 feet from the Rio Grande.

Table 2. The Mean River Water Level, Depth to Groundwater Table, EC, and SAR estimated in groundwater wells and the river during June to September 2014 when the river was flowing and during October 2014 to May 2015 when the river was not flowing, in Radium Springs, Leasburg, Las Cruces and Mesquite, NM.

Well Number	Well Distance from River (ft)	Groundwater Table Depth (ft)	Groundwater Table Depth (ft)	Groundwater EC (µS/cm)	Groundwater EC (µS/cm)	SAR	SAR
		River flow	No River flow	River flow	No River flow	River flow	No River flow
MES_41R	0 to 1600	18.2 (15.6-20.7)	19.0 (18.8-19.3)	1938 (1636-2120)	1849 (1752-1968)	3.0 (2.6-3.2)	2.9 (2.6-3.2)
MES_43R		14.8 (12.8-18.5)	16.6 (15.4-17.3)	1482 (1086-1949)	1591 (1428-1762)	3.6 (3.2-4.0)	4.3 (3.7-4.6)
MES_15R	>1600 to 3200	19.8 (18.7-23.0)	21.1 (19.3-22.8)	1533 (1456-1573)	1513 (1354-1618)	2.4 (2.2-2.5)	2.4 (2.2-2.8)
MES_11R		14.1 (13.3-15.4)	13.9 (13.4-14.7)	1702 (1612-1799)	1671 (1585-1732)	6.0 (5.7-6.6)	5.9 (5.8-6.2)
MES_12R		16.4 (14.6-18.9)	15.9 (14.9-17.3)	1416 (1165-1616)	1612 (1384-1682)	3.2 (3.1-3.5)	3.8 (3.4-4.6)
MES_13R		22.6 (21.1-24.3)	22.6 (22.2-23.4)	1928 (1425-2300)	1574 (1507-1700)	4.7 (2.9-7.3)	3.7 (2.4-5.5)
MES_16R		22.2 (20.9-23.3	*20.5 (20.1-21.2)	2024 (1828-2320)	2387 (1905-2960)	5.3 (5.1-5.5)	5.1 (4.3-6.4)
MES_48R		**13.4 (10.3-17.6)	16.1 (14.4-16.8)	3365 (1700-4460)	3742 (2830-4290)	5.1 (4.4-6.3)	4.7 (4.2-5.4)
MES_8R		11.9 (11.1-13.3)	12.9 (11.5-14.1)	3245 (3070-3390)	3260 (3080-3380)	6.3 (6.1-6.8)	6.2 (5.2-7.4)
MES_42R	>3200 to 4900	18.8 (17.8-20.1)	18.5 (18.3-19.0)	1736 (1587-1836)	1549 (1473-1692)	3.3 (3.2-3.4)	3.4 (3.0-3.8)
MES_19R		21.5 (19.3-24.5)	19.8 (19.3-20.9)	2250 (2090-2470)	2525 (2170-2790)	4.1 (4.0-4.2)	4.0 (3.7-4.1)
MES_20R		28.7 (28.1-29.2)	*26.2 (25.0-28.2)	1860 (1793-1944)	2398 (1720-2970)	4.0 (3.7-4.4)	3.5 (3.1-4.5)
MES_18R		26.1 (24.8-28.3)	25.7 (24.8-28.5)	1862 (1312-2920)	2405 (2260-2560)	4.0 (3.5-4.9)	4.2 (3.5-4.7)
MES_45R	>4900 to 6500	40.4 (39.6-40.8)	40.1 (39.5-40.9)	2420 (2260-2550)	2430 (2300-2510)	3.5 (2.9-4.0)	3.6 (3.3-4.0)
MES_7R		16.3 (15.5-16.9)	16.7 (16.5-17.0)	2034 (1821-2280)	1314 (986-1748)	2.5 (1.9-3.7)	2.0 (1.1-3.1)
MES_25R		27.5 (27.3-27.8)	26.6 (26.4-27.6)	841 (707-1252)	640 (558-692)	2.2 (1.2-2.9)	2.1 (1.5-2.7)
MES_6R		22.0 (21.7-22.6)	21.0 (20.6-21.6)	2109 (1986-2210)	2057 (1869-2220)	3.6 (3.4-3.9)	3.6 (3.3-4.1)
MES_17R	>6500	36.0 (35.6-36.2)	*34.7 (33.9-36.0)	2592 (2460-2720)	2857 (2740-2960)	3.6 (3.4-3.9)	3.5 (3.3-3.7)

