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# Feasibility of Managed Aquifer Recharge
# Conejos County, Colorado

**Prepared for**

**San Luis Valley Irrigation Well Owners, Inc.**

**Prepared by**

**HRS Water Consultants, Inc.**

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# Executive Summary

HRS Water Consultants, Inc. has completed the study of recharge feasibility of four test sites in Conejos County, as authorized by San Luis Valley Irrigation Well Owners, Inc. (see Figure 1 for test site locations). Based on the results of this study, HRS has concluded as follows.

- In our opinion, based on this study, recharge infiltration rates are sufficiently high at all four sites that any one of them would allow recharge at rates high enough for a managed aquifer recharge project of up to several thousand acre-feet per annual diversion period (estimated for the purposes of this study as 60 days), and possibly more.

- Each of the four sites tested has individual hydrogeologic characteristics, including whether confidence exists as to the continuity of the hydrologic pathway to points of probable recharge accretions. Therefore, the infiltration rate at each test site is only one of several factors that must be considered in assessing the physical feasibility of managed aquifer recharge. These factors are discussed in this report, and conclusions are presented for each test site.

- Two of the tested sites, Punche Arroyo and San Antonio (see Figure 2), were primarily intended to test the feasibility of recharge into the unconfined aquifer. The other two sites, Conejos West and Bountiful West (see Figure 3) were primarily intended to test the feasibility of recharge into the confined aquifer in its recharge area near the western edge of the Conejos River valley.

- Because the rates of infiltration were high at each site tested, it is difficult to establish the relative priority of each site on that basis. Other hydrogeologic characteristics, and other non-hydrologic factors, including legal and administrative factors, must be considered. Overall, however, for each site we conclude as follows:

- The best combination of high infiltration rate and strong confidence in an unconfined aquifer accretion pathway occurs at the San Antonio site. Recharge at this site, or at a site in the surrounding area between the Conejos River and the San Antonio River, would cause accretions to both streams.

- Two sites, the Conejos West site and the Bountiful West site, in our opinion, are located so that they predominantly recharge the confined aquifer, although some contribution to the unconfined aquifer cannot be ruled out based on this study. Recharge at the Conejos West site most likely would accrue to the gaining reach of the Conejos River generally below Manassa. Recharge at the Bountiful West most likely would accrue to LaJara Creek or LaJara Arroyo.

- The Punche Arroyo site would provide a high infiltration rate. However, the presence of multiple perched water tables complicates the hydrogeology, and some recharged water, estimated at 0.8 to 1.2 feet per day, would percolate downward to a deep regional water table and thus would not accrue to the San Antonio River.

- In our opinion the results of the four recharge tests are:
  - Scalable up to sizes that would involve recharge rates in the range of 5 to 20 cubic feet per second for managed aquifer recharge (within stated limits as discussed in our report).
  - Transferable (within stated limits) to other areas in the vicinity of each test site.
  - Reliable for the purposes and objectives of this study.

# Table of Contents

**Tables**



**Figures**

**Appendices**

- Photographic log of field activities
- Lithology observed at piezometers
- Test Trench Layout
- Hantush Mathematical Expression for Recharge Mounding
- Piezometer completion reports and monitoring well permits

# 1 Introduction

This report documents a study of the feasibility of recharging ground water at four selected sites, all of which are located in Conejos County, Colorado (see Figure 1). The study documented in this report was done by HRS Water Consultants, Inc. ("HRS"). HRS was authorized to perform this study by the Board of Directors of the San Luis Valley Irrigation Well Owners, Inc. ("SLVIWO" or "Well Owners") according to a Scope of Work provided by HRS and approved by the SLVIWO Board of Directors. The HRS personnel who worked on this evaluation were Vance Campos, Hydrogeologist; Reid Polmanteer, Hydrogeologist; James W. Schloss, EIT, Hydrogeologist (formerly of HRS); Marielle Sidell, Technician; and Eric J. Harmon, P.E., Project Manager (Principal Hydrogeologist). This report was prepared by Vance Campos, Reid Polmanteer, and Eric Harmon.

The study area for this hydrogeologic evaluation focused primarily on four recharge test sites located in Conejos County, CO (see Figure 1) but also included review of the hydrogeology of the San Antonio / Conejos River watershed in the San Luis Valley as it pertained to this study. The study area generally is described as the San Luis Hills on the east, the Mogote volcanic escarpment on the west, the CO – NM state line on the south, and LaJara Creek on the north (see Figure 1).

This study involved research, review, and evaluation of existing references and data; consultation and coordination with members of the Well Owners, Agro Engineering, and others. As part of this study, HRS personnel visited all of the test sites and adjacent localities within the study area on multiple occasions. The site visits allowed HRS to observe firsthand the surface topography, geology, soils, and local ditches and streams as they pertain to the feasibility of ground water recharge. In addition, HRS personnel performed field investigations, water level and hydrogeologic observations, and recharge testing as part of this study. The field work included observation of soils and alluvial materials in the test trenches and piezometers, observation of drilling and completion of 8 piezometers; water level measurements, and recharge infiltration-rate tests at test pits excavated for that purpose.

The primary objectives of this study are:

- Determine whether ground water recharge is physically feasible at four specific study sites in Conejos County.
- Provide the SLVIWO Board of Directors with conclusions and recommendations to aid in decision-making on whether an augmentation plan may be developed using time-lagged accretion credits from recharging water from a surface source, such as Taos Valley no. 3 Ditch water, to help offset time-lagged well depletions.
- Provide a technical foundation for subsequent engineering that will be needed to:
    - Support a future augmentation plan, should the SLVIWO choose to make application for such a plan.
    - Support final design of one or more recharge facilities.
- Provide a technical basis and justification, if scientifically supportable, for recharging water from a surface source, such as Taos Valley No. 3 Ditch water, into the ground water system to offset head declines and aid in sustaining confined aquifer artesian pressure and unconfined aquifer water levels in the study area.

The last of these objectives directly addresses stated goals of Colorado Senate Bill 222:

- Prevent injury to surface water rights by ground water pumping.
- Return the San Luis Valley's aquifer system to a sustainable condition.

Based on our investigations made during this study, HRS has developed conclusions as to the feasibility of ground water recharge at each of the four recharge test locations. This report discusses our hydrogeologic investigation, and presents our conclusions as to the hydrogeologic feasibility of recharging water from the Taos Valley Ditch no. 3 or other available surface water sources at the tested sites.

# 2 Methods of Investigation

The ground water recharge testing project that is the subject of this report was based primarily on acquisition of new data from field testing and measurements done as part of the project tasks. HRS personnel performed field investigations including observation of piezometer (monitoring well) drilling and completion, water level measurements, and recharge pilot testing at each of three sites. In addition, HRS collaborated with personnel of Agro Engineering and Davis Engineering. Agro provided general project oversight on behalf of SLVIWO, and performed measurements of confined aquifer wells in a network that encompassed the study area, to enable a better understanding of the slope and direction of movement of ground water in the confined aquifer (i.e. the potentiometric gradient). Davis Engineering performed elevation surveys of the confined well monitoring network, and of the new piezometers constructed as part of this study.

HRS is familiar with the hydrogeology of this area. HRS personnel have conducted hydrogeologic studies and investigations in the San Luis Valley, including the areas encompassed by the study area and the watersheds of the Conejos River, the San Antonio River, La Jara Creek, and the Alamosa River, since approximately 1979.

## 2.1 Hydrogeologic Criteria for Recharge Feasibility

There are several hydrogeologic criteria that should be considered in establishing whether or not a particular site is feasible for a recharge project. The test sites initially were selected with the idea that they are more likely than some other localities within the overall study area to be feasible for recharge, based on our pre-testing knowledge of the hydrogeology, and information from the Well Owners and others as to where it may be feasible to convey surface water to recharge sites. The testing program was planned to determine whether certain criteria are met with respect to the hydrogeologic feasibility of a recharge project at each site tested. These criteria are:

1. Whether infiltration rates at the selected sites are sufficiently high to allow recharge to take place in amounts suitable for the purposes of the Well Owners.

2. Whether the water level gradients and hydrologic pathways for recharge accretion can be defined well enough that we have confidence in where recharge accretions accrue (i.e. through which aquifer layers, and at what reach on which streams), at a feasibility level of investigation.

3. Whether there is a combination of sufficient thickness and sufficiently high hydraulic conductivity in the unsaturated zone of alluvial or outwash sediments below surface soils but above the regional water table[1] to allow recharge to take place in amounts considered feasible by the Well Owners. For example, the disadvantage of a relatively thin unsaturated zone may be offset by the advantage of high hydraulic conductivity (K) and high specific yield (Sy).

Criteria of a non-hydrogeologic nature, that should be borne in mind with respect to the overall feasibility of recharge at a given site or area include:

- Hydrogeologic criteria for recharge feasibility are addressed in this study. There are other factors that pertain to the overall feasibility of a recharge project. These factors include potential financial, legal, and administrative constraints; Conejos region stakeholder acceptance; land access, source water availability, and source water conveyance from source to recharge site. These factors are beyond the scope of this study, but also should be considered.

- This study has assessed the hydrogeologic feasibility of recharge at each of four sites in the study area. Included in this study is a preliminary estimate of the locations and timing of recharge accretions from each site. These are provided for the Well Owners as a guide for making decisions regarding feasibility of managed aquifer recharge. A large recharge project, potentially involving several thousand acre-feet per year of recharge, is



[1] In the context of ground water recharge, this zone is also called freeboard.

likely to require one or more transient RGDSS model runs with the recharge location and timing included along with regional well pumping, streamflow, surface water diversions, drain flows, and other inputs, in order to assess the timing and location of large-scale recharge at a level of confidence needed for technical defense of a Water Court application.

## 2.2 Recharge Tests: Data Sources and Test Methodology

The data sources and methods of review, investigation, and testing used in this study included the following:

- Initial onsite field meetings and several follow-up discussions by telephone and in person with Mr. Kirk Thompson, Mr. LeRoy Salazar, and several of the Board members of the SLVIWO, including Mr. Jack Gilliland and Mr. Sam Vance, for project scoping, land access permission, well selection and measurements, and recharge test site selection.
- Reviewed well records of confined and unconfined aquifer wells encompassing the study area.
- Collected and evaluated published geologic and hydrogeologic maps encompassing the study area.
- Collected and reviewed published and unpublished hydrogeologic reports, soils data, maps, and hydrologic data in the study area.
- Reviewed topographic mapping coverage of the study area, including USGS topographic maps, historic documents such as General Land Office and early topographic maps, and LIDAR digital elevation model (DEM) coverage.
- Worked with a local, licensed well drilling contractor (Heersink Well Drilling) and observed the drilling of new piezometers; described the subsurface lithology, and documented the completion of 7 new shallow (unconfined) piezometers and 1 new deep (confined) piezometer.
- Worked with Mr. J. C. Gilliland and Mr. Michael Vance to excavate the required recharge test pits at the four chosen test sites.

- Observed and described soil and subsoil lithology in the test pits.
- Installed dataloggers to collect antecedent water level data before testing.
- Collected and analyzed infiltration rate data at each recharge test location, and collected and analyzed water level mounding and recession data at piezometers centered at each test location.
- As an adjunct to the recharge infiltration testing, HRS performed constant head permeameter tests of the near-surface soil material near each recharge test site.

## 2.3 Recharge Tests: Major Tasks

The major tasks enumerated in HRS' authorized Scope of Work for this study were similar for each of the recharge test sites, and are summarized below.

1. <u>Install piezometers (monitoring wells)</u>

At each test site, it was necessary to construct piezometers (monitoring wells) to aid in establishing the slope and direction (i.e. gradient) of the near-surface (RGDSS model aquifer layer 1, "L1") water table in the Punche Arroyo and San Antonio study areas. At the Conejos study area, it was necessary to install one piezometer in the deeper aquifer (nominally called "confined, model Layer 3) in the RGDSS, but not actually confined at this location). The piezometers also were used to measure water level rise and fall in the subsurface associated with the recharge tests. One of the piezometers at each of the four recharge study areas was constructed at the center of the area chosen for the recharge testing.

The piezometers, with the exception of one – at the Bountiful West site - have been surveyed for elevation. HRS coordinated with Agro Engineering and Davis Engineering to have this work done.

A HRS hydrogeologist was onsite for the installation of each piezometer to observe and collect lithologic descriptions of aquifer materials encountered and to provide documentation of the layers and lithologies.

2. Establish water table gradients

This task included review and evaluation of water level measurements in existing wells that were collected by Agro Engineering before the irrigation season, in late winter, 2014. Wellhead elevations were surveyed and provided to HRS by Davis Engineering. During February, 2014, HRS met onsite with Well Owners' representatives, and with Agro Engineering, and aided in selection of existing wells for these measurements.

The water level data were needed to help establish the direction and rate of movement of ground water in the confined aquifer (RGDSS aquifer layer L3), which consists of primarily of basalts (a dark gray to black volcanic rock) and interbedded sediments. Accurate, time-concurrent water level measurements, with surveyed elevations, are necessary to ascertain the direction and rate of ground water movement, and to help determine whether recharged water at each of the three study areas would accrue to the unconfined aquifer, the confined aquifer, or both.

In addition to ascertaining the slope and direction of ground water movement, HRS has made estimates of accretion rates and probable locations of recharge accretions, should the Well Owners choose to go forward with a recharge project at one or more of the test sites. These aspects are discussed in this report.

3. Aquifer Testing

The Scope of Work for this study contemplated providing water for each of three recharge tests by pumping an adjacent existing high-capacity well that draws water from a deeper aquifer layer (RGDSS model layer 3). Therefore, because well pumping was planned, HRS felt it would be beneficial for the overall fund of hydrogeologic information in the Conejos / San Antonio region to use this information to define the transmissivity (T) of the confined aquifer layer (L3) at all three study areas. However, test logistics were such that it was much more practical to use test recharge pits of a manageable size, which meant that the recharge rates were limited to manageable rates, generally in the range of 45 to 85 gallons per minute (gpm) .

Therefore, at HRS' recommendation, and after discussion with Agro Engineering and with the agreement and authorization of the SLVIWO Board, it was decided that study funds would be more beneficially used to achieve the overall project objectives of evaluating the feasibility of ground water recharge, by adding one more recharge test at a fourth location, called Bountiful West, instead of performing the confined aquifer pumping tests as originally scoped.

4. Ground Water Recharge Testing

A key task of this study was to perform a recharge test at each of the original three sites, and also at a fourth chosen recharge test site (see Figure 1). Based on initial site reconnaissance in February, 2014; follow-up reconnaissance by HRS and others in April and June, 2014, we identified three recharge test sites in the study area. A fourth test site was selected later, in November 2014. Three of the four test sites are located within approximately ½ mile (or less) of an existing production well. All four sites are near a lined irrigation reservoir, from which (with the permission of the reservoir owners) water was provided to the recharge test sites for testing purposes. The authorized Scope of Work contemplated that if reservoirs or wells for water supply were not located within a practical distance, the feasibility of ground water recharge could be done at a first-approximation level by performing 3 to 5 in-situ permeameter tests of the near surface soils present at each test site. HRS was able to test each of the four sites by pilot-scale recharge testing, so that the in-situ permeameter tests were not necessary. However, as an adjunct to the recharge testing, HRS performed at least one in-situ permeameter test in near-surface soils, allowing us to compare infiltration rates of the uppermost 1 to 2-foot thick soil zone, with the alluvium and outwash material below the surface soils.

# 3 Study Area

The study area for this investigation generally encompasses the portion of the San Luis Valley defined by the San Luis Hills on the east, the Mogote escarpment on the west, LaJara Arroyo on the north, and the Taos Valley no. 3 Ditch on the south (see Figure 1).

## 3.1 Recharge Test Sites

Within the general study area, four particular study sites were selected for testing the feasibility of ground water recharge. These test sites, shown on Figure 1 are:

- Punche Arroyo Recharge Test Site: a site south of the Rio San Antonio and north of the Taos Valley no. 3 Ditch, located near the intersection with County Roads E.5 and 16, as shown on Figure 1. This test site is near Punche Arroyo. This test site is on land owned by Mr. Aniceto Lucero, who gave HRS permission for access to install piezometers and perform the recharge test. (see Figure 2 for location).

- Rio San Antonio Recharge Test Site: a site located approximately two miles east of Antonito, near County Road G, between Roads 15 and 16. This site is approximately halfway between the Conejos River (south channel) and the Rio San Antonio, as shown on Figure 1. This test site is on land owned by Mr. Jack Gilliland, who gave HRS permission for access to install piezometers and perform the recharge test. (see Figure 2 for location.)

- Conejos West Recharge Test Site: a site near Conejos County Road 12, approximately halfway between Roads L and M. This is within the recharge area of the confined aquifer, near the Los Mogotes escarpment to the west (see Figure 3). This test site is on land owned by Mr. Jack Gilliland, who gave HRS permission for access to install piezometers and perform the recharge test.

- Bountiful West Recharge Test Site: A site near Conejos County Road R, approximately 0.8 miles west of County Road 13. This site also is within the recharge area of the confined aquifer, near the Los Mogotes escarpment to the west (see Figure 3). This test site is on land owned by Bountiful Farms (Mr. Sam Vance and Mr. Michael Vance) who gave HRS permission for access to install piezometers and perform the recharge test.

# 4 Hydrogeology

The entire study area is within the alluvial and glacial outwash plain of the Conejos River and the San Antonio River and their tributaries. Over the past several million years of geologic time, these streams, and their ancestral equivalent streams, have coursed through this area, eroding and transporting rock materials from the west and southwest, in the southeastern San Juan Mountains and their southern extension, called the northern Tusas Mountains. Glacial action during several episodes of glaciation ending approximately 10,000 years ago, and stream action at varying levels of energy throughout much of the past 1 million years or more, have provided large volumes of rock materials deposited throughout the study area. These materials generally consist of discontinuous layers and lenses of silty sand, sand, gravel, and cobbles. Clay is not present in thick, continuous layers in the alluvial and outwash deposits, although previous studies have found that there is sufficient silt and clay to form localized "perched" water tables in some areas such as the Punche Arroyo and Conejos West test sites[2].

On a more regional scale in the study area, the Alamosa Formation "blue clay series" tends to have sufficient aggregate thickness and lateral continuity of clay layers to form a confining layer that separates the overlying unconfined aquifer layer (RGDSS model layer 1) from the underlying confined aquifer layers (RGDSS model layers 3 and 4). In general, the blue clay series is called aquifer layer 2 in the RGDSS model. The blue clay series extends into the northern and eastern part of the study area, generally north and east of the town of Manassa, but does not underlie any of the four recharge test sites (see Figure 4). Most, although not all, flowing confined-aquifer wells in the study area are within the area depicted on Figure 4 as being within the Alamosa Formation "blue clay series".

[2] Perched water table: a locally high water table, usually separated from a deeper water table by an underlying layer of relatively low hydraulic conductivity.

## 4.1 Hydrogeologic Conceptual Models of Test Sites

It is important to the feasibility of ground water recharge to understand the hydrogeology of each of the four recharge test sites based on the available data. A written or graphical description of the nature of the subsurface materials that control the movement of water, and the flow system of the ground water in the subsurface, is called a conceptual hydrogeologic model. A conceptual model is a hypothesis developed based upon available evidence.[3] At each of the four test sites, the authors' hydrogeologic conceptual model differs sufficiently that it was important to test the recharge capacity of each site, and to check the hydrogeology at each site by means of piezometer drilling, water level measurements, recharge testing, and also by review of previous hydrogeologic reports, maps, and data pertinent to the study area. At each site, the testing and data evaluation has led the authors to refine the conceptual hydrogeologic models. The following sections describe our hydrogeologic conceptual models of each test site.

### 4.1.1 Punche Arroyo test site

In the Punche Arroyo area, our conceptual hydrogeologic model is generally as follows. An oblique aerial view and an illustrative cross-sectional depiction of the aquifer layering at the Punche Arroyo test site are shown in Figure 5 and Figure 6.

- Surface soils, mapped as Graypoint "gravelly sandy loam" are generally relatively coarse and well drained.[4]
- Below surface soils, there is a layer coinciding with RGDSS modeled aquifer layer 1 ("L1") that generally consists of 20 to 70 feet thickness of relatively coarse, permeable sand, gravel, and cobbles, composed of stream alluvium and glacial outwash.

[3] Betancur T. V., Palacio C. T., and Escobar, J.F. M., 2012, Conceptual Models in Hydrogeology, Methodology and Results. University of Bogota, Colombia. www.intechopen.com/download/pdf/27980. Accessed 11/15/2014.
[4] Soil Conservation Service, 1980, Soil Survey of Conejos County Area, Colorado. USDA, 144 pages and 17 maps.

- In most areas south of the San Antonio River, a zone of saturation exists in this layer, which is recharged by seepage from the San Antonio River, Punche Arroyo, ditch seepage, and irrigation return flow. Although driller's logs of wells generally do not indicate complex stratigraphic layering in L1 in this area, some data indicate multiple water tables within L1.
- Water tables in this L1 zone, where saturation occurs, generally are perched above a deeper, regional water table. The slope and direction of the water table in L1 are not clear from the existing data, and may change depending on the season and the amount and source of recharge water. Water levels graphed against the midpoint of screened intervals in wells in the Punch Arroyo test area show distinct clustering of water levels: one cluster in the approximate 40 to 75 foot screen midpoint range and one deeper cluster in the approximate screen midpoint range of 100 to 150 feet (see Figure 7.)
- Layers of basaltic rock of the Servilleta Formation interbedded with fine to coarse grained sediments (RGDSS model layer 2 "L2" and probably also L3 in this area) exist beneath the L1 alluvium / outwash.
- A deeper zone of saturation, representing a regional water table with a gradient to the south or southeast, generally following the contours of the Punche Arroyo subdrainage, exists within the Servilleta basaltic rock layers and sediments (L2 & L3).
- The water within the Servilleta is sourced by downward percolation of seepage from the overlying alluvium and outwash (L1), and also (further west, near the town of Antonito), by direct infiltration of seepage from the San Antonio River where the Servilleta is in direct contact with the bed and banks of the river.

### 4.1.2 San Antonio test site

The San Antonio recharge test site is located approximately halfway between the Conejos River on the north and the San Antonio River on the south. In this area our conceptual hydrogeologic model is generally as follows. An oblique aerial view and an illustrative cross-sectional depiction of the aquifer layering at the San Antonio test site are shown in Figure 8 and Figure 9.

- Surface soils are mapped as Graypoint gravelly sandy loam. These soils are generally relatively coarse and well drained.[5]
- Below surface soils, there is a layer coinciding with RGDSS aquifer layer 1 (L1) that generally consists of 40 to 100 feet thickness of relatively coarse, permeable sand, gravel, and cobbles, composed of stream alluvium and glacial outwash. A majority of well logs in this area, between the two rivers, indicate the presence of a relatively continuous clay layer, or layers, a few tens of feet below ground surface, that coincides with Layer 2 of the RGDSS model ("L2").
- In most areas between the San Antonio River and the Conejos River, a zone of saturation exists in the coarse alluvial /outwash layer above the clay layer(s). This alluvial layer is probably recharged by downward percolation of seepage from the rivers and from ditch seepage and irrigation return flow. Water levels graphed against the midpoint of screened intervals in wells in the San Antonio test area show distinct clustering of water levels. A single cluster representing most wells in the area is in the approximate 25 to 80 foot screen midpoint range and a few deeper wells with screen midpoints deeper than 200 feet (see Figure 10).
- Water table observations in zone of aquifer Layer 1 indicate ground water movement from the center of this area, where water levels are higher due to recharge, to the north and south, toward both rivers, where elevations are generally lower. Due to the presence and a continuous hydrologic pathway to both rivers, the recharged water at this test site most likely would accrue to both the Conejos River and the San Antonio River through the L1 alluvial / outwash layer.
- Basalt, a generally dark colored volcanic rock of the Servilleta Formation, comprising RGDSS layer 2 in this area), exists beneath the L1 alluvium / outwash only in the southernmost part of this area, near the San Antonio River. North of a line generally coinciding with the San Antonio River, volcanic rocks of the Hinsdale Formation, and interbedded layers of Los Pinos sediments (together comprising Layer 3 of the RGDSS), exist at depths greater than approximately 40 to 200 feet.
- Ground water within the Hinsdale / Los Pinos has a more regional flow path than the L1 alluvium / outwash layer. This layer probably receives some ground water sourced by

[5] Ibid.

downward percolation of seepage from the overlying alluvium and outwash (L1) through the L2 silt/clayey layer, although the majority of the water in this layer is probably sourced from seepage from the Conejos and San Antonio rivers at locations further west, by direct infiltration of seepage from the rivers and from ditch seepage in areas where clay layers are thinner and less continuous than they are in this area.

### 4.1.3 Conejos West test site

The Conejos West recharge test site is located approximately 3 miles northwest of the Conejos River at its nearest point (near Highway 285; see Figure 1) An oblique aerial view and an illustrative cross-section of the general hydrogeologic layering of the Conejos West test site are shown in Figure 11 and Figure 12.

In this area, our conceptual hydrogeologic model is generally as follows.

- Surface soils are mapped as Platoro "gravelly sandy loam", and are generally well drained.[6]
- Below surface soils, there is a layer coinciding with RGDSS aquifer layer 1 (L1) that generally consists of 30 to 60 thickness of relatively coarse, permeable sand, gravel, and cobbles, composed of stream alluvium and glacial outwash. A majority of well logs in this area indicate the presence of thin, discontinuous clay lenses, from a few feet to a few tens of feet below ground surface. A continuous confining clay layer is not seen in well logs in this area. The nearest point of the Alamosa "blue clay" confining clay series is approximately 2 to 2 ½ miles northeast of this test site.
- In this area north and west of the Conejos River, relatively close to the Mogote volcanic escarpment, a zone of saturation exists at least seasonally in the coarse alluvial /outwash layer (L1). This alluvial layer is probably recharged predominantly by downward percolation of seepage from ditches in this area, which have been reported to HRS to have relatively high seepage rates (Craig Cotton, Division 3 Engineer, verbal communication, 2014).

[6] Ibid.

- Water tables in the L1 layer in this area generally indicate probable discontinuous lateral ground water movement, and a predominance of vertical (downward) ground water movement. This indicates a likelihood that relatively little water is transmitted in a continuous near-horizontal pathway through Layer 1 from this area to the Conejos River, although this is not definite with the available data. Although there is considerable data scatter, water levels graphed against the midpoint of screened intervals in wells in the Conejos West test area show little if any clustering of water levels. The water levels in this area generally tend to increase with increasing depth of screen midpoint, indicating a downward gradient throughout the depth interval of water wells in the area (see Figure 13).
- Layers of basaltic rock of the Hinsdale Formation, and interbedded layers of Los Pinos sediments (together comprising Layer 3 of the RGDSS), exist at depths greater than approximately 20 to 100 feet throughout this area.
- Water levels in the L3 Hinsdale / Los Pinos aquifer layer are generally in the range of 120 to 200 feet deep in this area. This locality is part of a regional recharge area for the L3 ("confined" aquifer) in the Conejos / San Antonio region.
- Ground water level and confined head measurements within RGDSS aquifer layer 3, (the Hinsdale / Los Pinos in this area) shows a regional flow path toward the gaining reach of the Conejos River that generally is located between the Conejos / San Antonio River confluence, east of Manassa, and the Conejos / Rio Grande confluence located about 10 miles further downstream. Thus water recharged to L3 at this location would not accrete at the nearest point on the Conejos River, only about 3 miles southeast of the test site, but instead most likely would accrete in the gaining reach of the Conejos River at or downstream of the Conejos / San Antonio River confluence.

### 4.1.4 Bountiful West test site

The Bountiful West recharge test site is located approximately 3 miles south of LaJara Arroyo at its nearest point and approximately 5.5 miles NW of the Conejos River at its nearest point (see

Figure 1) An oblique aerial view and an illustrative cross-section of the general hydrogeologic layering of the Bountiful West test site are shown in Figure 14 and Figure 15.

In this area our conceptual hydrogeologic model is generally as follows.

- In this area, located within approximately ¼ mile of the eastern edge of the Mogote volcanic escarpment, surface soils are thin, mapped as Garita "cobbly loam" or Luhon "gravelly loam"[7]. These soils are described in the SCS soil survey as "well drained" to "excessively drained". We observed the soil to be generally composed of silty sand with varying amounts of coarse, angular basalt clasts and rounded alluvial gravel and cobbles.
- The Alamosa blue clay series is seen in well logs within approximately 0.5 to 1 mile east of this test site, although it is not present at the test site.
- Alluvial or colluvial layers, probably equivalent to RGDSS model layer L1), exists commonly near the test site, but not at the test site itself. These alluvial layers are most likely recharged predominantly by downward percolation of seepage from ditches in this area, which have been reported to HRS to have relatively high seepage rates.
- Layers of basaltic rock of the Hinsdale Formation, and interbedded layers of Los Pinos sediments (together comprising Layer 3 of the RGDSS), exist at depths greater than approximately 30 to 100 feet throughout this area. Hinsdale basalt lava flow rock is seen in outcrop within 0.5 miles west and 1.2 miles north of this test site.
- Water levels in the L3 Hinsdale / Los Pinos aquifer layer are generally in the range of 40 to 120 feet deep in this area. This locality is part of a regional recharge area for the L3 ("confined" aquifer) in the Conejos / San Antonio region.
- Ground water gradient within the Hinsdale / Los Pinos (L3) in this area generally shows a regional ground water flow path to the NNE, toward LaJara Arroyo, LaJara Creek, and (more distant) the Conejos River. The nearest live stream for which there is likely to be a hydrologic connection with the Hinsdale / Los Pinos appears from available evidence to be LaJara Creek or LaJara Arroyo, about 3.3 miles north at its closest point to the test site. Thus the majority of the water recharged to L3 at this location is postulated to accrete to LaJara Creek or LaJara Arroyo 3.3 miles north, and a minority percentage of

[7] Ibid.

any recharged water is likely to accrete at the nearest point on the Conejos River, about 7.5 miles east of the test site.

# 5 Piezometer Installation

As part of the recharge study, it was necessary to install new piezometers (monitoring wells) in and near the test sites. The purposes of the piezometers for this project were to allow pre-test water level monitoring, monitoring of water level mounding during recharge testing, and recovery (i.e. dissipation) of the recharge mound following test cessation. In addition, the piezometers are permanent installations suitable for long-term monitoring of the water table at their respective locations.

## 5.1 Piezometer Drilling and Construction

With the authorization of SLVIWO, Heersink Drilling (Colorado License no. 1393) was retained to construct new piezometers (i.e. monitoring wells) at the four test sites. The number of piezometers and the depth of the piezometers varied by location, due to different data needs at each test site. Location, elevation, and depth information for the eight piezometers constructed for this project are summarized in Table 1, at the back of this report. Each of the piezometers was used to ascertain local stratigraphy and to measure water levels before, during, and after the recharge tests at each site.

A HRS hydrogeologist was onsite for the installation of the piezometers to observe and describe the aquifer materials encountered in the drilling, and to provide documentation of the subsurface lithologies encountered at each location, and to monitor the drilling, casing installation, and development. Each piezometer was drilled by Heersink using a brief well specification by HRS. They were drilled pursuant to a test-drilling notification to the Colorado DWR (State Engineer's Office; SEO) prior to drilling. Following drilling and completion, construction reports were filed with the SEO, and permits for permanent monitoring well status were applied for by HRS on behalf of SLVIWO, and permits were subsequently approved by the SEO (with the exception of the Bountiful West piezometer, which we are recommending be plugged). Lithologic descriptions for each piezometer and copies of the monitoring well permits for each piezometer, and photographs of the drilling and an example of the completed wellheads are attached in the Appendices to this report.

Each of the piezometers was constructed in a similar manner. All were drilled by alternately drilling and driving steel casing, installing 4-inch solid casing or well screen (Schedule 40 PVC) in depth intervals as directed by HRS' hydrogeologist. Each piezometer has the following construction materials:

- 4-inch ID Schedule 40 PVC solid casing and factory-slotted well screen (depth and interval vary by well). (Note: the deepest piezometer, Conejos Deep, was completed using 6" ID steel solid casing 0-170', and perforated 170' – 258' TD.)
- End cap on bottom of deepest screen section.
- 6-inch protective steel casing.
- Approximately 2 ½ feet casing stickup above ground surface (varies by well).
- Lockable Aluminum well cap.
- 2-foot square concrete well pad, 4 inches thick.

## 5.2 Subsurface Lithology at Test Sites

Subsurface lithology observed in the piezometers drilled for the recharge testing varies at each test site, although the Punche Arroyo and San Antonio sites had similarities, and the Conejos West and Bountiful West sites also had similarities. The detailed lithologic descriptions of each piezometer are attached in the Appendices to this report. The general stratigraphy at each site and surrounding area are described in Section 4 of this report.

Three of the four sites, Punche Arroyo, San Antonio, and Conejos West, all had the distinct well rounded, cobbly, gravelly, coarse alluvium or glacial outwash immediately below the surface soil horizon, with varying amounts of caliche coating common in the upper 3 to 4 feet. These were the materials tested at each of these sites, and at all three sites proved to have high infiltration rates (see Section 6 of this report).

