Arrowhead Tunnels Project Special Uses Permit – Geo-Sciences Specialist Report

Geotechnical – Geology – Hydrogeology Specialist Report

The Arrowhead Tunnels Project is a portion of the larger Metropolitan Water District (MWD) Inland Feeder Project and involved the construction of two water conveyance tunnels located beneath the San Bernardino National Forest. The tunnel construction included almost 50,000 linear feet of tunnel and spanned more than eleven years. The San Bernardino National Forest issued and managed a Special Uses Permit to MWD allowing construction within the confines of the National Forest. Before, during and after construction groundwater dependent resources were and continue to be a primary concern of the Forest Service. Considerable multi-disciplinary and multi-agency work was performed by many technical specialist over the course of the project. This work included evaluation of construction techniques, hydrogeologic context, groundwater impacts and their effects on groundwater dependent resources, and groundwater recovery. Additional considerations have been made with respect to future needs and potential effects on those resources. This report covers that work from the Forest Service Geosciences perspective.

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Geotechnical- Geology-Hydrogeology

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Section 1. Impact and Recovery

Mining History

The intent is not to give an in depth understanding of the project history from start to finish, but give a brief overview of the mining history and its tie with impacts to the groundwater dependent resources within the project area. The goal is to provide enough information to allow a general understanding of current geotechnical, hydrogeologic and associated hydrologic conditions within the context of the initial conditions within the project area. This information will then hopefully provide an understanding of the recommendations to be implemented in the new US Forest Service Special Uses Operations and Maintenance Permit for the Metropolitan Water District of Southern California (MWD) Arrowhead Tunnels project. For additional project information the reader is invited to review the US Forest Service Administrative Project Record and specialist's reports and MWD's as built documents.

Mining History has been divided into three sections based on chronological commencement of construction. Therefore the first phase of construction to be addressed is identified as City Creek and was initiated at the location of the east portal of the eastern tunnel alignment. As this portal is located proximal to the mouth of City Creek Canyon, it has become known as the City Creek Tunnel. Years after this section was completed, construction started up again, this time initially at the western end of the eastern tunnel located in Strawberry Canyon and moving to the east. This section has been dubbed the Arrowhead East Tunnel (AHE or AET). The final portion of construction began shortly after Arrowhead East commenced and started out of Waterman Canyon. This is actually a separate tunnel alignment that runs from Waterman Canyon at the eastern portal westerly to the Devil's Canyon Portal. This portion of the project is known as the Arrowhead West Tunnel (AHW or AHT).

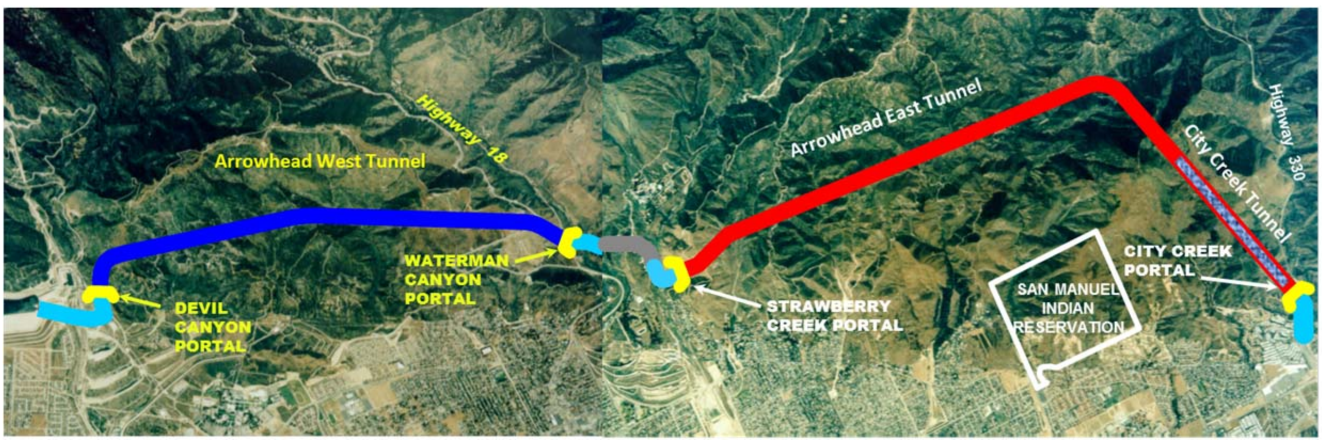


Figure 1. Layout of the three Arrowhead Tunnels Alignments.

City Creek Tunnel

Construction of the 8000 foot section of City Creek portal began in May of 1998 and shortly thereafter mining of the 19-foot diameter sub-horizontal hole, that would become one of the Inland Feeder Project's water conveyance tunnels, began. A conventional type of tunnel boring machine (TBM) used in typical dry or semi-dry hard rock mining was determined to be sufficient. No provisions were made for reducing the flow through the heading into the tunnel save a probing and grouting program. Under this program a probehole is drilled out in front of the TBM heading (the leading edge of the TBM which grinds or spalls the rock). Rock quality is determined by ease of drilling and the amount of water contained within the rock ahead of the TBM is assumed proportional to that which is produced from the probehole. One drawback to this technique is that unless sufficient probeholes are established, a water bearing fracture can be missed by the probehole. If ground ahead of the TBM is deemed unstable or has too much water, then theoretically the probehole can be used as a means of forcing grout into the rock mass ahead which ideally cements it together and provides a stable and impermeable bulkhead through which mining can continue. As the TBM progressed forward, a concrete liner made of precast sections was installed behind the TBM with the purpose of ensuring the hole remained open until the final 12-foot inside diameter steel liner could be installed. The initial concrete liner was fit into the tunnel and held against the rock walls by way of a strut installed at the crown.

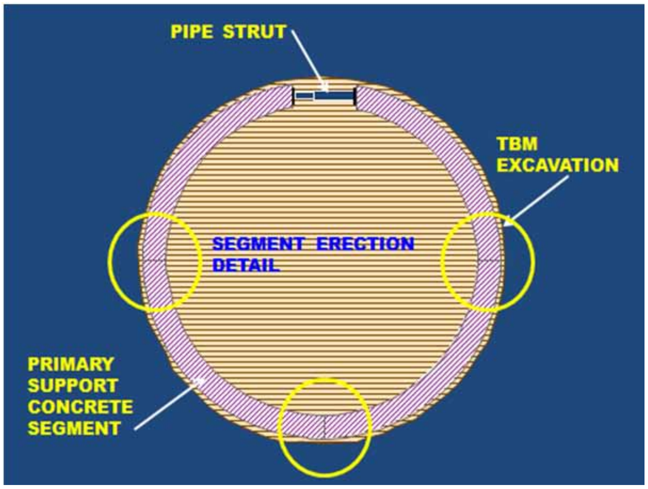


Figure 2. Layout of initial concrete liner segment.

Mining progressed as planned under relatively dry conditions and by mid- July of 1998 after approximately 1000 feet of forward progress the contractor was pushing through the North Branch of the San Andreas Fault (now called the Mill Creek Fault, (Willis, Weldon II, & Bryant, 2008)) passing from alluvial and sedimentary units into cataclastic gneiss and migmatite. At this time the first water was flowing into the City Creek portal from inside the tunnel (MWD). By late July of 1998 the water lever in well 913 started an anomalous decline. Well 913 is located next to the North Branch of the San Andreas and only a few hundred feet to the east of the tunnel alignment. During August and September of that year mining was progressing through the San Manuel Fault System (MWD) which is located about 3000 feet from the portal. During the latter part of August the lower piezometer in Well 912, which is located on the south side of the San Manuel fault in the gneiss, started to respond by a displaying a decline in pressure. By mid-September the TBM was located below the south ridge to McKinley Mountain, approximately 4500 feet from the portal and on 18 September, after several days of sheared rock and interspersed marble zones, flow into the tunnel jumped up to over 100 gpm. By mid-

October the rock ahead of the TBM was increasingly sheared. Forward progress was slow. Both the upper piezometer in well 912 and Well 911, both located on the north side of the San Manuel fault (gneiss with inter-bedded marble layers), began to quickly loose pressure as well. In late September inflows to the tunnel (coming out of the City Creek portal) were over 200 gpm (MWD) and by mid-October water flowing out of the City Creek portal was over 500 gpm.

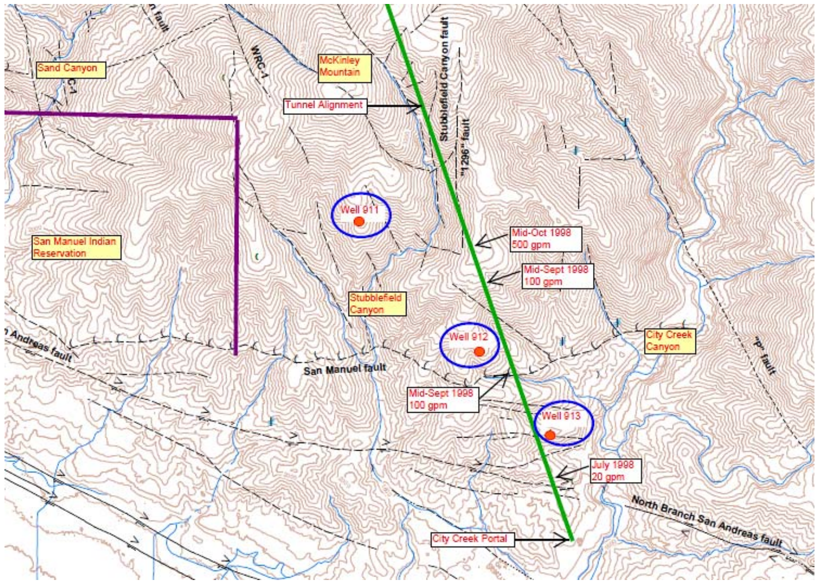


Figure 3. Progression of TBM and groundwater discharge to City Creek Portal.

At this time the first tunnel related impacts to surface waters were starting to manifest. A group of horizontal wells on private property in Stubblefield Canyon, approximately 2000 linear feet (LF) to the west of the tunnel alignment and due south of Well 911, dramatically began to decline in production. Additionally flows at a monitored stream site near the mouth of the canyon, Stream Site 622, exhibited significant decline as well.

In early November the TBM was encountering substantial shearing associated with a north-south trending lineament known as the "1296" fault. Rock quality was greatly diminished and flow of water into the tunnel increased to over 700 gpm (Metropolitian Water District of Southern California, 2000). Mining ceased as probing and grouting efforts intensified in an attempt to stabilize the ground. Over the next few months forward progress was reduced by half as the ground became increasingly sheared and groundwater pressures increased.

After 6000 total linear feet of mining, in early January 1999 the TBM encountered another north-south lineament, the Stubblefield fault. Groundwater flowing into the un-lined tunnel spiked above 1000 gpm and averaged approximately 950 gpm. Forward progress stopped as attempts to control inflows and move through the sheared ground intensified once again. By now the Stubblefield well cluster, originally with yields averaging 50 to 60 gpm, were producing only about 6 gpm (USGS, 1999). Other surface water sites to the east of the tunnel alignment were starting to present noticeable reductions in flow.

With the Stubblefield fault zone behind the TBM, forward progress again increased in February but groundwater inflows into the tunnel were typically greater than 1400 gpm with spikes of up to almost 1800 gpm. By this time the San Manuel Tribe and the US Forest Service became actively involved in assessing mining activities and effects.

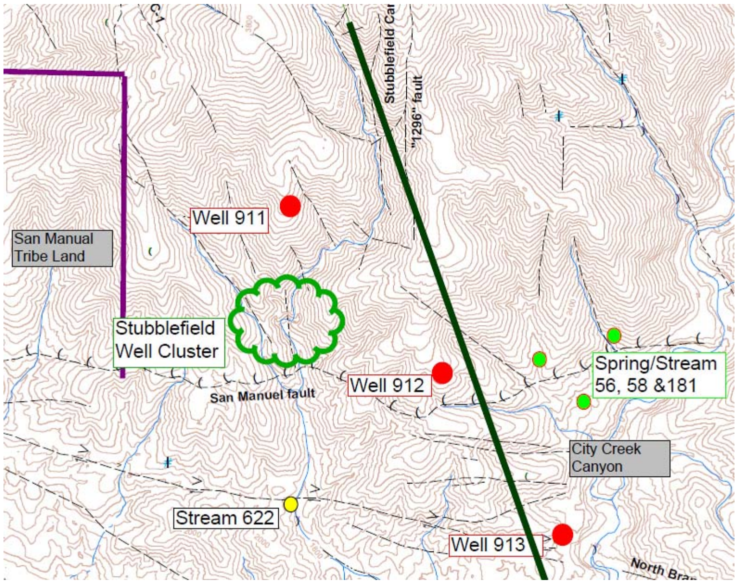


Figure 4. Apparently affected ground and surface water sites.

In April of 1999 mining was ceased at a distance of 8008 linear feet from the City Creek portal. A bulkhead of grout and concrete was built ahead of the completed un-lined tunnel and the effort focused on halting groundwater entry into the tunnel. These efforts included the reduction of hydrostatic pressure encompassing the tunnel by drilling laterally into the rock in order to facilitate faster drainage of the surrounding rock. Once pressures and subsequently groundwater inflows were brought down, cutoff grouting was initiated. This involved forcing of a cementatous material back into the drilled pressure relief holes at a pressure higher than the surrounding hydrostatic pressure. The attempt was to fill the joints along the tunnel alignment with an impermeable material which would effectively stop groundwater from pouring into the tunnel and out to City Creek.

By mid-May of 1999 flows into the tunnel were generally brought down to below 1000 gpm. Average inflows a month later were about half that and by late August flows into the tunnel were approximately 350 gpm. By this point the cumulative quantity of groundwater extracted from the area to the south of Mckinley Mountain was greater than 400 million gallons and still increasing. The effects of this loss were evident as all of the groundwater in the vicinity of the wells that were initially impacted was now severely impacted. Well 911 exhibited the greatest decline with almost 200 feet of drawdown. Additionally impacts to surface water sites in the vicinity were clearly discernible. Yield from the Stubblefield well cluster to the west was in the neighborhood of 2.5 gpm and flow had ceased at the mouth of the canyon at monitored Stream Site 622. To the east of the alignment along some small tributaries to City Creek, flow had dried up completely or had been reduced to a trickle. These sites included Spring Site 56 and down canyon Stream Site 151 along with a neighboring tributary Spring Site 58. Other sites in the vicinity may have also been affected, but pre-impact monitoring was of such short duration that effects are inconclusive.