MES_26R	28.3 (28.2-28.6)	28.5 (28.0-29.1)	9877 (3450-13500)	5615 (3320-8340)	15.7 (5.8-19.4)	8.0 (5.0-13.1)
MES_44R	39.8 (39.6-39.9)	40.8 (40.5-41.0)	1839 (1527-2070)	1598 (1459-1673)	3.1 (2.7-3.4)	2.7 (2.4-2.8)
MES_47R	**37.5 (33.0-39.2)	40.1 (39.6-40.9)	588 (519-665)	524 (467-600)	0.5 (0.4-0.7)	0.5 (0.3-0.7)
MES_46R	36.9 (32.1-45.4)	38.6 (38.4-38.7)	1312 (1132-1453)	1508 (1474-1620)	2.6 (2.5-2.6)	2.4 (2.3-2.5)
MES_14R	**35.9 (31.4-37.6)	38.7 (38.2-38.9)	2150 (2120-2190)	2112 (1964-2180)	1.6 (1.5-1.7)	1.6 (1.4-1.8)
MES_10R	31.1 (30.3-31.8)	31.4 (31.0-32.0)	4935 (4720-5210)	4875 (3860-5720)	12.2 (11.2-13.7)	12.6 (11.4-14.4)
MES_9R	32.1 (30.3-36.6)	30.7 (30.4-31.0)	2835 (2750-2900)	2908 (2820-2960)	6.1 (6.0-6.2)	6.0 (5.5-6.8)
MES_5R	20.5 (19.9-21.5)	20.0 (19.8-20.3)	2842 (2520-3120)	2415 (1710-2590)	4.4 (3.8-4.8)	4.4 (3.9-4.7)
RIVER	2.4 (0.9-3.6)	0.0	425 (256-554)	0.0	1.9 (0.6-3.0)	0.0

The mean depths to GWT with * indicates that the mean rise in GWT observed in a well during no river flow period was significant ($p \leq 0.05$): The mean depths to GWT with ** indicates the mean rise in GWT observed in a well during river flow is significant ($p \leq 0.05$).

The shallowest depth to the groundwater table during river flow was 10.3 feet, recorded in well MES_48R within 1600 to 3200 feet from the river east of Las Cruces and the deepest depth of 45.4 feet for well MES_46R located within 4900 to 6500 feet from the river, south of Las Cruces. The average depth to groundwater table in the entire stretch along the Rio Grande for periods of river flow was 22.9 feet. When there was no-flow in the river, the shallowest depth to the groundwater table was 11.5 feet in well MES_8R located east of Las Cruces within 1600 to 3200 feet from the river with greatest depth of 41 feet. The well (MES_44R) with the greatest depth to groundwater table was located north of Las Cruces, beyond the 6500 feet range from the river (Table 2). The average depth to groundwater table in the area when there was no-flow in the river was about 28 feet.