Although all of the alluvium and glacial outwash material was derived from erosion and deposition of rock materials derived from the volcanic rocks common in the Conejos River and San Antonio River headwaters, none of the piezometers at the Punche Arroyo test site or the San Antonio test site penetrated in-place volcanic rock layers. The Punche Arroyo piezometers, in particular, were seen to have varying grain sizes, with coarse to fine grained sediments in lenses or layers. It is believed that these changes of lithology with depth are one cause of the multiple water tables observed in this area. At the San Antonio test site, fewer fine-grained layers were observed, and the coarse, cobbly alluvium or glacial outwash appears to be less anisotropic[8] than it is in the Punche Arroyo area.

At the Conejos West test site, a coarse, cobbly alluvium / glacial outwash layer exists immediately below sandy, silty surface soils, down to a depth of approximately 35 to 40 feet (see Photographic Log in the Appendices to this report). Caliche coating is common in the 2 to 3 foot range. At 35 feet, a weathered silty / clay layer, interpreted as a probable thin, weathered volcanic ash layer, exists on top of a weathered and fractured basalt lava flow drilled in the depth interval of approximately 40 to 68 feet. The first sign of water saturation at this site was seen at approximately 38 feet, in the weathered ash unit. Below the lava flow, the drilling again encountered alluvium, with a mix of grain sizes that ranged from silt or clay to large gravel or cobbles in size. The Conejos West deep piezometer, drilled to a depth of 268 feet, had a final static water level that averaged approximately 163 feet below ground surface in the fall of 2014.

The Bountiful West site had very little alluvial or outwash material. This site had a thin sandy silt or silty sand topsoil layer on top of a rubble zone of weathered, caliche-coated basalt clasts at only 3 to 5 feet below ground surface (see Photographic Log in the Appendices to this report). Below the weathered zone is a relatively unweathered, although fractured, zone of vesicular olivine basalt, interpreted to be a lava flow of the Hinsdale Formation. The piezometer was dry to total depth (20 feet) before and after our recharge testing.

[8] Anisotropic: having different geologic or hydrologic characteristics vertically and horizontally.

# 6 Recharge Testing

An important part of this study was the pilot-scale recharge tests. Four recharge tests were performed: one at each of the four test sites.

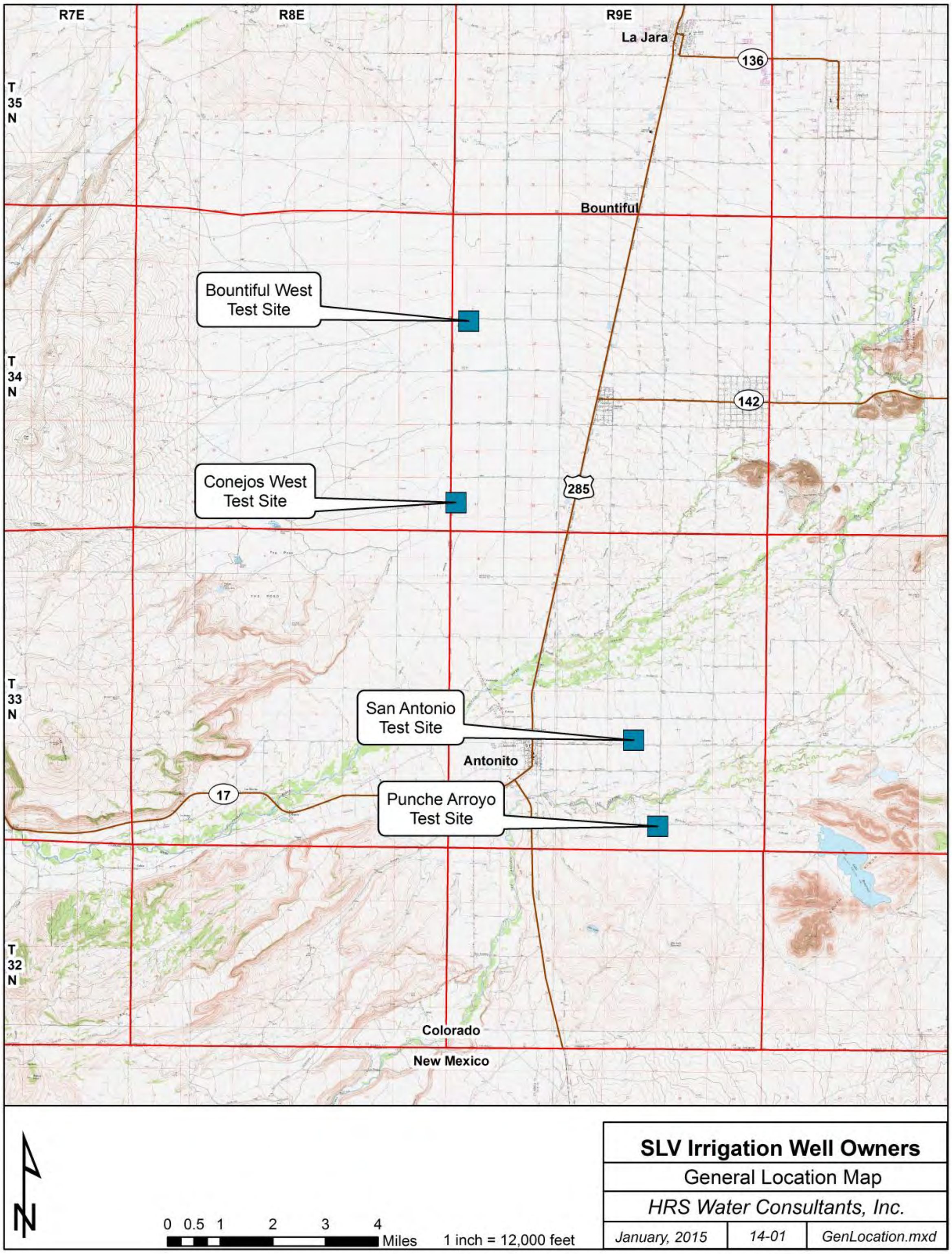


Figure 16 shows the test site locations. The test dates were 9/22/2014, 10/7/2014, 10/8/2014 and 12/19/2014 for the Punche, San Antonio, Conejos West, and Bountiful West test sites, respectively. See Figure 1, Figure 2, and Figure 3 at the back of this report for locations of each test site, and the Photo Log appendix for representative photographs of the testing.

## 6.1 Recharge test procedures

A recharge test consists of a several basic elements: a trench of known size, at least one monitoring well (piezometer), and a source of water at a constant rate. As an example, Figure 17 shows the test layout for the San Antonio test, with the trench dimensions and well location. At each site, a U-shaped trench was dug using a backhoe. The backhoe work was graciously provided by Mr. J. C. Gilliland and Mr. Michael Vance. At each site, the central piezometer was drilled first, to allow access for the drilling and the rig-tender truck, and the trenches dug after. This allowed the central piezometer (or two, shallow and deeper, at the Punche Arroyo site), to be placed near the center of the U shaped trench. This configuration allowed the center rise of the induced rise and fall of water table due to the infiltration of water from the recharge test trench. Appendix B show the test trench and piezometer layouts for all the sites. For each recharge test, water was pumped out of a nearby lined irrigation reservoir using a small centrifugal pump, conveyed through a temporary pipeline, and discharged through a flow meter into the test trench.

Programmable water level transducer / data logger units were used to measure water levels in the monitor well and to measure the stage in the pit during the recharge test. The dataloggers were programmed to record water levels (actually the pressure due to the height of water above the transducer) at one minute intervals. A flow meter was used at each test to record inflow rate and volume. A calibrated, totalizing McCrometer meter was used at the Punche Arroyo site, and a calibrated circular orifice weir was used at the other three test sites. Flow rate was measured near each discharge location, and was monitored on a continuous basis throughout each test.

Before the start of each recharge test, the pipeline, pump and various measurement devices were readied. Precautions were taken at the discharge point to disperse the flow and avoid eroding the trench, thus possibly changing the geometry and wetted area of the trench. The pump was started at a planned start time, to begin discharging water into the recharge test trench. There is a natural maximum infiltration rate which depends on the materials characteristics and the trench bottom and side area at each site. Early in the test, the flow rate needed to be adjusted to find the maximum infiltration rate to avoid overtopping the trench.

There is a time lag before any water level increases can be seen at the monitor well. The time lag is due to the wetting of the unsaturated zone between the bottom of the test trench and the underlying water table. After enough time, a “mound” of water begins to build at the water table beneath the test trench, causing a local rise in water table. The water level mound rises until enough of a gradient builds to cause horizontal flow into the aquifer. The height of the mound depends on the aquifer characteristics, test rate, and trench wetted area. Measurement of water levels in the piezometer(s) and the test trench continued after turning the pump off. The duration of the recharge test depends on the goals of the test. For our purposes in this study, a test of sufficiently long duration was needed to enable us to measure changes in the water table and any future hydrogeologic changes in the subsurface that may arise with the recharge of large amounts of water in a managed aquifer recharge facility. It was expected tests of at least 48 hours would be needed to hydrate any clay present in the subsoil materials and to reach a pseudo-steady-state (i.e. leveling off) condition of the recharge mound on the water table, however each test reached steady-state within 6 to 10 hours of commencement.

There are three aquifer parameters which can be determined by this method of recharge testing. The first is infiltration rate: any ponded water in a recharge facility will infiltrate at certain rate. The best way to determine this is to fill a trench and measure the stage decline of water in the test trench, from a steady-state level to empty after the water has fully infiltrated. We monitored water level in the trench on a continuous basis during the test, and also measured infiltration rate by means of transducer / data loggers and by manual measurements, at the end of each of the four recharge tests. The water table mound height, measured in the central piezometer, was used to determine the hydraulic conductivity and the specific yield of the deeper aquifer materials below the test trench.

### 6.1.1 Infiltration Rate Tests

This section presents a brief summary of the infiltration test results for all the sites. Each site is discussed in detail later in Section 6 of this report. At the end of each recharge test, immediately after the pump is shut off, the trench is full of water. By recording the test trench stage decline over time an infiltration rate was computed. Figure 18, Figure 19, Figure 20 and Figure 21 show the stage decline data at each test site.

The stage decline curve at the San Antonio test site (Figure 19) shows a result typical of the tests. There were two linear segments in the stage decline curve. Linear trend lines were fitted to the straight segments of the stage data. Infiltration rate is represented by the slope of the trend line segment. Table 2 shows the results. The lowest infiltration rate (25 ft/day) was seen at the Bountiful West site, where the shallow (top 3 ft) lithologic description is a silty sand (although very cobbly). The silt has likely accumulated in the pore spaces of the deeper volcanic rock, slowing infiltration. An infiltration rate of 25 ft/day is rapid, but slower than measured infiltration rates of the other test sites. The lithology of the other three sites all show a coarse mix of sand, gravel and cobbles in the upper layers, with minimal fines.

Overall, high infiltration rates demonstrate the near surface materials, below the first 2 to 3 feet of surface soil, are favorable to ground water recharge. The highest measured infiltration rate of 38.1 ft/day was the San Antonio site and the lowest of 25 ft/day was at the Bountiful West site. These results also explain the large ditch losses which occur in the area.

### 6.1.2 Soil Hydraulic Conductivity Tests

As an adjunct to the infiltration rate tests, which tested the zone below the surface soils, HRS also performed one to two tests of the saturated surface soil hydraulic conductivity (K) at each test site. The purpose of these tests was to estimate whether the surface soil K differed significantly from the subsurface soil K (the zone generally below 5 feet deep, which was, at all test sites, below the zone of identifiable surface soil development). This was done to verify whether, at each site, the surface soils would need to be removed in order to achieve the best infiltration rates, should the SLVIWO choose to go forward with a managed aquifer recharge project.

HRS used a constant-head testing procedure for the soil K tests, using a Guelph™ soil permeameter to keep a constant head of water in a hand-augered borehole. Photographs of the permeameter field setup can be found in the Photographic Log Appendix to this report. The results of the surface soil K tests are shown in Table 3. In general, the tests show that the surface soil K is somewhat less than the K of the underlying alluvial and glacial outwash sediments (at Punche Arroyo, San Antonio, and Conejos West) and the underlying basalt lava flow (at Bountiful West), a result that was not unexpected. Overall, the results are relatively consistent, and show that higher infiltration rates could be achieved at each site by first stripping the upper 2 to 4 feet of soil material, to expose the underlying higher-K material.

### 6.1.3 Theory of Ground Water Mounding

The general theory of ground water mounds under recharge basins is given in a paper by M. S. Hantush[9]. The paper gives an analytic solution of mound height for the case of a rectangular recharge area. The theory assumes the aquifer is homogenous, isotropic and has a flat impermeable base. Also the theory assumes a constant rate of recharge. At our four test sites, even within a single aquifer layer such as the RGDSS model layer L1, we see the evidence of sublayers having different characteristics, which introduces judgment in applying the Hantush solution.

Hantush's mathematical solution is shown in the Appendices to this report. The expression defines horizontal hydraulic conductivity (K) and specific yield (Sy). The two parameters control the size of the mound. If Sy and K are both small the mound will grow rapidly. At some point the mound will form a gradient large enough that water will flow horizontally which is

[9] Hantush M.S., 1967, Growth and Decay of Groundwater Mounds in Response to Uniform Percolation, Water Resources, Vol. # No.1 P227-234.

controlled by K. One of the limiting factors in recharge is head space (sometimes called "freeboard") which is the thickness of the unsaturated zone above the water table. If head space and Sy are small, a mound will grow to the surface, come into direct fully-saturated contact with the overlying recharge facility, and thus limit the amount of recharge. The best case for recharge is a moderate Sy and a large K, meaning a mound would never grow to surface, and recharge would dissipate relatively rapidly in a horizontal direction.

We have used the programing language Octave™ to evaluate Hantush's expression. This allows us to try different sets of K and Sy values, within reasonable ranges, to see which set of values of K and Sy provide the best fit to the measured rates of mound rise and fall, and the overall mound height, that we measured in the four recharge tests.

## 6.2 Recharge test results

### 6.2.1 Punche Arroyo test site results

The Punche Arroyo test site (see Figure 2) was the first recharge test performed, and it involved early operational issues that were solved for the other tests. Figure 22 shows the water level changes. The first test at this site was done on September 22nd repeated on September 23rd. The first recharge test was scheduled to run overnight unattended (but measured by our dataloggers), but ended early due to premature pump stoppage. The exact time recharge ended in the first test is not known. The second recharge test lasted approximately 7 hours. Constant flow rate into the test trench was not achieved in the second test due to pump rate changes, and therefore results were not analyzed. The first test yielded good results and analysis is discussed below.

Figure 22 shows the water level rise and fall on September 22nd and 23rd. There was a period of 109 minutes during which the unsaturated zone wetted. After the wetting period, there is a rise over next two hours, which then flattens out over the next 6 hours. We identify this feature of the curve to be indicative of a single layer of constant hydraulic conductivity and specific yield.

At some point around 2:00 a.m., recharge stopped and water levels declined. Initially, water levels declined slowly and after some time dropped rapidly. The period of slow decline is interpreted to correspond to the period of the test trench draining. The rapid decline is interpreted to represent the period after the trench has drained. After both phases of testing, on September 22nd and September 23rd, the water levels did not return to the pre-test starting level. One possible interpretation is a slightly, upwardly concave or "cup shaped" aquitard lens or flat layer below the test site retains water atop causing downward leakage to occur at a slower rate. There may also be other feasible explanations.

Figure 23 shows the same data as Figure 22 but in terms of saturated thickness and minutes from the start of water level rise. Parameters fitting results are K= 100 ft/day and Sy= 0.20. In the analytic solution curve-fitting procedure, we have estimated that the recharge ended at 675 minutes. The calculated ("curve fit") values fit the test measurements fairly well. Over the time period from zero to 400 minutes the fit is very close. The middle time period from 450 to 650 minutes does not fit as well as the earlier period. This was the time period when unattended equipment was changing the recharge rate. We postulate recharge continued at a lower rate for a period causing a delay in the water level drop for a time. The later period from 750 to 1150 minutes matches fairly well.

The early part of the test shows a reasonably good curve fit at aquifer parameter values of K= 100 ft/day and specific yield (Sy) = 0.20. These are reasonable values for an aquifer of this type. This layer extends from 18 feet below ground level (BGL) upward to surface soils 2 to 3 feet below ground surface. At the Punche Arroyo site there were two piezometers installed near the center of the U-shaped test trench. The shallow piezometer water levels are seen on Figure 22 and show the effects of recharge. The second, deeper, piezometer did not show any water level rise during the time of the recharge test. There are multiple silt or clay layers seen in the lithologic log below the shallow piezometer. We postulate that over the time of the test the finer-grained layers slowed and dissipated any sign of the recharge from this test.

### 6.2.2 San Antonio test site results

Figure 24 shows the water level rise and subsequent fall of the test at the San Antonio test site, performed on October 7th, 2014. The initial pre-test water level in the center piezometer was 32.5 BGL. After flow into the recharge pit began, the water levels rose after a 24 minute delay while the unsaturated zone wetted. Then, there is a water level rise lasting approximately 5 hours. We interpret this part of the water level rise to be indicative of the presence of an alluvial or outwash layer of constant hydraulic conductivity (K) and specific yield (Sy). When water levels reach 22.3 feet from ground level, a relatively abrupt change occurs in the rate of rise. Water levels rose 1.2 feet in 9 minutes. This rise we interpret as being indicative of a layer with a lower value of specific yield, such as a higher percentage of clay or silt in the alluvium. In the lithologic description for the San Antonio West piezometer, located approximately ½ miles WSW of the test site, an interbedded clay was noted at 20 to 22 feet BGL. After the steep rise, a much slower rate of rise continues until flow to the recharge pit was stopped at 17:20. The slower rate of rise indicates a much higher hydraulic conductivity above 21 feet. The water level declined after flow ceased, but did not quite return to the initial pre-test value.

Figure 25 shows the same data as in Figure 24, but in terms of saturated thickness and minutes from the start of water level rise. Hantush's analytic expression uses those variables. The initial saturated thickness was 5.5 feet. The recharge applied in the test builds a ground water mound on top of this initial saturation.

Because of the layered nature of the alluvial / outwash deposits at the San Antonio site we divided the analysis into an early time and a late time period. The early period is from zero to 300 minutes and the late period is from 350 to 550 minutes. For the early time period, the analytic expression with values of K = 18 ft/day and Sy= 0.26 best matches the measured values.

The late period from 350 to 550 minute shows only a small rise in water levels. In order to fit this period different parameters are needed. Using an initial saturated thickness of 15.5 feet , K =

100 ft/day and Sy= 0.26 the analytic expression approximately matches the measured water levels. The fit is not perfect, but it shows that the hydraulic conductivity (K) is much higher. We did not attempt to fit parameters to the period from 300 to 350 minutes, where the steepest rate of rise occurred.

The test at the San Antonio test site shows the complex nature of the shallow aquifer (RGDSS Layer 1, "L1") in the region. The water level data show the various different sub-layers within this aquifer layer, and the different aquifer parameter values that are representative of this layer. There is a layer above 22 ft BGL that has a high hydraulic conductivity. Below this is a clay or silt-rich sublayer less than 2 feet thick. From 23 to 32 feet BGL a lower K layer is present.

### 6.2.3 Conejos West test site results

The recharge infiltration pilot test at the Conejos West site was performed on October 8th, 2014. Figure 26 shows the water level rise and fall during the recharge test. There is delay of 29 minutes, during which the unsaturated zone wets. After this period the water level rose 10.3 feet over the next 57 minutes. The steep rate of rise indicates a layer or lens of relatively low specific yield and hydraulic conductivity. In the lithologic description for the Conejos shallow piezometer, located at the center of the U-shaped test trench at this site, interbedded silts or clays are seen from 23 to 35 feet BGL. The steep rate of rise abruptly ended when the water level reached 14.5 feet BGL, and the water level rose at a much lower rate which we interpret as indicative of a sublayer of relatively high hydraulic conductivity. Recharge ended at approximately 15:00 on October 8th, and for one hour water levels declined relatively slowly. This corresponds to the time when the stage in the test trench was declining. At 16:00 the pit was drained, and the water level then declined at a much steeper rate. At 19:00 the steep decline ended. Over next 13 hours the water level declined by 0.1 ft. After the test the water level did not return to the initial value, possibly due to the presence of water retained on top of an aquitard lens, below the site which has filled during recharge. The water so retained apparently is leaking downward at a slow rate.

Figure 27 shows the same data as in Figure 26 but in terms of saturated thickness and minutes from the start of water level rise. We have divided the analysis into early and late time corresponding to the two sublayers identified above. The early time period is from zero to 60 minutes and the late period is from 100 to 400 minutes. The parameters which appear to provide the best fit to the early time period are K= 7 ft/day and Sy= 0.08. The late time period is well matched with K=100 and Sy=0.26. These parameter values are reasonable. The higher values are indicative of clean, coarse alluvium or outwash, and the lower values are indicative of the same alluvial or outwash material with a relatively minor percentage of silt or clay present that reduces the K and Sy values.

### 6.2.4 Bountiful West test site results

The Bountiful West test site was selected later than the other test sites, and so was not tested at the same time. It was tested on December 19, 2014. Figure 28shows the water level rise and fall in the central piezometer during this recharge infiltration test. There is a delay of 65 minutes from the start of recharge until the mound started to rise, again, in our interpretation, indicating a period when the unsaturated zone wetted. The water table mound rose for 139 minutes. We interpret this rising water level period as being indicative of a layer of relatively constant specific yield (Sy) and constant hydraulic conductivity (K). The rate of water level rise became slower as the mound grew to 1.6 feet in height. After this, the water level stopped rising and for the next two hours of the test, the water level remained constant. We believe this indicates the presence of a layer of high hydraulic conductivity above 17.3 feet BGL. Recharge was stopped at 16:05 and water levels began to fall. Over the next 6 hours water levels returned to 0.36 feet above the starting value. After this the water levels recovered more slowly. The lack of a complete return to the pre-test starting value we interpret as a retainage of moisture that filled in the interstices of fine grained materials contained in fractures and joints of the basaltic lava flow underlying the test pit that were dry before the test but filled during recharge. The water thus retained is leaking downward at a slow rate.

Figure 29 show the Bountiful West tests data in terms of saturated thickness and elapsed time from the start of mound rise. The initial saturated thickness was zero (i.e. the central piezometer was dry at its total depth of approximately 20 feet). The aquifer parameter values that best fit the time from zero to 150 minutes are Sy = 0.26 and K = 1,300 ft/day. 1,300 ft/day is a very high K, but high values in this range are not uncommon due to secondary permeability that has developed in cooling joints or fractures in competent volcanic rock layers. We have extended our calculation to 1,000 minutes, which is the receding part of the ground water mound.

We did not attempt to fit the period of the test from 150 minutes to 270 minutes. In the other recharge tests we observed a slight rise in water levels when the mound curves flattened. This occurred at the San Antonio site and the Conejos West site. At the Bountiful West test site we saw no rise at all for 2 hours. We conclude there is a horizontal fracture at 17.3 feet BGL which drains water rapidly away. The calculated values from 250 minutes onward only roughly match the measurements. We believe the general trends are correct, but exact matches of aquifer characteristics cannot be made.

The Bountiful West site shows the interesting properties of fractured basalt. The hard, competent, and relatively unweathered volcanic rock material encountered during the drilling of the central piezometer originally led us to expect a low infiltration rate. However, in basalts secondary permeability caused by cooling joints and fractures oftentimes are the dominant controls on the aquifer properties. At this site we see K =1300 ft/day and Sy= 0.26 and a fracture at 17.3 feet BGL which has a higher K value which caused the mound to stop rising. During the drilling of the central piezometer, a bit drop was noted at about 18 feet depth, which is probably indicative of the presence of this fracture.

# 7 The Hydrologic Pathway: Gradients and Accretions

The gradient of ground water consists of two parts: the slope and the direction of a water table surface (for an unconfined aquifer) or a confined potentiometric surface (for a confined aquifer). At each test site within the study area, it was necessary to estimate the continuity of the ground water gradients vertically and horizontally to aid in determining which aquifer layer(s) (i.e. unconfined or confined layers) would be recharged, and whether there is hydrologic continuity between each test site and the nearest perennial or intermittent stream or its hydrologically-connected, saturated alluvium.

In a recharge situation, the transient mounding of the water table induced by a recharge event at each site is superimposed on the ambient ground water gradient. Recharge-induced mounding constitutes a local increase in pressure (in physical terms, an increase in potential energy). The mounding-induced pressure dissipates radially, in all directions away from the centroid of recharge (assuming horizontally isotropic aquifer conditions at the recharge sites). This means that even with the existence of a pre-recharge gradient that shows a preferential direction, the induced recharge from a particular site will accrue most strongly at the nearest points on a stream, no matter what the pre-recharge gradient happens to be. The gradient is important in establishing hydrologic continuity of the recharge pathway. That is, if discontinuities show up in the gradient, then the nearest point on a stream may need to be changed to accommodate geologic discontinuities or irregularities.

In our experience, there is a common misconception that pumping depletions or recharge accretions follow the pre-pumping or pre-recharge gradient; i.e. the pre-existing gradient caused by ground water recharge and discharge (also called the direction of downgradient ground water "drift"). In an aquifer system with a hydrologically continuous pathway to a river or other constant-head aquifer boundary, the idea that depletions or accretions follow a pathway defined by the gradient of the water table is incorrect. Instead, the correct interpretation is that the point at which any depletions or accretions in a hydrologically continuous aquifer will accrue will be at the nearest reach of the nearest stream that is hydrologically continuous with the aquifer layer being pumped or recharged. This is because depletions or accretions are hydraulic pressure effects that propagate through the aquifer, not solute transport effects that depend on movement of individual molecules of water through the aquifer. The misconception that depletions or accretions move in a downgradient direction defined by a gradient caused by pre-existing recharge and discharge is described in a recent USGS publication on stream depletions:

> A common misunderstanding regarding streamflow depletion is that the rates, locations, and timing of depletion are dependent on the pre-pumping rates and directions of groundwater flow in an aquifer. … Provided that sufficient surface water is available to meet the pumping demand, a new steady-state condition will eventually be reached in which the rate of storage change is zero and the entire pumping rate can be accounted for as increased recharge and decreased discharge. It is important to understand that depletion is independent of the natural, pre-pumping rates of recharge and discharge. … The independence of depletion and rates and directions of groundwater flow in most systems allows calculation of depletion by a number of different methods. These methods include analytical solutions, superposition models, and groundwater-flow models (see "Analytical and Numerical Modeling" section). In using either analytical solutions or superposition models, the natural rates and directions of groundwater flow are ignored.[10]

Thus the locations of depletions and return flow accretions are not dependent on the ambient slope and direction, or gradient, of ground water flow, so long as there is hydrologic continuity between the recharge location and the stream.

## 7.1 Gradients and Recharge Accretions

Based on lithologic and aquifer layer information, and on water table and confined aquifer head data from this study (Agro Engineering measurements in the confined aquifer and HRS measurements in the new piezometers), from recent calibrated RGDSS model results, and also from the Rio Grande Water Conservation District database[11], we have:

- Determined that hydrologic continuity from recharge point to stream does exist, to the best of our knowledge based on available data and this testing program, at each of the four sites tested. Each site has individual characteristics of the accretion pathway that are discussed individually.

[10] Barlow, P.M., and Leake, S.A., 2012, Streamflow Depletion by Wells—Understanding and Managing the Effects of Groundwater Pumping on Streamflow. U.S. Geological Survey, Circular 1376 p. 40).

[11] http://www.prinmath.com/rgwcd/. Accessed various times between September 2014 and January 2015.

- Determined the aquifer layers recharged and the most probable nearest point of accretion and accretion reach on the stream(s) for each test site.

Based on our estimates of gradients, hydrologic continuity, and points of accretion, HRS has made calculations of the estimated rate of recharge accretion, and accretion reach length, for the Punche Arroyo, Bountiful West, and Conejos West sites. These estimates are preliminary, and are provided to aid the Well Owners for decision-making as to whether, and where, a managed aquifer recharge should be constructed and operated.

The accretion estimates were modeled using a Glover analysis with AWAS software provided by Colorado State University's Integrated Decision Support group (IDSCSU). The software is restricted to allow the user to calculate a single accretion reach of variable length. In calculating the accretion from the San Antonio site, which is considered to recharge both the Conejos and San Antonio due to its proximity to both streams, a variation of the Glover analysis using image wells was modeled using the open-source computer code called Octave™. The input parameters used are shown in Table 4. These parameter values are believed to be representative of the modeled aquifers between the point of recharge and the likely point of accretion. A 60-day injection 'slug' of 1,000 acre-feet (i.e. 500 ac-ft/month, 16.67 ac-ft/day, about 8.4 cfs) was considered to be a valid estimate of seasonal recharge volume that may be available from the Taos Valley No. 3 water right, or another similar water right. Higher recharge volumes certainly may be available, but the timing and location of accretions is not dependent on the volume recharged. Output parameters are based on this volume of recharge input. Estimates of accretion rate and reach length for each site are provided in Table 5 and are analyzed in the following sections on a site by site basis.



### 7.1.1 Punche Arroyo Test Site

As described in Section 4 of this report, at the Punche Arroyo test site and surrounding area a zone of saturation generally exists in the uppermost aquifer layer (RGDSS model layer 1, "L1"), composed of gravelly / cobbly alluvium and outwash, with many lenses or layers of finer-grained materials. Water level data in this area, including Rio Grande Water Conservation District's (RGWCD's) RG-96 A, B, and C series of piezometers as well as the piezometers drilled for this study, show that multiple water tables at different depths occur within L1, and also show that there is a strong downward gradient. Water tables in L1 in this area, where saturation occurs, generally are perched above a deeper, regional water table that exists in L2 and/or L3 (Servilleta Formation basalts interbedded with sediments) and drain downward toward to the regional water table in the Servilleta.

The slope and direction of the uppermost water table in L1, based on the existing data, is consistent with the surface elevations in the San Antonio River in the closely adjacent reach of the stream approximately ½ miles north of the test site (see Figure 30). This is shown by water levels in Punche Shallow piezometer, and also in the RG-96A piezometer. Deeper water levels in the alluvium / outwash (possibly RGDSS model layer 2 in this area) appear to be primarily toward the east, mimicking the general topography of Punche Arroyo, as shown in Punche site Center Deep, East, and North piezometers, and also by the RG-96C piezometer. The deepest water table identified in this area is in the Servilleta Formation (RGDSS model layer 3 in this area), appears to have a gradient also to the east and south, down Punche Arroyo. These conclusions are in close agreement with the conclusions of Talbot (1991)[12] and HRS Water Consultants, Inc. (2012)[13]. Water table mapping in this area by Crouch (1985)[14] and Johnson & Bauer (2012)[15] are regional in scope, and do not show this area in detail.

The shallow piezometer data (Punche Shallow and RG-96A) show continuity of the hydrologic pathway from the Punche Arroyo test site to the San Antonio River approximately ½ mile north, but at the same time there is significant downward movement of ground water to a deeper water table that would not allow accretions to the San Antonio River. Thus, managed aquifer recharge

[12] Talbot, W.R., 1991, Punche Valley Ground-Water Study Southeast Conejos County, Colorado. U.S. Bureau of Reclamation in cooperation with the Colorado Division of Water Resources. 31 pages, plus appendixes and plates.
[13] HRS Water Consultants, Inc., 2012, Hydrogeologic Mapping Review of Conejos / San Antonio Region. RGDSS final memorandum prepared for the CWCB / CDWR, July 17, 2012. 29 pages plus plates.
[14] Crouch, T.M., 1985, Potentiometric Surface, 1980, and Water Level Changes, 1969-1980, in the Unconfined Valley –Fill Aquifers of the San Luis Basin, Colorado and New Mexico. USGS HA-683, Sheet 1 of 2.
[15] Johnson, P.S., Bauer, P.W., February 2012, Hydrogeologic Investigation of the Northern Taos Plateau, Taos County, New Mexico. New Mexico Bureau of Geology and Mineral Resources Final Technical Report, Open File Report no. 544, 78 pages plus appendices.

at this site would need to be done at a rate sufficient to overcome the loss of accretions to the San Antonio River due to downward leakage from a (presumably shallow) recharge facility to the deeper, regional water table. HRS has analyzed the available data from piezometers RG-96 A, B, and C for the period 2001 – mid-2014 to estimate the rate of the downward leakage.

Figure 31 shows the water levels, measured approximately monthly, for RG-96A, B, and C. These hydrographs clearly show the seasonal influence of recharge due to water in nearby ditches and Punche Arroyo, and possibly a smaller amount of percolation from nearby irrigation return flow. The highest annual water levels in the shallowest piezometer, RG-96A, typically occur in early June. Water levels in RG-96B and RG-96C are progressively deeper, showing the strong downward gradient in this area. By graphing the difference in water level elevations in RG-96A and RG-96C, and dividing the result by the difference in midpoint screen depth of these two wells, we have formed an estimate of the downward gradient over time (see Figure 32). This shows that the magnitude of the downward gradient varies with time, reaching its peak usually in early June, typically when ditches in this area are diverting water. At all times, however, the downward gradient approaches unity, varying between approximately 0.8 and 1.2 feet per day, averaging about 0.9 feet per day downward. This is a very large vertical gradient, much higher than we would expect for fully saturated, Darcian flow conditions. This strengthens the conclusion that there are several progressively deeper perched water tables in this area, and that water moves downward through vadose[16] zones from one water table to the next deeper water table.