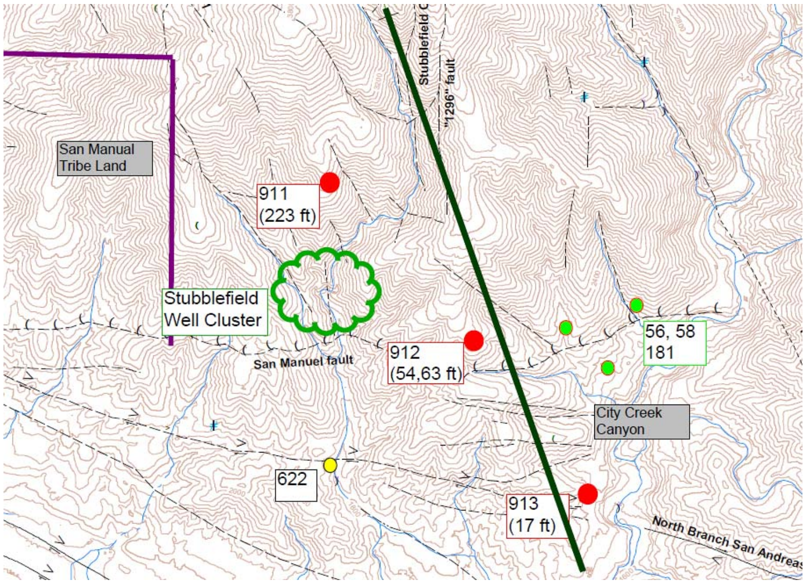


Figure 5. Locations of sites with known impacts. Groundwater sites (red) additionally list maximum impact.

Modeling by Forest Service Consultant Bob Bianchi showed a trough of depression along the completed tunnel alignment and extending east toward City Creek drainage and west to the east fork of Stubblefield Canyon (Bianchi, 1999). It is believed that faulting to the west of the alignment including a prominent northwest trending lineament, the WCR-1 fault which extends from Stubblefield Canyon up to the N-fault in the upper part of Sand Canyon, may have prevented significant extension of the trough into the confines of the San Manuel Indian Reservation (Lubischer, 2012).

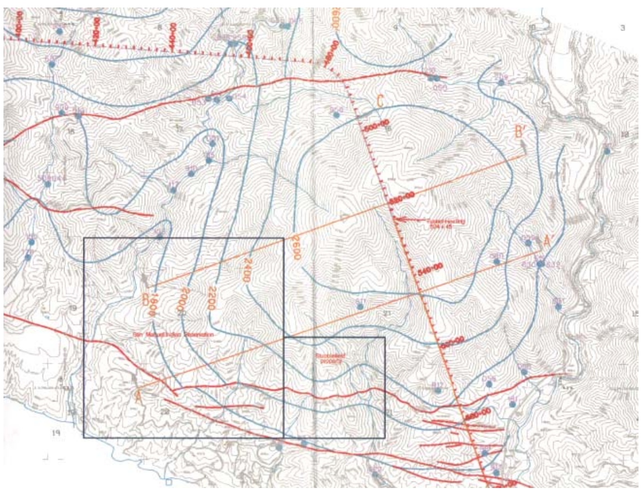


Figure 6. Pre-Tunnel groundwater contours, 1995.

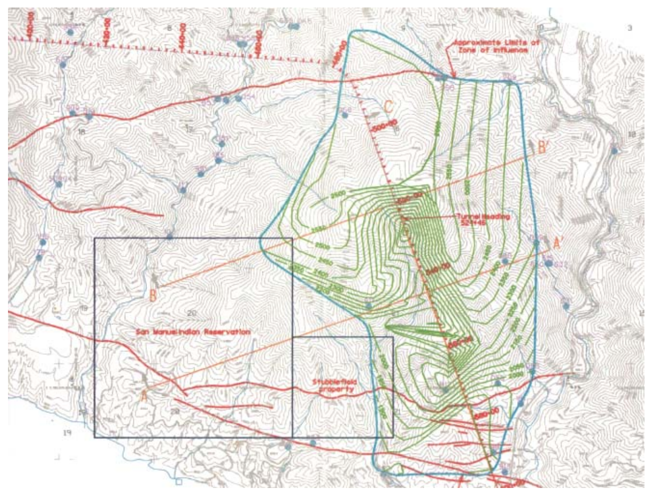


Figure 7. Groundwater contours as of July 1999 showing trough of depression.

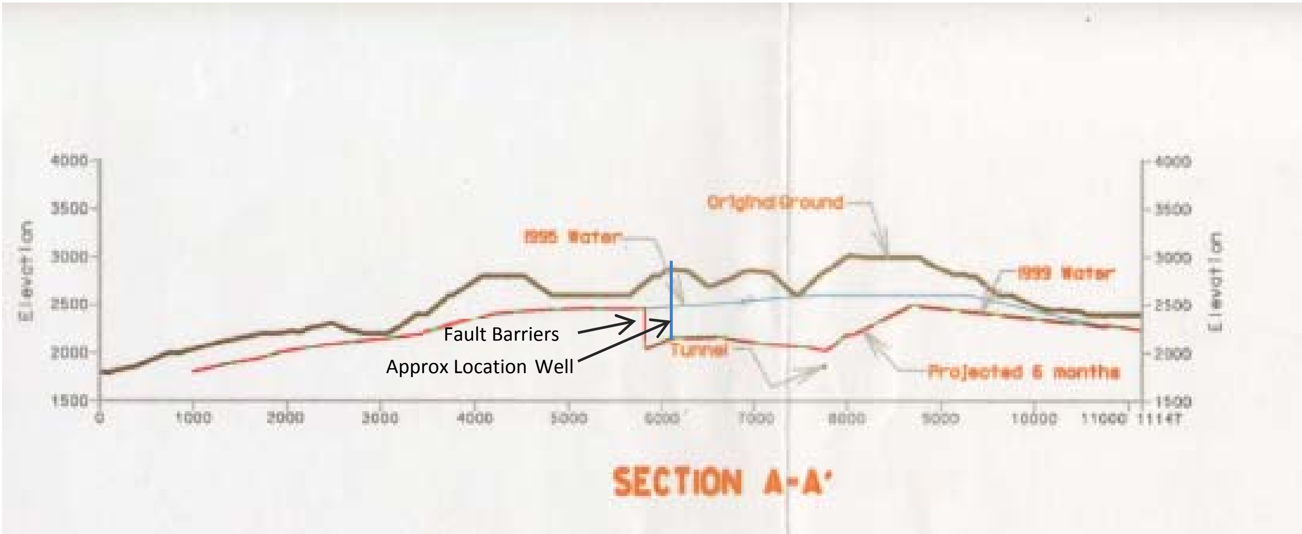


Figure 8. Cross section showing groundwater levels before and during construction.

From September to December 1999 cutoff grouting continued and permanent pressure relief valves were installed. These valves would allow controlled release of water in the rock and facilitate installation of the final steel pipe liner. Flows into the tunnel would consistently be between 250 and 350 gpm over the course of the next year and would not diminish completely until the tunnel was sealed in 2001.

Lining of the tunnel with the 12-foot diameter steel pipe commenced in August of 2000, starting at the bulkhead and moving toward the City Creek portal. This liner consisted of sections 10 to 20 foot in length with a wall thickness which varied from ½- inch to 7/8-inch depending on proximity to faulting. The pipe was transported to the site and welded in place. In January 2001 as the last of the steel pipe was set in place backfill grouting began which was used to effectively seal the annular spaces between the concrete segments and the mined rock.

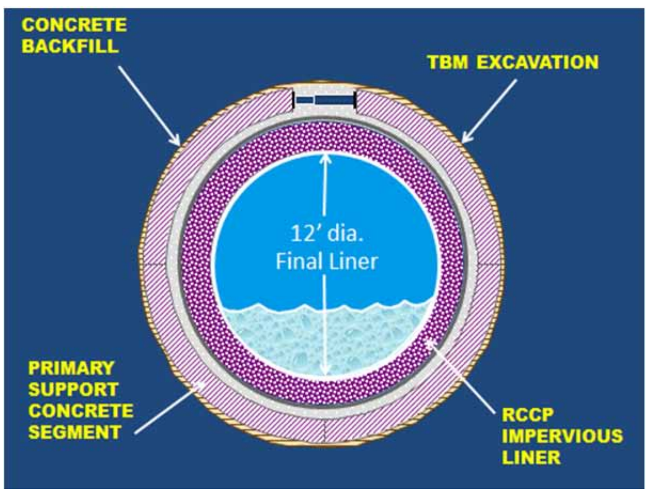


Figure 9. Final liner concept.

Contact grouting is a backfill grouting technique that fills the space between the concrete segments and the steel pipe. This provides support and strengthens the steel liner while also preventing longitudinal movement of water. This activity commenced in late May of 2001 and finished 3 months later. During the last months of construction a series of piezometers were installed in the crown of the tunnel. The purpose being to measure hydrostatic pressure along the length of the tunnel and track changes in groundwater head and hopefully recovery. In all 14 piezometers were installed starting just north of the San Manuel fault and continuing to the bulkhead. The first readings were taken in late August and continued roughly monthly until they were removed during final tunnel construction in April of 2008.

By August of 2001 the final sealing of the bulkhead and the portal was taking place and on the 25th of September the last of the groundwater flowed from the City Creek Portal. The City Creek portion of the eastern tunnel alignment was effectively sealed. By this point in time construction was completed on 8008 linear feet of tunnel over a period of 3 years and 4 months with a loss of approximately 685 million gallons of groundwater from below the south and west slopes of McKinley Mountain.

Arrowhead East Tunnel

Termination of mining on the City Creek portion of the Arrowhead East Tunnel initiated a re-design of the TBM's, the primary lining system (concrete liners), and mining techniques and procedures. The primary modification to the TBM came with an attempt to construct a machine that could mine in hard rock yet behave similar to an earth pressure balanced (EPB) machine which is used in soft ground conditions with hydrostatic pressure. The EPB machine has features which allow the TBM to adjust the pressure inside the machine to match the pressure exerted by the ground on the TBM face. The goal was to allow mining to continue while the groundwater pressure was 3 Bars (100 feet of water head) and to be able to shut out 10 bars of pressure (~335 feet of water head). In addition, sealable ports were added to the front or head of the TBM and to the side shield which allowed the miners to drill holes through the TBM into the rock. These drilled holes are called probeholes and serve several purposes. First the miners able to use the probeholes to assess ground and groundwater conditions up to approximately 150 feet ahead of the TBM. Additionally grout could be pumped into the probehole under pressure. The goal with this latter technique is to fill the local fractures with a grout mixture that would decrease the permeability (rate at which water flows through the material, rock or soil) of the rock. Additionally grout can be added to improve the quality of crumbling rock by essentially gluing it together.

A huge advance in the lining system included the design and use of the gasketed bolted concrete segments. This was a system that had been developed and used in Europe, but not as of yet in the United States. Each 5-foot long segment was comprised of 6 pieces which were specifically designed for this project and constructed in a local plant. Each piece was surrounded by a rubber gasket that would seal against the neighboring segment piece and exclude water under a pressure of 550 feet of head for Arrowhead West and 900 feet of head for Arrowhead East. Bolting the segments together was necessary to both achieve the design water tight seal, and to assist in properly aligning the segments. In order to assist with contact grouting, grout holes were molded into the segments, as mentioned above, and fitted with a water-tight plug.

Figure 10. Set of gasketed sections used to construct 5-foot concrete segment

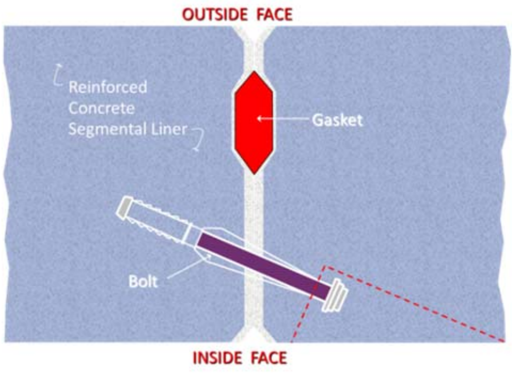


Figure 11. Joint detail of abutting segment sections

Additionally water resource monitoring was increased and intensified. Three monitoring wells were drilled around the San Manuel reservation which included extensive borehole logging and geophysical testing. Roughly 3-1/2 years later in mid-August of 2003, mining began again on the Arrowhead East Tunnel from Strawberry Canyon at the west end of the alignment.

As the TBM moved eastward through the quartz monzonite rock quality appeared to be good and the rock face ahead of the TBM was dry or damp with no water flowing into the tunnel. In late November, about 1700 feet from the Strawberry Canyon portal, the TBM passed through a fault known as the FRS-2 fault and barely slowed down. Mining continued for another 1000 feet in this manner averaging a bit over 4 rings or 21 feet per day of forward progress.

In the second half of December, 2600 feet from the west portal, the first groundwater inflows into the tunnel were recorded at about 50 gpm. For the next 10 days drilling and grouting of probeholes ensued in an effort to decrease groundwater inflows. These first efforts were successful and verification holes were drilled which met the established criteria, of less than 0.3 gpm/linear foot, which allowed forward movement.

In January 2004 forward progress began again but groundwater heads increased and geology became more challenging as more shearing was encountered. Inflows were stabilized at around 30 gpm. The rock proved to be more abrasive than originally accounted for and issues with the TBM screw auger surfaced. The screw auger is responsible for moving the spalled rock from behind the heading (the cutterheads reside in the heading), in a space known as the plenum, to the conveyor belt inside the shield. From here the material is transported back to muck carts and removed from the tunnel via a rail system. By the end of January the screw auger was so worn that it could no longer move material out of the plenum. A new auger was ordered from Germany and it took until March before installation was complete. During that time groundwater was flowing into the tunnel at an average rate of 35 gpm.

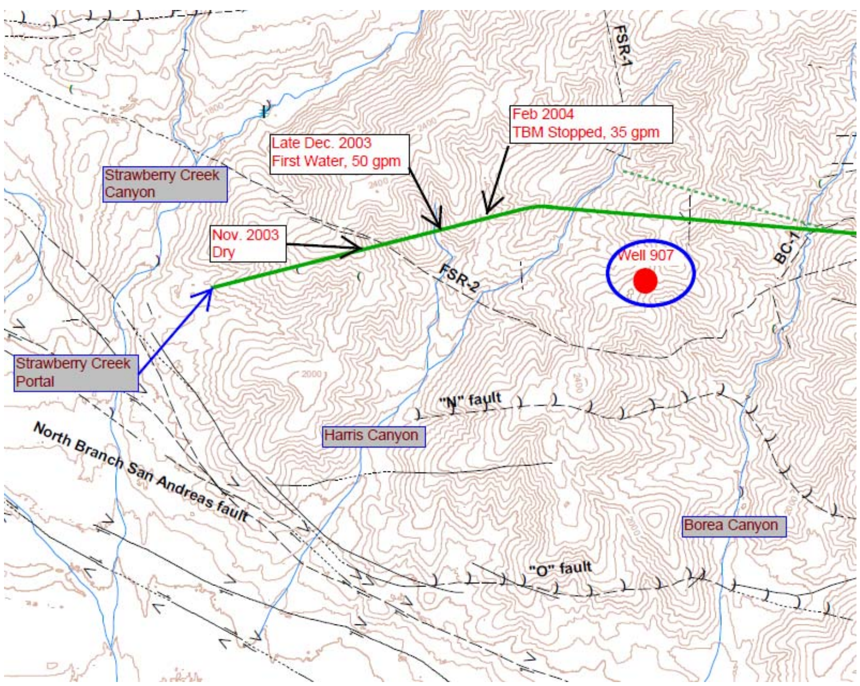


Figure 12. Initial progress on Arrowhead East from Strawberry Creek portal.