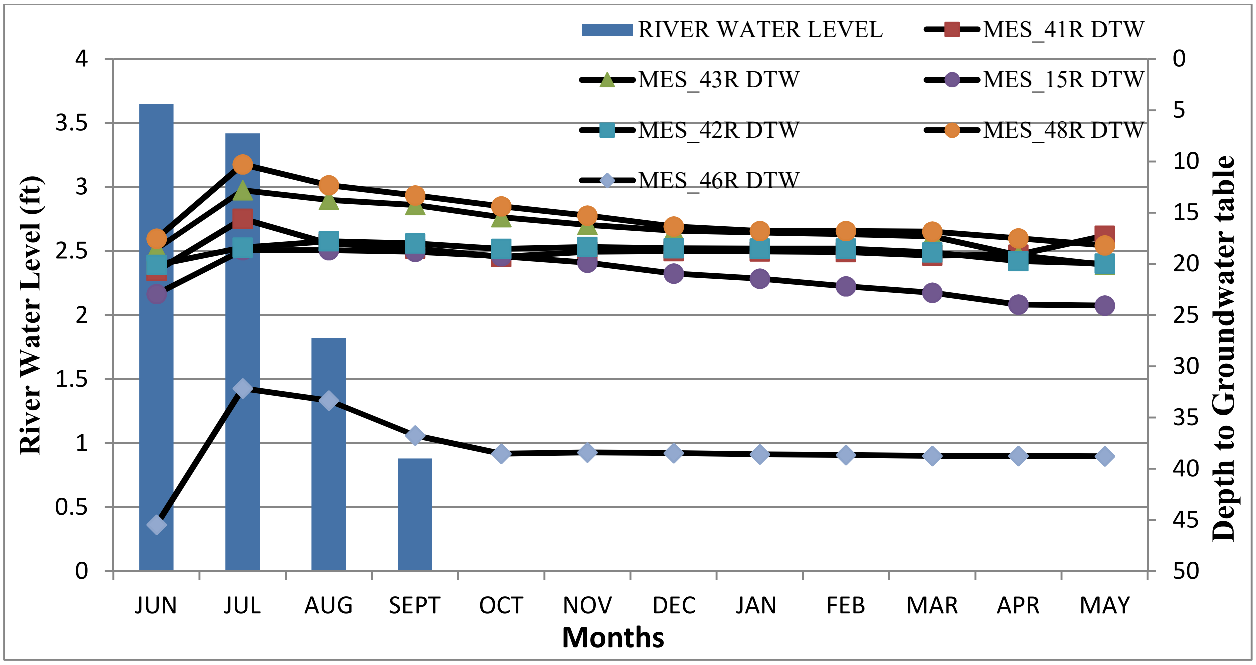

Figure 3. Monthly average river water level during periods of river flow (June to September, 2014) and average depth to groundwater table (DTW) during periods of river flow and no-flow (June to May) of selected wells from Radium Springs south to Mesquite

The average drop of groundwater depth in each of the wells (Figure 3) during periods of no-flow (October to May) was around two feet. The wells beyond 6500 feet from the river (of which most were located in Las Cruces) had the greatest depth to groundwater table during the study period (Table 2). The groundwater table during periods of river flow ranged between 10.3 to 45.4 feet and the depth to the groundwater table in the area at the times when there was no-flow in the river ranged between 11.5 to 41 feet. Most wells observed an average decline in groundwater table depth when there was no-flow in the river (Table 2). However, the wells such as MES_20R, MES_18R, MES_25R, MES_6R, MES_17R, and MES_9R were found to show an average drop in the groundwater table when the river was flowing.

The EC results obtained from this portion of the study area during river flow showed that wells southwest of Las Cruces located beyond 6500 feet (see Table 2) from the river recorded the lowest EC values. The lowest EC of 519µS/cm was measured in a well (MES_47R) located west of Las Cruces beyond 6500 feet from the river. The highest or peak EC value of 13,500µS/cm was measured for groundwater in a well (MES_26R) beyond 6500 feet from the river, north of Las Cruces. The average EC determined for groundwater during river flow was 2,341.4µS/cm.

However, when there was no river flow, the wells in the above locations measured the least and highest EC values of 467µS/cm and 8,340µS/cm, respectively, with an area average of 2,266.5µS/cm. Likewise in other areas the EC measured in river water were low compared to all well positions (Table 2).

A lowest SAR of 0.4 was calculated at site MES_47R, 6500 feet beyond the river during river flow west of Las Cruces. The highest SAR of 19.4 at site MES_26R was determined for the area north of Las Cruces, 6500 feet beyond the river. An average SAR of about 4.5 was calculated for groundwater from this stretch of the study area. At the time when there was no-flow in the river, well MES_47R saw a reduction in SAR to about 0.3 and well MES_10R recording highest value of 14.4. A no-flow period average of 4.12 SAR was computed for the wells in that part of the study area (from Radium Spring to Mesquite).

For the area below Mesilla Dam to Canutillo, all wells within 1600 feet from the river, in addition to about 33% of wells beyond 6500 feet from the river had a rise in the calculated mean of depths to the groundwater table during river flow periods (Table 3). The average depth to groundwater table in wells between 1600 to 6500 feet had a decline in the depth to the groundwater table when the river was flowing (Table 3).

Table 3. The mean River Water Level, Depth to Groundwater Table, EC, and SAR estimated in groundwater wells and the river during June to September 2014 for the section when the river was flowing and during October 2014 to May 2015 and when the river was not flowing, below Mesilla Dam to Canutillo, NM.