In addition, from analysis of the different times when the shallowest (RG-96A) and deepest (RG-96C) piezometer reach their annual highest and lowest water levels, we have estimated the rate of vertical downward travel of the wetting front from screen midpoint in RG-96A (estimated at 20 feet depth) to screen midpoint in RG-96C (63.7 feet depth). Table 6 shows this analysis. Based on the 2001 through mid-2014 data, we conclude that the average "order of magnitude" lag time for the peak to travel from RG-96A down to RG-96C is approximately 51 days. For the 43.7 vertical feet from screen midpoint to screen midpoint, this suggests an average rate of wetting-front travel of 0.9 feet per day. The low point from RG-96A to RG-96C is reached in

[16] Vadose: unsaturated zone.

less time, only about 14 days on average for the available data points. This also suggests at least a partially unsaturated zone (i.e. vadose zone) travel path, as the unsaturated hydraulic conductivity (K) is dependent, among other things, on the volumetric percent of water content of the sediments, and this is likely to change seasonally, in step with the seasonal nature of ground water recharge.

Thus, if the Punche Arroyo site is selected for managed aquifer recharge, the rate of input to the recharge facility must be able to overcome up to 0.9 ft/day of downward leakage to the deeper, regional aquifer, which would be a commensurate amount of loss of accretion to the San Antonio River. For example, using a 1.0 acre recharge facility at 1,000 ac-ft in 60 days (about 16.67 ac-ft/day), the hypothetical recharge rate (not accounting for possible reductions due to siltation or biofouling) may be as high as 16.67 feet per day. However, the actual amount of accretions to the San Antonio River must be reduced by the downward leakage, so the net accretions are more likely to be the actual measured infiltration, minus 0.9 feet per day: over 60 days at one acre area, this would amount to a reduction of 54 acre-feet.

A zone of saturation exists within a layer of coarse, unconsolidated material considered to be represented as layer 1 in the RGDSS model. For the Glover AWAS accretion timing estimate, this recharge site was modeled as unconfined due to the presence of this zone. This zone is considered to be in contact with the San Antonio River just under half a mile away, as discussed previously. Figure 33 shows a typical analytic calculation response: there is a rapid initial rise in accretions over the first 8 to 12 months, and a significant tailing of the accretions at later times. In this estimate, approximately 75% of the initial 60-day recharge period results in accretions that occur within 4 years of injection, and 95% of the accretion from the initial 60 day “slug” of recharge occurs within 9 years after recharge injection. Spatially, accretion typically occurs not at just one point, but instead typically occurs over a stream reach, with the largest amount of recharge occurring at the nearest point in hydrologic connection with the point of recharge, and the rest of the accretions occurring in diminishing amounts further upstream as well as downstream of the nearest point. For the Punche Arroyo site, most of the accretions are estimated to accrete within a 0.75 mile reach of the San Antonio River (see Figure 34). This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site.

### 7.1.2 San Antonio Test Site

At the San Antonio test site and surrounding area, as described in Section 4 of this report, a zone of saturation generally exists in the uppermost aquifer layer (RGDSS model layer 1, "L1"). Well logs show that this zone is composed of primarily of gravelly alluvium and outwash, with some lenses of finer-grained materials. Clay lenses or layers are sufficiently extensive below the L1 alluvial layer to form a continuous zone of saturation within L1 that is continuous from the San Antonio River, north across the study site, to the Conejos River. This is shown schematically on Figure 9. The continuity of a saturated zone in L1 in shown by available water table maps that include this area, including Crouch (1985, Plate 1), and HRS Water Consultants, Inc. (2012, Plate 5). This is also seen in the shallow clustering of water levels at or above the commonly reported depth range of water levels in wells in this area (see Figure 10). Most water wells completed greater depths in this area show progressively deeper water levels with deeper screened intervals, indicating a downward gradient. However, monitoring well data from this area (e.g. RGWCD MW - Wells NA03300927ADD and NA03300911CBB) show long term persistence of a saturated zone in L1, and downward leakage of water into deeper layers probably is small, although not zero.

From the foregoing discussion, we conclude that there is a continuous pathway for recharge accretions from this site to the adjacent perennial or intermittent streams, the San Antonio River to the south, and the Conejos River to the north of this site. Based on this study and the data currently available, our best estimate is that recharge would accrue to both the Conejos River and to the San Antonio River from recharge facility located at this test site. A site nearer the Conejos River, in general, would allow greater accrual of water to the Conejos and less to the San Antonio, and vice versa.

As previously discussed, the San Antonio recharge site is located between the San Antonio River and Conejos and recharge most likely will occur to both streams from a managed recharge facility at the San Antonio test site. Due to the complexity of the two-stream situation, a modified version of the Glover method was modeled analytically by HRS using the theory of image wells[17] using open-source Octave software. Figure 35) shows that approximately 62 percent of recharge will accrete along an approximately 1.26 mile long reach of the San Antonio River. Thirty-eight percent is estimated to accrete to a 1.65 mile reach of the Conejos River. Fifty percent of total accretion to both streams will likely occur by approximately four years following the slug of recharge, while 95 percent accretion will take 14 years. This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site.

### 7.1.3 Conejos West Test Site

At the Conejos West test site and the surrounding area, the uppermost aquifer layer is a layer that we interpret to coincide with RGDSS aquifer layer 1 (L1). As discussed in Section 4, that material is relatively coarse, permeable sand, gravel, and cobbles, with generally discontinuous layers of silt or clay, composed of stream alluvium and glacial outwash, and in many well logs is described as being 30 to 60 feet thick. At the Conejos West shallow piezometer, it was found to be 35 feet thick. A continuous confining clay layer is not seen in well logs in this area, although a clay-rich layer, interpreted as possibly a weathered volcanic ash, was seen on top of a basalt lava flow at 35 to 40 feet depth. The lateral persistence of this layer is not known. The nearest point of the Alamosa "blue clay" confining clay series is approximately 2 to 2 ½ miles northeast of this test site.

In L1 in this area, water levels generally indicate lateral ground water movement is not particularly continuous, although not many shallow wells exist in the area, and saturation may be seasonal in some areas due to ditch leakage and other seasonal recharge. The water levels are progressively deeper in wells with deeper screened intervals, indicating a strong vertical (downward) ground water movement (see Figure 13). As discussed previously, this indicates a possibility that some water recharged at this location may be transmitted along a pathway

[17] Ferris, J.G., et al, 1962, Theory of Aquifer Tests. U.S. Geological Survey Water Supply Paper WSP-1536-E.

through Layer 1 from this area to the Conejos River, although the majority of the evidence indicates downward movement to the confined aquifer.

Ground water levels and confined head measurements within RGDSS aquifer layer 3, which is the aquifer composed of interbedded basaltic lava flows and sediments, shows that the regional gradient and also the nearest flow path from this study site to a point of hydrologic connection with a stream, as being toward the gaining reach of the Conejos River generally located at or downstream of the Conejos / San Antonio River confluence, east of Manassa. Thus water recharged to L3 at this location, is less likely to accrete by means of a pathway through L1 to the nearest point on the Conejos River, only about 3 miles southeast of the test site, but instead is more likely to accrete through a L3 hydrologic pathway to the gaining reach of the Conejos River at or downstream of the Conejos / San Antonio River confluence.

Due to the absence of continuous layers of confining clays at this site (shallow confining clays exist east of the site at least two miles), and the lack of evidence for significant horizontal movement through the unconfined alluvium, for the purposes of the accretion timing estimate a the Conejos West test site, recharge was considered to have been through the confined (RGDSS Layer 3) aquifer and accreting to the Conejos River approximately 8.2 miles away. This location corresponds with the intersection of the confined aquifer and the enhanced vertical connection due to rock fracturing associated with the Manassa Fault zone, thus providing a hydraulic connection to the river[18]. The accretion timing was performed under a confined aquifer scenario, as this is judged to be most representative of the aquifer conditions along this accretion pathway. AWAS computed a rapid accretion of 75 percent volume reaching the river within one year, but a significant reduction in rate at later times with 95 percent volume of accretion requiring 23 years. Accretion was estimated to occur along a 7.6 mile reach of the Conejos River, generally corresponding to the well-documented gaining reach of the river (see Figure 36). This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site.

[18] HRS, 2012.

### 7.1.4 Bountiful West Test Site

The Bountiful West test site is only about ¼ mile east of the eastern edge of the Mogote volcanic escarpment. At this test site surface soils above the underlying basaltic lava flow rocks are only about 3 to 4 feet thick, generally composed of silty sand with varying amounts of coarse, angular basalt clasts and rounded alluvial gravel and cobbles. Well logs of wells within 1 mile of the Bountiful West test site show that as much as 30 to 40 feet of alluvial or colluvial material, probably equivalent to RGDSS model layer L1, exists commonly near the test site, but not at the test site itself.

The Alamosa blue clay series is seen in well logs within approximately 0.5 to 1 mile east of this test site, although it is not present at the Bountiful West test site.

Basaltic rock and interbedded layers sediments (Layer 3 of the RGDSS), exist at depths greater than approximately 30 to 100 feet throughout this area. Hinsdale basalt lava flow rock is seen in outcrop within 0.5 miles west and 1.2 miles north of this test site. As discussed in Section 4, this locality is part of a regional recharge area for the L3 ("confined" aquifer). Based on data from the this study (Agro Engineering, 2014), and from the RGDSS mapping and water levels from the RGWCD monitoring well network, the ground water gradient within the confined Hinsdale / Los Pinos (L3) in this area generally shows a regional ground water flow path to the NNE, toward LaJara Arroyo, LaJara Creek, and (more distant) the Conejos River. The available water level information also shows that there is a high likelihood of a continuous hydrologic pathway to these streams from the Bountiful West test site.

The nearest live stream for which there is likely to be a hydrologic connection appears from available evidence to be LaJara Arroyo or LaJara Creek, about 3.3 miles north at its closest point to the test site. It is also possible that a portion of the accretions due to recharging water at this site may accrete at the nearest point on the Conejos River, about 7.5 miles east of the test site.

The Bountiful West site is considered to have a stronger hydrologic connection to the LaJara Arroyo through the confined aquifer rather than the unconfined aquifer due to the presence of confining clay within an estimated 0.5 to 1.0 miles, and weak evidence for horizontal flow in the unconfined layer at this location. However, a connection through the unconfined aquifer cannot be ruled out from the available evidence, and therefore both conditions were modeled on a preliminary basis, using Glover computations within AWAS. The confined aquifer model (see Figure 37) shows rapid accretion of the 60-day recharge slug to La Jara Arroyo. Ninety percent of the recharge accretes to the stream within one year, and 95 percent within four years. The probable majority reach of accretion, as estimated by AWAS calculations, was 3.8 miles. However, the reach length was modified due to hydrogeologic constraints judged by HRS to be applicable in this area – most notably, the Alamosa Formation confining clay series to the east and north, and the presence of the Mogote volcanic shield and escarpment to the west, in our judgment would tend to restrict the probable zone of hydrologic contact to a shorter segment of the stream.

The unconfined aquifer scenario at the Bountiful West site is a strong contrast to the confined scenario output (see Figure 38). Ninety-five percent of the accretion volume is estimated to take 123 years and fifty percent accretion will require about 35 years. The unconfined aquifer is above the Alamosa Formation clays, and hydrologic connection to La Jara Arroyo or La Jarra Creek therefore is not hindered by the clays. Therefore, the hypothetical accretion reach length for the unconfined scenario (Figure 39) of 6.1 miles was not modified. As with the other sites, this result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site.

# 8 Conclusions

HRS Water Consultants, Inc. has completed the study of recharge feasibility of four test sites, as authorized by San Luis Valley Irrigation Well Owners, Inc. Based on the results of this study, HRS has arrived at conclusions with respect to the hydrogeologic feasibility of recharging surface water into the ground water system at the four recharge test locations for purposes of augmenting well-pumping depletions and aiding in achieving aquifer sustainability in the study area. Our conclusions are discussed below.

## 8.1 Feasibility of Recharge at Four Test Locations

Two of the tested sites, Punche Arroyo and San Antonio (see Figure 2) primarily were intended to test the feasibility of recharge into the unconfined aquifer. The other two sites, Conejos West and Bountiful West (see Figure 3) primarily were intended to test the feasibility of recharge into the confined aquifer in its recharge area near the western edge of the Conejos River valley. Based on this study, our overall conclusions are:

- In our opinion, based on this study, recharge infiltration rates are sufficiently high at all four sites that any one of them would allow recharge at rates high enough for a managed aquifer recharge project.

- However, each site has individual characteristics in terms of the hydrogeology, including whether there is confidence as to continuity of the hydrologic pathway to points of probable recharge accretions. Therefore, the infiltration rate at each test site is one of several factors that must be considered in an assessment of overall physical feasibility of managed aquifer recharge. These conclusions are discussed below for each individual test site.

### 8.1.1 Punche Arroyo Test Site Conclusions

- Infiltration Rate: At the Punche Arroyo site, the measured infiltration rate in our September, 2014, test was in the range of 24.2 to 31.7 ft/day. This range represents a high rate of infiltration. If only half of this rate could be expected in a managed aquifer recharge facility due to siltation or biofouling, a facility with a bottom area of only 1 acre should be capable of recharging approximately 720 acre-feet of water.

- Probable pathway of recharge accretions: This study, corroborated by other previous studies (e.g. RGDSS investigations; and Talbot 1991) has found hydrologic continuity in the upper aquifer layer, generally consistent with RGDSS layer 1 ("L1") between the area of this test site, and the San Antonio River approximately 0.6 miles north. The majority of the recharged water (minus any losses, as discussed below) would accrue to an approximately 0.75 mile reach of the San Antonio River or its saturated alluvium centered at a point nearest the recharge site. Preliminary Glover calculations indicate that approximately 75% of the initial 60-day recharge period results in accretions that occur within 4 years of injection, and 95% of the accretion from an initial 60 day "slug" of recharge occurs within 9 years after recharge injection. This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site. It is expected that use of the RGDSS calibrated numerical model, or another more localized numerical model, would result in faster recharge accretions.

- Continuity of the hydrologic pathway: The Punche Arroyo site has multiple perched water tables. The regional water table, in the Servilleta Formation volcanic strata (generally consistent with RGDSS model layer 2 or 3 in this area), is generally over 100 feet deep, and water that seeps downward to this layer would not, in our opinion, accrue as recharge to the San Antonio River. The rate of downward seepage from the upper layer (RGDSS aquifer layer L1) to the deeper, regional water table is as much as

0.8 to 1.2 feet per day, which would not be available to be credited as recharge accretion to the San Antonio River.

### 8.1.2 San Antonio Test Site Conclusions

- Infiltration Rate: At the San Antonio test site, the measured infiltration rate in our October, 2014, test was in the range of 26.9 to 38.1 ft/day. This range represents a high rate of infiltration. If only half of this rate could be expected in a managed aquifer recharge facility due to siltation or biofouling, a facility with a bottom area of only 1 acre should be capable of recharging approximately 840 acre-feet of water.

- Probable pathway of recharge accretions: This study, corroborated by other previous studies (e.g. RGDSS investigations; Crouch, 1985, and Talbot 1991) has found hydrologic continuity in the upper aquifer layer, generally consistent with RGDSS layer 1 ("L1") between the area of this test site and the Conejos River to the north as well as to the San Antonio River to the south. Using a 60-day estimated recharge "season", approximately 62 percent of recharge will accrete along an approximately 1.26 mile long reach of the San Antonio River. Thirty-eight percent is estimated to accrete to a 1.65 mile reach of the Conejos River. Fifty percent of total accretion to both streams will likely occur by approximately four years following the 60-day initial "slug" of recharge, while 95 percent accretion will take 14 years. This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site. It is expected that use of the RGDSS calibrated numerical model, or another more localized numerical model, would result in faster recharge accretions.

- Continuity of the hydrologic pathway: Beneath the San Antonio test site, clay lenses or layers are sufficiently extensive below the coarse, gravelly L1 alluvial layer targeted for recharge, to have allowed formation of a zone of saturation within L1 that is continuous from the San Antonio River, north across the study site, to the Conejos River. Some water, but on a percentage basis probably relatively little water, appears to percolate downward below L1 to deeper aquifer layers. Thus, in our opinion, water recharged at the San Antonio site would have a continuous unconfined hydrologic pathway to accretion zones along the San Antonio River to the south and the Conejos River to the north.

### 8.1.3 Conejos West Test Site Conclusions

- Infiltration Rate: At the Conejos West test site, the measured infiltration rate in our October, 2014, test was approximately 33.1 ft/day. This represents a high rate of infiltration. If only half of this rate could be expected in a managed aquifer recharge facility due to siltation or biofouling, a facility with a bottom area of only 1 acre should be capable of recharging approximately 993 acre-feet of water.

- Probable pathway of recharge accretions: This study, corroborated by other previous studies (e.g. RGDSS investigations; Crouch, 1985) has found hydrologic continuity from the recharge zone of the aquifer layer generally consistent with RGDSS layer 3 ("L3") between the area of this test site and the Conejos River approximately 8.2 miles east, at and downstream of the confluence of the Conejos River and the San Antonio River. Using a 60-day estimated recharge "season", an accretion timing calculation was performed under a confined aquifer scenario, as this is judged to be most representative of the aquifer conditions along this accretion pathway. AWAS computed a rapid accretion of 75 percent volume reaching the river within one year, but a significant reduction in rate at later times with 95 percent volume of accretion requiring 23 years. Accretion was estimated to occur along a 7.6 mile reach of the Conejos River, generally corresponding to the well-documented gaining reach of the river. This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site.

It is expected that use of the RGDSS calibrated numerical model, or another more localized numerical model, would result in faster recharge accretions.

- Continuity of the hydrologic pathway: Beneath the Conejos West test site and its surrounding area, water levels are progressively deeper in wells with deeper screened intervals, indicating a strong vertical (downward) ground water movement. There are relatively few data points in the upper aquifer layer (generally coinciding with Layer 1 of the RGDSS model aquifer layering) and thus there is a possibility that some water recharged at this location may be transmitted along a pathway through Layer 1 from this area to the Conejos River. However, the majority of the evidence indicates downward movement to the confined aquifer (L3) and a confined aquifer pathway for accretions to the Conejos River, as discussed above.

### 8.1.4 Bountiful West Test Site Conclusions

- Infiltration Rate: At the Bountiful West test site, the measured infiltration rate in our December, 2014, test was in the range of 2.7 to 25 ft/day[19]. This represents a high rate of infiltration, although it is the lowest range of the four sites tested. If only half of this rate could be expected in a managed aquifer recharge facility due to siltation or biofouling, and the average of this range is estimated, a facility with a bottom area of only 1 acre should be capable of recharging approximately 415 acre-feet of water. In our opinion the lower range is due to the lower-K silt fraction present in joints and fractures of the exposed basaltic rock layer recharged in this test.

- Probable pathway of recharge accretions: This study, corroborated by other previous studies (e.g. RGDSS investigations) has found hydrologic continuity from the recharge zone of the aquifer layer generally consistent with RGDSS layer 3 ("L3") between the area of this test site and LaJara Creek or LaJara Arroyo approximately 3.3 miles north fo the test site. The Alamosa blue clay series is seen in well logs within approximately 0.5 to

[19] Results have been corrected for 0.4 degree C temperature of the recharged water.

1 mile east of this test site, although it is not present at the Bountiful West test site. From the available evidence, it is not clear wither this pathway is under confined or unconfined conditions, or a combination of both. Using a 60-day estimated recharge "season", an accretion timing calculation was performed under both confined and unconfined aquifer conditions. The confined aquifer calculations show rapid accretion of the 60-day recharge slug to La Jara Arroyo. Ninety percent of the recharge accretes to the stream within one year, and 95 percent within four years. By contrast, in the unconfined aquifer calculation, ninety-five percent of the accretion volume is estimated to take 123 years and fifty percent accretion will require about 35 years. This result is intended to provide a first-approximation estimate for planning purposes. Actual large-scale recharge is likely to require one or more model runs of the calibrated RGDSS model to more accurately determine the timing and location of recharge accretions from this site. It is expected that use of the RGDSS calibrated numerical model, or another more localized numerical model, would result in faster recharge accretions.

- Continuity of the hydrologic pathway: Beneath the Bountiful West test site and its surrounding area, based on data from the this study (Agro Engineering, 2014), and from the RGDSS mapping and water levels from the RGWCD monitoring well network, the ground water gradient within the confined aquifer (L3) in this area generally shows continuity of the ground water accretion pathway to the NNE, toward LaJara Arroyo, LaJara Creek, and (more distant) the Conejos River. The available water level information also shows that there is a high likelihood of a continuous hydrologic pathway to these streams from the Bountiful West test site. The nearest live stream for which there is likely to be a hydrologic connection appears from available evidence to be LaJara Arroyo or LaJara Creek, about 3.3 miles north at its closest point to the test site. It is also possible that a portion of the accretions due to recharging water at this site may accrete at the nearest point on the Conejos River, about 7.5 miles east of the test site.

## 8.2 Scalability of Test Results

The recharge infiltration rate tests that were done as part of the authorized Scope of Work for this study were pilot-scale tests. This means that the sizes of the test trenches were large enough to allow testing of the infiltration rate in the alluvial / glacial outwash layers below the surface soils, but were kept to a manageable size relative to time and budget of this study. Thus, a valid question is whether the pilot-scale infiltration tests represent results that are realistic at a larger scale, should the Well Owners choose to go forward with a managed aquifer recharge project. Based on our work on this study, and on previous studies in the area in which HRS has been involved, we are confident that the test results at each of the four pilot test locations are scalable up to sizes that would involve recharge rates in the range of 5 to 20 cubic feet per second. This conclusion is supported by:

- The soil map units at all four recharge test sites, and areas surrounding the test sites, generally are described as "well drained" or "excessively drained" (SCS Soil Survey of Conejos County Area, Colorado, 1980).
- High infiltration rates were seen at all four recharge sites. The alluvial and glacial outwash materials at three of the four sites, and the fractured basalt at the fourth site (Bountiful West) are not localized just to the test sites. These materials are common in the areas surrounding the test sites, and are widespread in the valleys of the Conejos and San Antonio Rivers.
- Water table at all four sites is sufficiently deep that direct saturated hydrologic contact, and resulting reduction of infiltration rate, between the rising ground water mound due to recharge, and the overlying recharge facility, should not be an issue if a recharge facility is designed and operated appropriately.
- Corroborative evidence exists in the fact that many of the ditches in the areas of the recharge test sites are documented to have high seepage rates.

Higher rates of recharge may be possible, depending on the exact site selected, and on facility design, operation, management, and maintenance of the recharge facility, along with other variables.

## 8.3 Transferability of Test Results

Each test site represents the hydrogeologic characteristics at a particular location. Thus a valid question is: How far from each test site should the infiltration rate results be considered representative? Although no two test sites, even a nearby site, is likely to result in identical infiltration rates, in our opinion the results from each of the tests are representative of the aquifer characteristics in their particular hydrogeologic sub-provinces, which are much larger than just the test sites. Other locations would have different accretion timing, and possibly different accretion pathways. Based on similarities and differences in the hydrogeology within the overall study area, HRS estimates that the recharge infiltration test results are generally representative for the following areas.

- Punche Arroyo Test Site: The test results are considered generally representative of the area encompassed by the Punche Arroyo watershed generally north to the San Antonio River, south approximately 0.5 to 0.75 miles, west approximately two miles, and east approximately two miles. Beyond those approximate distance limits, different gradients, hydrologic pathways, aquifer layers, and characteristics may pertain.
- San Antonio Test Site: The test results are considered generally representative of the area encompassed by the San Antonio River on the south, the Conejos River (nearest channel) on the north, south approximately 0.5 to 0.75 miles, west approximately two miles, and east approximately 1.5 miles. Beyond those approximate distance limits, different gradients, hydrologic pathways, aquifer layers, and characteristics may pertain.
- Conejos West Test Site: The test results are considered generally representative of the area encompassed by the Mogote volcanic escarpment to the west; north and south approximately two miles, and east approximately one mile. Beyond those approximate distance limits, different gradients, hydrologic pathways, aquifer layers, and characteristics may pertain.
- Bountiful West Test Site: The test results are considered generally representative of the area encompassed by the Mogote volcanic escarpment to the west; north and south

approximately two miles, and east approximately ½ mile. Beyond those approximate distance limits, different gradients, hydrologic pathways, aquifer layers, and characteristics may pertain.

## 8.4 Applicability of Test Results

Based on the foregoing report and conclusions, HRS believes that we have met the goal of determining the feasibility of recharge, and whether the physical (hydrogeologic) criteria for a managed aquifer recharge can be met at each of the four sites tested. In our opinion the test results and the foregoing conclusions are valid and are representative within the general limits we have described. Also, it is our opinion that the results of this study provide sufficient information that the Well Owners can go forward with decision-making about whether to proceed with a managed aquifer recharge program to provide augmentation water and to aid in achieving sustainability of the aquifers in the study area.

# 9 Recommendations

The hydrogeologic interpretations and analyses documented in this report were performed using the most relevant data sources available to HRS. Supported by funding from CWCB and the Rio Grande Round Table, the Well Owners authorized and funded significant new data collection, in the form of water level measurements, elevation surveying of wellheads, piezometer drilling and completion, and recharge pilot tests at four selected sites in the Conejos – San Antonio study area.

In addition to the new data collected in this study, existing hydrogeologic data reviewed for this study included reports, maps, driller's logs of water wells, and confined aquifer pressures from wells located in the study area. In our opinion the evaluations made, and the conclusions drawn in this report are well supported by the available evidence, and no further evaluations or studies are needed in support of our conclusions.

However, should the Well Owners wish to move forward with a recharge-based plan for augmentation at one or more locations within the study area that are different than the sites tested in the present study, HRS recommends performing additional field studies to ascertain the particular hydrogeologic conditions relevant at each chosen location.

Also, because a full-scale managed aquifer recharge project is likely to involve recharging water at rates far exceeding our pilot test rates, HRS recommends as follows:

- Before final design of a full –scale managed aquifer recharge project, infiltration rate testing and test drilling to ascertain local material characteristics of the final site chosen, should be performed. A full-scale managed aquifer recharge project involving up to thousands of acre-feet per year should not rely solely on the test results from this study.

- Recharge accretion timing can be done in a simplified manner by analytic computation, such as we have done for this study, or it can be done using a small scale numerical model. As previously mentioned, the results of the Glover analytic calculations done in this study are intended to provide the Well Owners a first-approximation estimate for planning purposes of the timing and probable locations of recharge accretions.

- Large-scale recharge is likely to require one or more model runs of either a calibrated, local-scale model developed for that purpose, or, if the volume of recharge and distances of the accretion pathway are sufficiently large, the calibrated RGDSS model may be applicable to more accurately determine the timing and location of recharge accretions from a chosen site.

| SLVIWO Recharge Study Piezometer Summary | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Well Name | Permit No. | Depth (ft) | Ground Elevation North Side (ft MSL)* | MP Elevation (ft MSL)* | UTM Northing * | UTM Easting * | 1/4_40 | 1/4_160 | Sec | TWP | RNG | PM | Distance from South Sec Line (ft) | Distance from East Sec Line (ft) |
| ***Punche Arroyo Test Site*** | | | | | | | | | | | | | | |
| Punche Arroyo Center Shallow | 296043 | 18 | 7,819.87 | 7,821.90 | 4101615.152 § | 414192.963§ | NE | SE | 34 | 33 N | 9 E | NM | 2626 | 72 |
| Punche Arroyo Center Deep | 296042 | 57.5 | 7,819.85 | 7,822.74 | 4101613.324 | 414192.963 | NE | SE | 34 | 33 N | 9 E | NM | 2626 | 72 |
| Punche Arroyo North | 296041 | 57.5 | 7,818.12 | 7,821.66 | 4101878.213 | 414203.935 | SE | NE | 34 | 33 N | 9 E | NM | 3410 | 58 |
| Punche Arroyo East | 296048 | 57.5 | 7,806.23 | 7,809.74 | 4101617.264 | 415040.431 | NW | SE | 35 | 33 N | 9 E | NM | 2637 | 2670 |
| ***San Antonio Test Site*** | | | | | | | | | | | | | | |
| San Antonio Center | 296044 | 38.5 | 7,825.46 | 7,826.82 | 4104327.908 | 413435.692 | SE | SW | 22 | 33 N | 9 E | NM | 877 | 2607 |
| San Antonio West | 296045 | 38 | 7,838.10 | 7,840.20 | 4104123.450 | 412765.516 | SW | SW | 22 | 33 N | 9 E | NM | 126 | 4905 |
| ***Conejos West Test Site*** | | | | | | | | | | | | | | |
| Conejos Deep | 296046 | 258 | 7,837.50 | 7,839.94 | 4111481.334 | 407994.961 | SW | NW | 31 | 34 N | 9 E | NM | 2770 | 4706 |
| Conejos Shallow | 296047 | 38.5 | 7,837.01 | 7,839.38 | 4111515.9 § | 407980.3 § | SW | NW | 31 | 34 N | 9 E | NM | 2905 | 4785 |
| ***Bountiful West Test Site*** | | | | | | | | | | | | | | |
| Bountiful West Shallow | 53098-MH | 19.1 | 7718 § | 7821 § | 4117042 § | 408390 § | NE | NW | 18 | 34N | 9E | NM | 5080 | 3520 |
| * Meters, Zone 13, NAD 83. Surveyed by Davis Engineering 10.2014. § Estimated from handheld GPS and 1:24K topo map | | | | | | | | | | | | | | |

**Table 1**

## Infiltration Rates

| Site | High Rate (ft/day) | Low Rate (ft/day) |
|---|---|---|
| San Antonio | 38.1 | 26.9 |
| Conejos | 33.1 | ------- |
| Punche | 31.7 | 24.2 |
| Bountiful West | 25 [1] | 2.7 |

[1] The value was corrected for temperature.