Also during that time the first impact to groundwater manifested with acceleration in declining pressure (increase in recession) in the Well 970 hydrograph. Typically the wells in the project area (and by extension, much of the groundwater) undergo a gradual recession in pressure or head until rainfall is sufficient to provide recharge. Often this is during the El Niño seasons occurring on average every 5 years. In the case of Well 907, the hydrograph recession increased by a factor of almost 3 suddenly in

February of 2004. Well 907 is located on the ridge between Harris and Borea Canyons and potentially connected to the groundwater near the TBM through faulting.

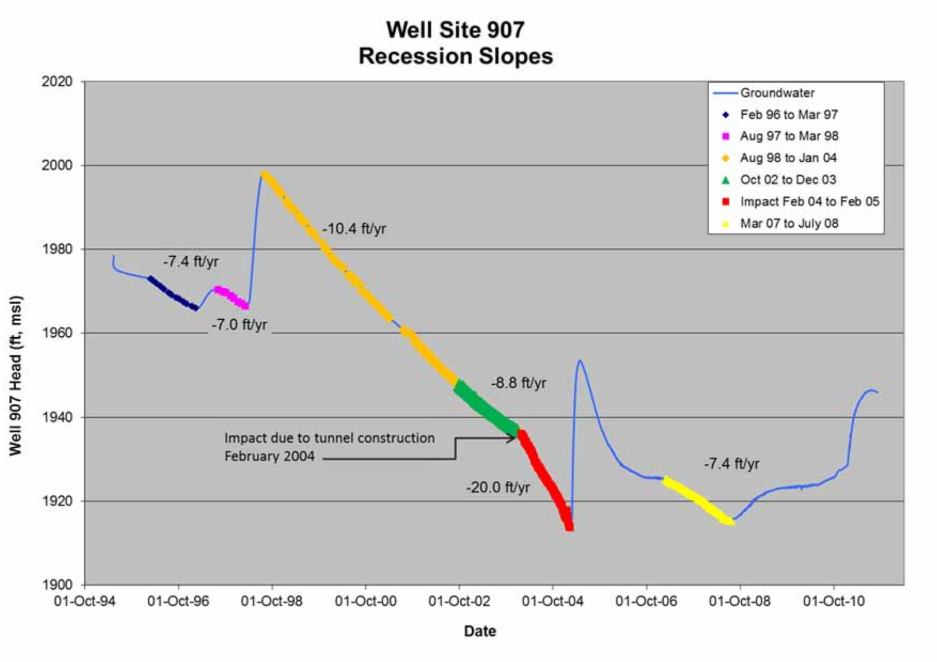


Figure 13. Hydrograph of Well 907 showing pre and post impact annual rates of decline in groundwater head.

In late March, about 4200 feet from the portal the first in-tunnel piezometer was installed. This instrumentation was to be installed every few hundred feet and would allow tracking of groundwater pressures in the rock surrounding the tunnel. These installations provided valuable information such as recovery of groundwater, compartmentalization of groundwater (especially relative to faulting) and were able give an indication of how effective the contact grouting program was and whether there was longitudinal connectivity in the annular space between the concrete segments and the country rock.

By mid-April the FSR-1 fault was encountered. Inflows increased to around 65 gpm and the first seepage of 15 gpm was added to groundwater coming out of the Strawberry Creek portal. Seepage was leakage of groundwater into the tunnel and occurring behind the TBM heading and trailing gear (generally from a distance of 600 feet or more back from the face of the TBM). This groundwater inflow into the tunnel is unrelated to the current mining operation. Rather it is an artifact of segment construction, erection, or ineffective grouting. Early on in the mining operation, difficulties arose in the placement and alignment of the concrete segments. The segments were constructed with high pressure gaskets which, when aligned properly and bolted together, formed an effective seal against groundwater seepage. During the early days of mining, the crews were learning and developing procedures for placement of these concrete segments. Skill came with time and experience. Consequently more leakage came from between the segments in the first year or so of tunnel construction. A second source of seepage came from the concrete segments themselves. Each segment was fitted with a plastic plug which could be removed so that the space behind the segment could be pumped with grout. Unfortunately these plugs were deficient in the number of threads required to hold out groundwater at higher pressures. As a result, many plugs leaked or blew out entirely as the tunnel progress forward into the higher groundwater pressures.

Figure 14. Segment grout hole in use

Figure 15. Leaky grout plug

New plugs were eventually installed and ultimately in the areas of high groundwater heads (or pressures) steel plates were bolted over each plug to hold it in place and further reduce the seepage of groundwater into the concrete lining.

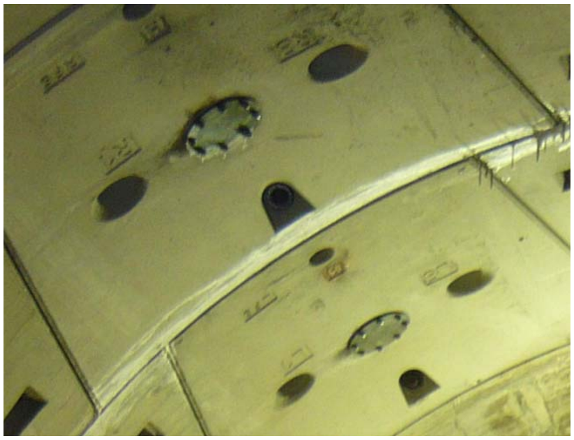


Figure 16. Steel Plates were installed over plugs in areas of high groundwater pressures

In late-April forward progress was met with diminished rock quality. The TBM was solidly into the westerly dipping Borea Canyon-2 fault zone and in early May the TBM became stuck. The mining crew worked for two months to free the machine. They were eventually successful by lubrication of the tailshield (the "can" behind the plenum where the screw auger is and where the concrete segments are erected) with a slippery clay called bentonite and employment of six 200 ton auxiliary jacks (in addition to the thrust rams built into the tailshield) used to push the TBM forward. By July the TBM was moving again but with much difficulty in the sheared ground. It would take 2-1/2 months to travel the 200 feet to clear the fault zone. During that time two more wells in Borea Canyon, first Well 953 followed by Well 908, initiated a response to tunnel construction by increases in the typical recession rates.

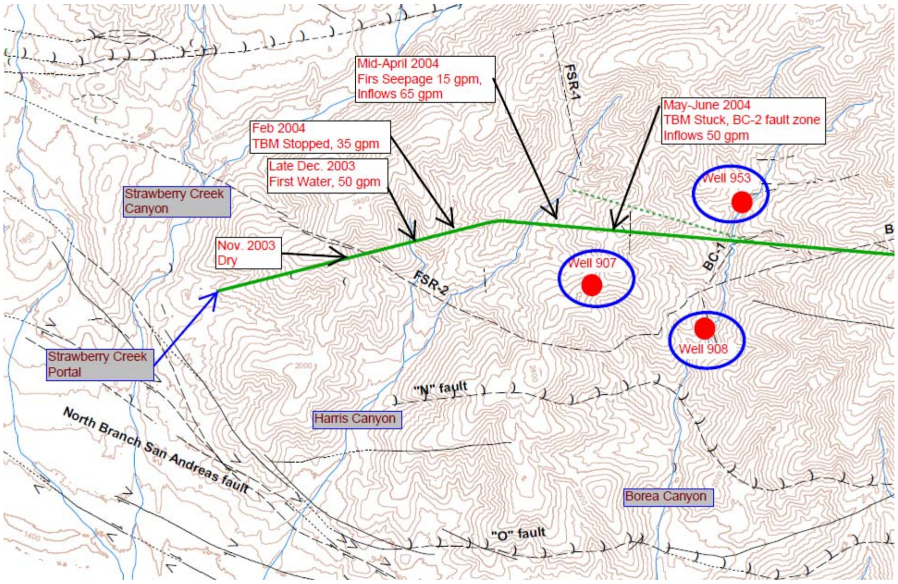


Figure 17. Mining progress through Harris Canyon

Within the next 2 weeks the TBM would gain 125 feet of progress only to be stopped on 1 November when the ground in front of the machine failed. The TBM was again stuck and would not move until early in the next year. Meanwhile groundwater inflows increased to 140 gpm and with this increase the both Well 953 and 908 increased their recession rates.

In mid-January of 2005 the TBM was freed again with the use of auxiliary jacks. Mining production increased as did groundwater inflows which were often over 200 gpm and peaking above 300 gpm.

In late April, after approximately 6800 feet of mining, the TBM passed the Borea Canyon-1 fault (BC-1) in the bottom of Borea Canyon and groundwater peaked out at over 400 gpm. Well 908, having started to recover in response to the early precipitation associated with the 2004-2005 El Niño precipitation season was now receding at a rate of 144 feet/year or 18 times its pre-impact rate of decline.

Generally from about July through October, as the runoff and water stored in surficial sediments diminishes, groundwater is the primary contributor to many of the stream and spring sites in the project area. In the spring of 2005 both monitored surface water sites in Borea Canyon, Spring Site 45 and down canyon Stream Site 154, exhibited a noticeable reduction in flow which was especially pronounced as the precipitation from the 2004-2005 El Niño precipitation season receded. Such an extreme season generally kept flows relatively high for several seasons through groundwater recharge. Subsequent studies indicated very good correlations between groundwater heads and surface water flows in this canyon. By July of 2005 construction impacts to groundwater dependent resources in Borea Canyon became evident. Mitigation using supplemental water was started at Sites 45 and 154.

By mid-July groundwater inflows were brought down to less than 100 gpm through extensive grouting. The TBM again passed through the Borea Canyon fault zone. Rock quality diminished but mining progressed without incident for the next 500 feet until the TBM was brought down for repairs in mid-August. It would take the next 3 months to cover the last 500 feet to the divide between Borea and Little Sand Canyons. During this time the TBM was intermittently stopped for repairs, for modifications or because it was stuck. During the last part of October, as the TBM encountered yet another shear (ground characterized by broken or crushed rock resulting from tensile or compressive stresses), inflows (which had been generally controlled to less than 100 gpm) doubled. By the early part of November the TBM was finally making its way under the western slope of Little Sand Canyon.

During the time from commencement of mining in August of 2003 to passing through Harris Canyon in October of 2004 and Borea Canyon in November of 2005, 27 months have passed, 9,500 linear feet of tunnel have been mined, and 110.5 million gallons of groundwater have passed into the tunnel.

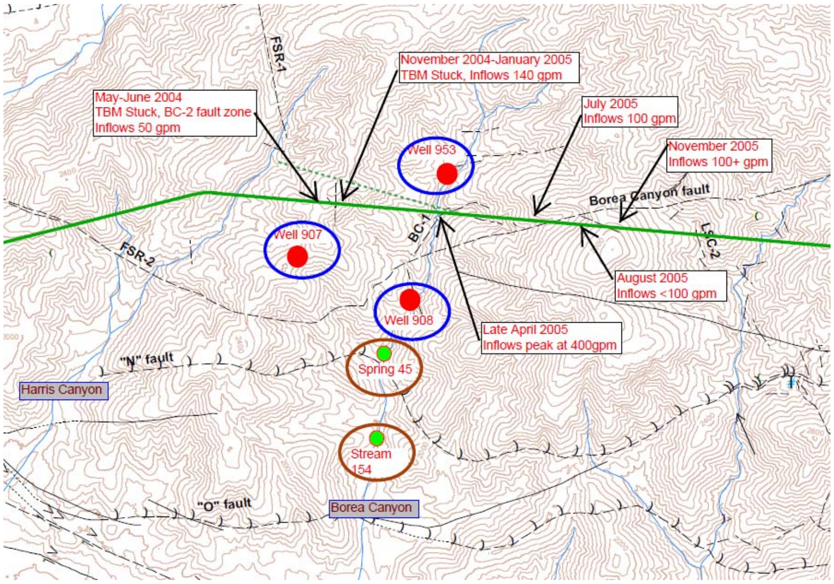


Figure 18. Mining progress and impacts through Harris Canyon

Over the next 6 weeks and 500 linear feet of mining groundwater flow into the tunnel from the heading climbed steadily up toward 600 gpm. The groundwater heads increased upon clearing the Borea Canyon fault zone. By the time mining was directly beneath the main drainage to Little Sand Canyon, heads more than doubled to almost 550 feet above the tunnel.

In mid-December, after approximately 10,000 feet of mining, the TBM was in the vicinity of the Little Sand Canyon-2 fault (LSC-2). Also along the LSC-2 fault about 2000 feet to the southeast is Well 909 which, in the latter part of December 2005, started to respond to groundwater depletion.

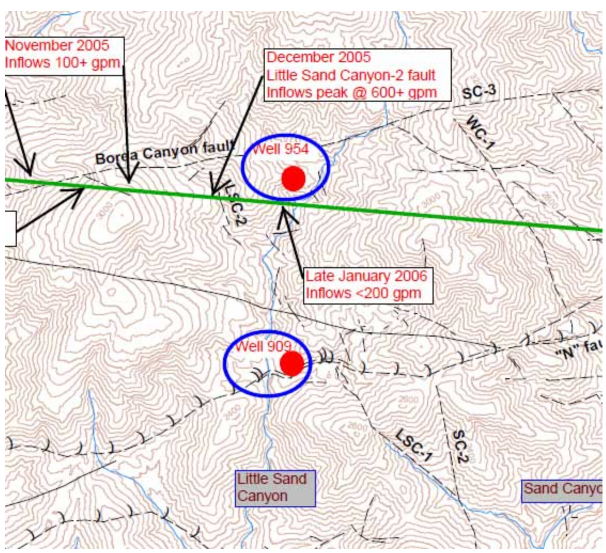


Figure 19. Early Little Sand Canyon effects.

After clearing the LSC-2 fault, inflows began to subside by about 50%. In late January, as the TBM approached the bottom of Little Sand Canyon, pressure in both upper and lower completions in Well 954 (less than 300 feet away) dropped dramatically (a completion is the sampled elevation range within the well. Some wells have multiple completions and may sample the same aquifer at different elevations or multiple aquifers penetrated by a single borehole). Over the course of the next month only 50 feet of tunnel was constructed, but almost 1 million pounds of grout was injected into the surrounding rock in an effort to stabilize the rock mass and reduce groundwater inflow to the tunnel.