Well Number	**Well Distance from River (ft)**	**Groundwater Depth (ft)**	**Groundwater Table Depth (ft)**	**Groundwater EC (µS/cm)**	**Groundwater EC (µS/cm)**	**SAR**	**SAR**
		River flow	**No River flow**	**River flow**	**No River flow**	**River flow**	**No River flow**
MES_2R	0 to 1600	20.8 (20.2-21.4)	21.6 (21.0-22.0)	993 (962-1046)	1260 (1199-1334)	3.0 (2.8-3.1)	2.9 (2.7-3.3)
MES_27R	>1600 to 3200	20.5 (18.2-26.2)	18.4 (18.2-18.8)	3825 (3480-4100)	4178 (3660-5070)	8.5 (7.5-10.6)	8.4 (7.6-9.4)
MES_1R	>3200 to 4900	18.3 (17.2-19.5)	18.0 (17.6-18.6)	2390 (2180-2920)	2258 (2150-2520)	10.8 (10.2-11.4)	11.0 (9.2-11.6)
MES_3R		19.8 (18.7-20.6)	*18.4 (17.9-19.7)	1379 (1173-1623)	1432 (1225-1932)	3.4 (3.2-3.9)	3.3 (3.1-3.5)

MES_4R		18.0 (17.6-18.6)	*17.3 (17.0-17.8)	2300 (2200-2440)	2422 (2290-2570)	6.8 (6.2-7.6)	6.6 (5.8-7.7)
MES_24R		18.7 (15.7-27.1)	15.9 (15.7-16.0)	2097 (2030-2160)	1996 (1954-2070)	10.0 (8.9-11.1)	8.7 (7.4-10.8)
MES_32R		22.0 (21.2-23.4)	21.1 (20.7-21.9)	3735 (3320-4080)	3605 (3310-4230)	7.6 (7.1-8.5)	7.9 (7.6-8.7)
MES_39R		23.1 (22.6-23.4)	22.1 (21.5-23.0)	1862 (1250-3320)	1585 (1293-1930)	4.2 (2.9-7.6)	3.1 (3.0-3.3)
MES_21R	>4900 to 6500	14.9 (14.2-16.2)	14.7 (14.4-15.4)	2867 (1790-3700)	2465 (1897-3060)	9.0 (7.9-10.1)	7.5 (7.3-8.5)
MES_51R		16.3 (15.7-17.0)	15.5 (15.1-15.9)	1972 (1925-2040)	2150 (1962-2260)	4.9 (4.6-5.7)	5.4 (4.9-5.6)
MES_22R	>6500	**12.9 (12.6-13.5)	13.9 (13.4-14.3)	3295 (2460-3960)	2150 (2020-2320)	15.7 (14.0-18.1)	19.2 (18.5-20.4)
MES_23R		19.1 (18.3-20.0)	*17.8 (16.4-18.6)	4560 (4350-5000)	4340 (4140-4580)	9.0 (8.3-9.7)	8.7 (8.4-9.2)
MES_30R		18.4 (18.2-18.5)	18.7 (18.6-18.9)	3307 (3260-3360)	3342 (3250-3380)	22.4 (22.2-22.7)	22.4 (21.7-23.3)
MES_28R		15.4 (15.3-15.6)	16.0 (15.7-16.3)	2795 (2760-2820)	2932 (2860-3020)	14.3 (13.5-15.4)	16.0 (15.2-17.6)
MES_52R		24.2 (23.7-24.3)	23.3 (21.6-24.4)	2200 (2040-2290)	2380 (2220-2660)	6.2 (5.9-6.9)	5.8 (4.8-6.8)
MES_49R		23.9 (23.6-24.3)	23.4 (23.1-23.7)	2134 (1807-2470)	2658 (1970-3700)	4.6 (4.0-4.8)	4.5 (3.8-5.4)
MES_38R		21.9 (21.4-22.3)	22.3 (22.1-22.6)	2157 (2070-2240)	2100 (2040-2210)	4.8 (4.7-5.0)	5.0 (4.7-5.1)
MES_31R		21.1 (20.8-21.5)	21.1 (20.9-21.3)	2670 (2420-2790)	2187 (2030-2440)	9.5 (9.4-9.6)	9.0 (8.6-9.5)
MES_53R		19.3 (18.7-20.4)	18.6 (18.3-19.2)	2860 (2350-3210)	3143 (2810-3380)	11.8 (10.9-13.5)	11.6 (9.5-12.8)
RIVER		7.0 (6.1-7.7)	0.0	791 (424-935)	0.0	3.0 (1.1-7.7)	0.0

The mean depths to GWT with * indicates the mean rise in GWT observed in a well during no river flow period was significant ($p \leq 0.05$): The mean depths to GWT with ** indicates the mean rise in GWT observed in a well during river flow is significant ($p \leq 0.05$).