## Example

The amount of water recharged over 60 days in a 5 acre pond would be:

5 acres × 33.1 ft/day × 60 days = 9930 acre-ft

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Table 2

| Soil Hydraulic Conductivity Test Results | | | |
|---|---|---|---|
| Test Site | Date Tested | Permeameter Test Location | Field Saturated Hydraulic Conductivity (ft/day) |
| Punche Arroyo | 10/7/2014 | 100' W of test trench | 2.1 |
| " | " | 80' NE of test trench | 4.9 |
| San Antonio | " | 100' N of test trench | 2.2 |
| " | " | 100' W of test trench | 1.7 |
| Conejos West | 10/8/2014 | 183' E of test trench | 18.8 |
| Bountiful West | 12/18/2014 | 100' N of test trench | 29.4* |
| * - corrected for water at 15° C. | | | |

Table 3

**Representative Aquifer Characteristics: Recharge Pathways from Test Sites to Estimated Points of Accretion**

| Site | RGDSS Aquifer Layer | Stream Receiving Accretions | Estimated Distance to Nearest Point of Accretion (miles) | Representative Hydraulic Conductivity (ft/day) * | Representative Aquifer Thickness (ft) * | Representative Aquifer Transmissivity ($ft^2$/day) | Representative Storage Coefficient ** |
|---|---|---|---|---|---|---|---|
| Punche Arroyo | 1 (unconfined) | San Antonio | 0.45 | 50 | 40 | 2,000 | 2.0E-01 |
| San Antonio | 1 (unconfined) | San Antonio | 1 | 100 | 25 | 2,500 | 2.0E-01 |
| | | Conejos River | 1.65 | 100 | 25 | 2,500 | 2.0E-01 |
| Conejos West | 3 (confined) | Conejos River | 8.2 | 50 | 200 | 10,000 | 3.5E-04 |
| Bountiful West | 3 (confined) | LaJara Arroyo | 3.3 | 50 | 200 | 10,000 | 3.5E-04 |
| | 1 (unconfined) | | 3.3 | 50 | 40 | 2,000 | 2.0E-01 |

* - RGDSS Model 6P94, November, 2014
** - RGDSS tests in Conejos / LaJara area

HRS Water Consultants, Inc.
January 2015

Table 4

**Recharge Timing and Reach Lengths based on Representative Aquifer Characteristics**

| Recharge Site | Boundary Condition | River of Accretion | Distance to Accretion Point on River (miles) | Length of 50% Accretion Reach (miles) | Length of Time for 95% Accretion to River (years) |
|---|---|---|---|---|---|
| Punche Arroyo | Unconfined | San Antonio | 0.45 | 0.75 | 8.8 |
| San Antonio | Unconfined | San Antonio | 1 | 1.26 | 13 |
| | Unconfined | Conejos | 1.65 | 1.65 | 16 |
| Conejos West | Confined | Conejos | 8.2 | 7.6 | 22.8 |
| Bountiful West | Confined | La Jara | 3.3 | 3.8 | 3.8 |
| | Unconfined | La Jara | 3.3 | 6.1 | 123 |
| SLV Irrigation Well Owners, #14-01 | | | | | HRS Water Consultants, Inc., January 2015 |

Table 5

| Average Lag Time for Vertical Ground Water Movement Between RG-96A and RG-96C | | | | | |
|---|---|---|---|---|---|
| Highest Annual Water Level | | | Lowest Annual Water Level | | |
| RG96A | RG96C | Lag Time Days | RG96A | RG96C | Lag Time Days |
| 6/6/2003 | 8/12/2003 | 67 | --- | | |
| 6/7/2004 | 7/12/2004 | 35 | 4/5/2004 | 3/3/2004 | -33 |
| 6/6/2005 | 9/12/2005 | 98 | 3/7/2005 | 3/7/2005 | 0 |
| 2006 | no peak observed | | | | |
| 6/6/2007 | 8/7/2007 | 62 | 3/6/2007 | 3/6/2007 | 0 |
| 6/3/2008 | 8/4/2008 | 62 | 5/8/2008 | 4/7/2008 | -31 |
| 7/6/2009 | 7/6/2009 | 0 | 3/10/2009 | 4/7/2009 | 28 |
| 6/2/2010 | 6/29/2010 | 27 | 4/7/2010 | 3/10/2010 | -28 |
| 8/4/2011 | 9/13/2011 | 40 | 6/2/2011 | 4/7/2011 | -56 |
| 6/11/2012 | 8/8/2012 | 58 | 5/8/2013 | 5/3/2013 | -5 |
| 2013 | no peak observed | | | | |
| 6/10/2014 | 8/7/2014 | 58 | 4/3/2014 | 4/3/2014 | 0 |
| | Avg High | 50.7 | | Avg Low | -13.9 |
| Data Source: http://www.prinmath.com/rgwcd/wells/370325105575201.htm | | | | | |
| | | | | | |
| 96A screen midpoint estimated: | | | 20 | | |
| 96C screen midpoint observed: | | | 63.7 | | |
| | | Difference: | 43.7 | Ft. | |
| Avg Vertical Rate of GW Travel: | | | 0.9 | Ft/day | |

Table 6

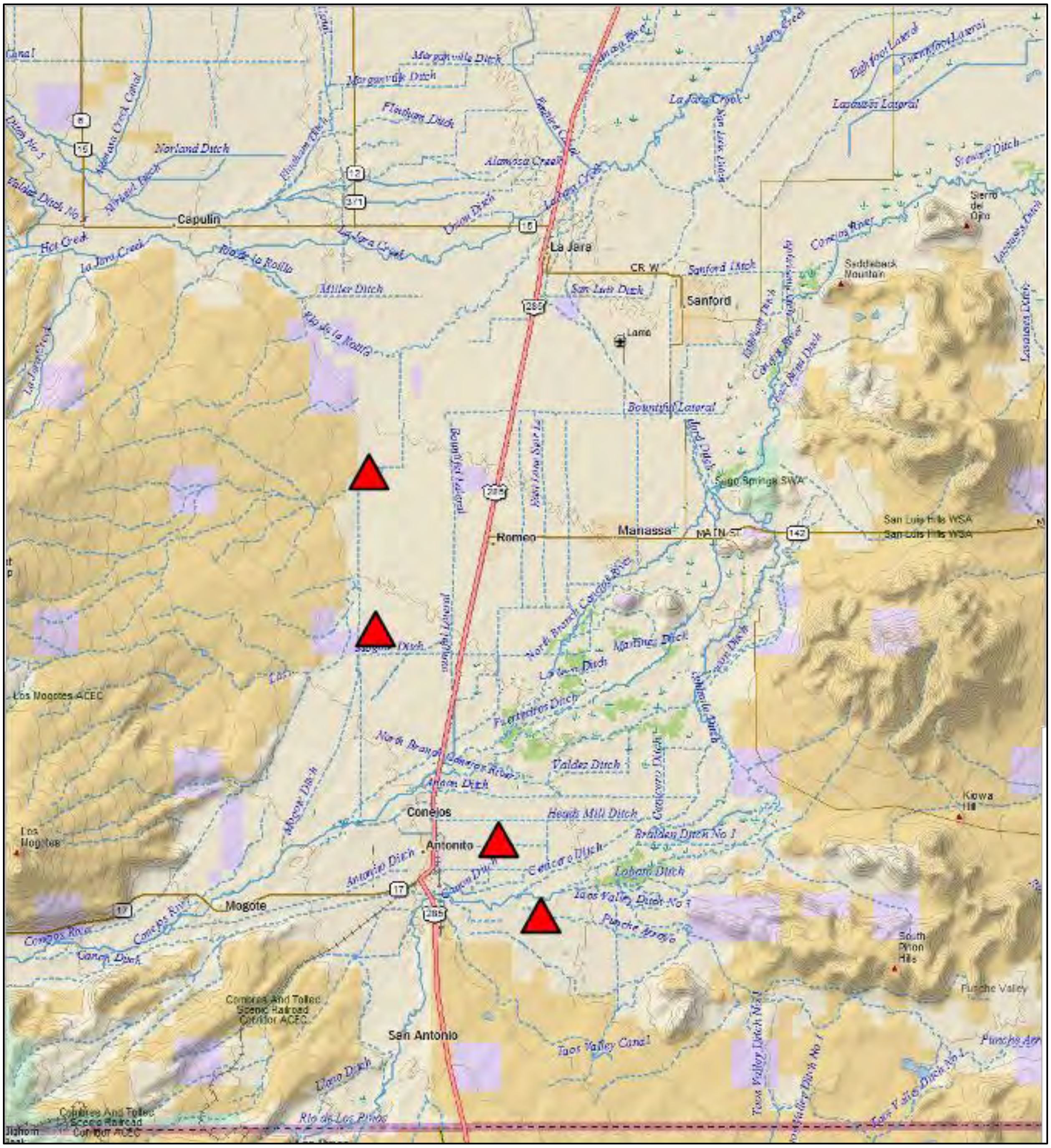


**Figure 1: General study area: San Luis Hills on the east, the Mogote volcanic escarpment on the west, the CO – NM state line on the south, and LaJara Creek on the north**

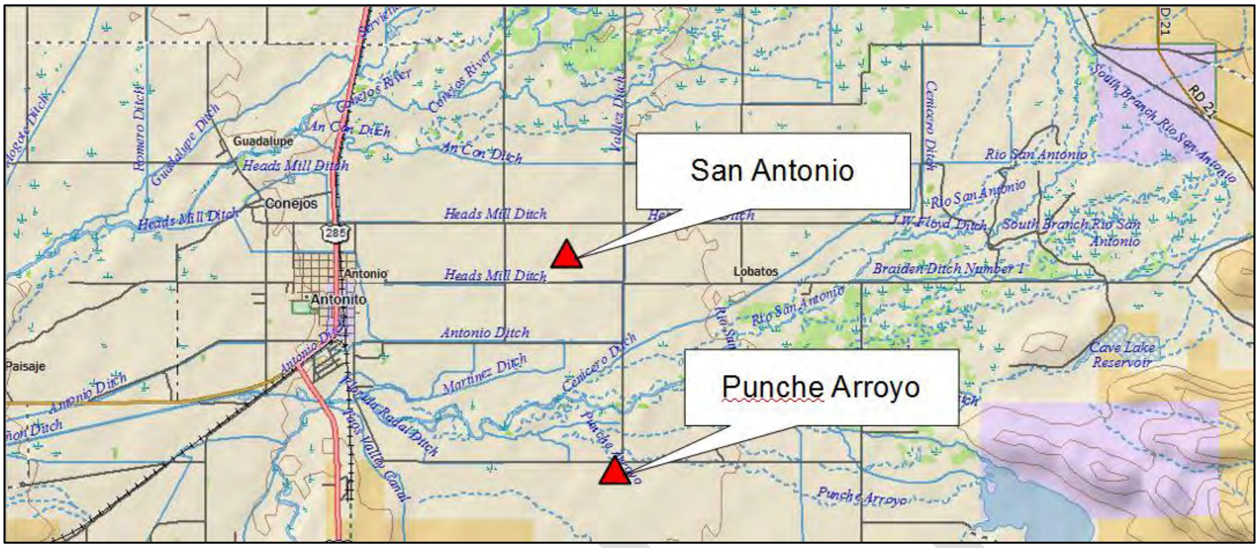


Figure 2: Locations of recharge test sites San Antonio and Punche Arroyo.

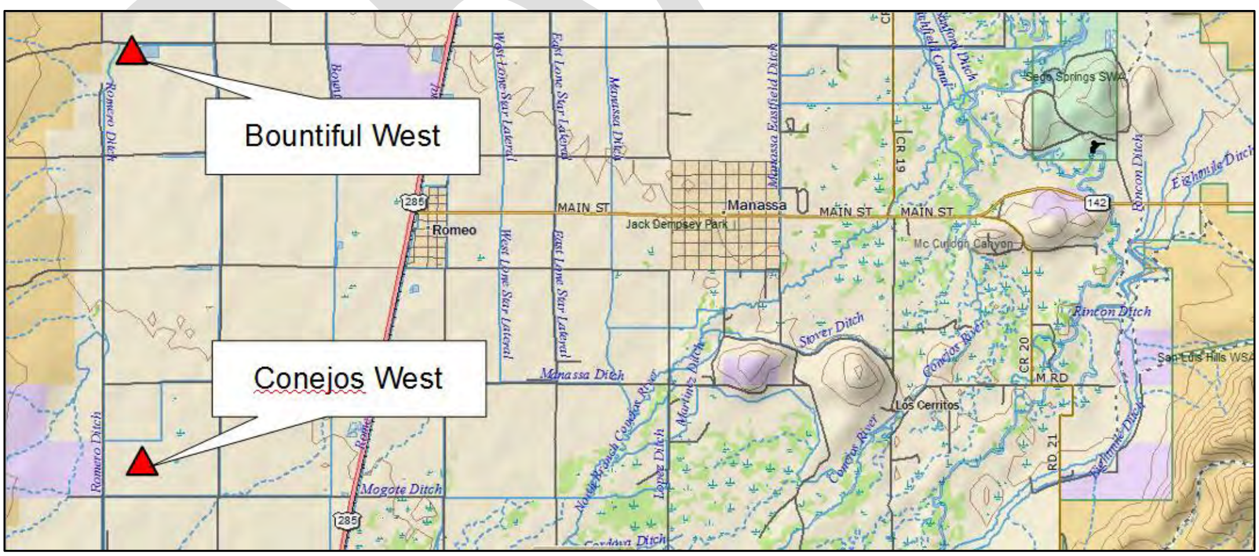


Figure 3: Locations of recharge test sites Conejos West and Bountiful West.

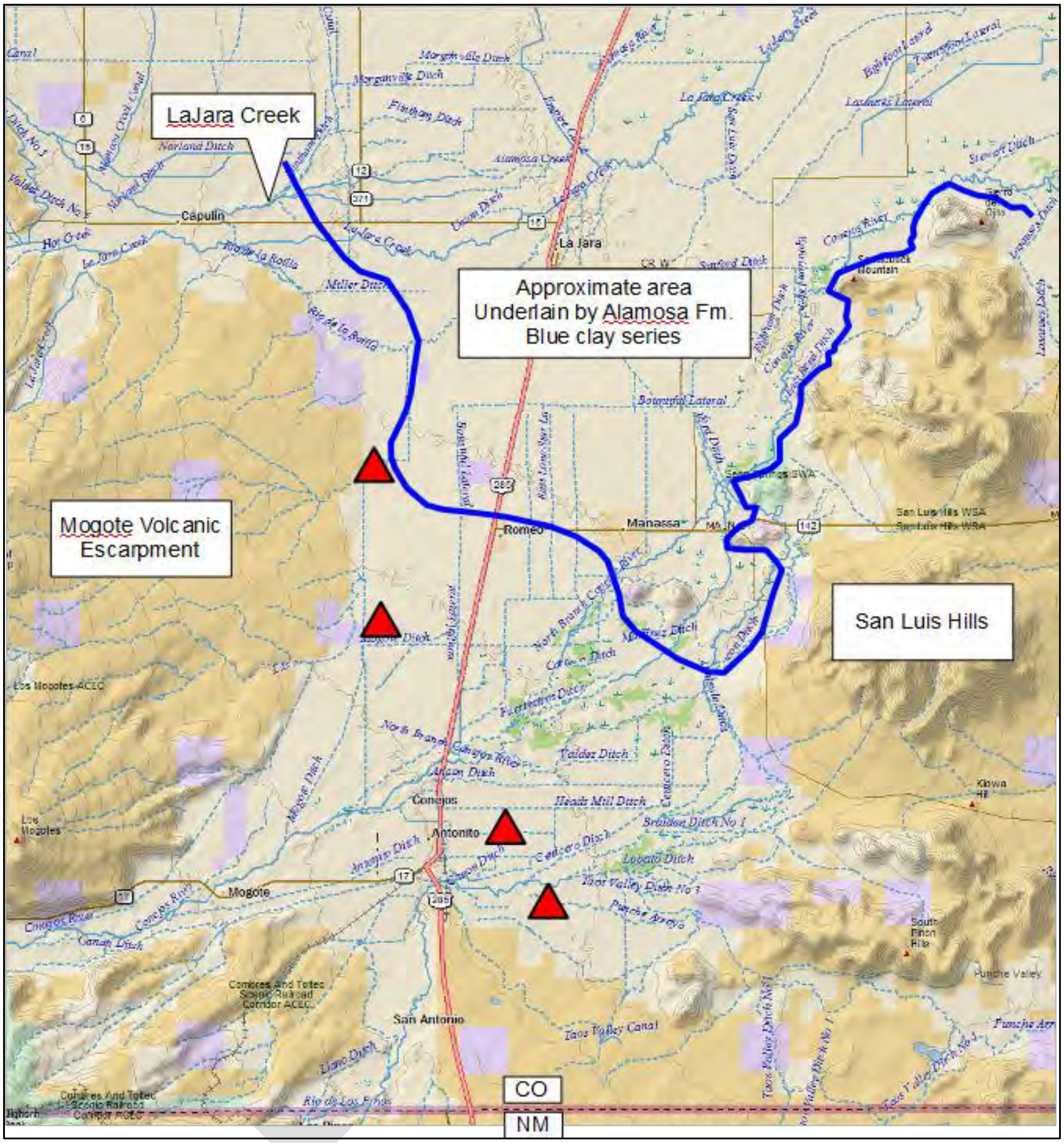


**Figure 4: Map showing approximate extent of the confining "blue clay" series of the Alamosa Formation in the study area.**

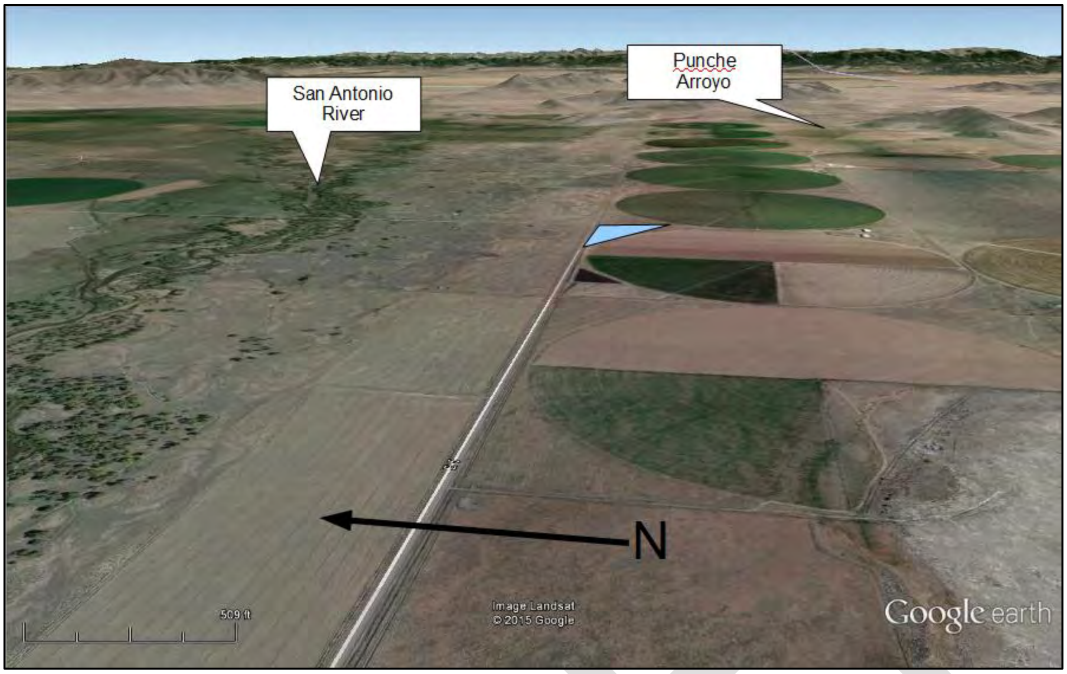


Figure 5: Oblique aerial view of the Punche Arroyo test site, shown in blue. Base from Google Earth imagery.

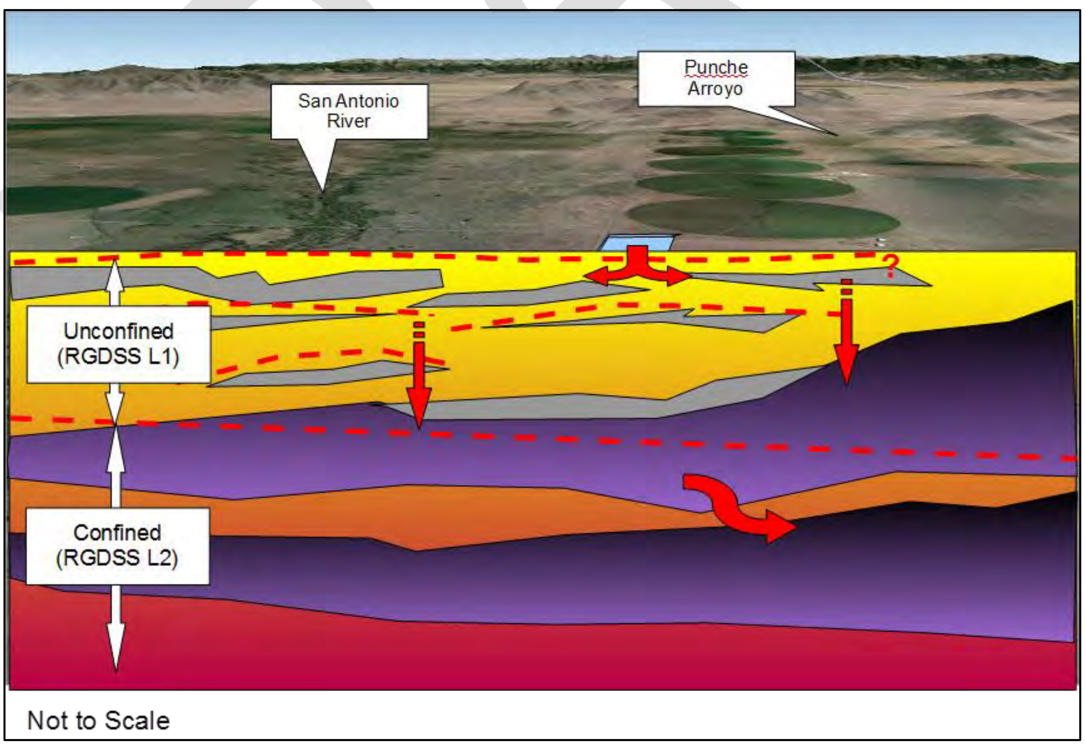


Figure 6: Conceptual hydrogeologic depiction of the Punche Arroyo test site.

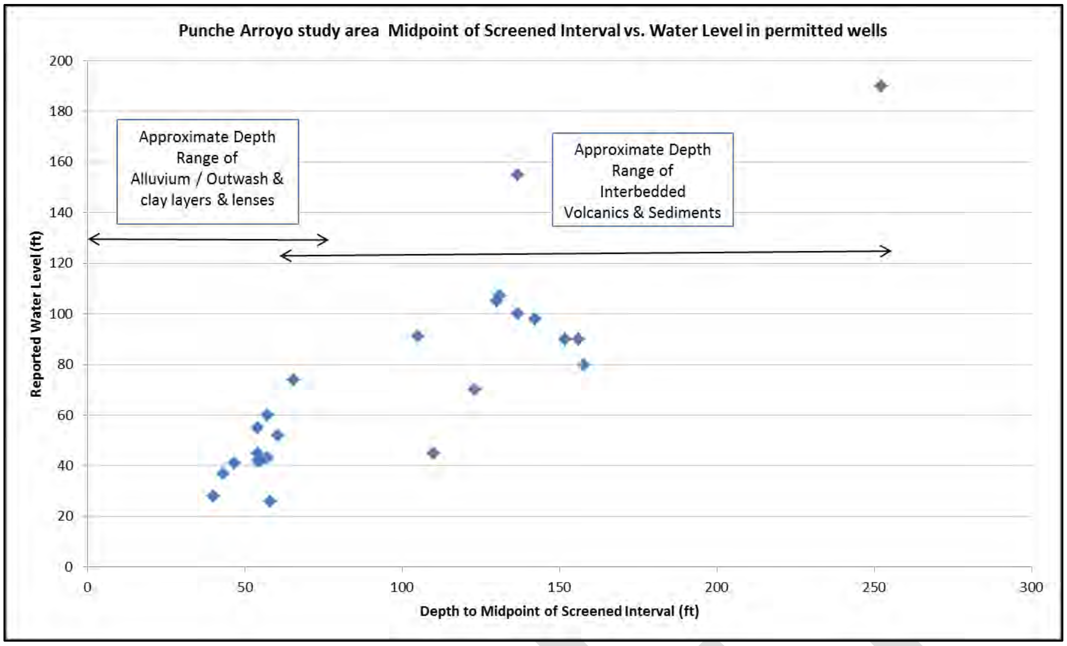


Figure 7: Punche Arroyo area: Midpoint of screened interval vs. water level in permitted wells.

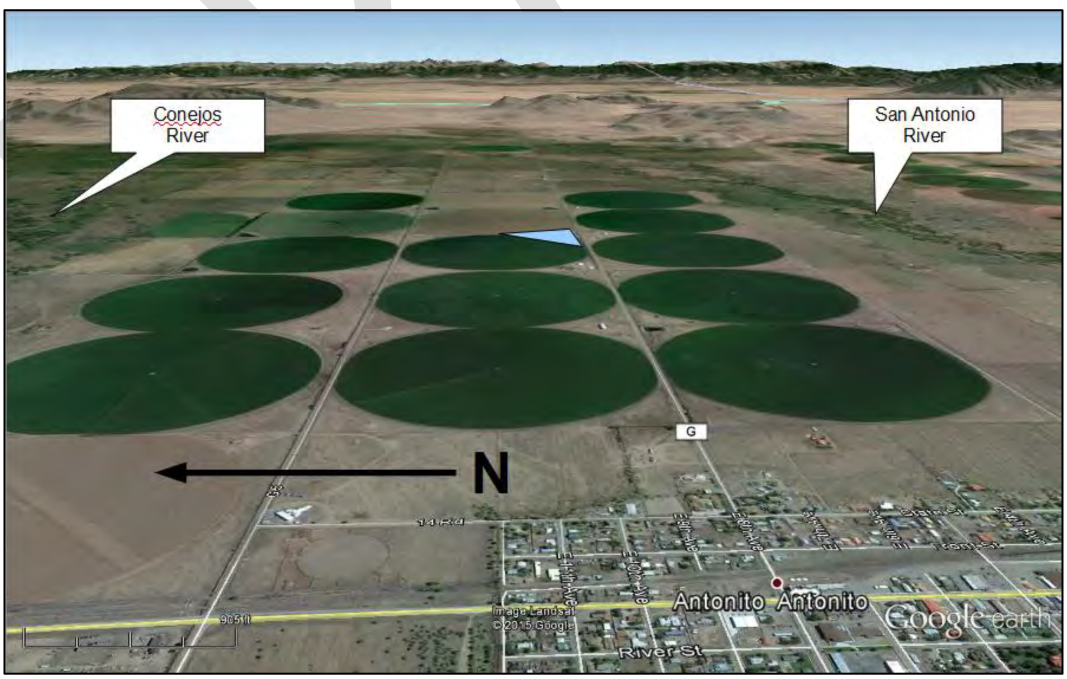


Figure 8: Oblique aerial view of the San Antonio test site, shown in blue. Base from Google Earth imagery.

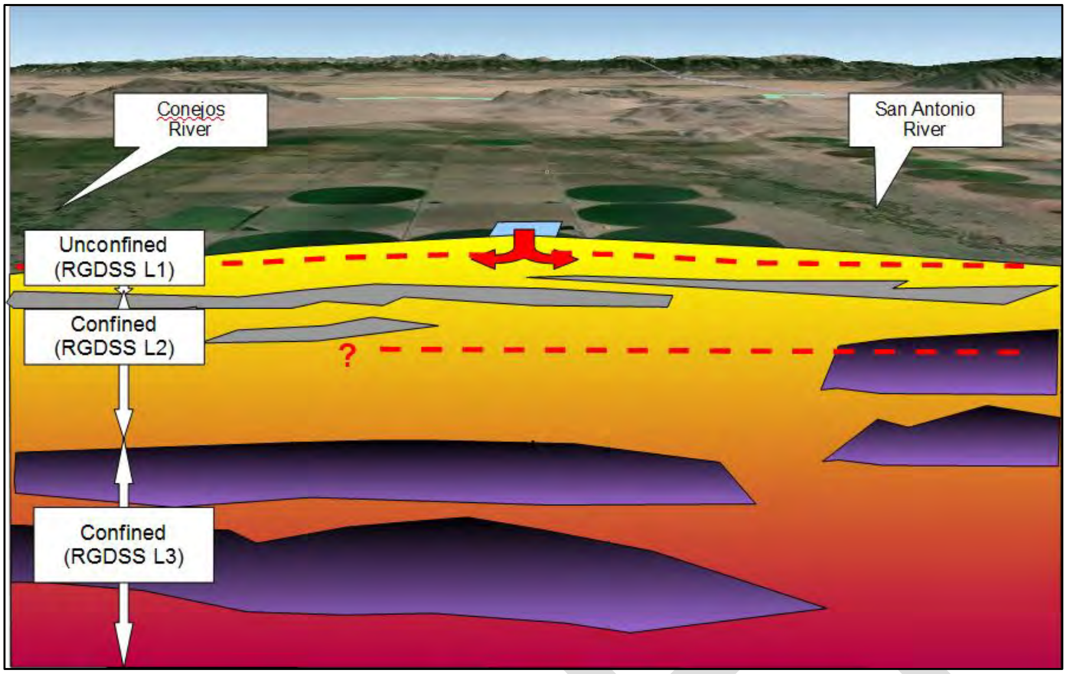


Figure 9: Conceptual hydrogeologic depiction of the San Antonio test site.

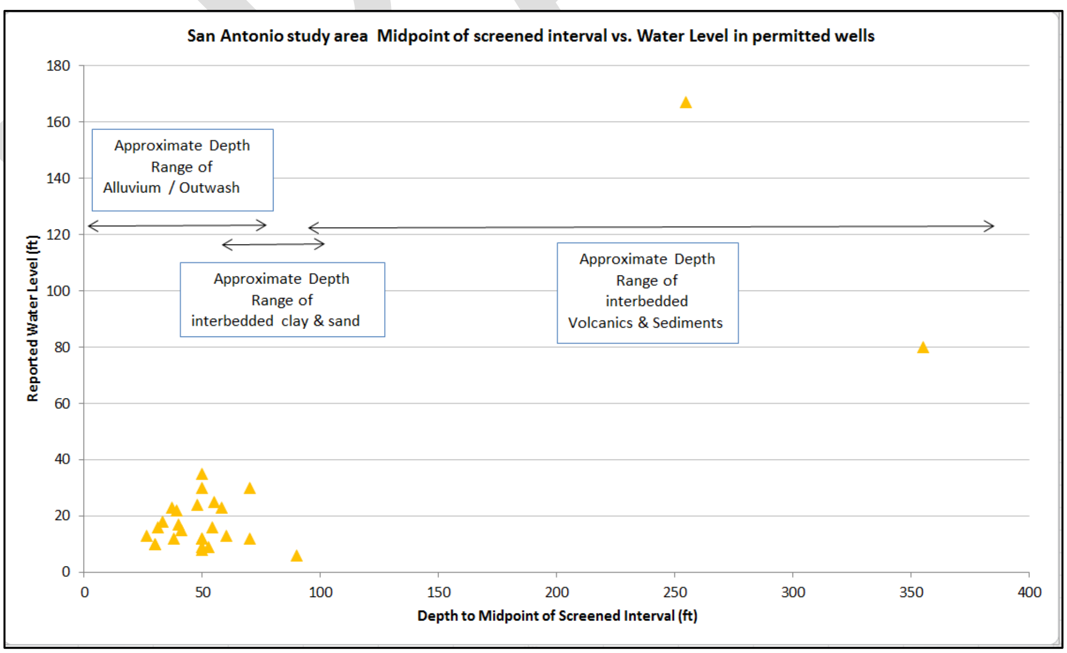


Figure 10: San Antonio study area: midpoint of screened interval vs water level in permitted wells.

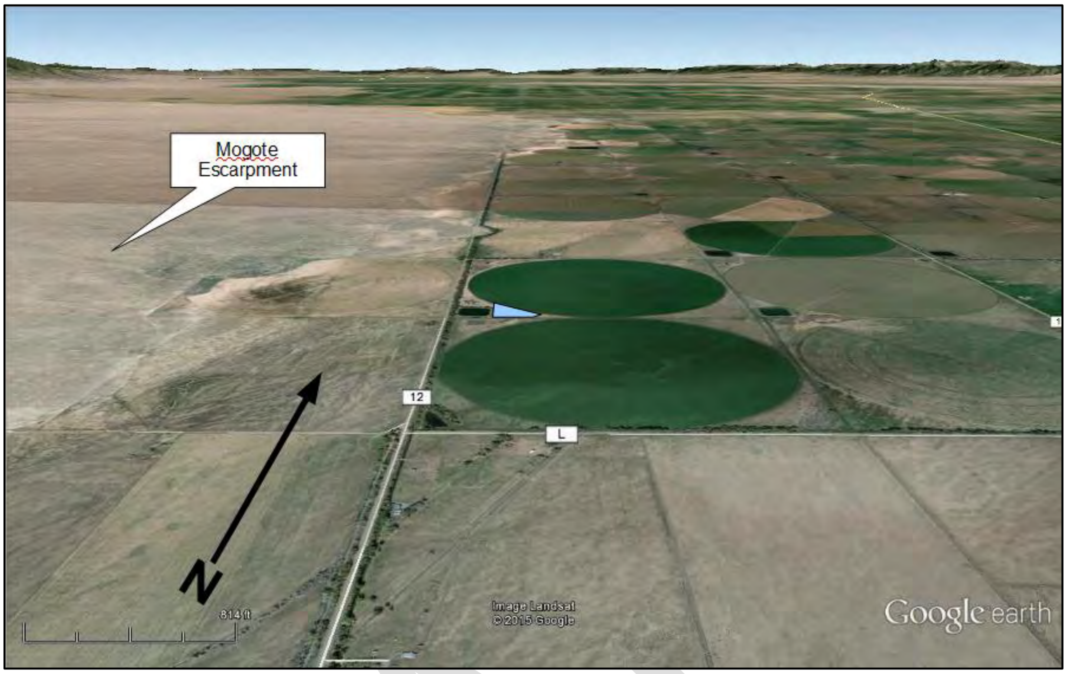


Figure 11: Oblique aerial view of the Conejos West test site, shown in blue. Base from Google Earth imagery.

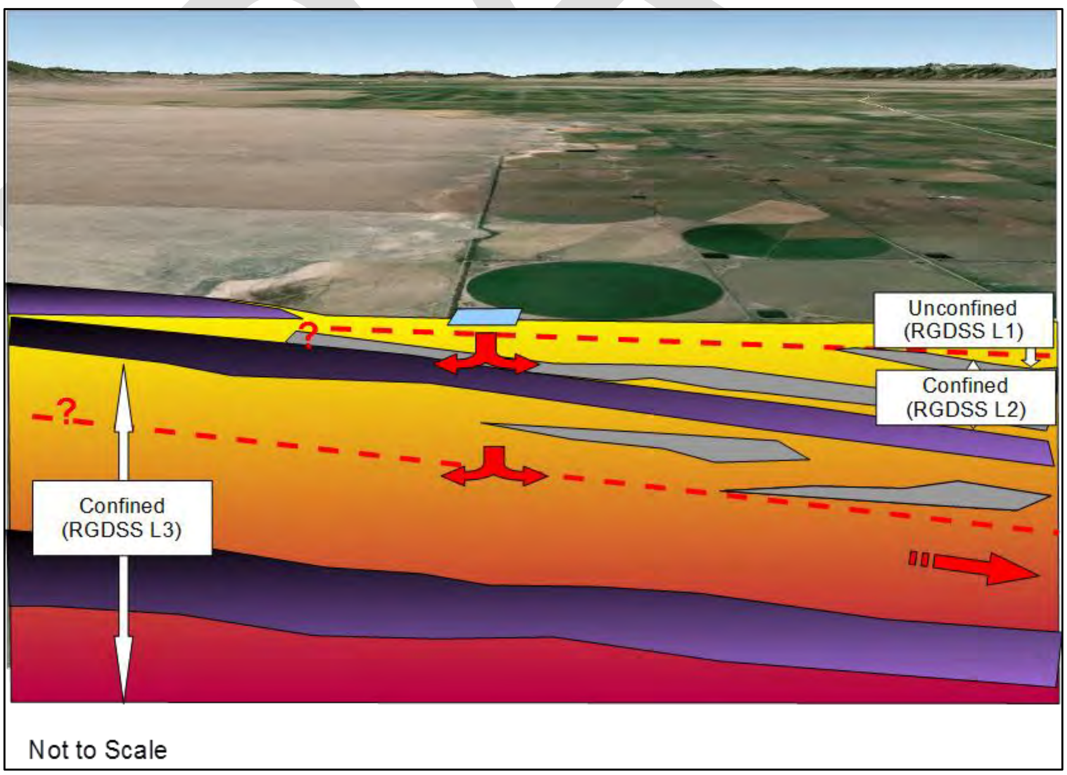


Figure 12: Conceptual hydrogeologic depiction of the San Antonio test site.