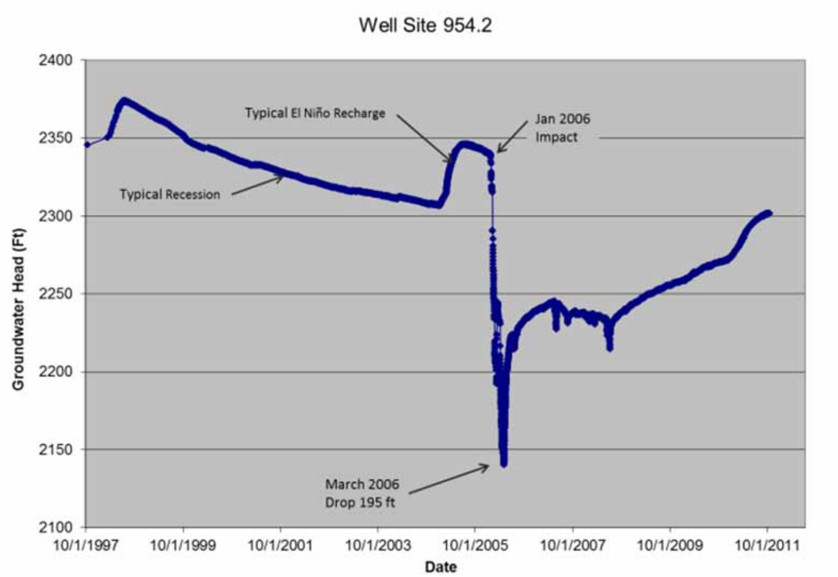


Figure 20. Hydrograph showing lower completion of Well 954.

As the TBM moved eastward to the margins of Little Sand Canyon, mining became difficult as groundwater heads increased to approximately 450 feet and rock quality continued to be poor due to shearing and alteration. Flow into the tunnel from the heading again surpassed 500 gpm.

By spring of 2006 concerns surfaced with regard to groundwater dependent resources within the canyon, particularly Spring Site 510 located in the upper canyon and proximal to well 909. This spring supports riparian vegetation and often provides year-round water to wildlife. By July mitigation infrastructure, installed the previous year, was activated and flows of 1-2 gpm were directed into a small guzzler established for wildlife.

Three additional surface water sites down canyon (Spring Site 44, Stream Site 509 located in a gaining reach of Little Sand Canyon, and Stream Site 155) would eventually manifest effects as a result of groundwater depletion, although these effects took several years to become apparent. As the TBM proceeded through the canyon, of the three wells in the Little Sand Canyon watershed only Well 958, which is located almost a mile to the south across two prominent features (N-fault & O-fault), would not manifest effects from tunnel construction related impacts to groundwater.

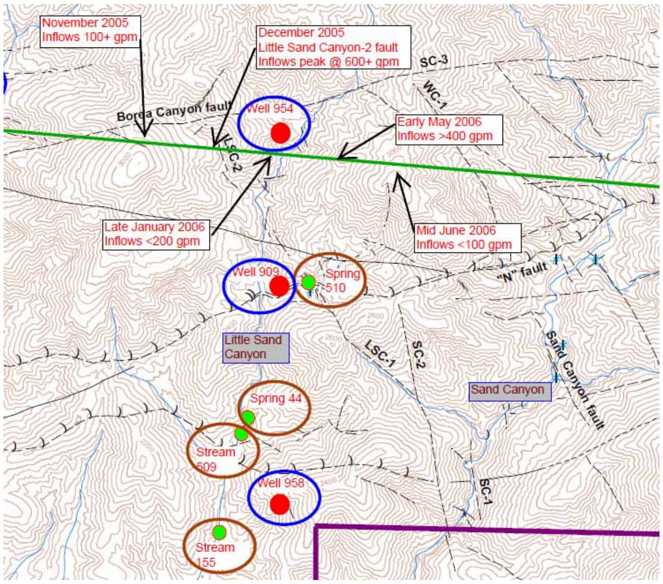


Figure 21. Mining progress and impacts to Little Sand Canyon.

By mid-June 2006 the rock quality appeared to improve; inflows dropped below 100 gpm and would stay that way for many months. The TBM was beneath the divide between Little Sand Canyon to the west and Sand Canyon to the east. From November 2005 when entering the western divide of Little Sand Canyon to leaving the Little Sand behind to the west about 8months later, 3000 feet of mining has taken place with 600 rings erected and 78.9 million gallons of water have drained from the mountain.

Mining progressed eastward beneath the west slopes of Sand Canyon. Inflows continued to be less than 100 at the heading but seepage along the length of the tunnel was increasing. Now at 50 gpm, most of the increase resulted from failed grout plugs in the concrete liner. The plugs simply could not withstand the increased hydrostatic groundwater pressures. By now new steel plugs had been delivered and construction crews were working to replace thousands of plugs even as mining continued.

By mid-July the TBM was pushing through the Waterfall Canyon-1 fault (WC-1). Groundwater inflows remained low but almost 400,000 pounds of grout was used to stabilize the ground. Potentially connected through this lineament is Spring Site 53 which is a small spring that supplies at least some flow most years to a west tributary to Sand Canyon. Sometime during the mid to late summer of 2006 this flow appears to have manifested project related effects.

Figure 22. Monitoring Spring Site 53 in a Sand Canyon Tributary

Mining continued steadily for months. Hydrostatic pressure from the groundwater had dropped to 350 feet of head and the rock quality was generally fair. Generally days of drilling probeholes ahead of the TBM and then grouting preceded days of mining forward and erection of concrete segments. It was not uncommon to achieve 50 to 60 feet (10 to 12 segment installations) of forward progress on mining days. By mid-September the TBM was beneath the canyon bottom and about 900 feet west and south of Well 955.

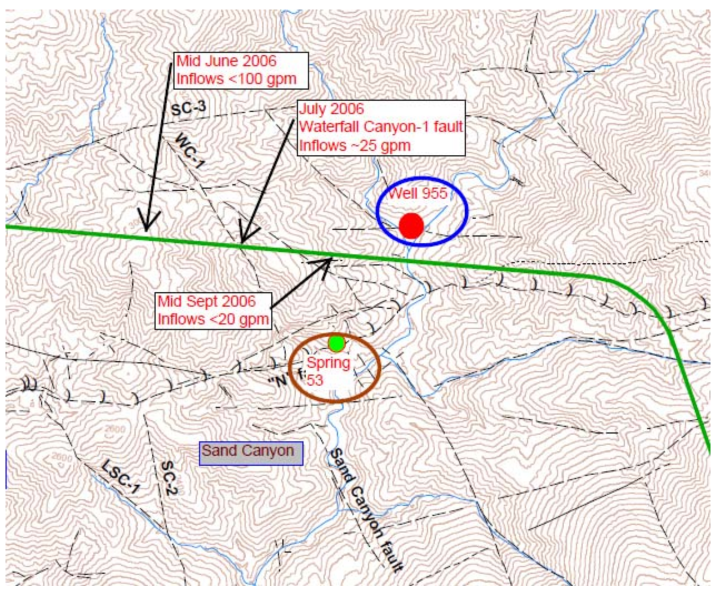


Figure 23. Early Sand Canyon effects, Summer/Fall 2006.

Although inflows remained low, the highly sheared ground provided direct conduits between the mining operation and groundwater dependent resources. The lower completion of Well 955was affected suddenly on 24 September and within one month head had dropped almost 100 feet. Well 955 has two completions, each being on different sides of the north dipping reverse fault known as the N-fault. The lower completion is a confined aquifer and is influenced by groundwater to the south of the N-fault which has a higher head than the groundwater to the north where the upper completion is located. The N-fault is the confining feature and acts as a semi-barrier or aquitard that prevents equilibration and allows an upward head gradient. Once the pressure in the lower completion dropped below the pressure in the upper completion the gradient reversed with the upper being higher pressure or head than the lower. During this time, in the first half of October, the upper completion head started to rapidly decline, being pulled downward by the reduction in pressure in the lower aquifer.

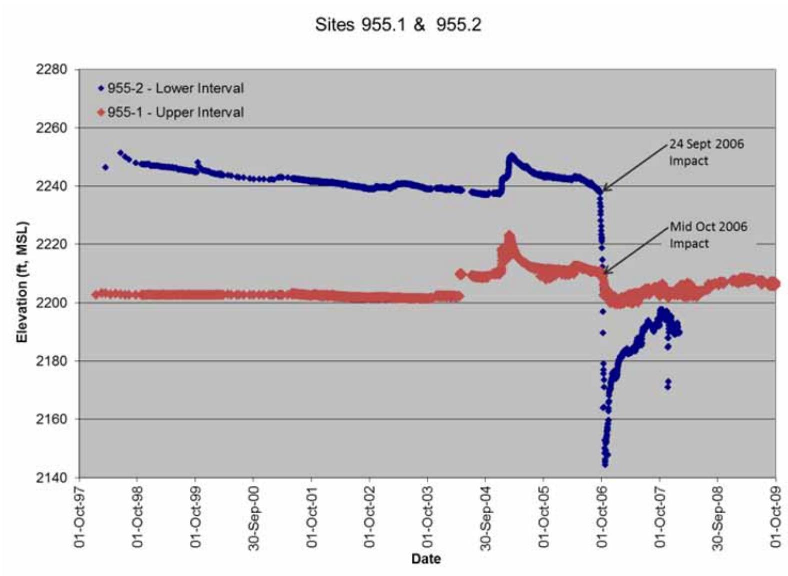


Figure 24. Hydrograph comparison between upper and lower completions (intervals) in Well 955 along with timing of impacts.

Progress was slow in November and December. The screw auger was worn and not removing ground material from the plenum well. As a result material piled up under the machine and pushed the shield up thereby skewing the TBM in the hole. Hand excavation was required to remove this material and put the TBM back into proper alignment. Mining started again briefly and after 60 feet was shut down. The screw auger was replaced. This would be the 4th replacement in the 16,000 feet of tunnel on Arrowhead East since mining began.

Mid-January 2007 saw resumption in mining and within two weeks a shear zone was intercepted. Inflows increased, mining progress slowed and by late February the lower completion of Well 956 was beginning to exhibit an anomalous pressure drop. Spring Site 48, located in the east fork of upper Sand Canyon approximately 700 feet north of the tunnel alignment and almost a half mile from Well 956 was showing signs of impact. By Mid-March the upper completion of Well 956 was impacted from tunnel construction as well. Planning and installation of much of the Sand Canyon mitigation was completed over the fall and winter months. Water was turned on at Spring Site 48 by early April and at Spring Site 53, Stream Site 636 and the terraces in the upper canyon above the alignment by mid to late May.

April and May were good mining months with improved mining conditions. Over 1100 feet of progress was made in these two months. Groundwater inflows into the tunnel averaged approximately 125 gpm but seepage into the tunnel was climbing. The plugs were problematic and unable to seal against the high groundwater heads. By early summer groundwater seeping into the tunnel from behind the heading would be over 100 gpm and eventually well over 200 gpm.

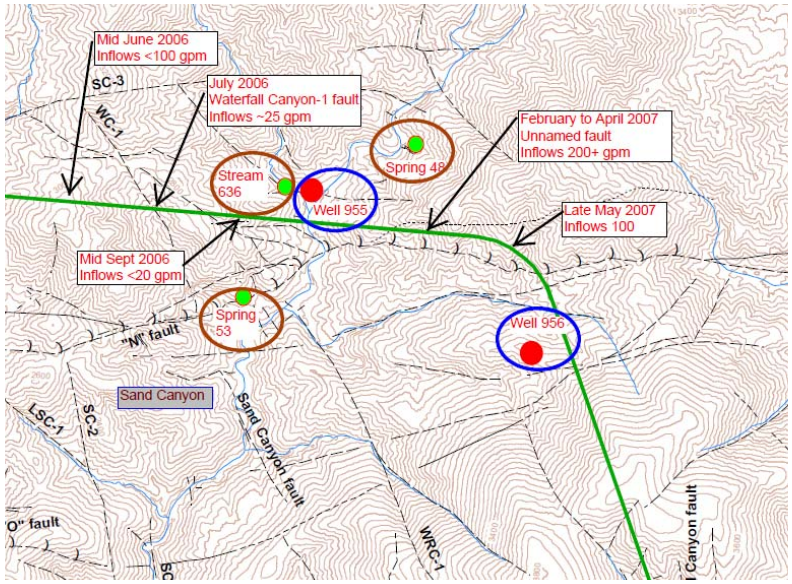


Figure 25. Upper Sand Canyon effects, Spring 2007.

By early summer Spring Site 54, located across Sand Canyon from Spring Site 53 was impacted. The lower portion of Sand Canyon was also noticeably drier. Flows on the tribal lands diminished and diurnal effects started to became significant. Of chief concern were a series of pools located below a flume used for flow monitoring. These pools, replete with riparian wildlife, were an important biologic resource to the tribe. As the flow at the flume diminished in the latter part of the day, the pools began to dry. The tribe wanted to maintain minimum flows in the lower canyon and proposed a June/July/August minimum at their flume of 15/10/5 gpm. MWD agreed to turn on water as needed they chose to apply mitigation water to the upper canyon areas as they felt this was presumably where the actual groundwater impact was occurring. Stream Site 117 in the mid-reaches of the canyon was monitored with a weir and was used as a comparison for determining lower canyon flows.

Mining continued at a good rate although the subsurface conditions were difficult. The TBM progressed through the N-fault. Groundwater heads were high and the ground ("ground" refers to the material in which construction is taking place, i.e. rock or soil) in front of the TBM was unstable. Probeholes were routinely used to drain water and reduce pressures in front of the TBM in order to make grouting more effective. This activity pushed groundwater inflows above 200 gpm. By September the TBM, then 19,500 linear feet from the Strawberry Creek portal, completed the curve and left the O-fault behind. Well 959 was impacted from tunnel construction, probably with the O-fault as the conduit. Additionally the seven northern most piezometers which were installed in the City Creek portion of the tunnel after it was lined were starting to decline for the first time since their installation seven years before. At this point the TBM was heading for the bulkhead and tie-in with the City Creek Section. Fortunately ground conditions had improved and groundwater inflows were reduced below 100 gpm as the TBM moved out of the quartz monzonite and into the diorite. Preparations were being made for the tie-in with City Creek.

October was a record breaking month with almost 900 feet of mining completed. Inflows remained below 100 gpm and are generally around 50 gpm but seepage was close to 160 gpm. There were less than 2000 feet of tunnel left to mine. All of the piezometers installed in the City Creek Section with exception of the two closest to the bulkhead were being removed.

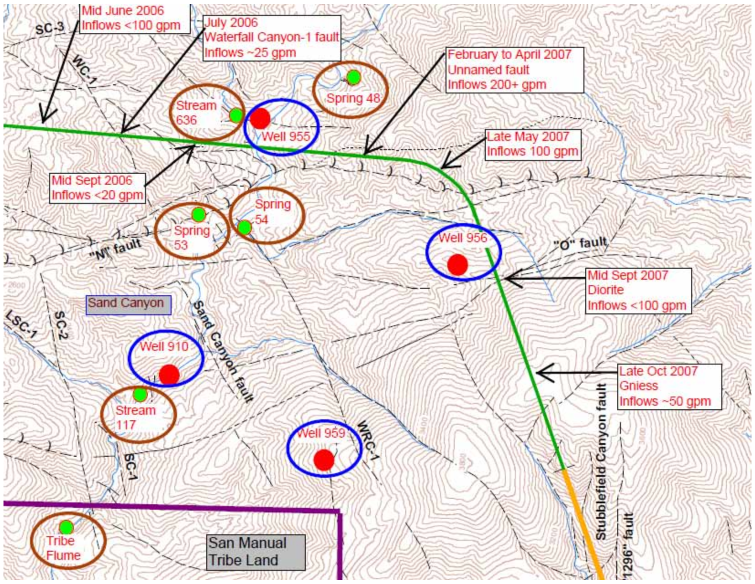


Figure 26. Sand Canyon progress and effects, Fall 2007.