When the river was flowing below the Mesilla Dam area, the shallowest depth to groundwater table of 12.6 feet was measured in well MES_22R sited in Berino beyond 6500 feet from the river. The deepest water table in the area during this period was near Vado elementary School. This 27.1 feet depth was measured in well MES_24R that was located about 4900 feet from the river. Moreover, the average depth to groundwater table below the dam at Canutillo was 18.3

feet. When there was no-flow in the river, the shallowest depth to the groundwater table was 13.4 feet at site MES_22R while the deepest was 24.4 feet at site MES_52R. The area average was 18.9 feet (Table 3). Again, the shallowest depths were measured in Berino and deepest near Canutillo about 6500 feet from the river.

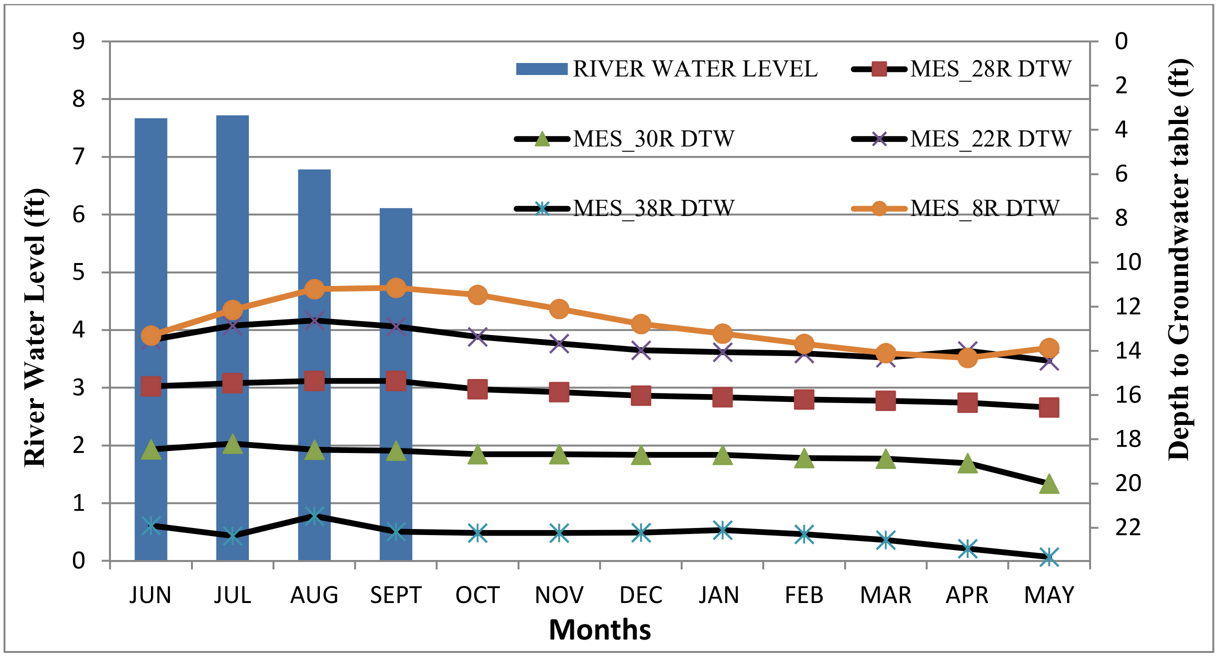

Figure 4. River water level during periods of river flow (June to September) and depth to groundwater table (DTW) during periods of river flow and no-flow (June to May) of selected wells in the areas below Mesilla Dam to Canutillo.

The wells (in Figure 4) observed a decline in the depth to groundwater table on an average of about 1.3 feet from October to May when there was no river flow.