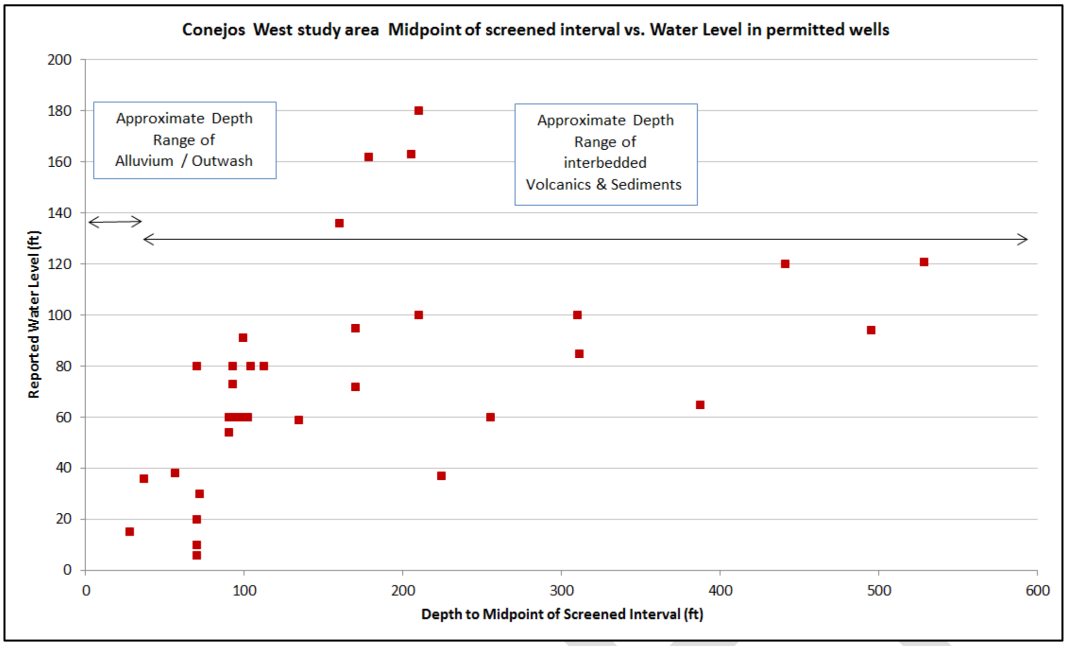


Figure 13: Conejos West study area: midpoint of screened interval vs water level in permitted wells.

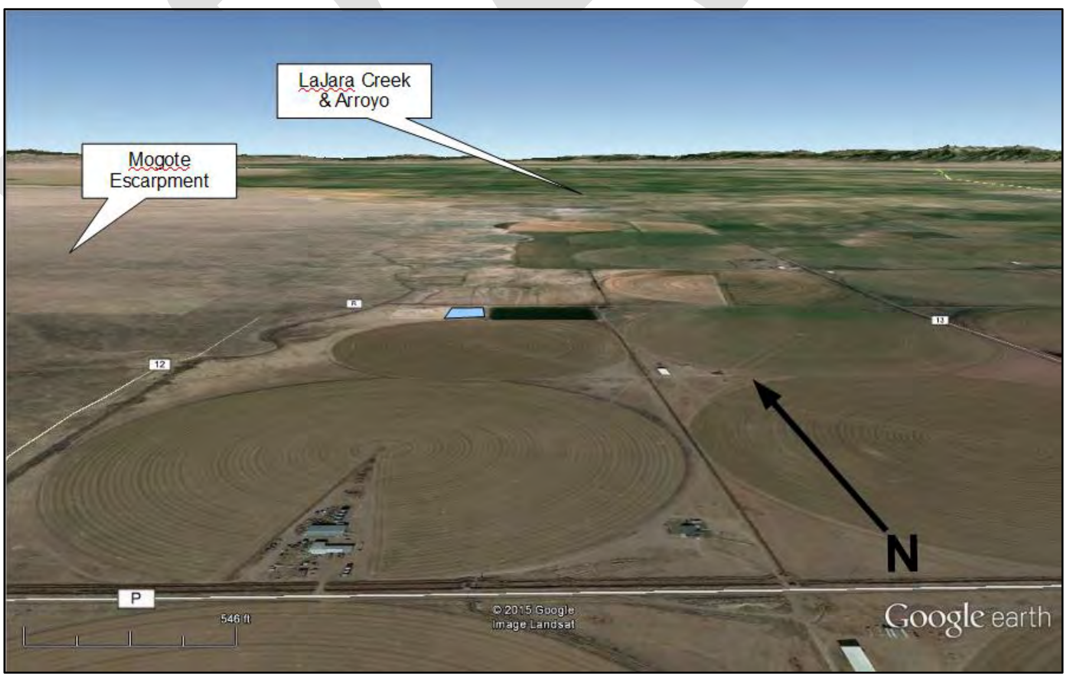


Figure 14: Oblique aerial view of the Conejos West test site, shown in blue. Base from Google Earth imagery.

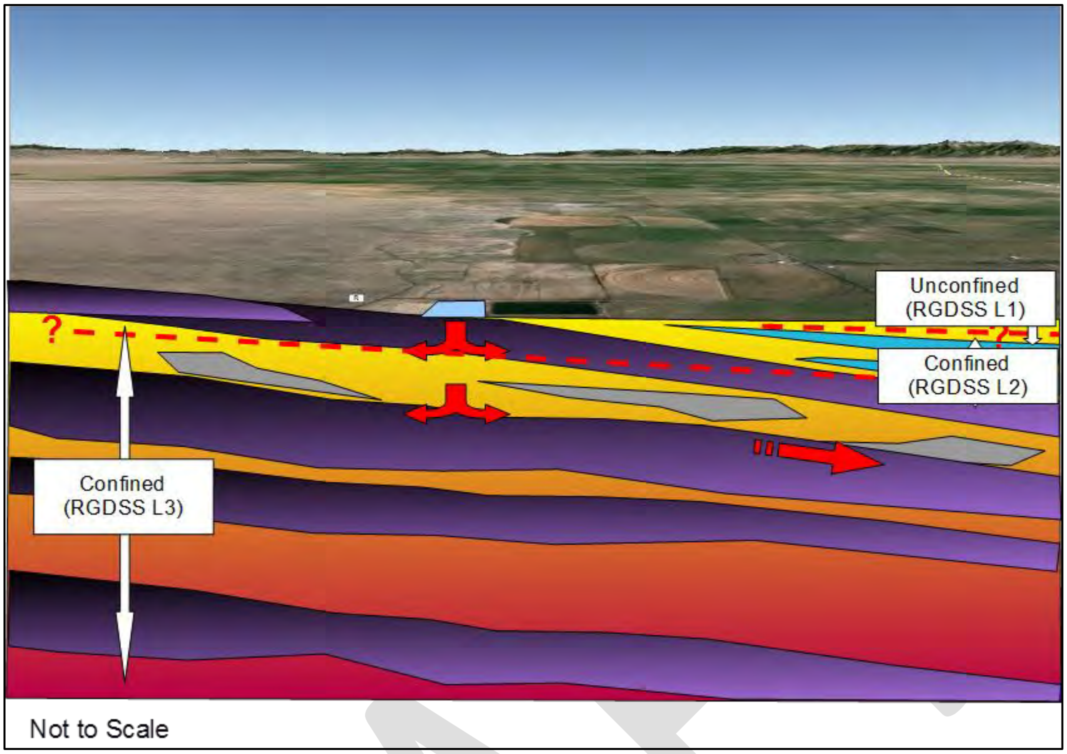


**Figure 15: Conceptual hydrogeologic depiction of the Bountiful West test site.**

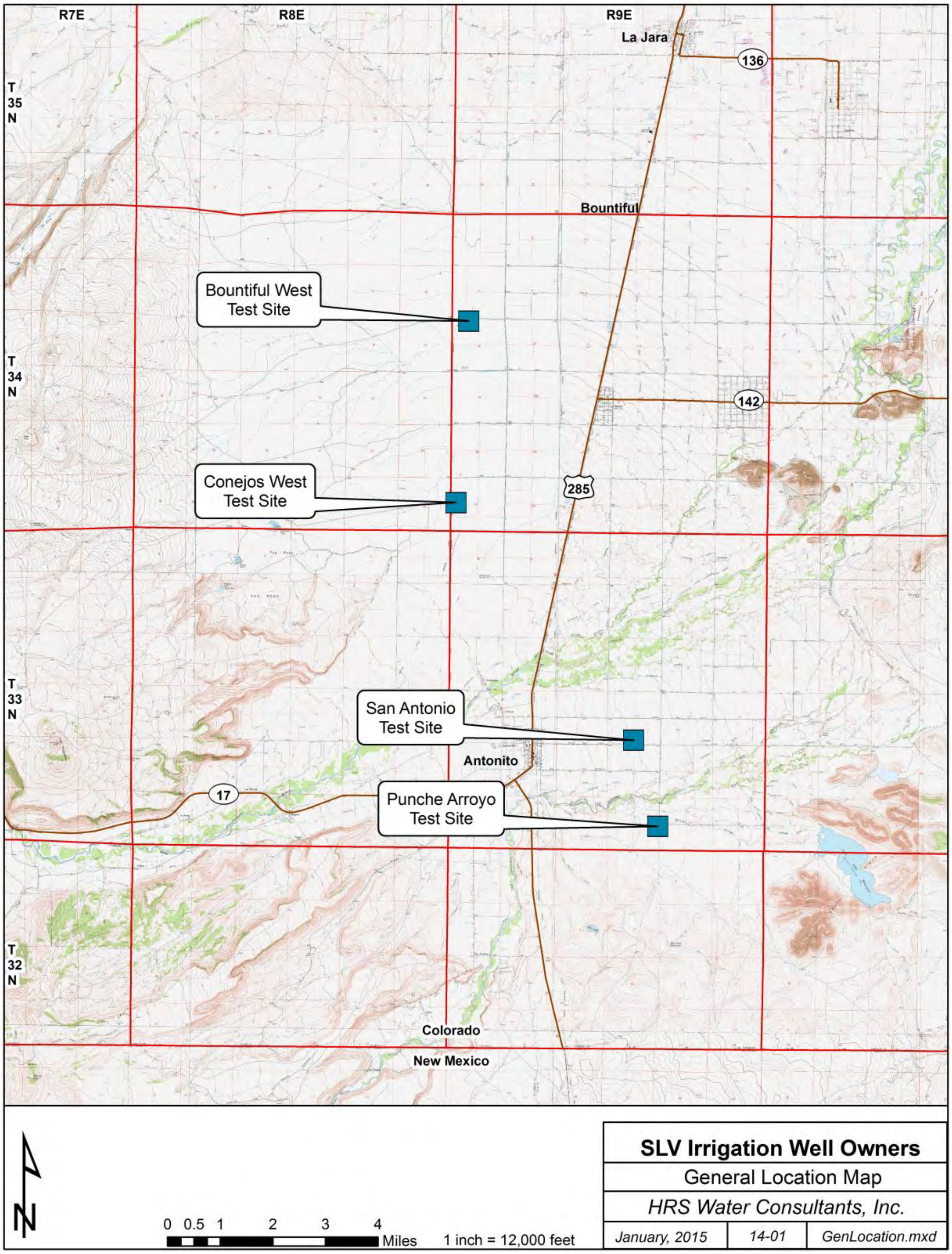


Figure 16: Test Site Location

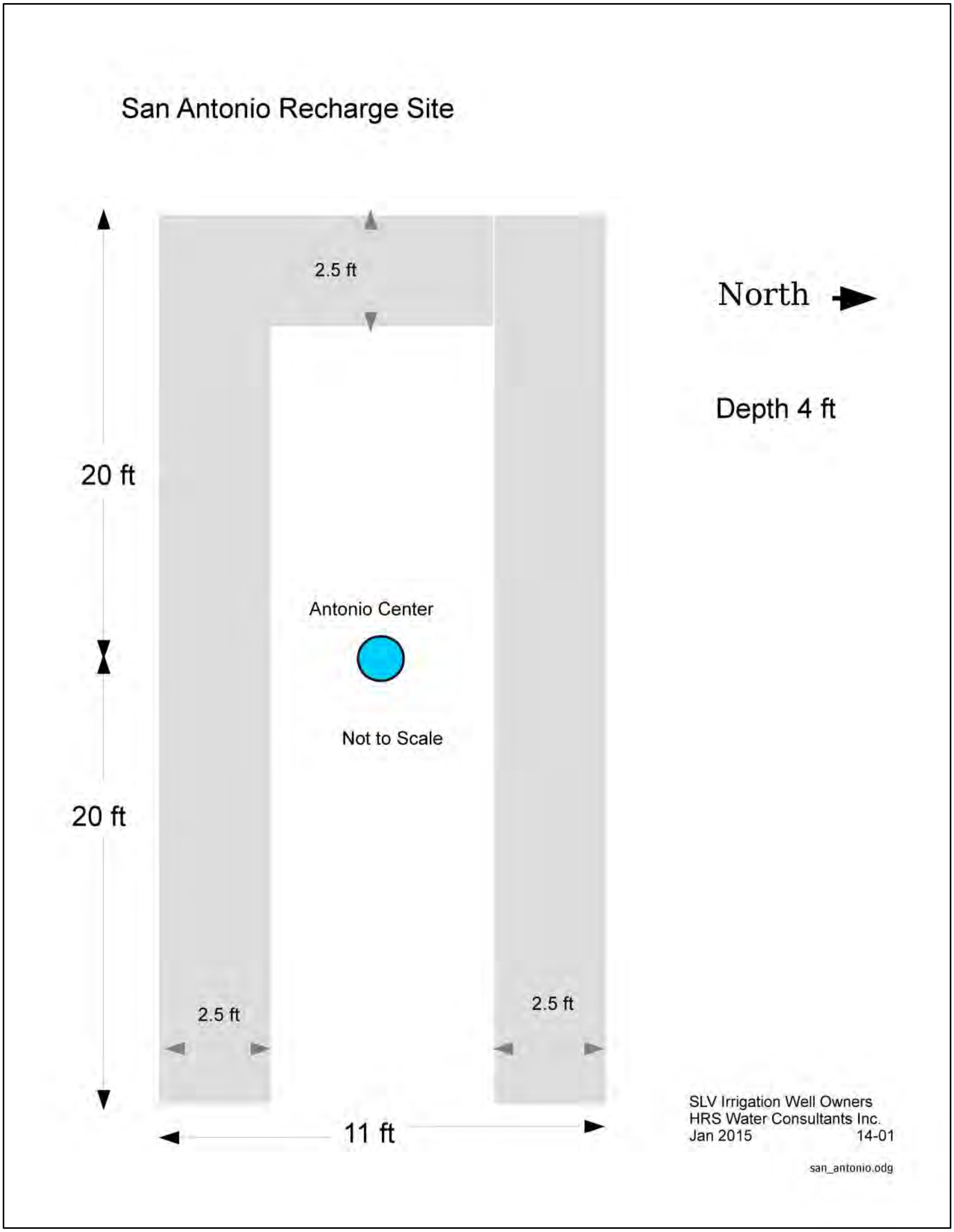


Figure 17: San Antonio Trench Layout

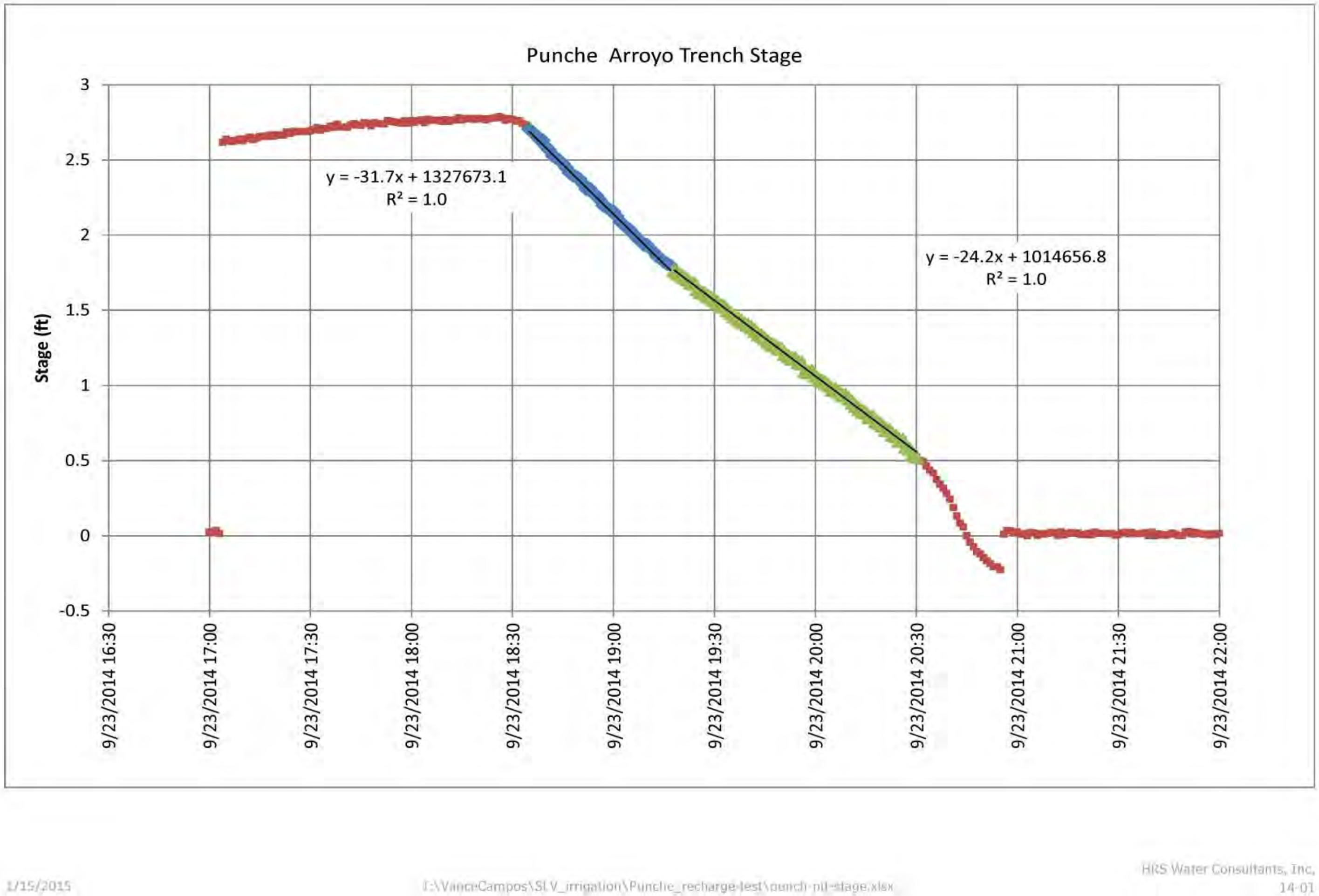


Figure 18: Punche Arroyo Trench Stage

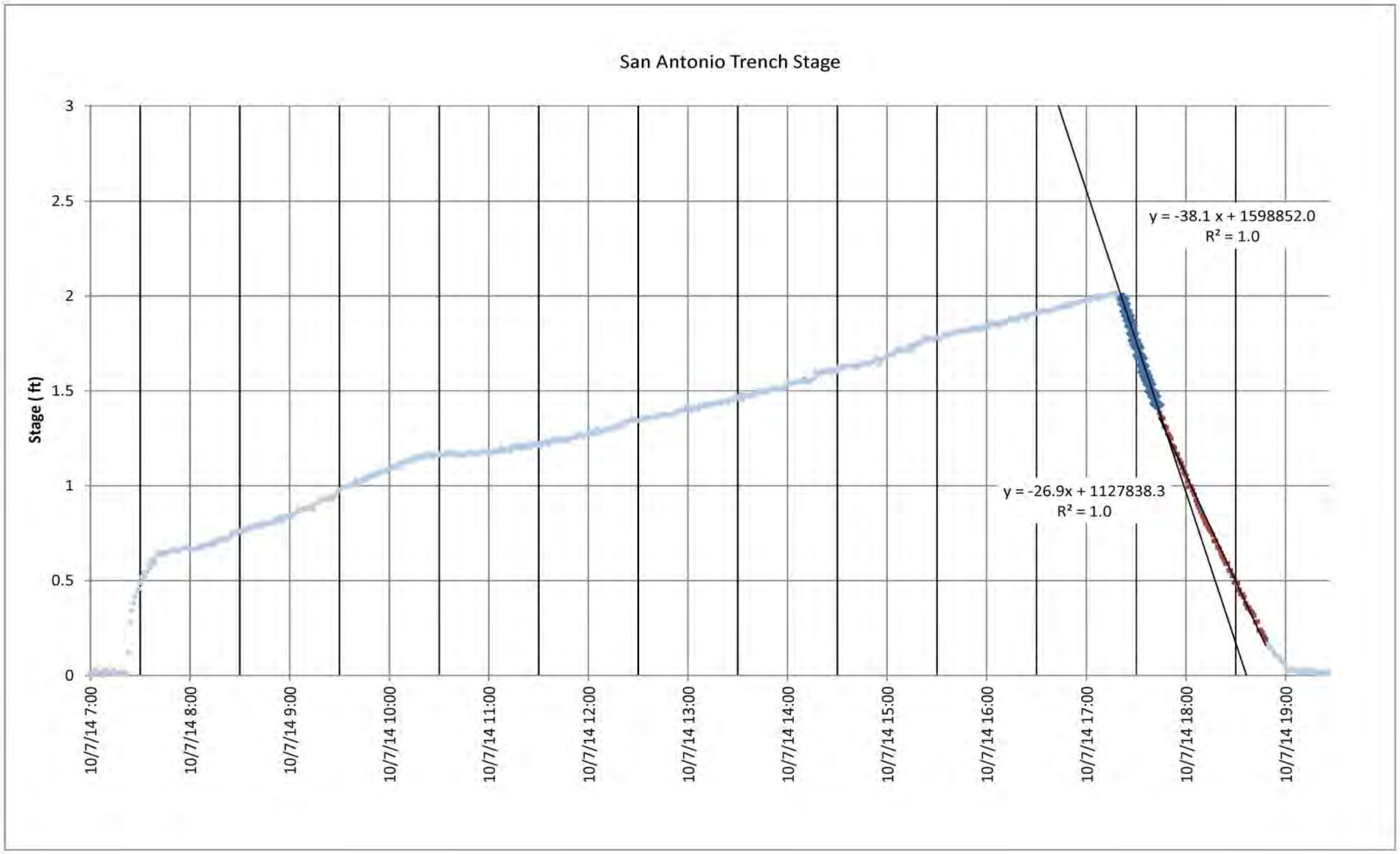


Figure 19: San Antonio Trench Stage

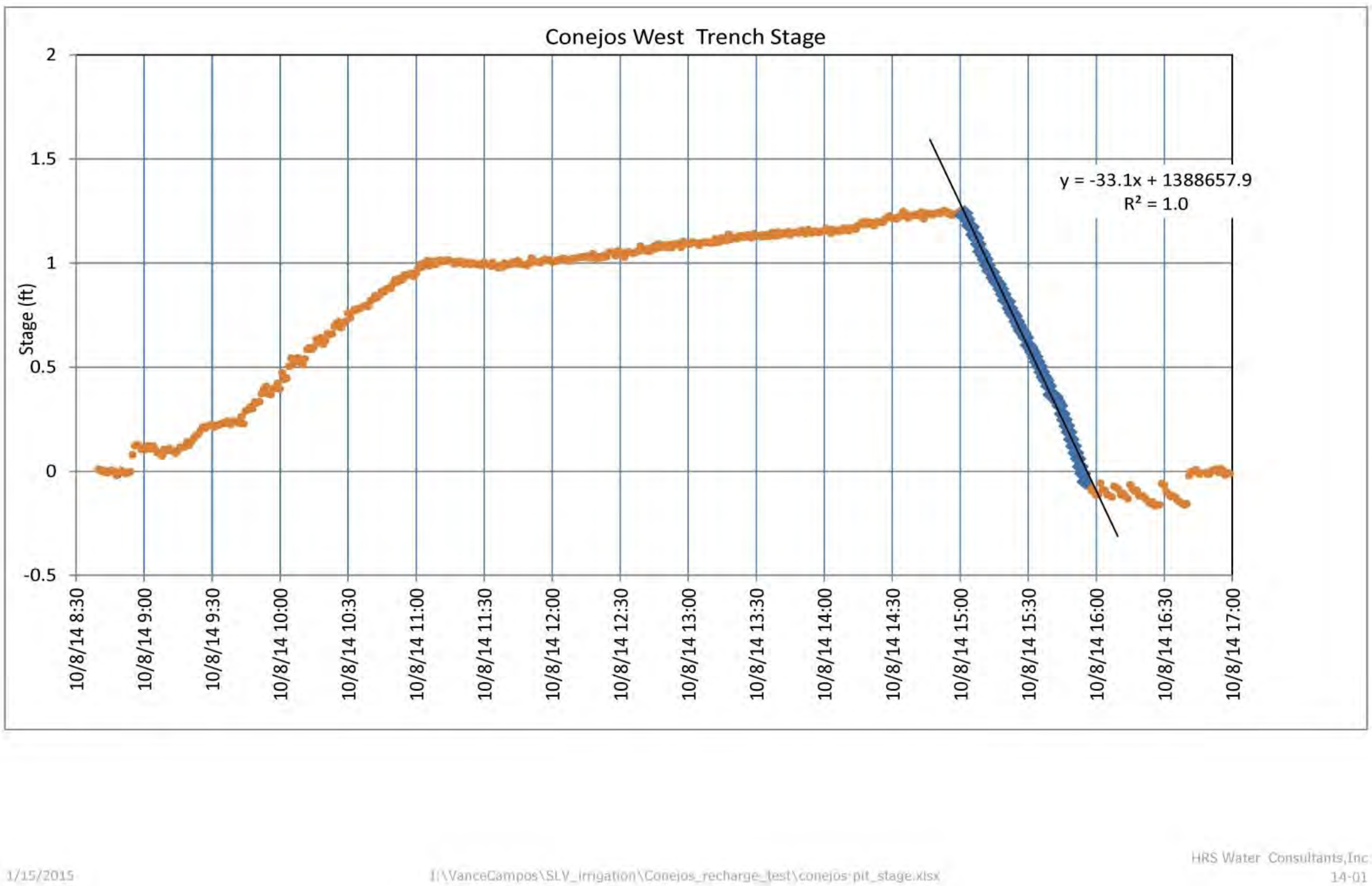


**Figure 20: Conejos West Trench Stage**

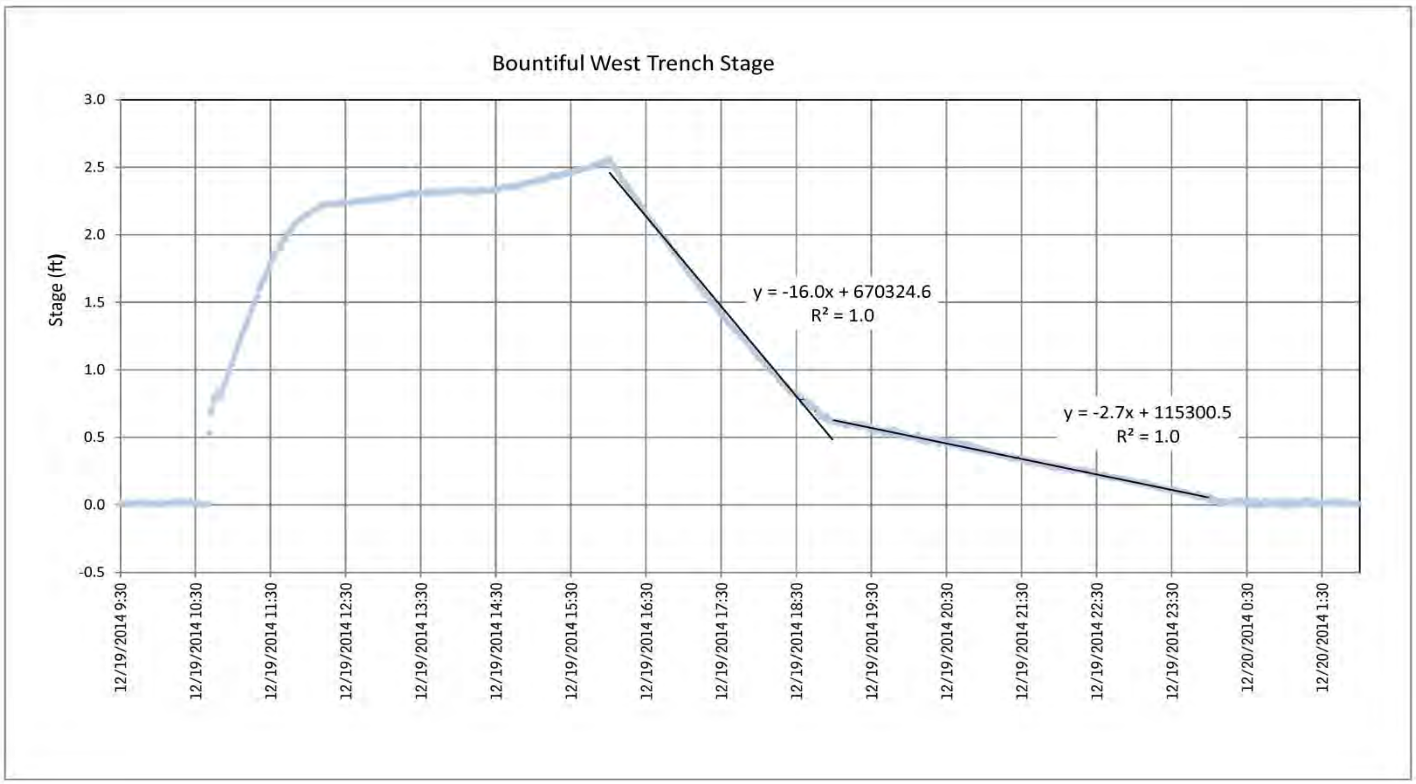


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**Figure 21: Bountiful West Trench Stage**