During the final approach to the City Creek bulkhead, concerns surfaced regarding the increase in head over the last 10 years and the ability of the bulkhead to structurally support these heads once the hydrostatic pressure within the bulkhead was drained off. By late December drainage within the bulkhead area was complete. The two piezometers closest to the bulkhead, which were the only ones still in place, lost up to 400 feet of head within a day. Two weeks later in mid-January of 2008, approximately 640 feet from the City Creek bulkhead, the TBM hit the sheared and raveling ground that had been so problematic during the City Creek mining operation almost 10 years earlier. Mining slowed to a standstill. Inflows went from 60 gpm to 260 gpm almost overnight. The City Creek piezometers lost additional pressure and Well 911 which had such heavy impact during the original City Creek portion of the project and was slowly recovering started to decline in response. However this response would be almost negligible in comparison to the original impact almost 10 years earlier.

The final approach to City Creek proved to be more difficult than anticipated and in early February of 2008 the TBM became stuck one final time. Eventually, on 1 April after a week of hand mining around the shield, the TBM was freed with only 500 feet of mining left to complete. This last bit of ground was covered quickly and one month later on 2 May 2008, after 22,185 feet of mining beneath the San Bernardino foothills, the Arrowhead East tunnel tied into the City Creek Section. Two weeks later the last of the groundwater from the heading flowed to the Strawberry portal. However seepage was well over 200 gpm. It would take months of bolting steel plates over the tops of the leaky plugs and eventually installation of the final liner to stop this flow. From the time the TBM progressed eastward from the Little Sand/Sand Canyon divide to its tie-in with the City Creek section, twenty-three months had passed and almost 9,700 feet of tunnel has been mined. Approximately 204.4 million gallons of groundwater flowed into the tunnel during this time with an additional 27 million gallons in the form of seepage in the months following mining.

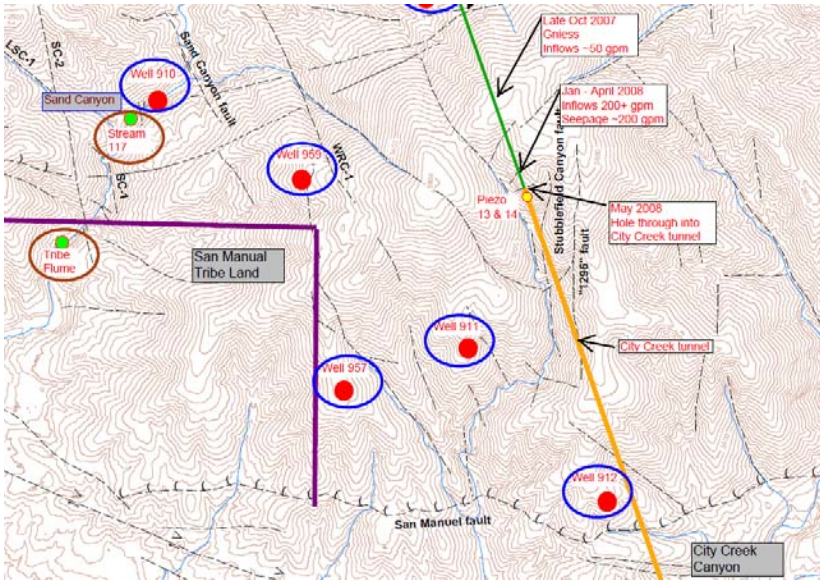


Figure 27. Sand Canyon to City Creek tie-in, Winter/Spring 2008.

For the next year construction consisted of contact grouting (filling the annular space between the concrete segments and the rock), installation of shunt flow collars (grout curtain extended circumferentially into the rock at discrete points along the alignment with the idea of impeding longitudinal flow in the section of the rock that was damaged from the mining process) and installation of the steel liners. Once the liners were in place the void between the concrete and steel liner was filled with an air entrained cellular concrete. This “filler” concrete material served two purposes. Primarily it was used to hold the steel liner in place and provide structural support; but it was also used as an impermeable barrier, in that space between the steel and concrete segments, which would provide an impediment to any longitudinal flow resulting from seepage into that space from outside the tunnel.


Figure 28. Loading pipe for installation


Figure 29. Concrete lined portion of steel pipe

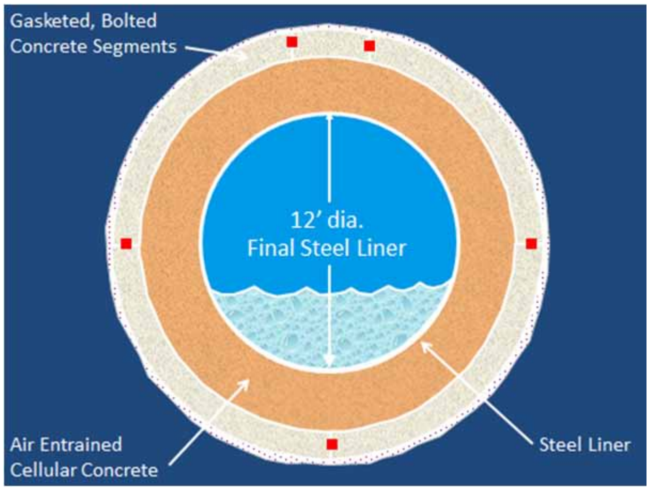


Figure 30. Conceptualized view of final construction

During most of this time until this last grouting operation sealed the lining, seepage in the neighborhood of 40 to 70 gpm flowed through the City Creek portal. This last bit of water added up to an additional 24 million gallons of groundwater. By late June of 2009 the entire eastern tunnel of the Arrowhead Tunnels Project, which consists of both the Arrowhead East portion and the City Creek Section, was complete. By this time 5 years and 9 months had passed since mining started at Strawberry Creek portal. During that time 4,438 concrete segments were installed for a distance of 22,190 feet of tunnel and 443.8 million gallons of groundwater passed into and out of the tunnel. This amounts to approximately 20,000 gallons per linear foot of tunnel.

Looking at the tunnel in its entirety, it took a total of 11 years and 2 months to complete approximately 30,000 linear feet of tunnel. Almost 1.13 billion gallons of groundwater was lost through construction of this tunnel with over 60% occurring in the first 8000 feet (or 26% of tunnel).

Arrowhead West Tunnel

Construction on the west tunnel started at the portal in Waterman Canyon and proceeded west toward the Devil's Canyon tie in with the pipeline coming down from Lake Silverwood. Unlike Arrowhead East, where mining started out in dry ground with gradually increasing groundwater heads, mining on the west tunnel almost immediately started out in rock containing water of moderate pressures. For this reason mining was started on Arrowhead East, enabling crews additional time to learn the machine and the skills needed to operate it. The contractor hoped that this knowledge and skill could then be transferred to the Arrowhead West mining operation.

Following an initial test section in early October, mining commenced on 21 October 2003. Immediately mining was fraught with difficulties. Instead of hard rock the portal was constructed through alluvial material and finished in weathered rock or regolith. The portal alluvium seeped water, as did the rock in the heading. Groundwater moving into the tunnel started off at about 15 gpm with about 8 gpm coming in from the portal area. The initial push lasted 4 days and gained 30 feet. On Friday, 25 October a large wildfire moved through the area destroying the TBM electrical conduit located outside the portal. Repairs occurred rapidly and mining resumed 2 weeks later. This second push lasted 2 week and gained 70 feet. In mid-November flow from the heading increased fourfold and the soft material in front of the TBM, unable to support itself, started to flow into the TBM effectively burying the front end. As crews worked to dig out the machine, ground continued to flow in. Eventually a cavern large enough to reach the ground surface was created.

Mining crews worked over the next month to fill the void with grout and stabilize the ground ahead of the void but the TBM would not move forward again until well into the new year. During October the foothills above San Bernardino had been denuded by exceptionally large wildfires. Nothing was left on the hillside to slow the overland flow from winter storms which made the soil and ash extremely mobile. On 25 December a rain event, dubbed the Christmas Storm, dumped 8-1/2 inches of precipitation in Lytle Creek Canyon (a few miles west of the project area) over a period of 24 hours. This intense storm mobilized slope material which became quite viscous as it hit the canyon bottoms. In the upper reaches of Waterman Canyon a hyper-concentrated flow, which is basically water, mud and debris, formed and swept down the canyon. This viscous mass sheared trees at their roots and removed boulders and buildings, including a church which housed approximately 40 people. The slurry continued down canyon and emptied massive quantities of water, mud and debris in to the portal and the tunnel to the TBM. As the operation was shut down for the Christmas holiday, no one was onsite when the flood occurred.

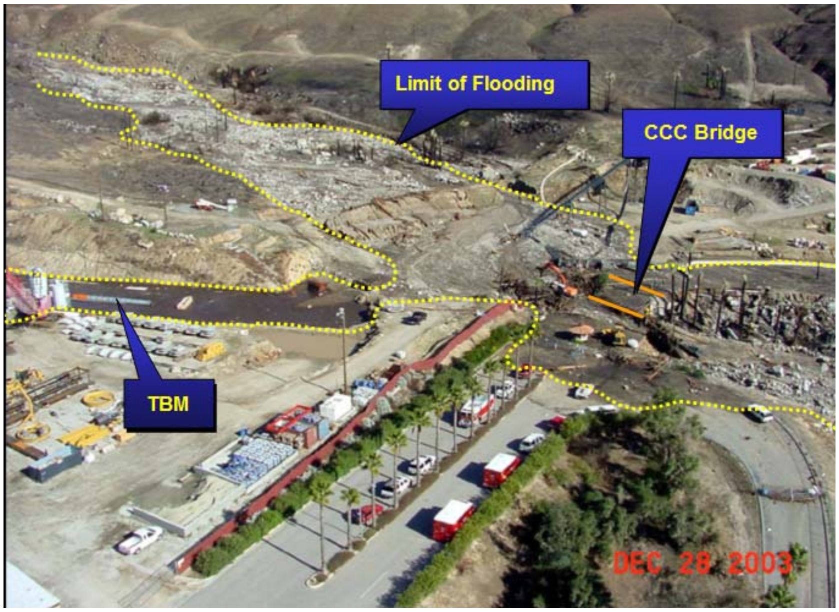


Figure 31. Flooding of Waterman portal and tunnel (courtesy of MWD)

The mining operation was completely shut down before it had a chance to resume. The next 3 months would be spent clearing the portal and tunnel of mud and debris. A significant rebuild of the TBM, especially the hydraulic systems, ensued.

By April of 2004 the TBM capabilities were restored and mining was ready to resume. Almost half a year has passed since mining commenced and only 115 feet of tunnel has been built. By mid-April mining progress has doubled. Groundwater inflows which were very low have also doubled. By the end of the month water moving from the ground into the heading will average about 30 gpm. Also by this time Wells 923 and197 show clear pressure drops as a result of mining. These wells are located very close the alignment and in the very blocky and sheared gneiss and marble resulting from the Arrowhead Springs fault.

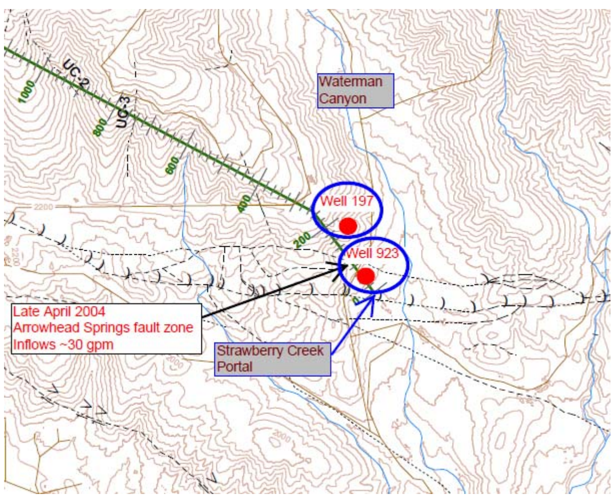


Figure 32. Early project effects at Waterman portal, Spring 2004

Mining progressed relatively smoothly and by late June the first 1,000 feet were complete. Groundwater inflows at the heading were generally above 100 gpm but below 200 gpm. Inflows steadily increased in July. On 1 July groundwater inflow at the heading was almost 200 gpm (Metropolitian Water District,

2004) and by mid-July it exceeded 400 gpm. Extensive grouting brought flows down to around 50 gpm within a few days and mining continued. This cycle continued and progress was made until 20 August when the rock broke out ahead of the heading and the machine became stuck. Heading inflows remained low but some of the drilled probeholes made in excess of 100 gpm. Hand mining around the TBM shield was performed by the mining crew and bentonite slurry was injected for lubrication. Efforts failed to free the TBM until, in late October, deployment of nine 430 ton auxiliary thrust rams were used to push the machine forward. By this point in time one year has passed from commencement of the operation and the TBM progressed 1400 ft west of the Waterman portal.

By mid-December heading inflows were peaking over 200 gpm and six weeks later, after crossing an unnamed northwest trending fault, peaks were over 500 gpm. The TBM was 2100 feet from the portal. With so much water coming in forward progress was difficult. By mid-February almost 700 gpm was flowing from the heading area and the TBM moved only 100 feet over the previous three weeks. Mining was suspended and intensive grouting to control groundwater flowing into the tunnel became the focus. Little forward progress would be made in April and May in an attempt to control water. Marble contacts were now seen in front of the TBM. Forward progress was slow. Water reduction efforts, while mildly successful when the TBM was stationary, were thwarted as soon as mining commenced. By July the TBM progressed 700 feet and was now 3000 feet from its starting point. Inflows were routinely 200-300 gpm with rather large spikes.

By mid-2005 the first surface water effects from tunneling became apparent at monitored Stream Site 17 which is located along the Arrowhead Spring fault approximately ½-mile from Site 923. Site 17 is located on private property along Highway 30 and was mitigated through irrigation by summer 2005 (Berg, Weekly MWD Tunnel Update by Neil Berg 050730, 2005).