Lowest EC of 962µS/cm was determined at site MES_2R near Canutillo in groundwater within 1600 feet from the river, when the river was flowing. A value as high as 5,000 µS/cm was measured in groundwater at site MES_23R close to Berino, about 6500 feet away from the river with an average of 2,560µS/cm in the areas below the Mesilla Dam to Canutillo. At times of no-flow, the lowest EC of 1,199µS/cm was recorded within 1600 feet from the river at site MES_2R near Canutillo. The highest for the period was 5,070µS/cm at site MES_27R, near Vado Elementary School within 1000 feet from the river. The area average was 2,557µS/cm. Generally, the river water EC was lower compared to groundwater from all wells within the area (Table 3).

The lowest SAR of 2.8 was determined for groundwater at site MES_2R near Canutillo within 1600 feet from the river during periods of river flow. The maximum SAR of 22.7 was found in a groundwater at site MES_30R near Anthony, about 6500 feet from the river. An average for the entire area was about 9.2. On the other hand, a minimum SAR of 2.7 was found in groundwater from Canutillo about 1600 feet from the river at periods when there was no-flow in the river. The maximum SAR of 23.3 was determined for groundwater from Anthony (at site MES_30R) in the area below the Mesilla Dam, beyond 6500 feet from the river. The season average SAR for this site was 8.8. In general, the maximum SAR found in the river water in the area was lower than groundwater from over 70% of the wells. Those with lower SAR than the river water were generally found within 4900 feet from the river.

CONCLUSIONS

Interestingly, all the study wells observed monthly changes in the measured parameters including depth to groundwater table, EC and SAR (the scale of the graphs lose some of the smaller changes). During periods of river flow in the Hatch-Rincon Valley, wells in the region generally showed a short initial increase (rise) followed by a decline in the depth to the groundwater table. An average of one foot decline during periods of river flow was observed and this was irrespective of the well's location from the river. However, the situation was different for one well within 1600 feet and another beyond 4900 feet from the river south east of Hatch. These wells exhibited a mean decline in the depth to the groundwater table at periods of no river flow.

The wells that had an initial increase in groundwater depth may have been caused by the fact that surface water was being delivered to farms in the area at this time. During this period it is likely that little pumping was occurring from the wells in the area. This would allow for water to seep from the river into the shallow groundwater. The result would be an increase in water level. However, the farms only received surface water for a short period of time and once the surface water delivery ended, pumping would resume. Pumping appears to have a quick impact on the groundwater table in this area. Considering that the Hatch area has a limited aquifer, this is likely the cause.

Equation 1, which had an R^2 value of 0.93, was developed to model the increase in groundwater level in the Hatch-Rincon Valley. It is believed that the equation would track water level increases during river flow when there is limited pumping from the aquifer. However, this equation was developed from one season of data and further data need to be collected to validate this equation.

During periods of river flow, EC values were measured in the areas south of Hatch about 1600 to 3200 feet from the river. Generally when there was no river flow, the water EC was lower for most wells compared to river flow periods, notwithstanding the well locations from the river. However, the contrast was observed in some of the wells within similar intervals from the river, which signifies that there may be other sources of salts and water within the area.

In the region from Leasburg through Las Cruces to Mesquite, the depth to groundwater table was generally shallow east of Las Cruces, with the greatest depth south of Las Cruces within 4900 to 6500 feet from the river, during periods of river flow. The depths to groundwater table in the area were generally deeper during periods of no-flow in the river compared to periods of river flow with a drop of two feet on average at no river flow periods. When water was flowing in the river, the wells closest to the river again had an initial increase in water level. This initial increase was modeled using the average increase in water level for the wells within 4900 feet of the river. The R^2 value of 0.9991 for the model equation was surprisingly high. It should be stressed here that this equation was for a two month period (May and June). After this initial period, the correlation was very poor.

However, the wells farthest away from the river had varied responses in water depth. Some wells saw increases in water level while others had continual decreases in water level. Many factors seem to be causing these varied changes. These wells are a long distance from the river (over 6400 feet) and it would take longer for the river water to move through the aquifer to this area. It is believed that there is also groundwater inflow to portions of this aquifer from the west.