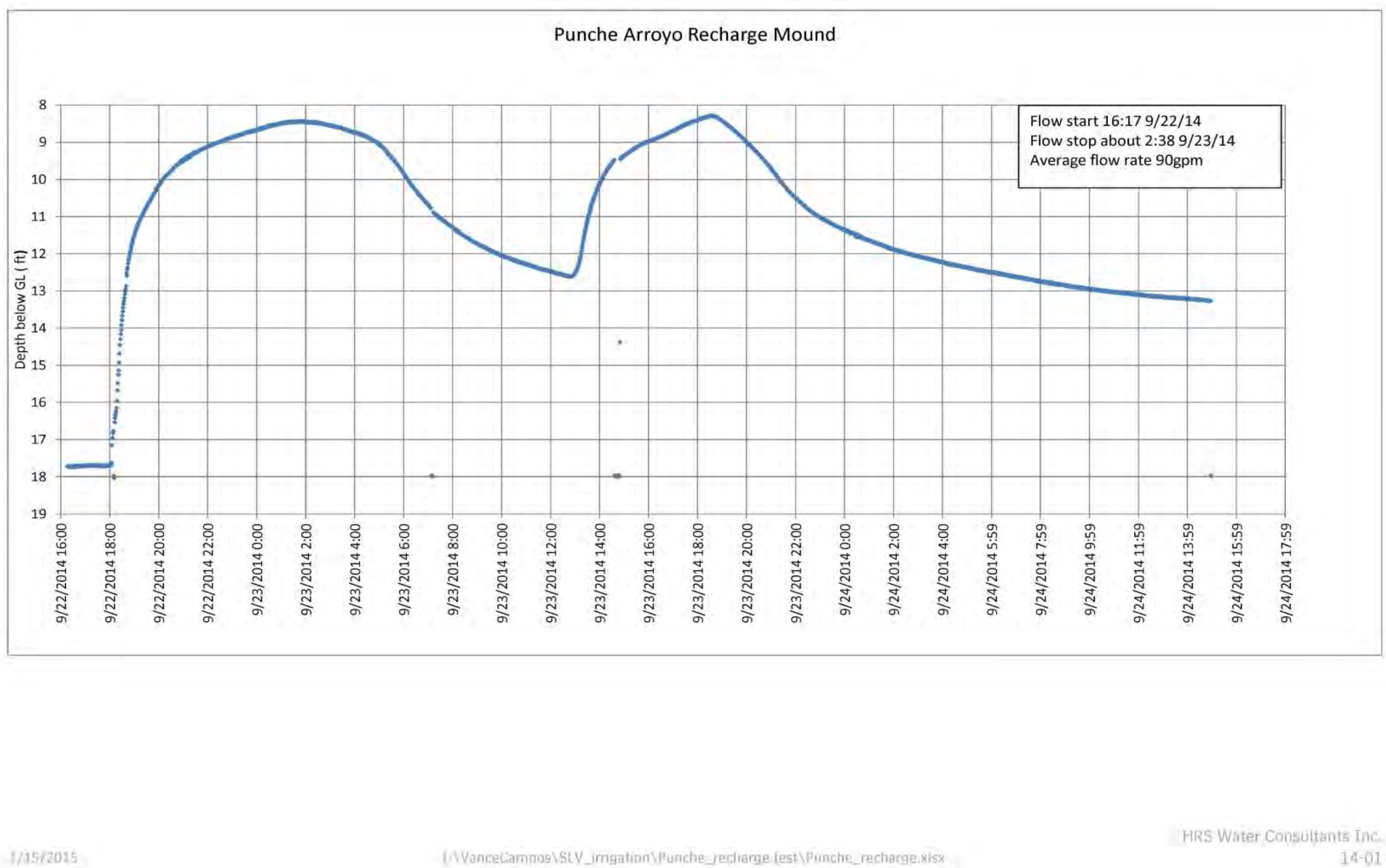


**Figure 22: Punche Arroyo Recharge Mound**

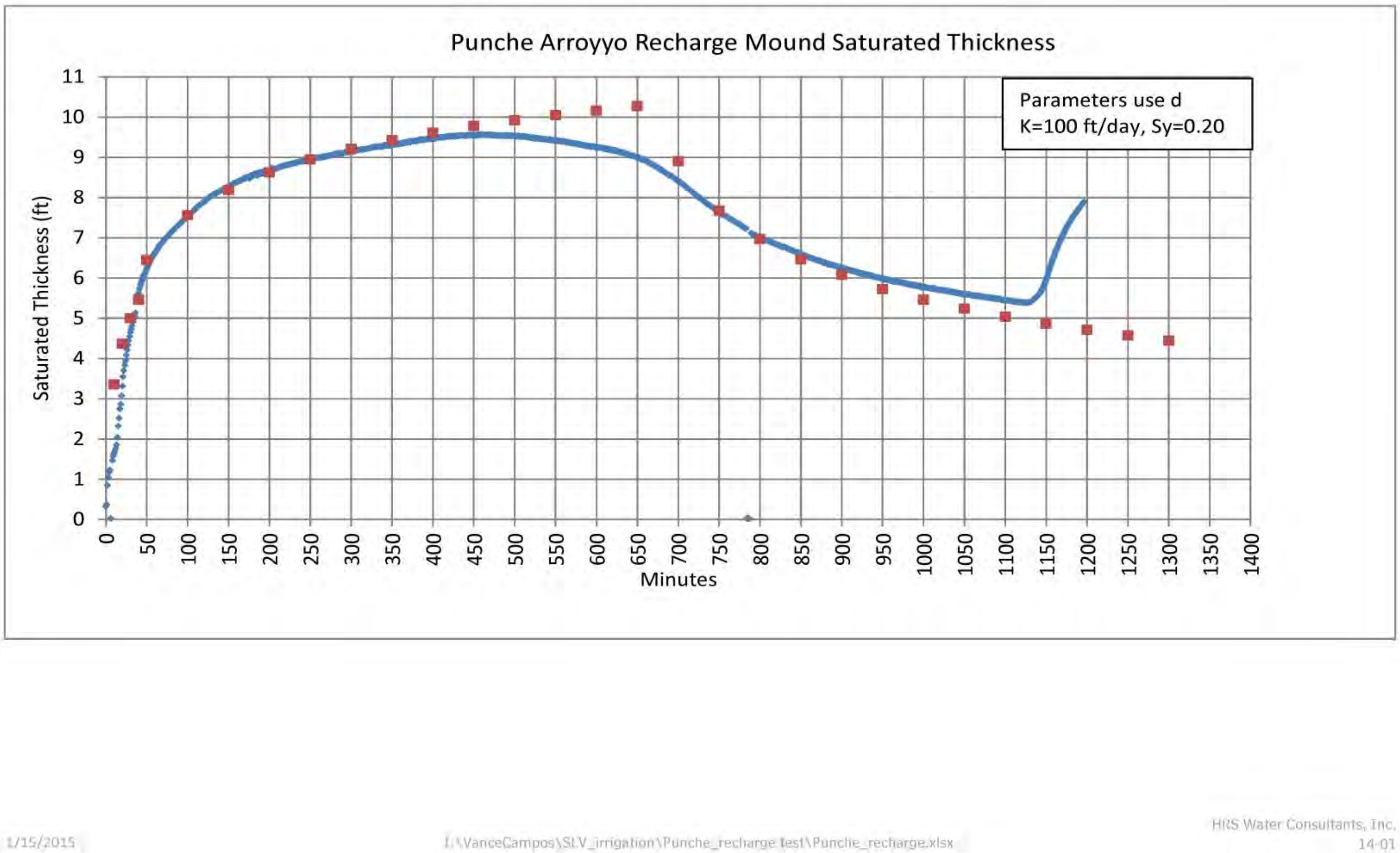


**Figure 23: Punche Arroyo Mound Saturated Thickness**

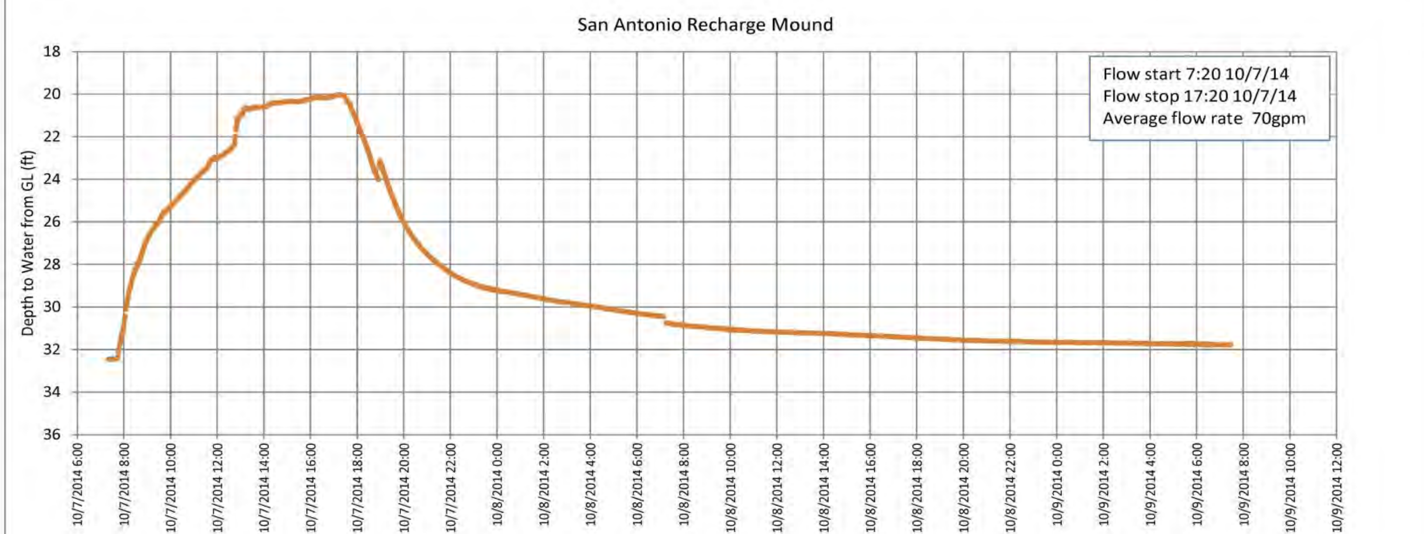


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**Figure 24: San Antonio Recharge Mound DTW**

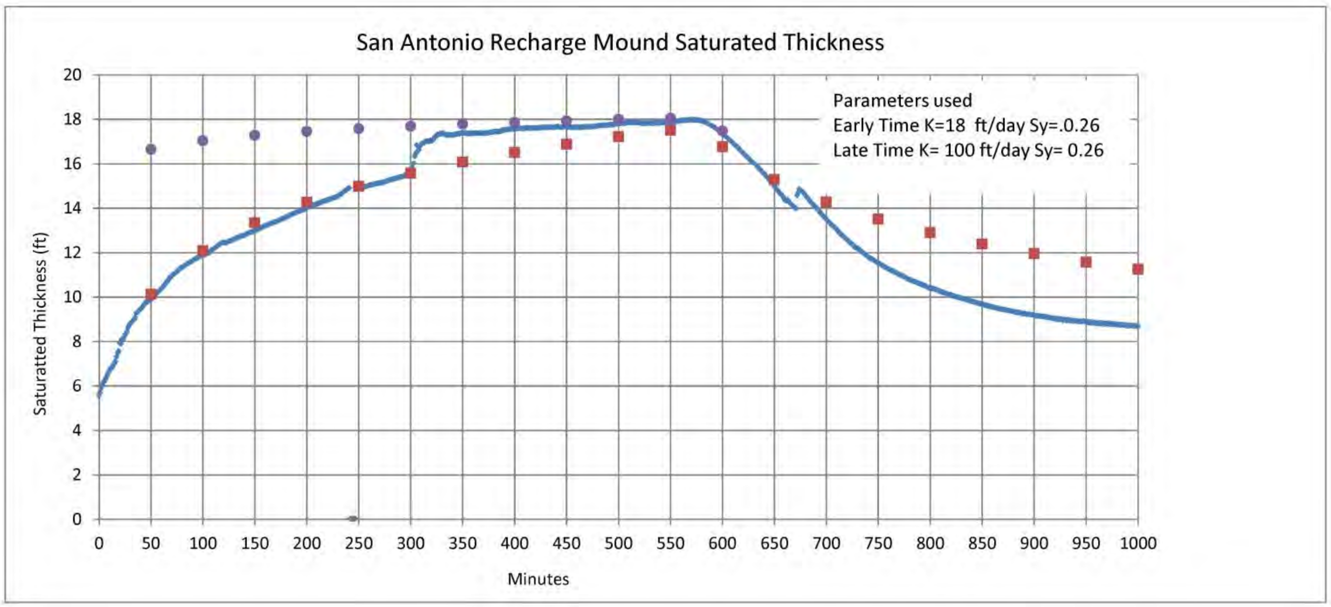


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**Figure 25: San Antonio Ssaturated Thickness**

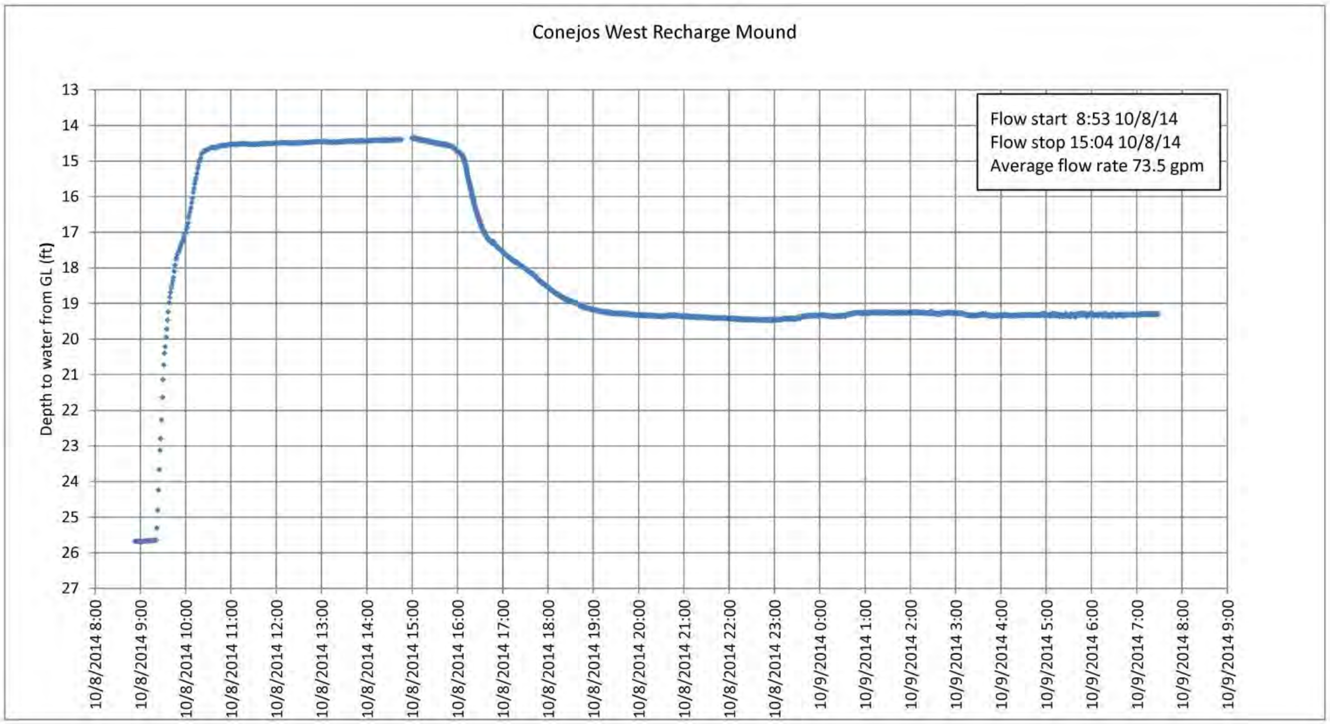


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**Figure 26: Conejos West Recharge Mound DTW**

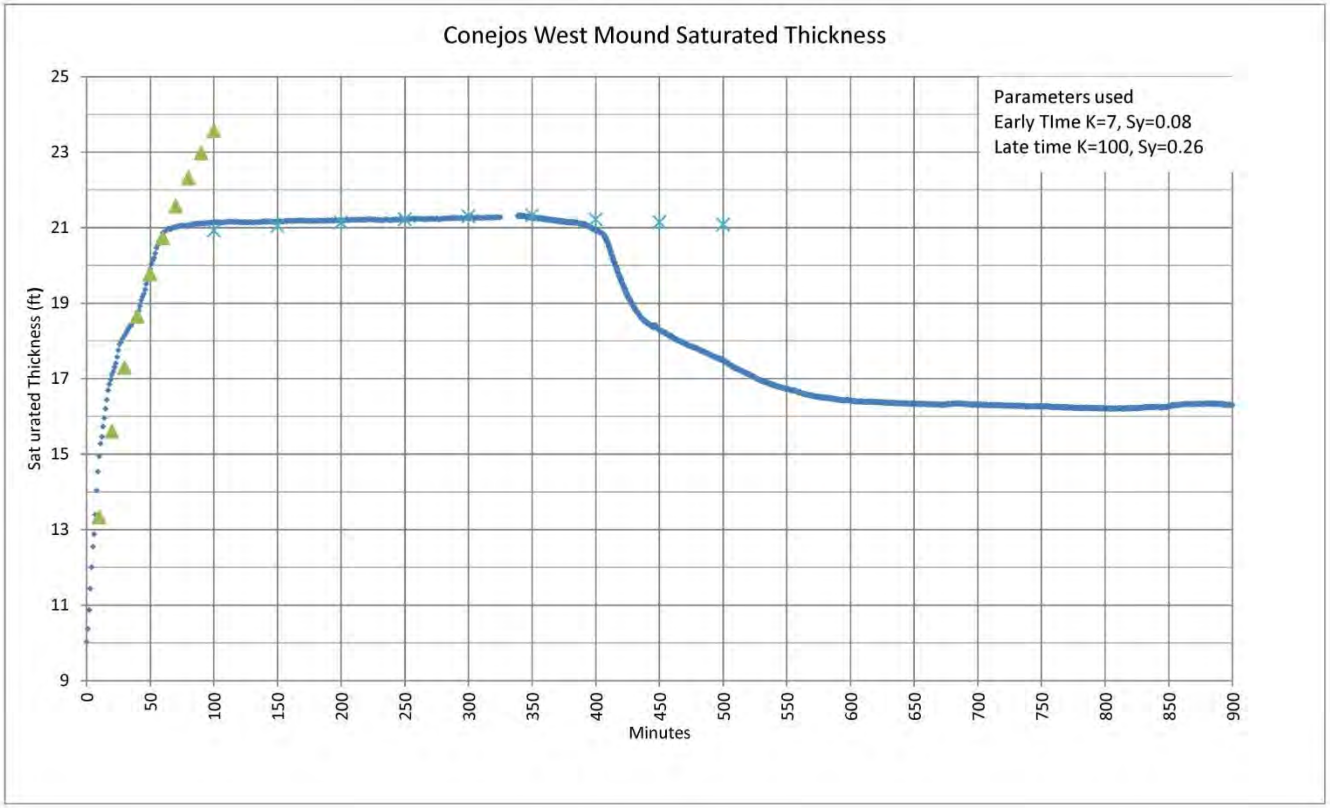


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**Figure 27: Conejos West Saturated Thickness**

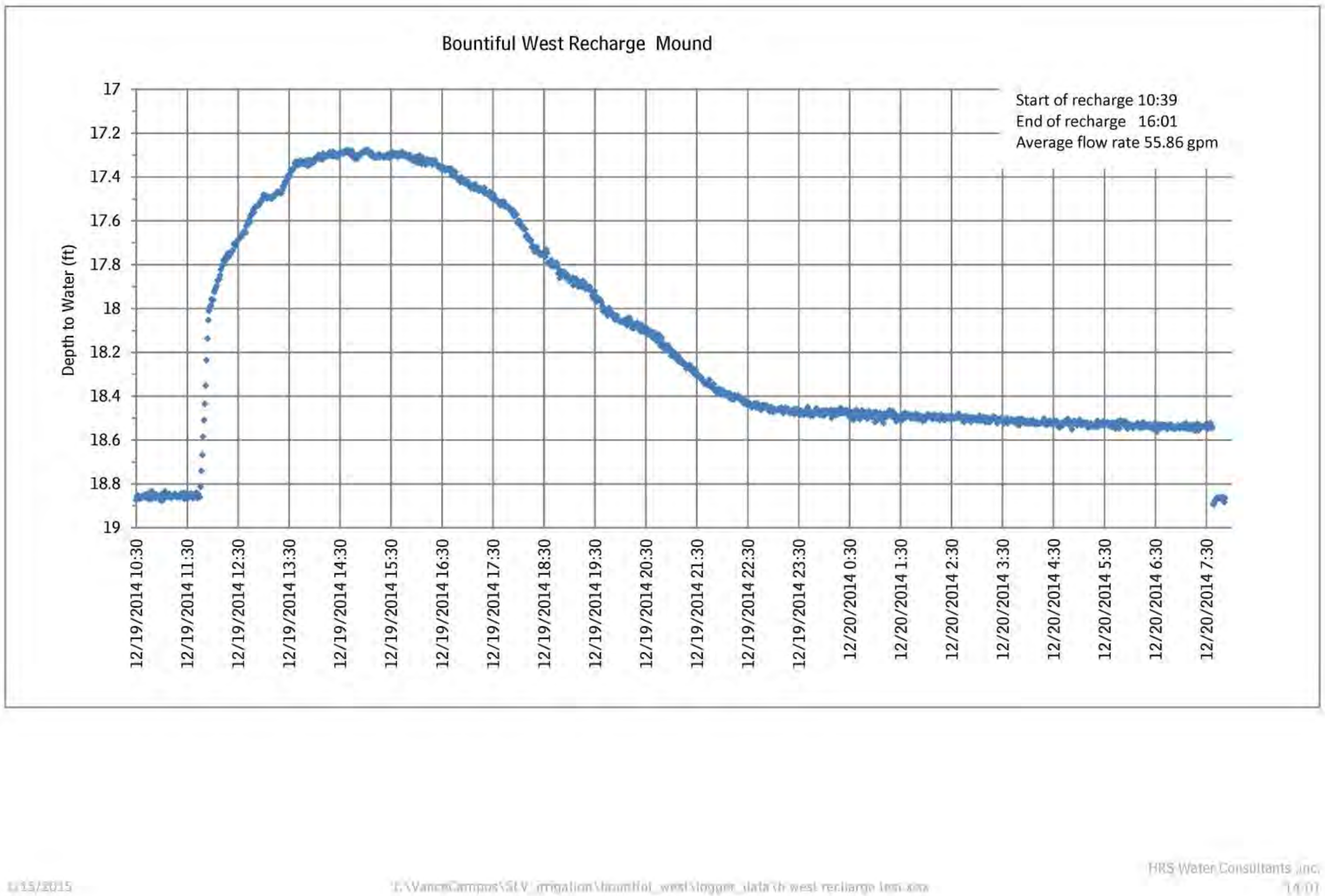



**Figure 28: Bountiful West Recharge Mound**

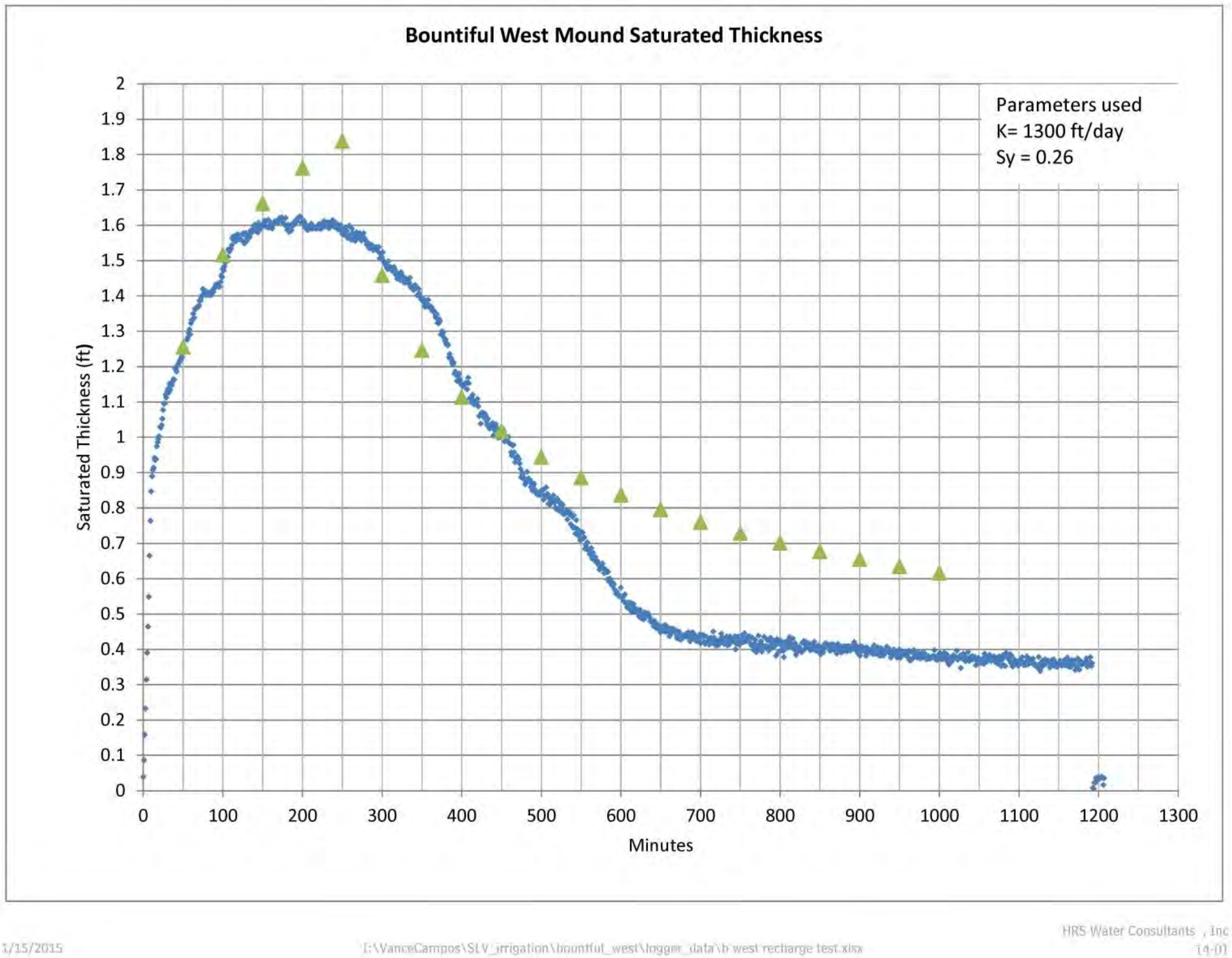



Figure 29: Bountiful West Saturated Thickness

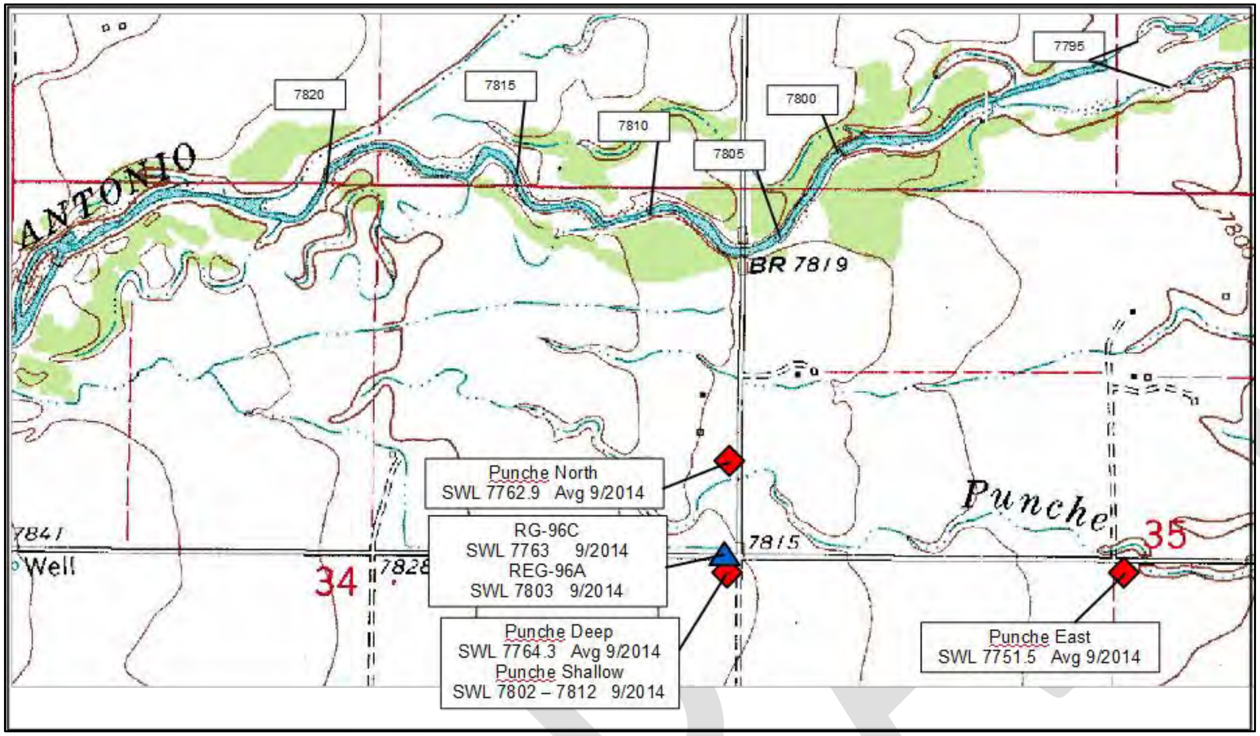



Figure 30: Comparison of Rio San Antonio elevations and water level elevations in piezometers in the Punche Arroyo study area.

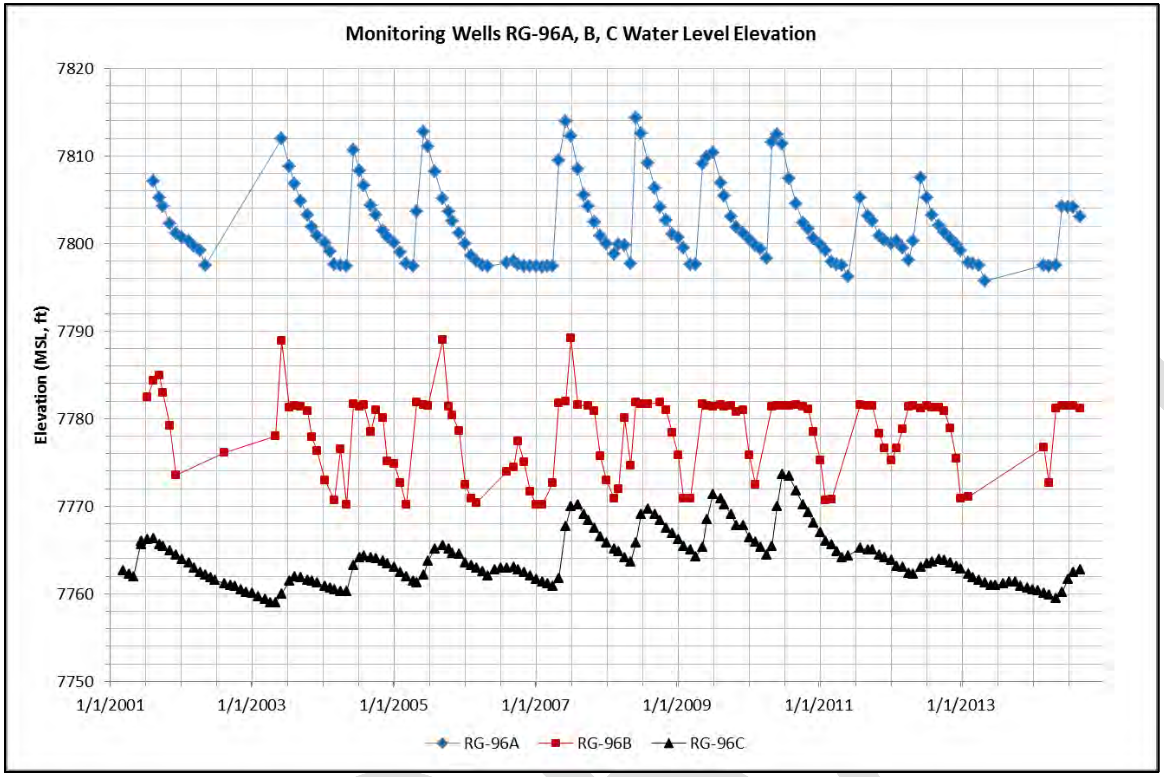



Figure 31: Water level elevations in RGWCD Piezometer triplet RG-96-A, B, C.