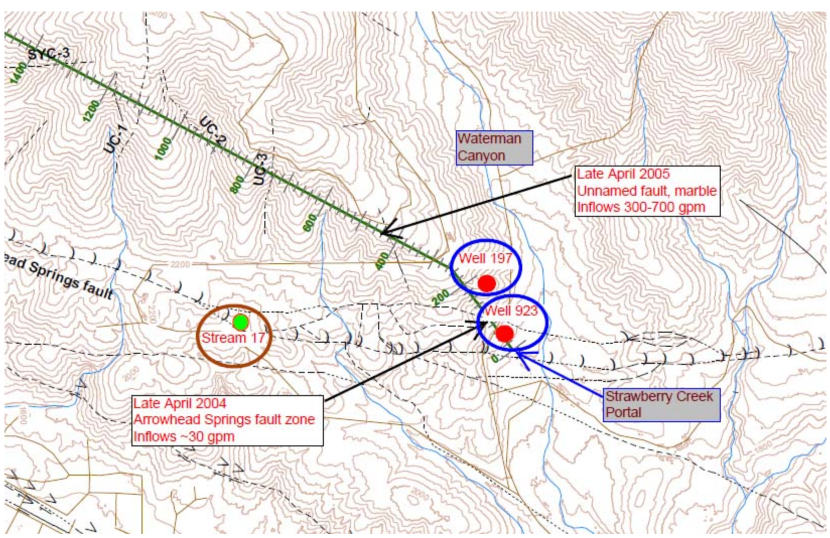


Figure 33. Progress and effects, Spring 2005

In August flow into the tunnel tipped over 800 gpm. Well 903, now about one half mile away, abruptly increased the rate of head loss by almost an order of magnitude. It was exhibiting the first indications of a mining related impact to groundwater, potentially with marble beds as a conduit. Two week later, the lower completion in Well 952, approximately ½ mile to the northwest of Well 903, appeared to be affected as well. The recession rate increased by a factor of four to five more than anything previously recorded. Additionally near the mouth of the adjacent canyon at the intersection of the UC-1 fault and the Arrowhead Spring fault, a small spring lost surface expression. This spring, Site 65 is also located on private land.

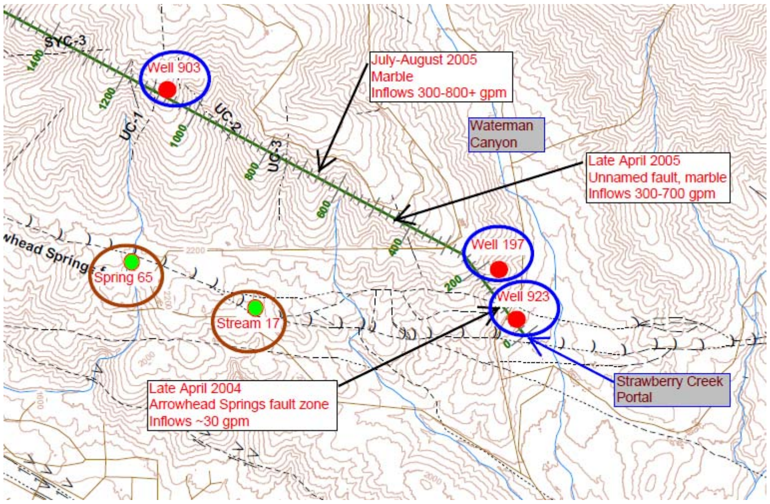


Figure 34. High groundwater inflows moving away from Waterman portal, Summer 2005

As the TBM progresses west toward Sycamore Canyon inflows are high, generally between 300 and 500 gpm. In mid-December the TBM has progressed 4500 feet from Waterman portal and was only 500 feet from Well 903 when Well 903 again abruptly increases its rate of declining groundwater head. At about the same time the lower completion in Well 952 also experienced an increase in rate of head loss.

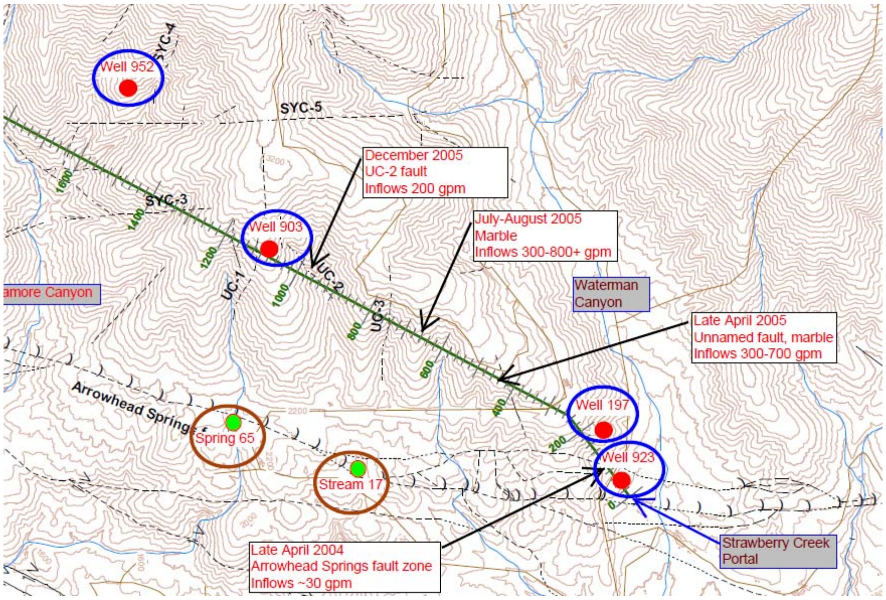


Figure 35. Progress and effects leaving Waterman portal, Late 2005

As mining progressed into Sycamore Canyon, over 1000 concrete segments had been erected, 5200 feet of mining was complete and more than 193 million gallons of groundwater flowed through the tunnel and out Waterman portal.

In January 2006 the TBM crossed the UC-1 fault and groundwater inflows into the heading area diminished for a few weeks. However the reprieve was short and by February they were over 300 gpm again. Through the first half 2006 groundwater was a constant problem. Water flowing into the heading area increased and then was brought down as large amounts of grout are injected into the ground. Rock was generally gneiss mixed with sections of marble. In mid-March groundwater inflows were again over 500 gpm and effects to Well 952 intensified.

As the TBM was moving under the east wall above Sycamore Canyon, the TBM encountered crushed, altered rock. The screw auger jammed and the TBM was stuck. Inflows increased to over 800 gpm and remained high for about 3 weeks. Intensive grouting was again used to decrease the amount of groundwater flowing into the tunnel. May was spent attempting to free the machine through hand mining and employment of 565 ton auxiliary rams to inch the TBM forward. A variety of mechanical issues had to be dealt with as well, including replacement of the screw auger. In June slow progress was made and over the next three and a half months 500 feet of additional tunnel was constructed through the blocky, sheared ground of the UC-1 fault. Slow movement combined with extensive grouting kept groundwater flows generally below 100 gpm.

As mitigation is continued at Stream Site 17 and starting at Spring Site 65 (Berg, 2006), MWD was preparing to install surface water mitigation systems in both Sycamore Canyon and Badger Canyon in anticipation of potential impacts to springs. Of particular concern in these west side canyons are some tiny crynobiotics associated with marble groundwater systems. Although these spring snails are barely visible, they are important indicators of longevity and health of riparian systems. Apparently they develop in a specific drainage over thousands of years and are therefore very specialized to the chemical constituents in the groundwater of that particular drainage, so much so in fact that a snail originating in one drainage cannot survive in an adjacent drainage. They are therefore indicators that the drainage has had groundwater dependent flow for thousands of years and therefore has not gone dry in the recent past. The decision was made to mitigate surface water effects and prohibit, if possible, effects to biota. Out of this decision much additional work ensued to determine what water could safely be used for mitigation.

Discussions on opening a new portal in Devil’s Canyon began. Mining had been slow and difficult thus far and there was fear that the rock quality could be of such a nature that it would be extremely difficult to mine effectively with the current TBM. Additionally the final segment was on a curve which could prove challenging by itself. Thoughts about mining at least the first 1,000 to 2,000 feet with conventional mining techniques were being considered. Exploratory drilling would commence during the coming winter as the current TBM would begin mining into the bend in the east half of this tunnel. It is thought that both of these activities would give engineers a better feel for what would be practical and a decision could be made based on the results.

As September ended and the TBM was freed yet another time, ground conditions improved and so did the rate of construction. By November the TBM was nearing the Sycamore-1 fault. A spring in the upper reaches of Sycamore Canyon, Spring Site 156, showed a noticeable decline in flow and was the first site on Forest Service land within the Arrowhead West portion of the project to receive irrigation water.

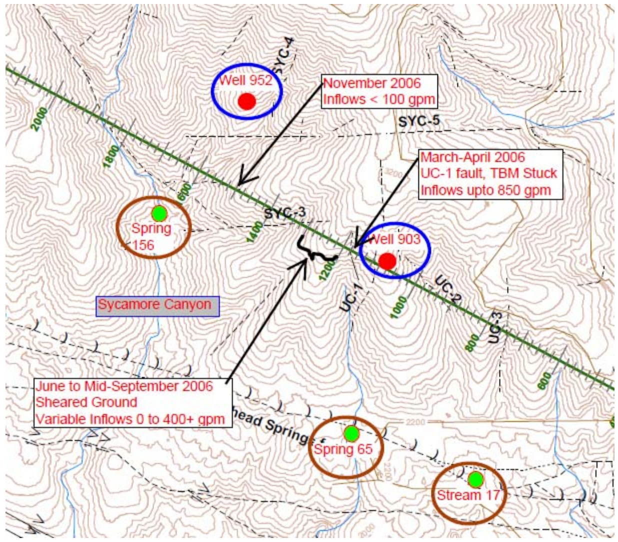


Figure 36. Mining progress and effects, Mid to Late 2006

Mining continued at a much improved pace until the new year. In January of 2007 at a distance of almost 8,600 feet from Waterman portal the TBM was well into Sycamore Canyon and running sub-parallel to the Sycamore-1 fault. Ground conditions were less than favorable. Sheared rock with clay gouge and slickensides were common. In early January the TBM became stuck for a brief period. Although water flowing in through the heading was not exceptional, on 11 January the upper completion in Well 902 initiated a rapid decline in pressure. Well 902 is located approximately 1,700 feet to the west on the ridge separating Sycamore from Badger Canyon. Six days later, as the TBM was again freed from the crumbling ground, the groundwater head in the lower completion of Well 902 declines. Marble layers were prevalent in and under the canyon and may have been responsible for such rapid pressure drops over long distances. Within a few days Well 951, located up the ridge from 902, was also impacted by tunneling.

By February drilling of a water well in Devil's Canyon was complete. This well was to be used to provide mitigation water in the event it was needed in any of the canyons with spring snails. These canyons included Devil's, Ben and Badger Canyons. Additionally a tank was set on Marshall Peak above Ben and Badger Canyons and mitigation infrastructure was installed as a contingency.

In late March the TBM approached the divide between Sycamore and Badger Canyons and was starting to negotiate the bend in the alignment. Probeholes were making upward of 300 gpm, but grouting was extensive and groundwater inflows were generally kept below 100 gpm and usually below 70 gpm. The current philosophy appeared to be aligned with intensified grouting to minimize groundwater inflows through the heading. Pressure changes however can propagate large distances in fractured rock, especially in marble when dissolution can enhance permeability. Well 195 and Well 196 started to increase rates of decline. Groundwater effects had now extended into the bottom of Badger Canyon.

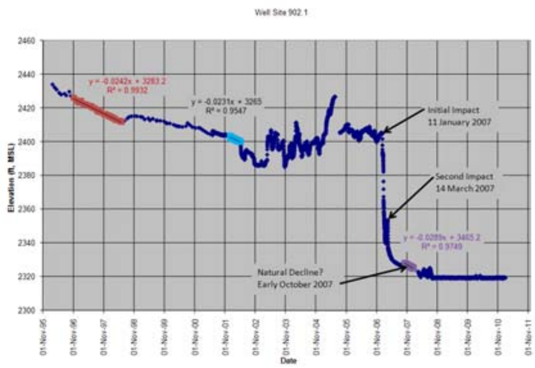


Figure 37. Well 902 Hydrograph shows tunneling impact from early 2007

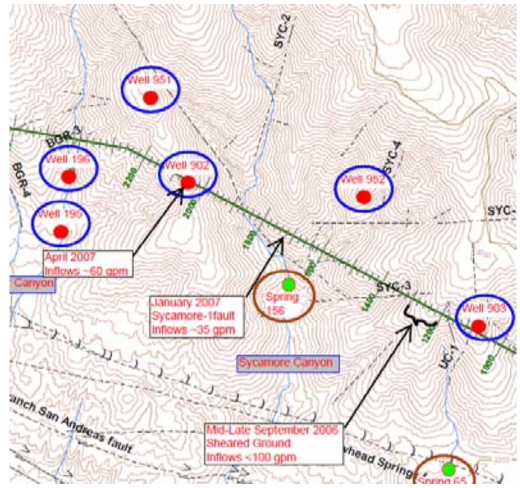


Figure 38. Mining progress and effects, Early 2007.

By April the TBM is just 50 feet to the south of Well 902 and at about the same elevation as the lower completion where the groundwater head had reached the elevation of the bottom of the borehole. From this point the pressure started to rebound as the TBM crossed into Badger Canyon. It had taken approximately 15 months to cross Sycamore Canyon almost doubling the distance from Waterman Canyon. With about 10,200 feet of mining complete, groundwater depletion in the Sycamore Canyon section, which includes seepage along the tunnel length, was on the order of 96.2 million gallons or less than half of the total amount in the first half of tunnel construction.

In June and July the TBM was averaging over 700 linear feet of forward progress each month. Mining through the first curve in the tunnel went well and was now past this curve. Additionally with the completion of exploratory drilling at Devil's Canyon, it appeared that mining conditions were favorable for use of the TBM and therefore no conventional mining needed take place in Devil's Canyon. Mining could continue to proceed from the east. The issue now was with seepage. In June seepage doubled with leaky plugs as the culprit. At this point in time seepage commonly exceeded heading inflows and by August was up to 60 gpm. Work was underway to replace and eventually plate the leaky plugs. The problem and solution were basically similar the Arrowhead East Tunnel.

Inflows of groundwater into the heading were generally below 100 gpm and usually between 40 and 60 gpm. The TBM was moving through the sheared gneiss and marble below the east and west forks of Badger Canyon. No other surface water sites appeared to show effects. It is believed that the separation of the marble and gneiss may have provided a barriers or aquicludes upon which the upper aquifers feeding the canyons are separated from the lower groundwater. The reality is that most of the wells on the Arrowhead West portion of the project had project effects, but unlike Arrowhead East, very few surface water sites did.

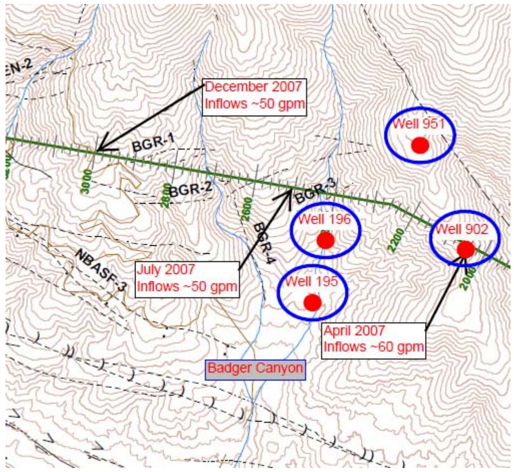


Figure 39. Mining progress and effects in Badger Canyon, 2007

By early December mining progressed to the boundary of Badger and Ben Canyons with a total of 15,000 feet mined. The section of tunnel that underlies Badger Canyon has taken approximately 235 days to complete with a groundwater loss of 36.4 million gallons. This equates to roughly 154 thousand gallons per day, which is a 25 percent reduction over the previous section and almost seven times less than water loss as a result of mining from Waterman portal to Sycamore Canyon.