Along this stretch of the study area, the highest EC of well water was observed west of Las Cruces about 6500 feet from the river at times of river flow, which was above the highest EC measured at periods of no river flow in the area. The EC values obtained during periods of no river flow were generally lower than when the river was flowing. On average, the SAR calculated during river flow periods were higher than those computed for no-flow periods.

The groundwater table depth in Berino was shallowest in the areas below the Mesilla Dam to Canutillo for both periods of river flow and no-flow. Conversely, the deepest depth to groundwater table was found in areas close to Vado Elementary School and Canutillo, likewise for periods of river flow and no-flow, respectively. On average, the depth to groundwater table in the area declined about 1.3 feet when the river was not flowing, however, some wells also saw a groundwater table decline when the river was flowing. During periods of both river flow and no-flow, the lowest EC was observed in groundwater near Canutillo, about 1600 feet from the river.

Groundwater (at average depth of 19.1 feet) in the area in Berino had the highest EC when the river was flowing, and an area close to Vado Elementary School had groundwater (at average depth of 18.4 feet) with the highest EC in a location about 3200 feet from the river during periods of no river flow. The maximum SAR was found in groundwater near Anthony, and minimum from near Canutillo at about 6500 feet from the river for both periods of river flow and no-flow.

During this study, 31 of the 58 observation wells saw an increase in EC. An additional 16 wells did not see a much of a change. As indicated earlier, many of the increases occurred while the river was flowing and recharging the groundwater with lower EC river water. Why is there an increase in many of these wells? To answer this question, the potential source of salts must be considered. One source could be from other groundwater flows. There may be some increase in EC from this source. However, considering that many water users claim that the groundwater quality was better 20 years ago and the groundwater flows likely existed at that time as well, the salts likely derive from somewhere else. New Mexico has been experiencing an extended drought. Many of the farmers indicate that in the last few years, they have been meeting crop water requirements using groundwater. In addition, in order to insure that crops receive sufficient water so that crop production is profitable, the water users tend to over irrigate. This excess water runs off the land or deep percolates into the soil. When this occurs, salts are washed from the land into the surface waters and into the groundwater. As this process continues, there will be an accumulation of salts in the groundwater. However, the study does not have conclusive data that this is true. More data are required.

This study has produced some interesting data, but more data is needed to determine if there is a continued decline in groundwater levels in some areas and continued increases in EC in other areas. Sources of salts need to be identified so that steps can be taken to reduce the salts in the groundwater. In addition, river-groundwater interaction has been validated further, but additional study is needed to try to understand if this interaction can be manipulated in a desired manner.

REFERENCES

Alley, W.M. and C.J. Taylor. 2001. The value of Long-Term Groundwater Level Monitoring, *Groundwater*. 39:801.

Anderholm S.K. 1993. Water-quality assessment of the Rio Grande Valley, Colorado, New Mexico, and Texas; shallow ground-water quality of a land-use area in the San Luis Valley, South-Central Colorado, 1993. USGS, Water-Resources Investigations Report 96-4144.

Aslan, A.S.T. and K.S. Gundogdu. 2007. Mapping multi-year groundwater depth patterns from time-series analyses of seasonally lowest depth-to-groundwater maps in irrigation areas. *J. Environ. Stud.* 16(2):183.

Bullock, Jr., H. Edward, and E.N. Raymond. 1980. Soil Survey of Doña Ana County Area, New Mexico. United States Department of Agriculture, Soil Conservation Service in Cooperation with the United States Department of the Interior, Bureau of Land Management New Mexico Agriculture Experiment Station.

Cay, T. and M. Uyan. 2009. Spatial and temporal groundwater level variation geostatistical modeling in the City of Konya, Turkey. *Water Environment Research*. Dec 2009. 81(12): ProQuest Environmental Science Collection. Pg. 2460.

Conover, C.S. 1954. Groundwater conditions in the Rincon and Mesilla Valleys and Adjacent Areas in New Mexico. USGS, Water-Supply Paper 1230.

Deb, S.K., M.K. Shukla, and J.G. Mexal. 2012. Simulating deep percolation in flood-irrigated mature orchards with RZWQM2. *Transactions of ASABE*. 55(6):2089-2100.

Dinka, M.O. 2010. Analyzing the extents of Basaka Lake expansion and soil and water quality status of Matahara irrigation scheme, Awash Basin (Ethiopia). PhD dissertation submitted to Boku University, Vienna, Austria.