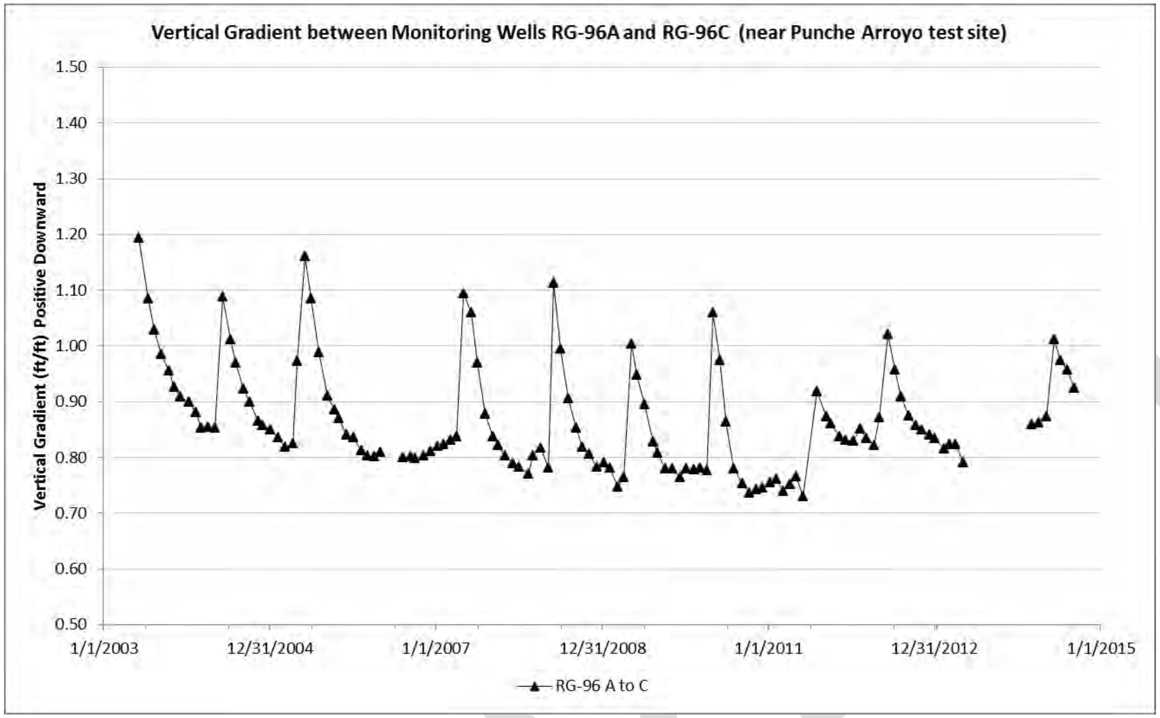



**Figure 32: Gradient of the water table between RG-96A and RG-96C.**

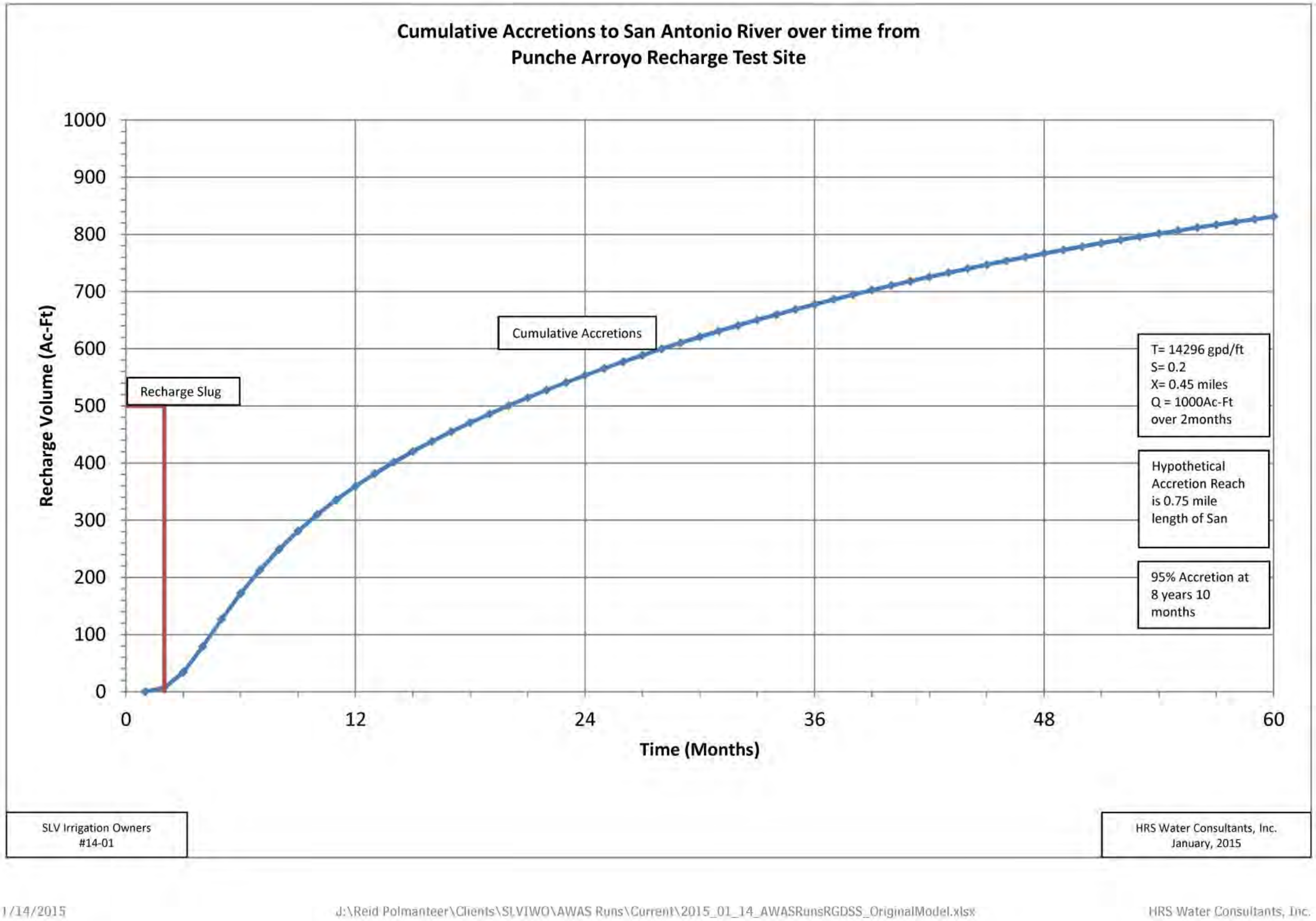



**Figure 33: AWAS Modeling Result for Punche Arroyo Site.**

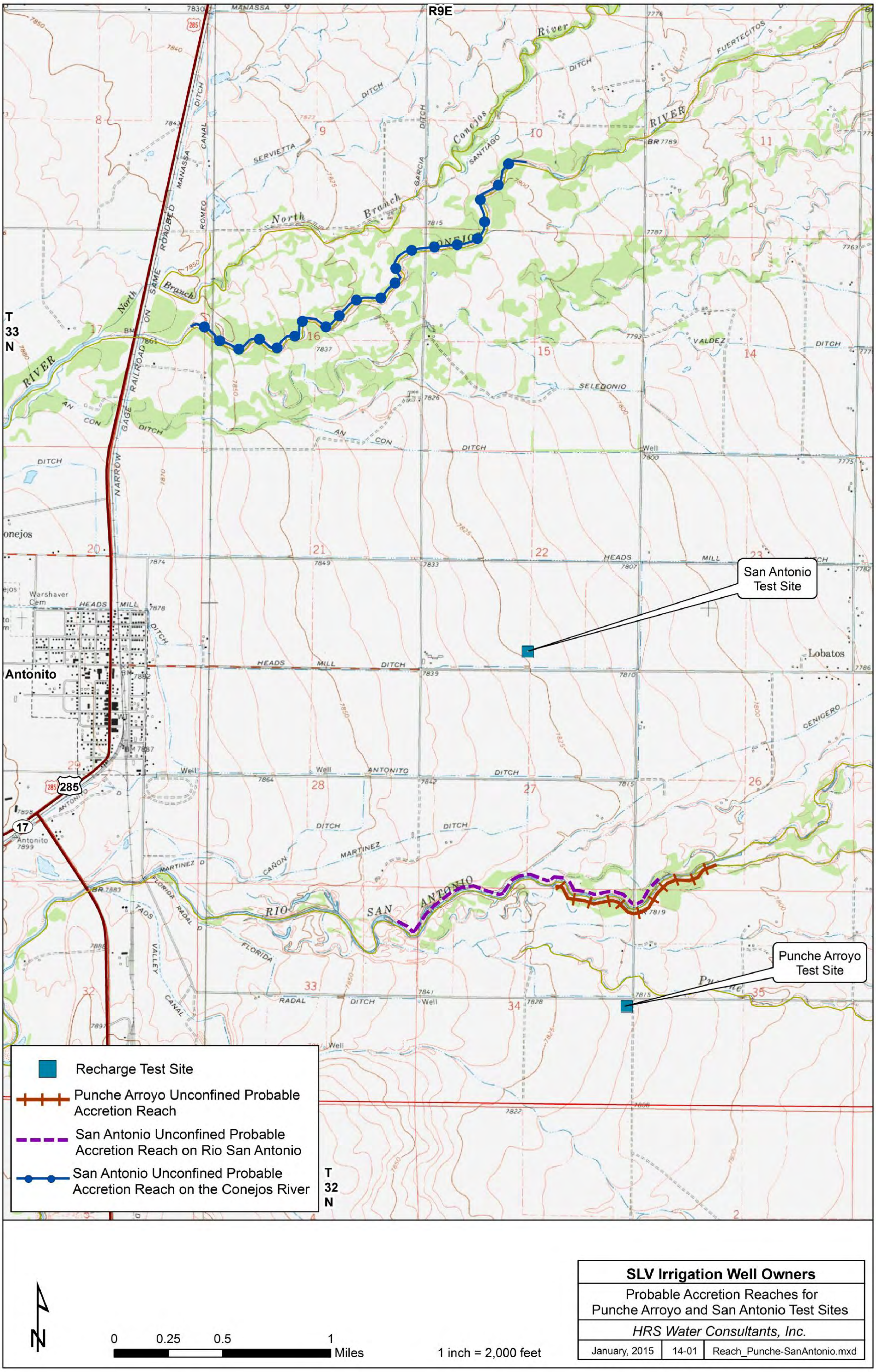



Figure 34: Probable Punche Arroyo Accretion Reach

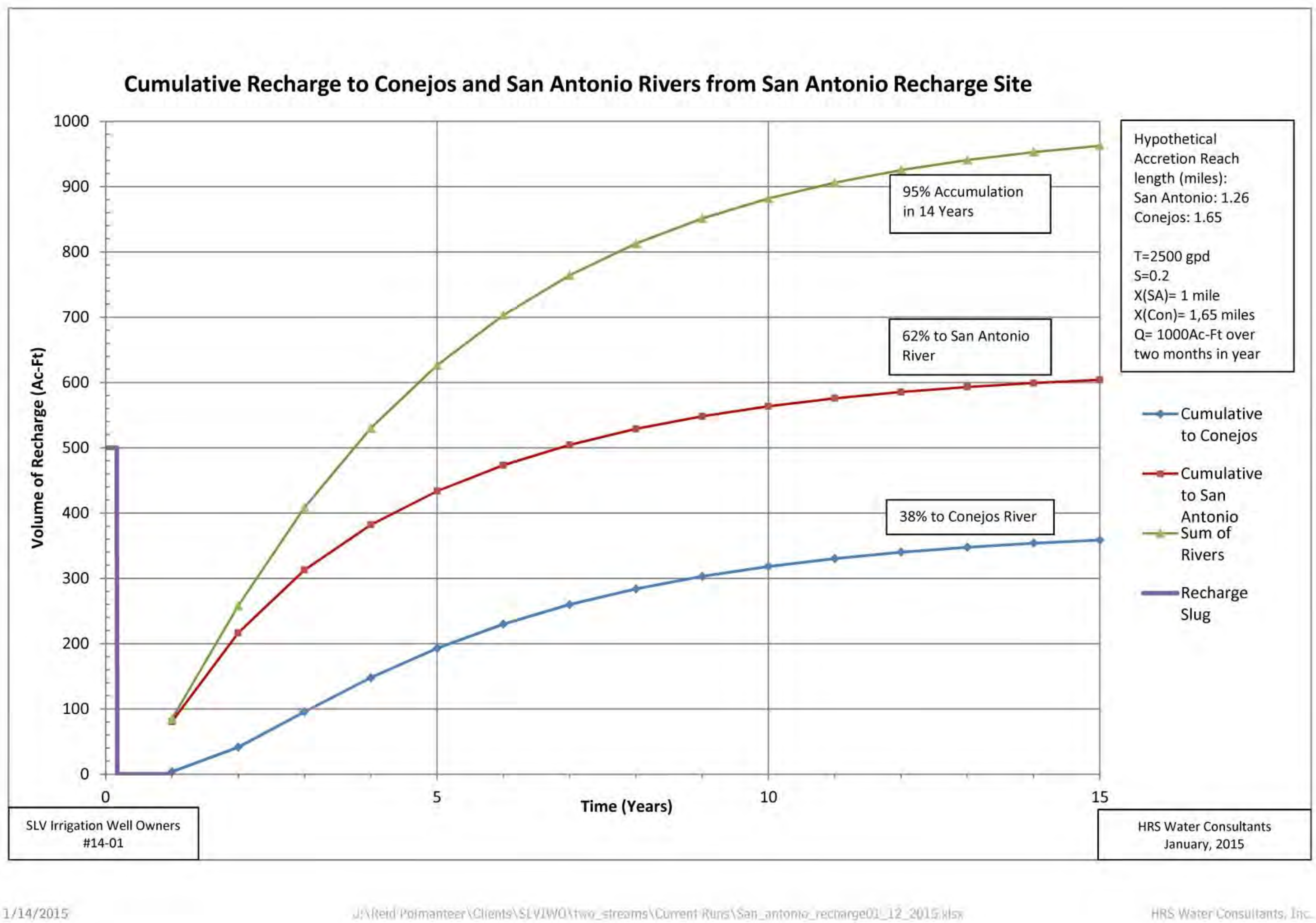



**Figure 35: Octave Modeling Result for San Antonio Site**

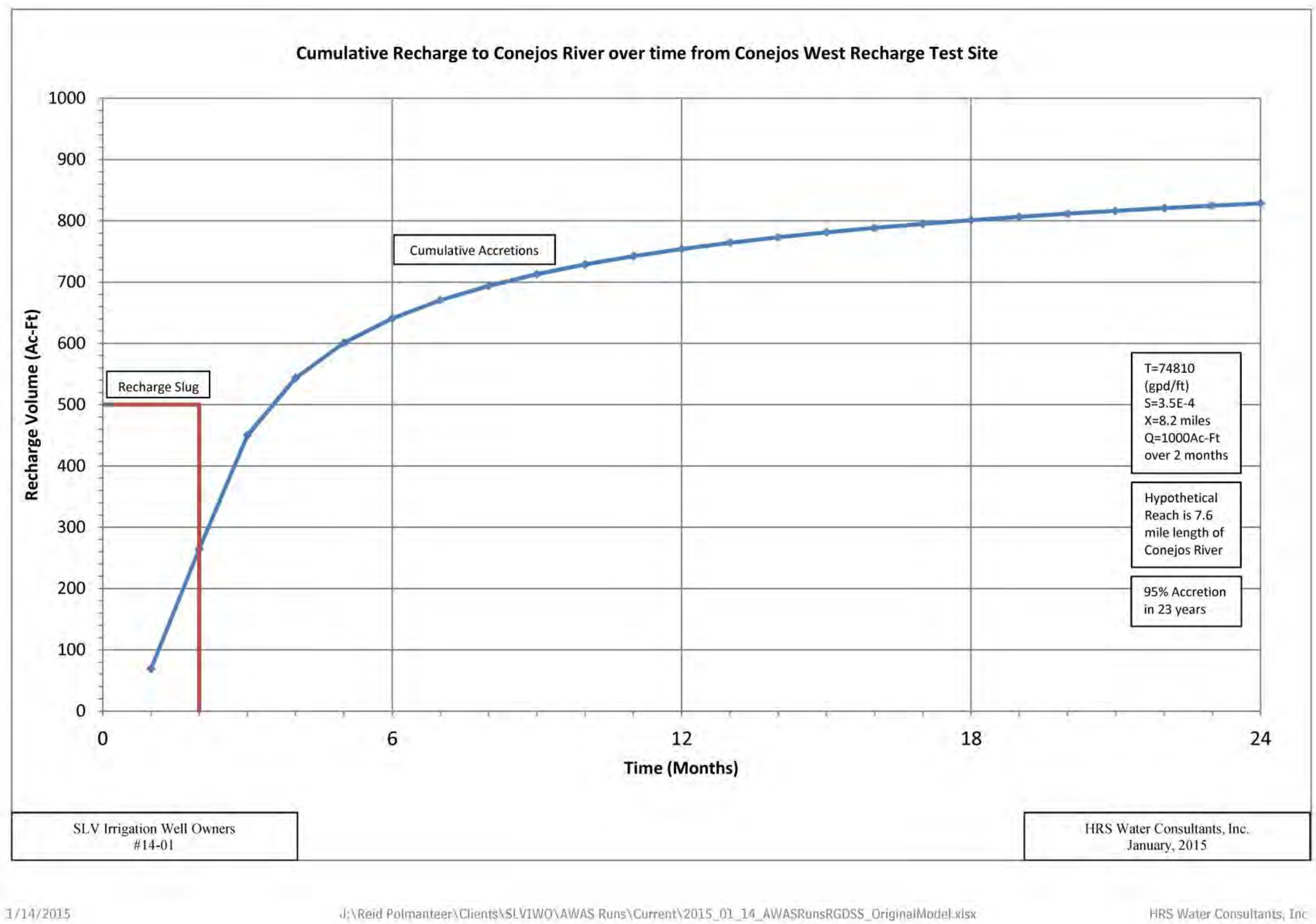



**Figure 36: AWAS Modeling Result for Conejos West Site**

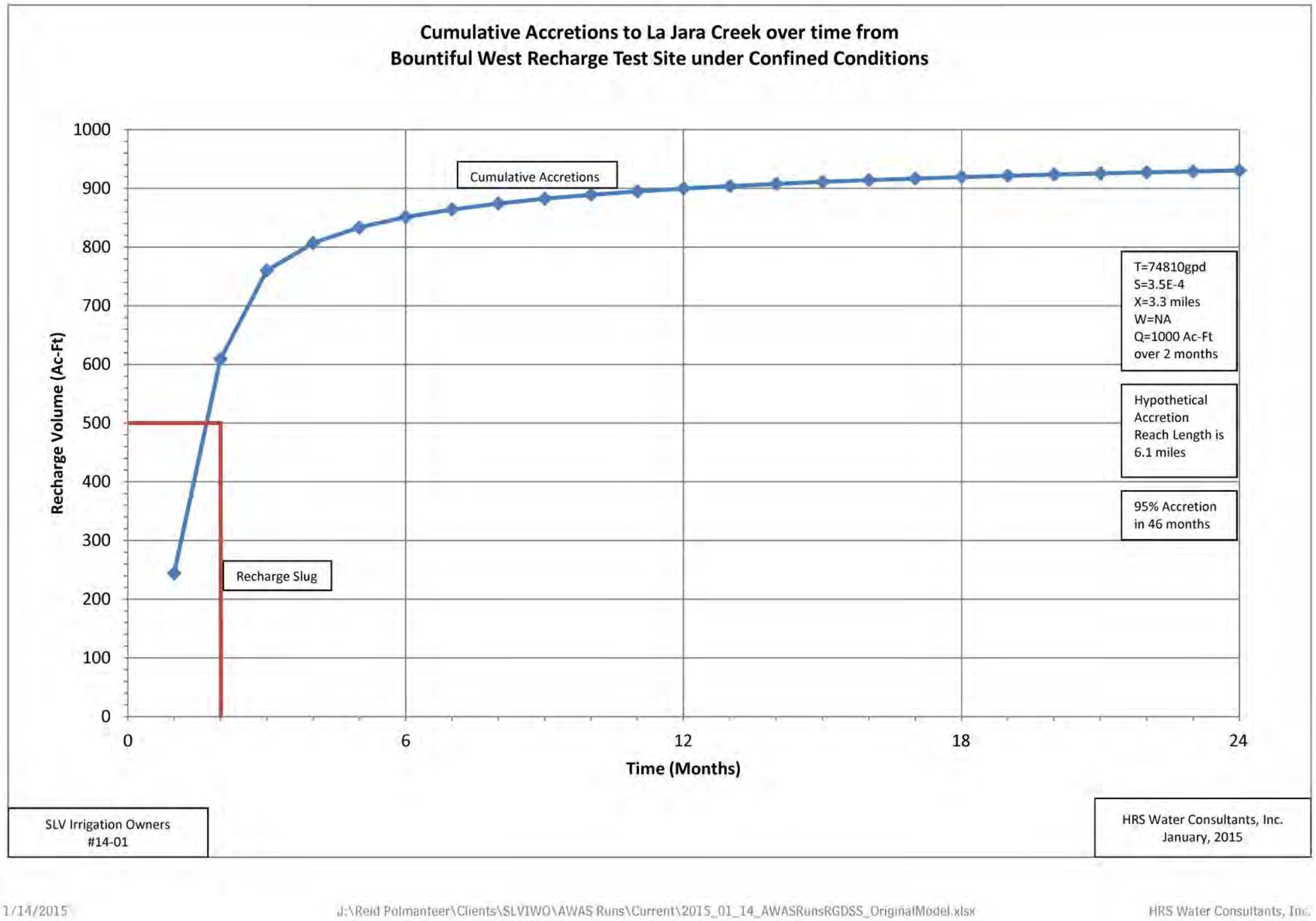



**Figure 37: AWAS Model Result for Bountiful West as Confined**

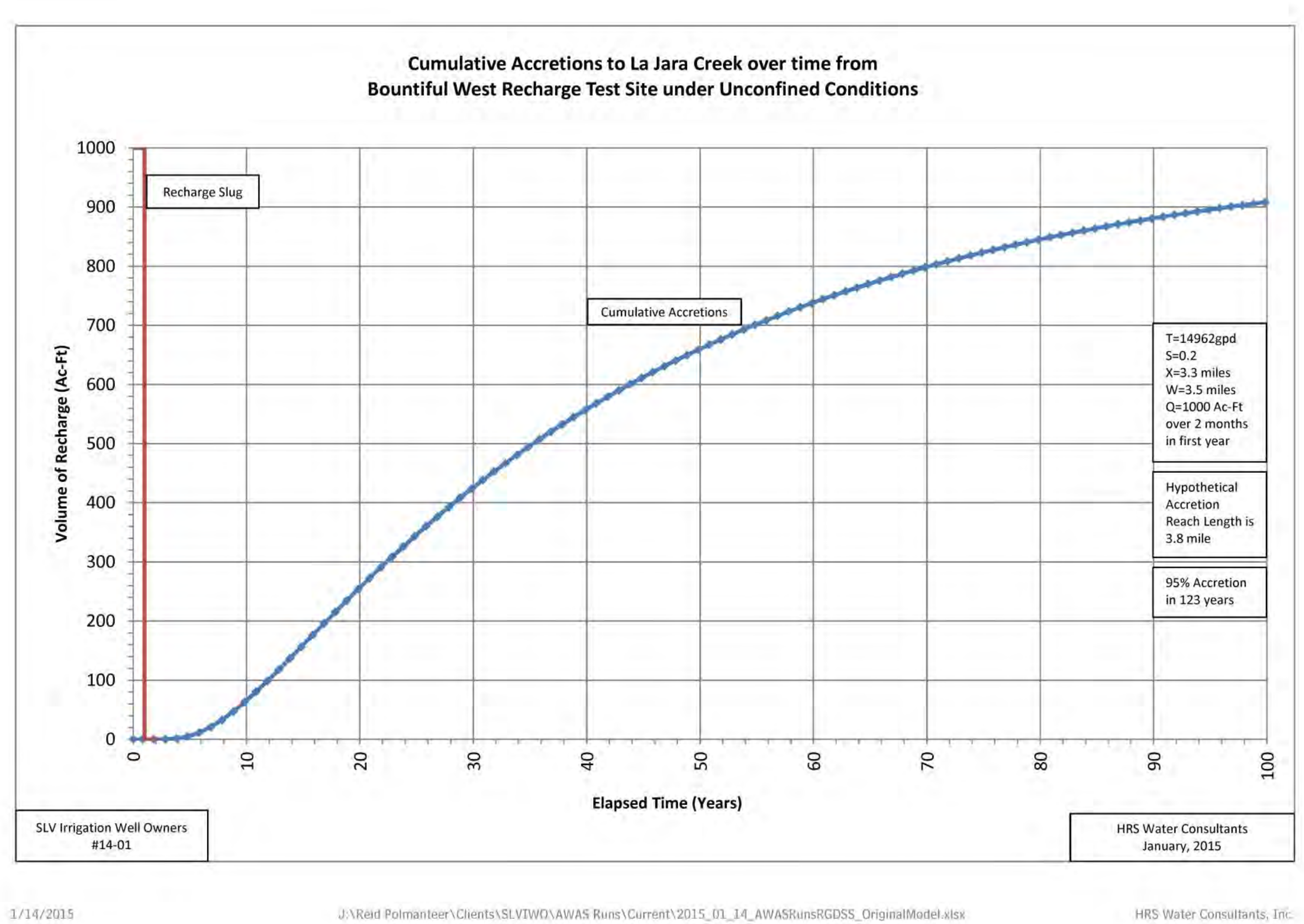



Figure 38: AWAS Modeling Result for Bountiful West as Unconfined

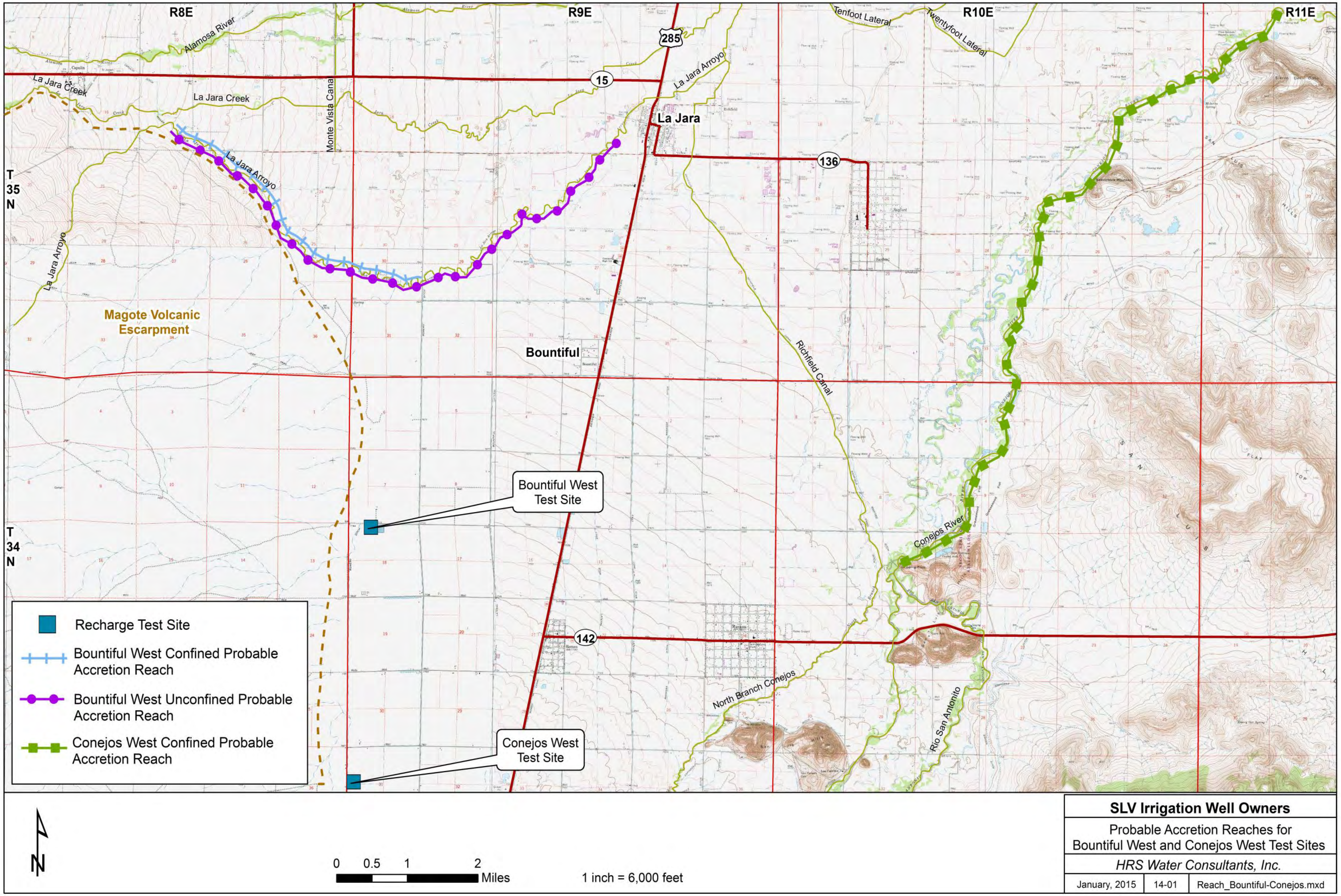



Figure 39: Probable Bountiful West and Conejos West Accretion Reaches

Appendix

Photographic Log of Field Activities

Figure 1: drilling rig set up at Conejos West test site. September, 2014.

**Figure 2: Installing 6” steel casing at Conejos West shallow piezometer. September, 2014.**


Figure 3: Drilling shallow piezometer at Bountiful West test site. December, 2014.


**Figure 4: Drilling shallow piezometer at Bountiful West test site. December, 2014.**


**Figure 5: Conejos West Site: wellhead completion at deep piezometer.**


**Figure 6: Measuring water level at Punche North piezometer. December, 2014.**

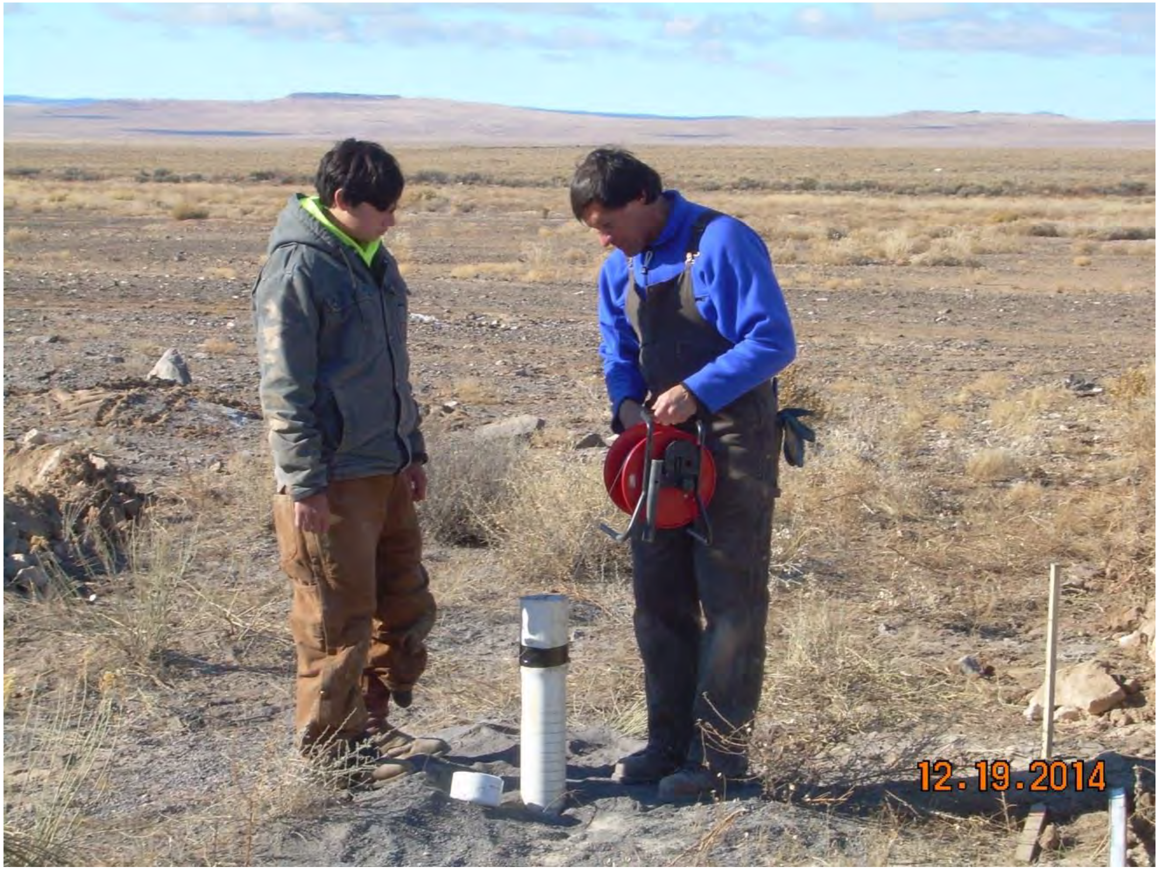



**Figure 7: Measuring water levels at Bountiful West piezometer. December, 2014.**

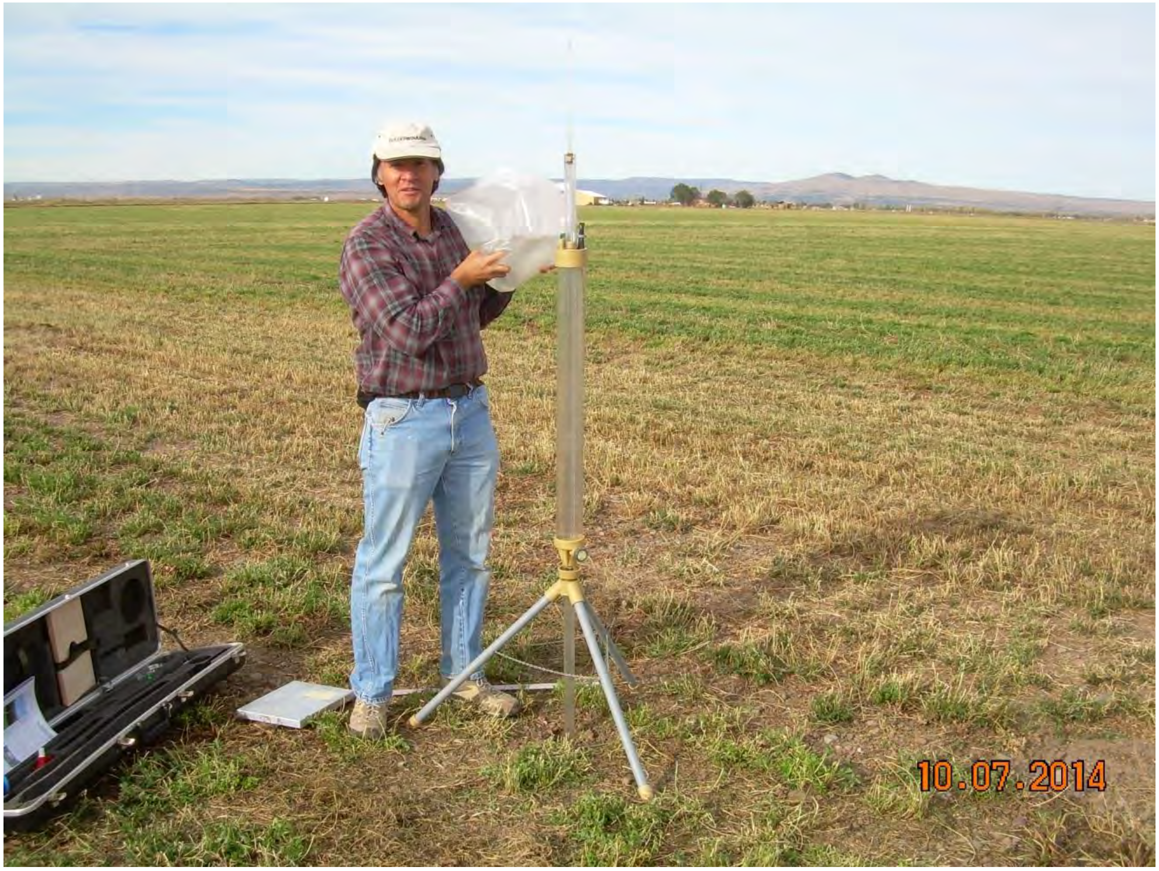



**Figure 8: Filling Guelph permeameter for soil permeability measurement. San Antonio test site. October, 2014.**


Figure 9: Measuring soil permeability. San Antonio test site. October, 2014.