With the end of 2007 mining proceeded below the east slope of Ben Canyon. Rock quality was highly variable, but not as much marble was encountered. Probeholes produced significantly lower amounts of water so the intensity of pre-excavation grouting was diminished. By mid-February the TBM was almost directly below Well 901 in the bottom of Ben Canyon. Neither Well 901, which fluctuates seasonally with stream flow, nor any of the surface water sites within the canyon appeared to be affected by mining. This fact further bolsters the supposition of a disconnect or barrier between the upper aquifer feeding the surface sites in the upper canyons and the lower aquifers which most of the wells have penetrated. Well 900 appears to be well into the lower groundwater and, on 16 February 2008, presented a significant drop in pressure. Although the well is 1,700 feet from the TBM, it penetrates both the marble and potentially several splays of the North Branch of the San Andreas fault (aka. Mill Creek fault, (McGill, Owen, Weldon, & Kendrick, 2011)) along with a potential extension of the Badger-2 fault. This last fault had run sub-parallel to the TBM for the last 2,500 feet which also coincided with the increase in chronic seepage.

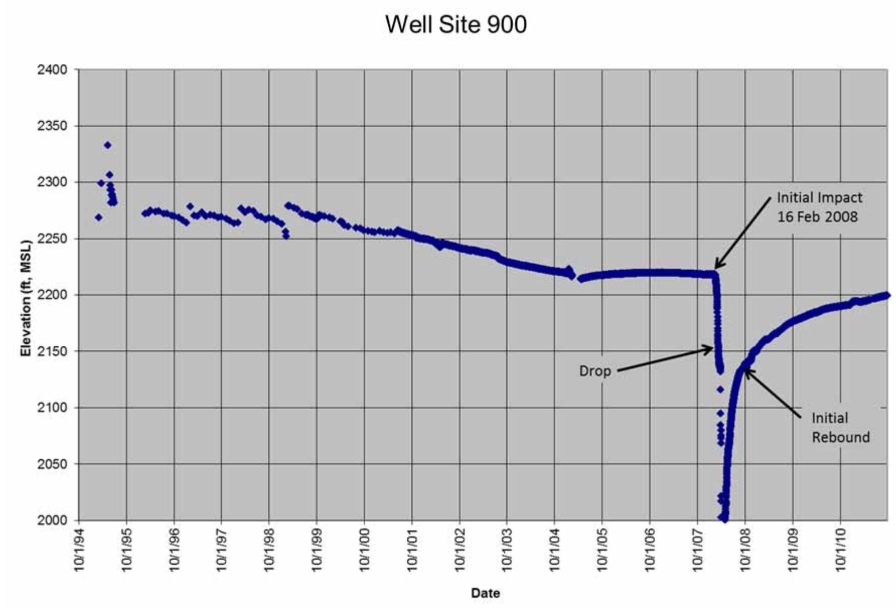


Figure 40. Hydrograph showing impact to Well 900

In April the TBM was well into the North Branch fault and groundwater flows into the heading area increased somewhat but were generally below 100 gpm. Grouting intensified. Forward progress slowed as ground became more difficult but groundwater heads were decreasing and by May inflows were generally below 50 gpm. Seepage was still high and exceeded heading inflow. The TBM was entering the final curve and by June over 18,000 feet of concrete lined tunnel was complete. There was now less than 1,500 feet to go.

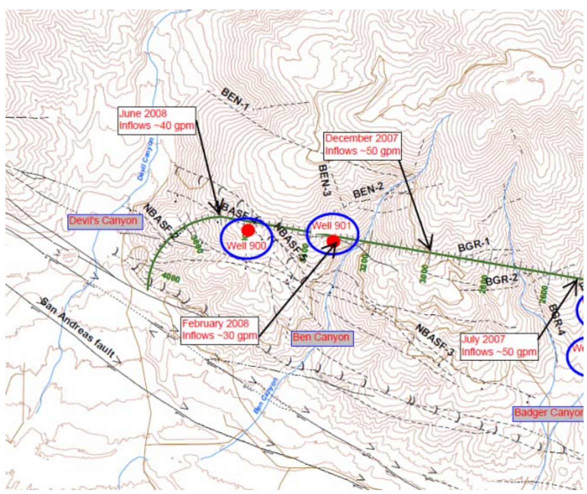


Figure 41. Mining progress and effects in Ben and Devil's Canyon, 2008

In the final days of mining, heading inflows dropped dramatically from 50 gpm in late-July to single digits by mid-August. Less than 1 week later, groundwater ceased to flow in from the heading. On 20 August 2008, before a gathering of hundreds of people, the west tunnel alignment was completed during the final push as the TBM shoved its way to daylight.

Figure 42. Arrowhead West TBM cutterhead immediately after emerging in Devil's Canyon during the Hole-Through Ceremony.

The primary objectives for the next few months included clean up and preparations for installation of the final 12-foot diameter steel liner. Part of these preparations included installation of specially placed Shunt-flow collars. These "collars" consisted of a grout curtain placed circumferentially through the concrete liner and 12 feet into the surrounding rock mass. The purpose of this "collar" was to inhibit groundwater flow which might travel laterally along the outside of the tunnel through the damaged rock. Placement was in good quality rock adjacent to poor quality rock with significant potential for groundwater flow. As part of preparation for installation, up to 12 pieces of steel pipe were delivered to and stockpiled at the jobsite each day (Mckeown, Various). Additionally the leaky plugs were being dealt with in a similar manner as Arrowhead East. Seepage continued at 55 gpm through the end of the year but was reduced to half that by February of 2009. By March of 2009 approximately 13,000 feet or two-thirds of the steel pipe installation was complete. In late June the last sections of the steel pipe were in place and the annular space between the concrete segments and steel pipe were filled with cellular concrete. With this the last of the groundwater ceased flowing through the portal area. In all 5 years and 9 months passed from commencement of mining at the Waterman portal. During this time 19,770 feet of tunnel excavation occurred with 3,954 concrete segments erected. A total of 378 million gallons of groundwater was removed from storage which equates to approximately 196 thousand gallons per day during active mining.

Geology & Groundwater

The San Bernardino National Forest falls within two distinct geomorphic provinces, the Transvers Ranges province and the Peninsular Ranges province. While the San Jacinto Mountains lie within the Peninsular Ranges province, most of the rest of San Bernardino National Forest, including the project area, are located within the Transvers Ranges province. The oldest rocks within this province consist of pre-batholithic crystalline rocks in existence for at least 1.7 billion years. During the later Proterozoic and much of the Paleozoic (a period consisting of over 700 million years) these continental basement rocks were overlain by sedimentary sequences deposited on the continental margins in a shallow marine environment (Matti & Morton, 2000). These sequences can be found throughout the San Bernardino Mountains and within the project area as ribbons and pendants of calc-silicate gneisses and marbles. These meta-sedimentary units were sheared and folded prior to Mesozoic batholithic activity although recent quaternary tectonics appears to have reactivated some of the ancient faults.

Mesozoic granitic rocks comprising the Transverse Ranges batholith occurred as two distinct plutons. The older rocks in the batholith have been dated as Triassic and early Jurassic. Some of these appear in the project area within the upper reaches of Arrowhead West. Subsequent plutonic emplacements probably occurred in the latter Jurassic (Jenkins & Rogers, 1967) and during the Cretaceous. This latter granitic pluton is common throughout the San Bernardino National Forest (Matti & Morton, 2000) and is the dominant rock within the Arrowhead East portion of the project.

Cenozoic rocks are sedimentary formations occurring in the southern margins of the San Bernardino Mountains. These Tertiary sandstones and conglomerates are found underlying the Quaternary sediments south of the North Branch of the San Andreas fault (aka Mill Creek fault, McGill, Owen, Weldon, & Kendrick, 2011). This is the dominant material in the early part of the City Creek segment. Additionally Quaternary alluvial material and landslides are found throughout the canyon slopes and drainage bottoms within the overall project area. Landslides are particularly prevalent in the western portion of Arrowhead West where faulting is particularly intense.

During the late Miocene/early Pliocene (roughly 5 m.y.a.), with final subduction of the Farallon Plate beneath the North American Plate and the displacement of its spreading center far to the south, the transform boundary we know as the San Andreas fault was essentially in place. The significance of this fault to the project area has been most notable over the last 2 million years as this project is located on the southwestern flank of the San Bernardino Mountains. These mountains are part of a group of transverse mountain ranges created by an east-west bend in the generally north-south aligned right lateral strike-slip San Andreas fault. The bend exerts a tremendous compressive stress along its boundary and is responsible for second order or subsidiary faulting which is a controlling geologic feature in the project area. Don Elder, former Forest Service Geologist for the project, suggests that the orientation and geometry of the second order faulting is consistent with the Riedel model of right simple shear. In this case the east-west faults accommodate compressive forces with reverse and thrust faulting while the north-south features are normal faults associated with extensional stress. Additionally the horizontal and vertical displacement along the fault zone is responsible for the juxtaposition of rocks of very different ages and formation environments.

The combination of varying lithologies and faulting/jointing provides for a challenging mining environment. In addition to rock quality, or the ability of the rock to maintain its integrity without collapse during construction, groundwater within the rock mass presents significant issues for mining. In any groundwater environment effective porosity determines how much water is stored in the material (storativity) and how well that water can move through the material for a given pressure gradient (hydraulic conductivity). As porosity refers to the amount of void space within a material, effective porosity refers only to that void space which is interconnected and can transmit fluid (air or water). In a crystalline rock environment effective porosity is generally fracture dependent. Fractures can occur anywhere within the rock mass and are related to stresses, either internal or external. Internal stresses can be generated during cooling or during changes in the external environment. For example, the formation environment of a pluton is very different (especially in terms of heat and pressure) than the environment at the earth's surface and the resulting internal stress as the pluton rises to the earth's surface is alleviated through fracturing. External fractures can be related to tectonics and in the project area this is the primary driver. Fracture intensity generally increases around faults and appears to decrease toward the center of the rock mass and with depth.

As mentioned above, for fractures to transmit stored water they must be interconnected. The result being in areas where faults are compressed or filled with clay gouge, water may not move quickly or freely from one side of the fault to the other. In these cases faults can present a barrier rather than a conduit to groundwater flow and groundwater heads can be very different from one side of the fault to the other. In this situation groundwater is assumed to be compartmentalized and evidence of this is seen in piezometers installed along the length of the tunnel as mining progressed. Additionally not all faults have open fractures as groundwater can bring dissolved minerals, especially in areas where hydrothermal conditions persist. These minerals eventually precipitate within the fracture closing flow paths and reducing effective porosity. Many older faults are actually in-filled with calcite and therefore have very few open fractures.

If the project area were divided into two sections based on geology, it would be immediately obvious that the Arrowhead West section is distinctly different than the Arrowhead East section. Construction of the Arrowhead West segment consisted of mining through primarily pre-Mesozoic carbonate facies. A compilation of fracture dip angles and dip directions produced by Don Elder, using 6 geotechnical boreholes scattered along the Arrowhead West alignment, shows what he terms as a "shot gun pattern" of observations (Elder, 2008).

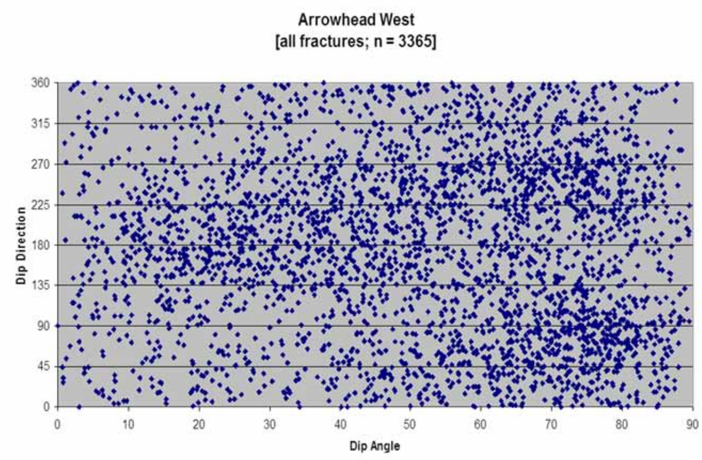


Figure 43. Chart depicting fracture orientations derived from acoustic televiewer data from selected AHW boreholes (Elder, 2008).

Essentially there appears to be no preference of fracture orientation and dip angle. This is probably related to the fact that there have been many episodes of faulting and fracturing of rock interspersed with 3 dimensional displacements. Don refers to this as a mélange. Groundwater flow seems to be related more to bedding of marbles and calc-silicate gneisses with mapped faults as a secondary, if at all, conduit to flow. The exceptions are the eastern and western ends of Arrowhead West where quaternary faulting is especially prevalent. These materials, especially the marbles, are more prone to dissolution by groundwater thus increasing the aperture size of existing fractures and improving conduits for groundwater flow. Therefore flow tends to be more dependent on lithologies, which are not continuous vertically. This is especially noticeable from vertical discontinuities in aquifer behavior. A prime example is Well 952 located on the ridge moving into Badger Canyon from the north. During the Hector Mine earthquake in October of 1999 the upper completion responded to the event with a positive pressure change while the lower completion responded with a pressure loss. Additionally the upper completion was isolated from the effects of mining in 2006, unlike the lower completion which lost almost 100 feet of head.

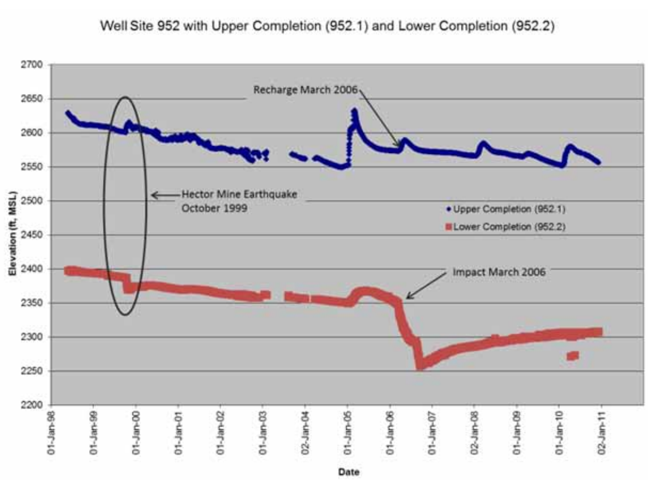


Figure 44. Comparative hydrographs for Well 952.

Arrowhead East on the other hand consists primarily of later Mesozoic and Cenozoic formations. Much of the fracturing is post Mesozoic and may be quaternary associated with the compressive bend in the

San Andreas fault. Don Elder's compilation of dip direction versus dip angle (in six Arrowhead East geotechnical boreholes) produces a different pattern from the "shot gun" pattern seen in Arrowhead West.