Frenzel, P.F. 1992. Simulation of Ground-Water Flow in the Mesilla Basin, Doña Ana County, New Mexico, and El Paso County, Texas. USGS, Water-Resources Investigations Report 91-4155.

Frenzel, P.F. and C.A. Kaehler. 1992. Simulation of groundwater flow in the Mesilla Basin, Doña Ana County, New Mexico, and El Paso County, Texas. Supplement to Open-File Report 88-305. USGS, Water-Resources Investigations Report 91-4155.

Hecker, S., K.M. Harty, and G.E. Christenson. 1998. Shallow ground water and related hazards in Utah. Utah Geological and Mineral Survey. Utah Department of Natural Resources Technical Publication. 110. 606 Black Hawk Way. Salt Lake City, Utah.

Helmuth, J., D. Johnson, S. Karklins, and D. Lindorff, D. 1997. Status of groundwater quantity in Wisconsin. Wisconsin Department of Natural Resources. PUBL-DG-043-97.

Jinglong, F., X. Xinwen, L. Jaqiang, Z. Jingfeng, L. Shengyu, W. Haifeng, Z. Jianguo, and Z. HongWei. 2008. The temporal and spatial fluctuation of the groundwater level along the Tarim Desert Highway. *Chinese Sci. Bull. 53(53).*

Kammerer, J.C. 2008. Largest Rivers in the United States. U.S. Geological Survey. http://pubs.usgs.gov/of/1987/ofr87-242/

Kernodle, J.M., 1992. Summary of U.S. Geological Survey ground-water-flow models of basin-fill aquifers in the Southwestern Alluvial Basins region, Colorado, New Mexico, and Texas. U.S. Geological Survey Open File Report 90-361. 81 p.

Kumar, D. and S. Ahmed. 2003. Seasonal behavior of spatial variability of groundwater level in a granitic aquifer in monsoon climate. *Curr. Sci.* 84(2):188.

Lee, W.T. 1907. Water resources of the Rio Grande Valley in New Mexico and their development. USGS Water-Supply Paper 188.

New Mexico Climate Center. 2008. “Climate of New Mexico.” 15 January 2008 http://weather.nmsu.edu/News/ climate-in-NM.htm.

Nickerson E. L. and R.G. Myers.1993. Geohydrology of the Mesilla Groundwater Basin, Dona Ana County, New Mexico, and El-Paso County, Texas. USGS, Water-Resources Investigations Report 92-4156.

Nickerson, E.L. 1994. Selected hydrologic data for the Mesilla ground-water basin, 1987, through 1992 water years, Doña Ana County, New Mexico and El Paso County, Texas. USGS. Draft.

Sharma H., M.K. Shukla, and S.K. Deb. 2013. Water conservation using partial root drying for drip irrigated Chile. USCID Conference, October 22-25. Denver, Colorado.

Sheng, Z., A. Michelsen, Y. Liu, B. Creel, T. McGuckin, and R. Lacewell. 2010. Statistical analysis of flow exchange and salt loading between the Rio Grande and underlying aquifers. *In Proceedings of World Environmental and Water Resources Congress*. Challenges of Change. *ASCE*. Reston, Virginia. USA.

Slichter, C.S. 1905. Observations on the ground waters of the Rio Grande Valley. Water Supply and Irrigation Paper No. 141.

Water Resources Data, New Mexico, Water Year 1997. USGS Water Data Report NM-97-1.

Weeden, C.A., Jr., and T. Maddock. 1999. Simulation of ground-water flow in the Rincon Valley area and Mesilla Basin, New Mexico and Texas. University of Arizona Department of Hydrology and Water Resources Publication No. 99-020.

Wilson, C.A., R.R. White, B.R. Orr, and G.G. Roybal. 1981. Water resources of the Rincon and Mesilla Valleys and adjacent areas, New Mexico. New Mexico Office of the State Engineer. Technical Report 43.

Witcher, J.C., J.P. King, J.W. Hawley, J.F. Kennedy, J. Williams, M. Cleary, and L.R. Bothern. 2004. *Sources of salinity in the Rio Grande and Mesilla Basin groundwater*. New Mexico Water Resources Institute, Technical Completion Report No. 330, New Mexico State University, Las Cruces, NM.