**Figure 10: Digging test trenches for recharge test at Bountiful West site. December, 2014.**


Figure 11: Infiltration rate testing. Conejos West test site. October, 2014.

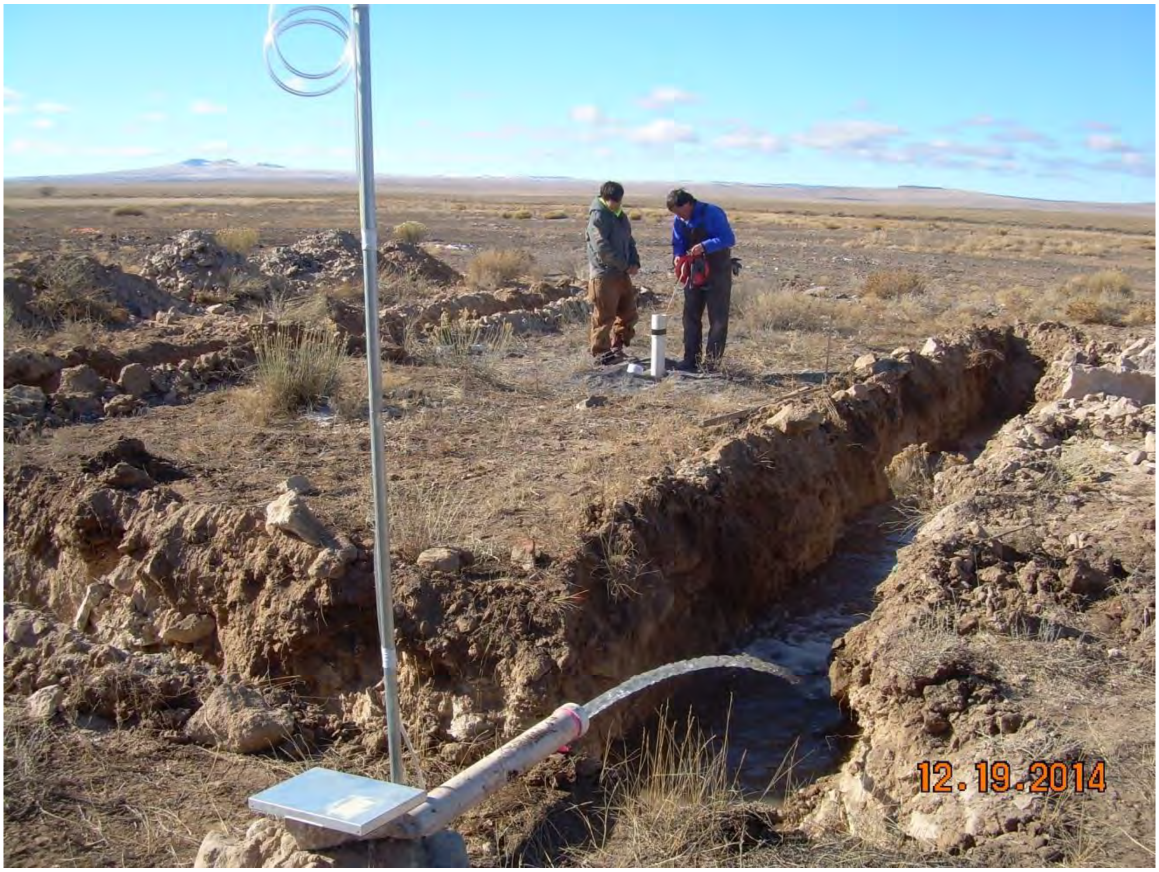



Figure 12: Infiltration rate testing. Bountiful West test site. December, 2014.


**Figure 13: sandy silt soil material, with caliche-coated weathered basalt underneath. Bountiful West test site. December, 2014.**


**Figure 14: silty loam topsoil underlain by cobbly, gravelly outwash / alluvium. Conejos West test site. October, 2014.**


**Figure 15: Rio San Antonio looking upstream from CR-16, near Punche Arroyo test site. October, 2014.**


Figure 16: Rio San Antonio looking upstream from CR-16, near Punche Arroyo test site. December, 2014.

**Table A.1**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Punche Arroyo test site: Center Monitoring Well (shallow and deep)
Date Drilled: 8/25/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 18 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Light brown, gray, dark gray. Upper 2' caliche coating on gravel and cobbles. Sub-angular to sub-rounded, up to 2" rounded gravel. |
| 17 | Water zone no. 1 (clear water visible in discharge hose) |
| 18 – 20 | Sand & gravel with inter-bedded clay. Interbedded clay with medium to coarse grained sand. Light brown, yellowish orange. |
| 20 – 27 | Sand & gravel: Medium to coarse grained sand, small gravel. Sub-angular to sub-rounded, 2" rounded gravel. |
| 27 – 30 | Sand & gravel with inter-bedded clay. Interbedded clay with medium to coarse grained sand. Light brown, yellowish orange. |
| 30 – 33 | Sand & gravel: Medium to coarse grained sand, small gravel. Light brown, gray, black. Sub-angular to sub-rounded, 1" rounded gravel. |
| 33 – 40 | Sand & gravel with inter-bedded clay. Inter-bedded clay with medium to coarse grained sand and small gravel. Light brown, yellowish orange. Sub-angular to sub-rounded, up to 1" gravel. |
| 38 | Water zone no. 2: (clear water visible in discharge hose) |
| 40 – 55 | Silt, sand, and gravel: Silt, medium to coarse grained sand, medium gravel. Dark gray, gray, black, tan, white. Sub-angular to sub-rounded, up to 2" rounded gravel. |
| 55 – 60 | Sand & gravel with inter-bedded clay: Inter-bedded clay, medium to coarse grained sand, medium gravel. Dark gray, gray, black, light brown. Sub-angular to sub-rounded, up to 2" rounded gravel. |
| 58 | Water zone no. 3 (clear water visible in discharge hose) |

(Notes:  Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.)

**Table A.2**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Punche Arroyo test site: East Monitoring Well
Date Drilled: 8/26/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 25 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Light brown, gray, dark gray. Sub-angular to sub-rounded, up to 2" rounded gravel. Caliche coating on gravel & cobbles in upper 1 to 3 feet. |
| 17 | Water zone (clear water visible in discharge hose) |
| 25 – 45 | Sand & gravel with inter-bedded clay: Inter-bedded clay, medium to coarse grained sand. Light brown, yellowish orange, gray, dark gray, black, tan. Sub-angular to sub-rounded, 1" rounded gravel. Sample is mostly medium to coarse grained sand sized particles with grains coated in clay. |
| 45 – 50 | Silt, sand, and gravel: Silt, medium to coarse grained sand. Light brown, yellowish orange, gray, dark gray. Sub-angular to sub-rounded. |
| 50 - 60 | Sand & gravel with inter-bedded clay: Interbedded clay, medium to coarse grained sand. Light brown, tan, gray, dark gray. Sub-angular to sub-rounded sand, up to 2" rounded gravel. |
| | (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |

**Table A.3**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Punche Arroyo test site: North Monitoring Well
Date Drilled: 8/26/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 15 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles; caliche coating upper 3 ft. Light brown, gray, dark gray, black, white, tan. Sub-angular to sub-rounded, up to 3" rounded gravel. |
| 15 – 30 | Sand & gravel: Mostly medium to coarse grained sand, some large gravel. Light brown, gray, dark gray, black, white, tan. Sub-angular to sub-rounded. Noted increase in sand content. |
| 30 – 35 | Sand & gravel with inter-bedded clay: Inter-bedded clay, medium to coarse grained sand, small gravel. Yellowish orange, light brown, gray, dark gray, tan. Sub-angular to sub-rounded. |
| 35 – 50 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Light brown, gray, dark gray, black, tan. Sub-angular to sub-rounded, up to 3" rounded gravel. |
| 50 – 60 | Sand & gravel with inter-bedded clay: Inter-bedded clay, medium to coarse grained sand, small gravel. Yellowish orange, light brown, gray, dark gray, tan. Sub-angular to sub-rounded. |
| | (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |

**Table A.4**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Conejos West test site: Shallow Monitoring Well
Date Drilled: 8/18/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 23 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, light brown, light red. Sub-angular to sub-rounded, up to 3" rounded gravel. (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring. Caliche coating in upper 3 to 4 feet; disseminated caliche in soil.) |
| 23 – 35 | Sand, gravel, cobbles with inter-bedded clays: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, light brown, light red. Sub-angular to sub-rounded, 3" rounded gravel, inter-bedded clay. (Notes: Sequence of thinly interbedded clays in alluvium.) |
| 35 – 40 | Clay, sandy: Fine to medium grained sand, silty to clayey. Light brown to yellowish orange and light reds. (Notes: May be a weathered volcanic ash) |
| 38 | Water zone |
| 40 – 60 | Basalt/Volcanics: Fine grained sand sized, broken. Dark gray to black, reddish to light brown. (Notes: Fractured pieces approx. 2 inches at 42-43 ft.) |

**Table A.5**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Conejos West test site: Deep Monitoring Well
Date Drilled: 8/18/2014 – 8/19/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 30 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles, caliche coating upper 3 feet. Gray, dark gray, black, white, light brown, light red. Sub-angular to sub-rounded, up to 3" rounded gravel. (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |
| 30 – 35 | Sand, gravel, and cobbles with interbedded clays. Interbedded clay with medium to coarse grained sand, large gravel, fragments of larger cobbles. Clay colors: light brown & yellowish orange, sand & gravel color: Gray, dark gray, black, white, light brown, light red. Sub-angular to sub-rounded with up to 2" rounded gravel. Some larger rounded cobble fragments. (Notes: Sequence of thinly interbedded clays in alluvium.) |
| 35 – 40 | Clay, sandy: Clay, fine to medium grained sand. Light brown to yellowish orange, light reds. (Notes: May be a weathered volcanic ash) |
| 38 | Water zone no. 1 (clear water visible in discharge hose) |
| 40 – 68 | Basalt/Volcanics: Dark Gray to Black, Reddish to Light Brown. (Notes: Fractured pieces approx. 2 inches at 42-43 ft. and at 57-60 ft.) |
| 60 | Water zone no. 2 (clear water visible in discharge hose) |
| 68 – 72 | Clay, sandy: Clay with fine to coarse grained sand. Yellowish orange, light brown. |
| 72 – 100 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of cobbles. Dark gray, gray, black, yellowish orange, light red, white. Sub-angular to sub-rounded, rounded gravel up to 3". (Notes: alluvial depositional environment. Sands, gravels, cobbles are volcanic provenance). |
| 100 – 118 | Silt, sand, and gravel: Silt, medium to coarse grained sand, small gravel. Gray to dark gray. |

| | |
|---|---|
| 118 – 148 | Clay, sandy: Clay, silt, fine to coarse grained sand. Clays: Yellowish orange, light brown. Sands: Gray and black. (Notes: inter-bedded sands in clay). |
| 148 – 210 | Sand & gravel with inter-bedded clay: Clay, silt, fine to coarse grained sand, large gravel. Dark gray, black, yellowish orange. Sub-angular to sub-rounded sands. (Notes: sands & gravel with inter-bedded clays). |
| 171.3 | Water zone no. 3 (clear water visible in discharge hose) |
| 210 – 250 | Clay with sand & gravel: Clay, fine to coarse grained sand. Yellowish orange, light brown, black. (Notes: clay with inter-bedded sands and gravels). |
| 250 – 270 | Sand & gravel: Silt to coarse grained sand, small gravel. Light brown, tan, yellowish orange, black. Sub-angular to sub-rounded. Noted what appeared as fine-grained sandstone at 260 ft. +/- . Possible weathered tuff. |

**Table A.6**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
San Antonio test site: Center Monitoring Well
Date Drilled: 8/21/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 15 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, tan. Sub-angular to sub-rounded, up to 3" rounded gravel, caliche coated upper 2 to 3 ft. (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |
| 15 – 30 | Silt, Sand, gravel, and cobbles: Silt, fine to coarse grained sand, small gravel. Gray, dark gray, brown, light red. Sub-angular to sub-rounded, 1" rounded gravel. (Notes: noticed an increase in silt content, mostly silt to medium and coarse grained sand). |
| 30 – 35 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, tan. Sub-angular to sub-rounded, up to 3" rounded gravel. (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |
| 35 – 40 | Sand & gravel with inter-bedded clay: Clay (inter-bedded), medium to coarse grained sand. Light brown, dark gray. Sub-angular to sub-rounded, up to 1" rounded gravel. |
| 38 | Water zone (clear water visible in discharge hose) |

**Table A.7**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
San Antonio test site: West Monitoring Well
Date Drilled: 8/22/2014

| Depth (ft. BGL) | Lithology |
|---|---|
| 0 – 20 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, tan. Sub-angular to sub-rounded, up to 2" rounded gravel, caliche disseminated and coating gravels / cobbles in upper 2 to 3 ft. |
| 20 – 22 | Sand, gravel, inter-bedded clay: Inter-bedded clay, fine to coarse sand, small gravel. Light brown, yellowish orange, gray. (Noted a thin inter-bedded clay between 20 – 22 ft.) |
| 22 | Water zone (clear water visible in discharge hose) |
| 22– 30 | Sand, gravel, and cobbles: Medium to coarse grained sand, large gravel, fragments of larger cobbles. Gray, dark gray, black, white, tan. Sub-angular to sub-rounded, up to 2" rounded gravel. |
| 30 – 40 | Sand & gravel with inter-bedded clay: Clay (inter-bedded), medium to coarse grained sand. Light brown, dark gray. Sub-angular to sub-rounded, up to 1" rounded gravel. |
| | (Notes: Alluvial depositional environment, sands, gravels and cobbles appear to be of volcanic provenance with small crystal growth and coloring.) |

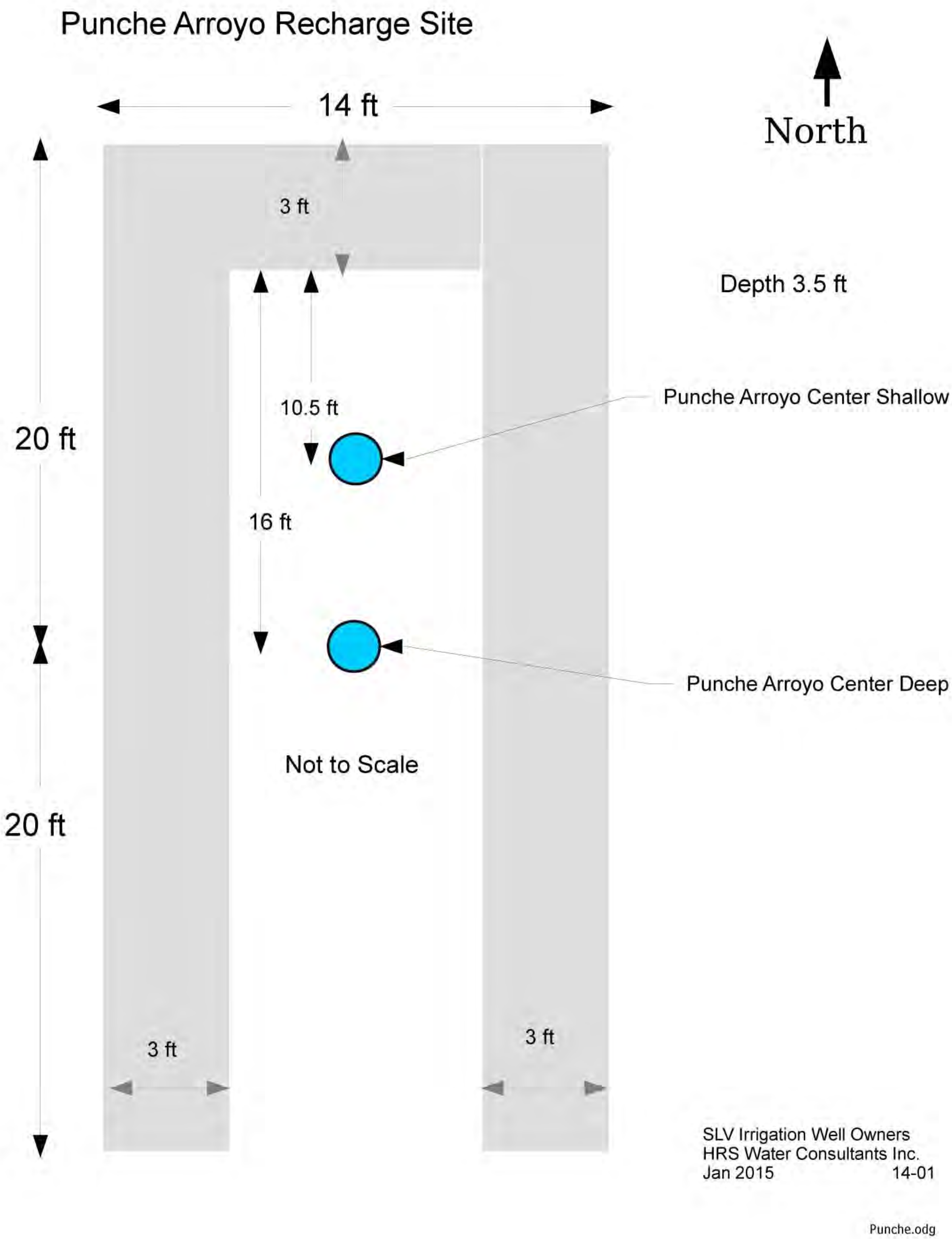
**Table A.8**

Lithologic Description
San Luis Valley Irrigation Well Owner's Association
Bountiful West test site: Center Monitoring Well
Date Drilled: 12/18/2014

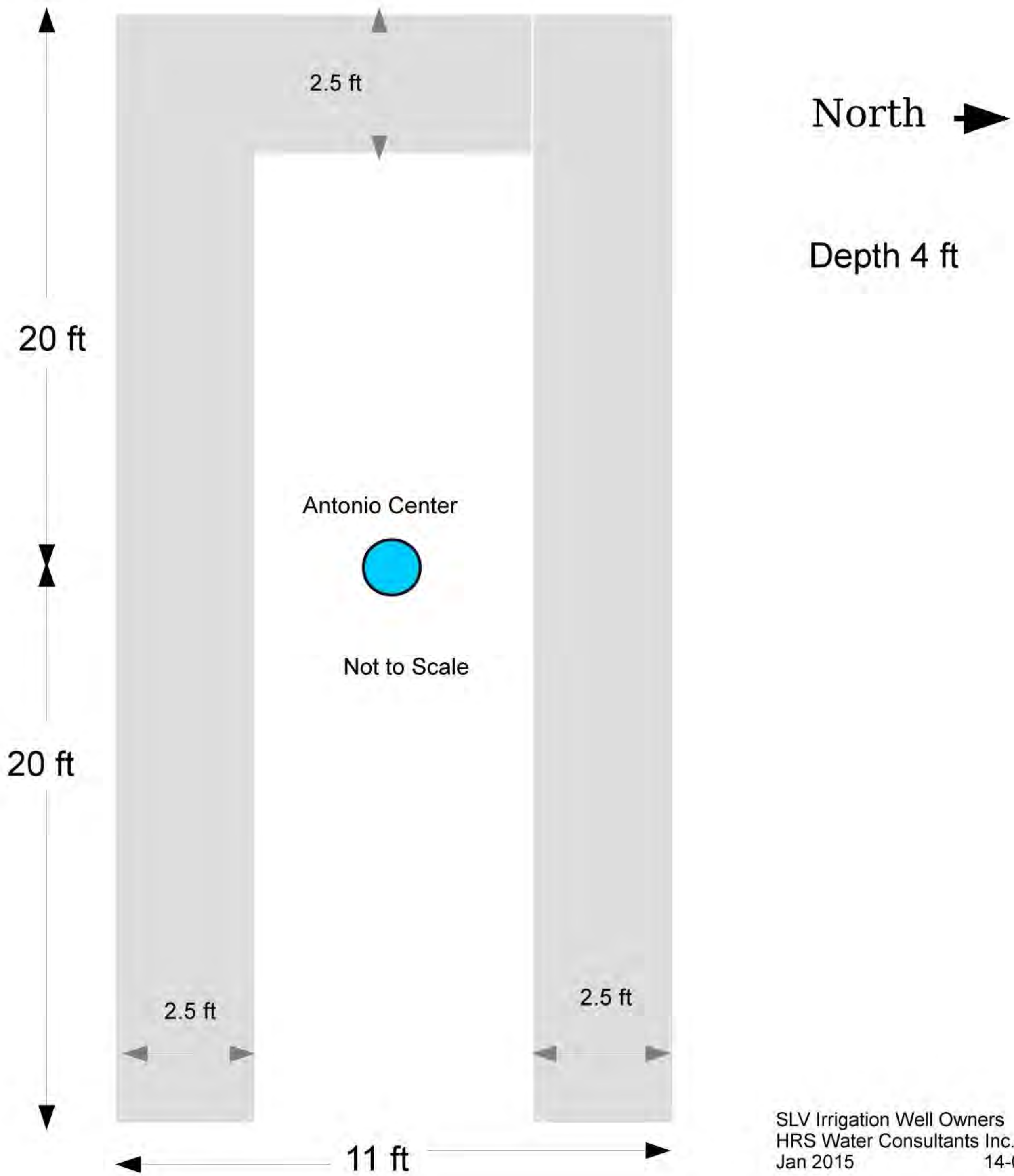
| Depth (ft. BGL) | Lithology |
|---|---|
| 0-3 | silty sand, dry. Disseminated caliche. |
| 3-6 | hard gray volcanic rock, weathered, heavy caliche coating on cuttings. Dry. |
| 6-11 | same as above, less caliche. Dry. |
| 11-15 | hard dark gray volcanic rock, no caliche. Drilling slower, ~ 0.5 ft/min. Dry. |
| 15-16 | same as above, slightly softer. Dry. |
| 16-18 | dark gray vesicular volcanic rock. Some samples vesicular; some amygdaloidal. Rock appears relatively unweathered. |
| 18-19 | same as above. Slight bit drop noted at 18.5'. Possible fracture or joint. Dry. |
| 19-20 | hard, dark gray volcanic rock, vesicular, olivine present, relatively unweathered. Dry. Total depth 20 feet drilled. |

Notes: some precipitate noted on 5 to 10% of cuttings in upper 10' of borehole. Precipitate appears siliceous. Tan to orange amygdule infilling. Yellow-green to brown olivine noted in most samples.

Appendix Trench Layout


Punche Arroyo Recharge Site
14 ft
North
3 ft
Depth 3.5 ft
10.5 ft
Punche Arroyo Center Shallow
20 ft
16 ft
Punche Arroyo Center Deep
Not to Scale
20 ft
3 ft
3 ft
SLV Irrigation Well Owners
HRS Water Consultants Inc.
Jan 2015 14-01
Punche.odg

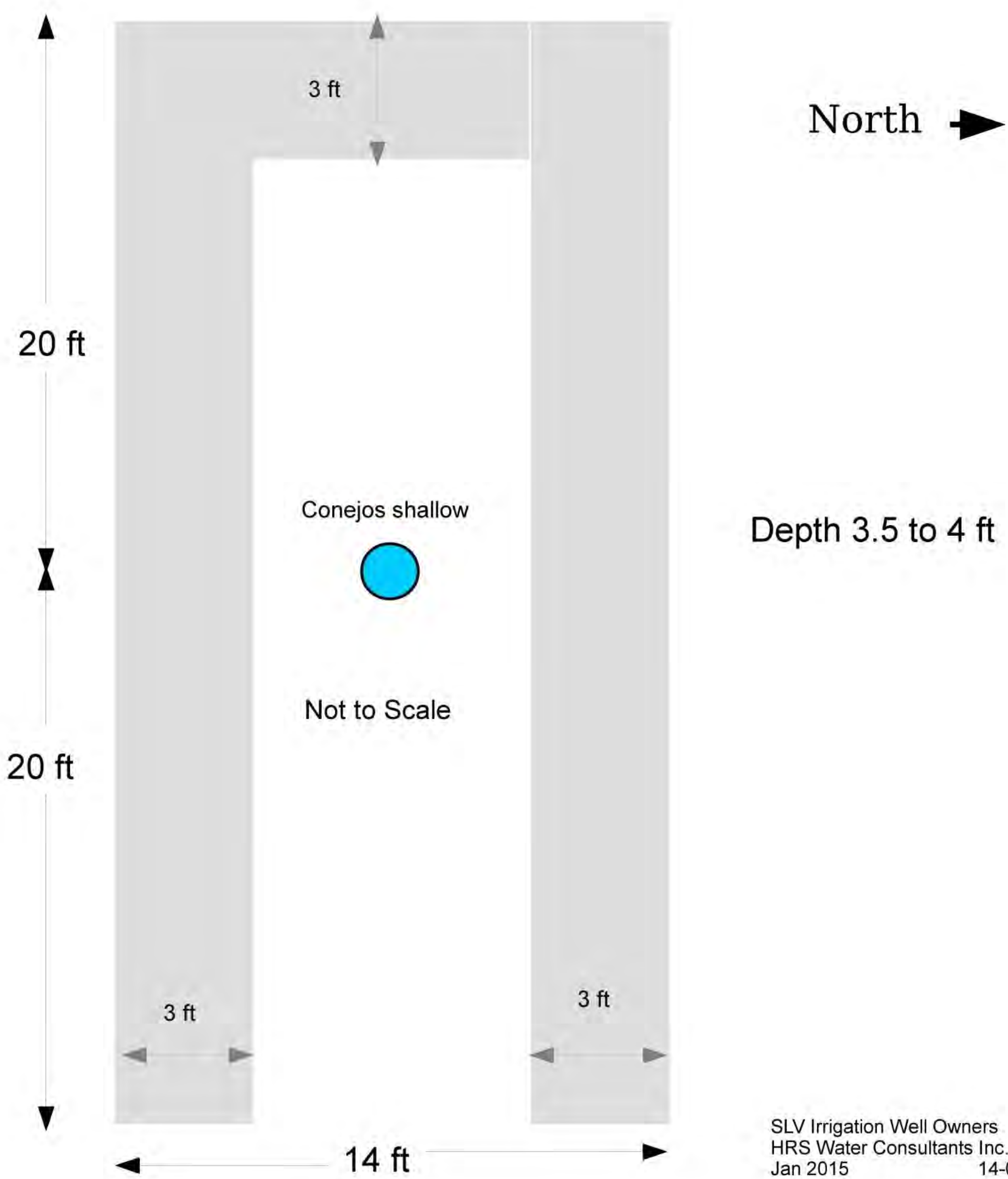
# San Antonio Recharge Site




SLV Irrigation Well Owners
HRS Water Consultants Inc.
Jan 2015 14-01

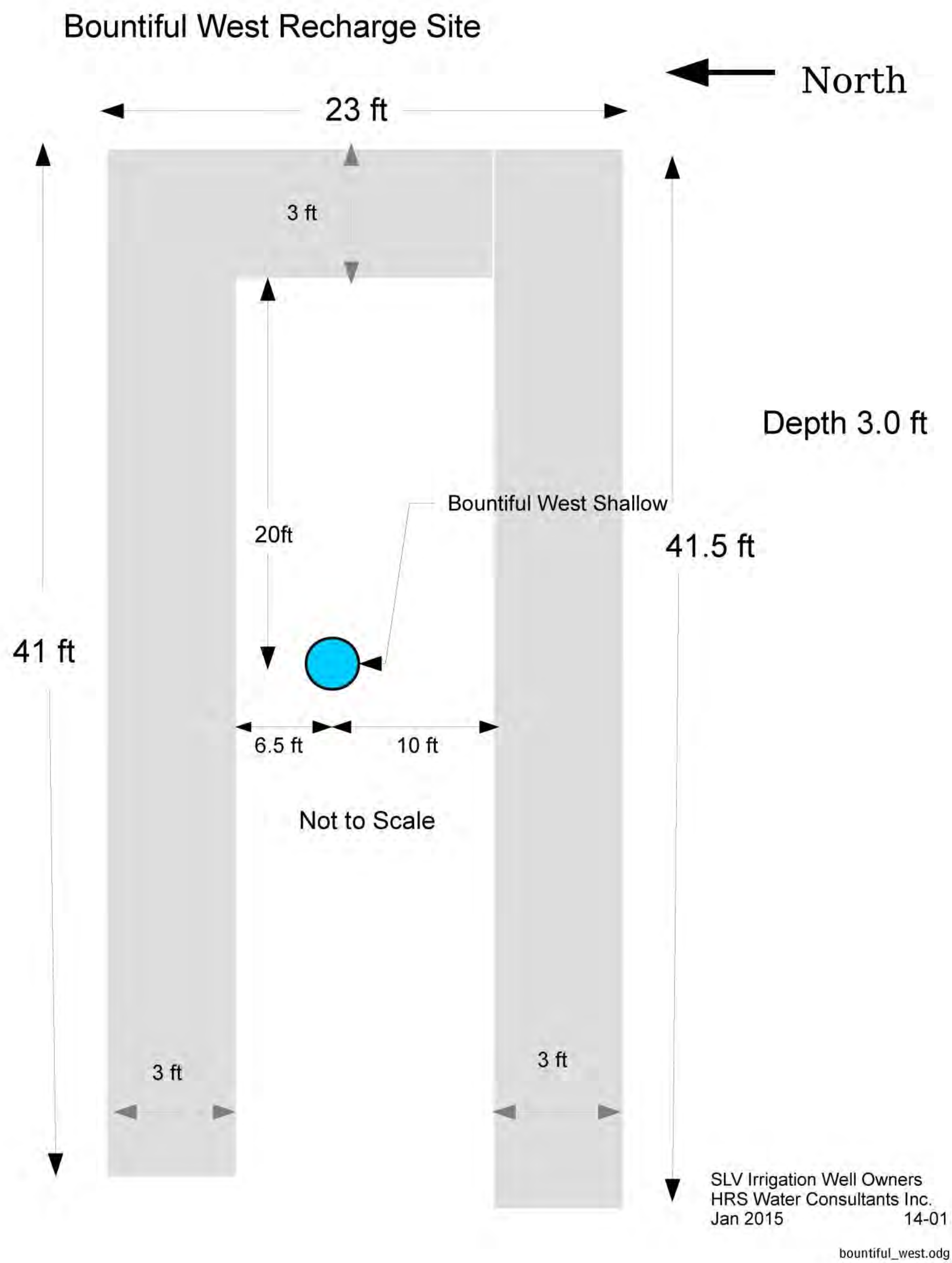
san_antonio.odg

Conejos West Recharge Site




SLV Irrigation Well Owners
HRS Water Consultants Inc.
Jan 2015 14-01

Conejos.odg


Bountiful West Recharge Site
North
23 ft
3 ft
41 ft
41.5 ft
Depth 3.0 ft
20ft
Bountiful West Shallow
6.5 ft
10 ft
Not to Scale
3 ft
3 ft
SLV Irrigation Well Owners
HRS Water Consultants Inc.
Jan 2015
14-01
bountiful_west.odg

Appendix Hantush Equation

Hantush derives an analytical expression for the rise and fall of a groundwater mound which forms due to a constant applied recharge. The solution assumes a rectangular area 2b by 2a in size. Recharge is applied from time zero to $t_0$ . Equation 3 gives the height of the mound (h) at any time t and and x/y. The first term is the positive recharge solution, the second term (image term) is negative recharge starting at $t_0$. The second term is zero for times less than $t_0$ . Octave was used to evaluate the expressions. Octave numerically integrates equation 1.

1) $$W(\alpha,\beta) = \int_0^1 erf\left(\frac{\alpha}{\sqrt{\tau}}\right) erf\left(\frac{\beta}{\sqrt{\tau}}\right) d\tau$$

2) $$Z(x,y,t) = \left(\frac{W_m \cdot \nu \cdot t}{2 \cdot K}\right) \cdot \left[ W\left(\frac{(b+x)}{\sqrt{(4\cdot\nu\cdot t)}}, \frac{(a+y)}{\sqrt{(4\cdot\nu\cdot t)}}\right) + W\left(\frac{(b+x)}{\sqrt{(4\cdot\nu\cdot t)}}, \frac{(a-y)}{\sqrt{(4\cdot\nu\cdot t)}}\right) + W\left(\frac{(b-x)}{\sqrt{(4\cdot\nu\cdot t)}}, \frac{(a+y)}{\sqrt{(4\cdot\nu\cdot t)}}\right) + W\left(\frac{(b-x)}{\sqrt{(4\cdot\nu\cdot t)}}, \frac{(a-y)}{\sqrt{(4\cdot\nu\cdot t)}}\right) \right]$$

3) $$h^2(x,y,t) - h_i^2 = Z(x,y,t) - Z(x,y,t-t_0)$$

| | |
|---|---|
| $2 \cdot b$ | - width of the recharge area |
| $2 \cdot a$ | - length of the recharge area |
| $W_m$ | - applied recharge rate |
| $S_y$ | - Specific yield |
| K | - hydraulic conductivity |
| $h_i$ | - initial saturated thickness |
| $\bar{b}$ | - average saturated thickness |

$$\nu = \frac{(K \cdot \bar{b})}{S_y}$$

Note that $\frac{W_m \cdot \nu \cdot t}{2 \cdot K}$ is linear in time.

Appendix

Piezometer completion reports and monitoring well permits

*(to be included in final report)*