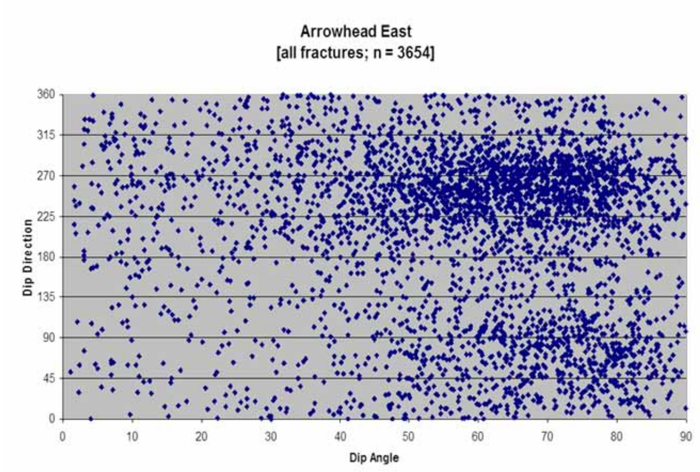


Figure 45. Chart depicting fracture orientations derived from acoustic televiewer data from selected AHE boreholes (Elder, 2008).

In this case there is a preferential fracture alignment of approximately 0° and 180° (north-south direction) with most fractures dipping fairly steeply at 50° to 80° from horizontal. Groundwater seems to be much more fracture driven on this part of the project and compartmentalization of the groundwater appears to be more prevalent. The result for mining is that moving from one side of a fault to the other can produce a substantial increase in groundwater head and subsequently more water flowing into the tunnel. For instance, during August of 2005 the TBM was moving through the Borea Canyon fault zone which appears to have intersected the TBM under the divide separating Borea Canyon from Little Sand Canyon. Just prior to this groundwater heads were approximately 250 feet above the tunnel and inflows were limited to approximately 50 gpm or less. After clearing the fault groundwater heads increased to over 400 feet above the tunnel and inflows to the heading area swelled to 200 gpm and eventually to almost 600 gpm.

In addition to the ponding of groundwater, the faults on the Arrowhead East portion of the project appear to be more responsible for directional effects. While the fault can present a pressure barrier from one side to the other, it can also allow transmission longitudinally and determine preferential flow paths. The greatest example comes from Mike Fahy, the USGS groundwater hydrologist working on the project. He documents the example from the City Creek portion of the project where mining inflows produced much larger effects to a well (Well 911) more distal to the tunnel than another well (Well 912.1) located just to the west of the tunnel alignment. Both wells are located in the rock unit north of the San Manuel fault. Well 911 is connected to the tunnel through a series of faults while 912 appears to potentially be located in the bulk mass of the rock body.

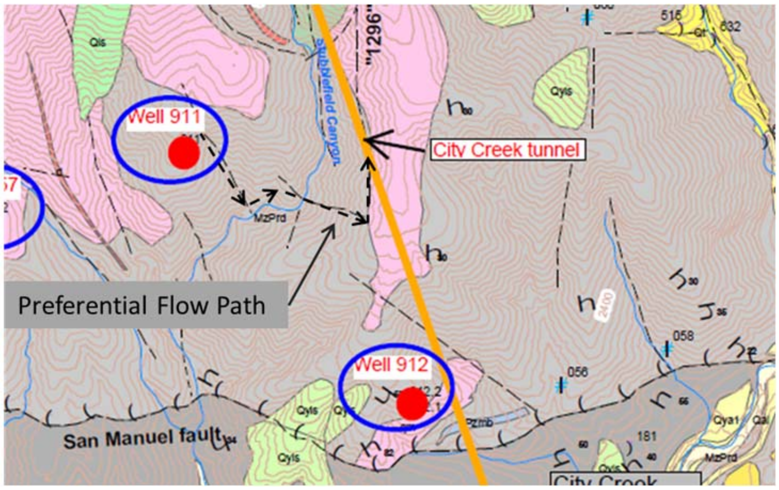


Figure 46. Geology map depicting preferential flow path from Well 911 to tunnel.

The propensity of north-south fracture alignments additionally assists in the transport of groundwater from areas of high head in the northern upper canyons to lower head areas to the south. In a fractured rock environment the intersection of a water bearing feature such as a fault with the ground surface can produce as spring or seep if groundwater heads are sufficiently high (at or above the land surface). This effect can be compounded upon intersection with a barrier feature which ponds water up gradient, effectively increasing the head. An example of this is seen in Borea Canyon where the N fault, an east-west aligned reverse fault potentially increases groundwater head up canyon of the fault. At this point in the canyon lies an adit (Spring 45) which generally flows year-round and is very groundwater dependent. As the TBM approached the area below the canyon bottom in the winter of 2005 the well downstream of the alignment, which had been recovering, was re-impacted. By the spring of that year Spring 45 was also severely impacted. The alignment appears to be connected directly to both the groundwater site and the surface water site through a roughly north-south lineament known as the Borea Canyon-1 fault.

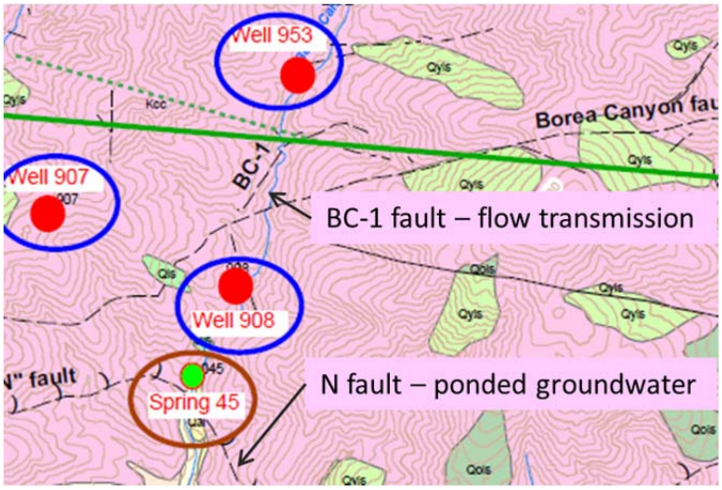


Figure 47. Geology map showing Borea Canyon faults.

Precipitation and Recharge

Annual precipitation in the San Bernardino National Forest is highly variable. It ranges from about 7 inches (Current Results) on the desert northern and eastern fringes to about 35 inches (NWS) on the mountain tops with a winter snowpack. The temperate zones located on the edges of the inland valleys to the south and west average approximately 16 inches of rainfall annually. Most of the precipitation occurs in the winter as the offshore high pressure shifts somewhat southward allowing storms to swing southward. These storms, originating from the north pacific, dump significant precipitation on the coastal parts of the Pacific Northwest with only moderate to minimal amounts left by the time they're received in southern California. During the summer months this high pressure moves northward, effectively blocking precipitation from this source for most of the state (WRCC). On average about every 5 years a warming of surface waters in the eastern south pacific is accompanied by a surface high pressure in the western south pacific. This phenomenon, termed El Niño, brings large amounts of moisture up from the southwest and is often responsible for intense winter rain and associated widespread flooding in southern California (Wikipedia).

Precipitation patterns in and adjacent to the project area have a profound effect on groundwater behavior. This is especially true of the heavy precipitation associated with the El Niño phenomenon. Many of the monitored aquifers within the project area only display significant recharge during the larger precipitation years that generally occur during this event. Seasonal rain can bring a small bump or perturbation in shallower unconfined aquifers, but the general overall trend is a receding groundwater head.

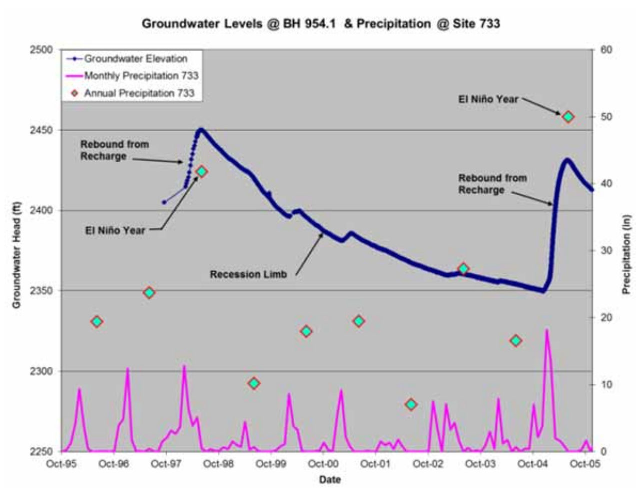


Figure 48. Groundwater head hydrograph for Well 954.1 showing precipitation at City Creek Ranger Station.

Timing is important as well. Most rainfall occurs from December to April although it can begin as early as October or finish with a few rainy days in mid-June. When this rainfall is spread out over a period of days per event, more of the water appears to augment recharge of the deeper aquifers. Rain which occurs in the summer generally comes from the east as the monsoons move through Arizona and Nevada. This precipitation is sporadic, intense and generally provides no recharge, only short-term runoff in the streams. Temporally, most aquifers start responding to precipitation between January and March and are generally finished by mid-summer. For the purpose of analyzing precipitation-recharge relationships the water year is taken from 1 October to 30 September.

Groundwater recharge can be local or regional or a combination of both. A few shallow aquifers within the project area are very responsive to local recharge and show an increase in head almost on an annual basis. The graph below depicts a well located in Ben Canyon which is almost certainly isolated from the lower aquifer by bedding planes which serve as an aquitard. The well is an open standpipe and water level in the well is close to the elevation of the channel bottom to the east. In this case the flow from the channel itself may provide a recharge avenue for the shallow aquifer.

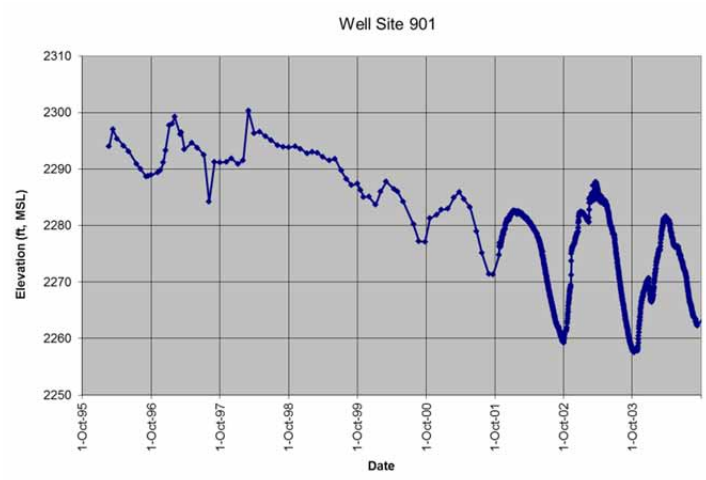


Figure 49. Groundwater head hydrograph for Well 901

Aquifers fed by regional sources may have greatly attenuated response to seasonal precipitation, or may appear to have no response at all. Changes in head may be less variable and groundwater may have traveled many miles from its origin at the ground surface. Groundwater still travels as a response to stress put on the aquifer, such as flow to a spring or pumping, but if the system is large in contrast to the change in gradient the system will dampen the response due to annual precipitation variability. For example, groundwater levels at the City Creek sites such as Well 912 vary only a couple of feet throughout the year. It is thought that recharge to this aquifer (prior to impact in 1998) is more of a regional nature potentially originating from the San Bernardino Mountains, perhaps Lake Arrowhead 15 miles to the north.

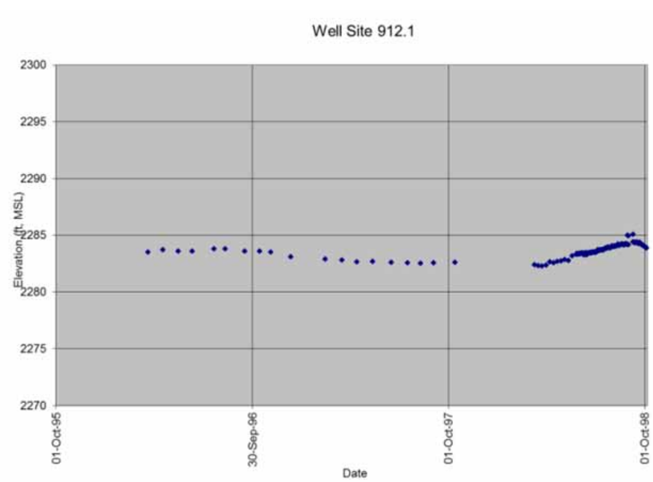


Figure 50. Groundwater head hydrograph for Well 912.1

Many of the aquifers potentially have a combination of local and regional sources for recharge although often times one appears to control the short-term behavior of the groundwater.

Recharge can be followed in wells with nested piezometers (multiple completions). In areas where groundwater moves vertically from high head to low head the upper and lower transducers will mimic each other. In Well 954 in upper Little Sand Canyon water moves downward from above. This is typical of several wells in the project area including Well 956 in Sand Canyon (AHE), and Well 951 in Badger Canyon (AHW). Other areas may well exhibit the same response, but not all boreholes have more than on piezometer installed.

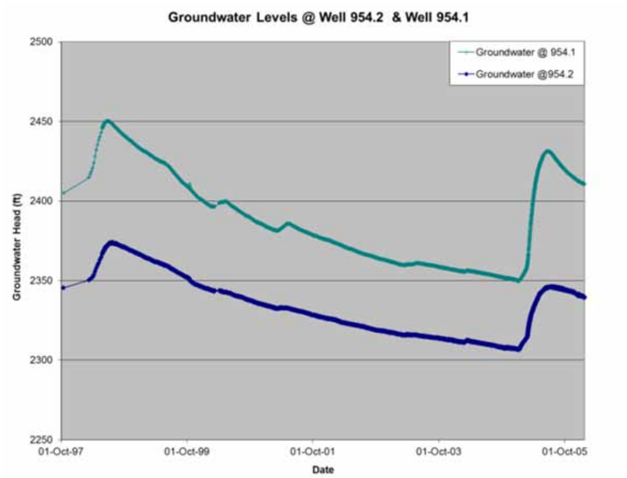


Figure 52. Groundwater head hydrograph for Well 954.

The County of San Bernardino Department of Public Works operates a large number of rain gages that are scattered throughout the county primarily for the purpose of providing impending flood warnings to the local areas. Many of these gages have been evaluated as proxies for precipitation in suspected recharge areas. Although only a very small amount of precipitation which touches the ground actually reaches the groundwater aquifer (often on the order of 0.1 to 1 % for fractured rock aquifers), seasonal quantities over a long period of time allow a loose quantification of trends. Since recharge is spatially variable, associating long-term trends of gages in different geographical areas with a well helps to identify potential recharge areas for that well/aquifer.

Not all rain gage sites provide good data for analysis. Many gaged sites don't span years appropriate to monitoring; for instance rain gage 2370 is near Borea Canyon but this gage was only operated for 1-year, 1980 to 1981. Others have good ranges but are missing a lot of data. This is particularly problematic if the missing data is during the winter when precipitation is present. The high elevation gages have their own unique problems when snow contributes significantly to precipitation in the wintertime. Unless the data is corrected for snowfall, the gage will under represent total precipitation. With all of the potential data integrity issues, these gages are used as a best-guess correlation with area rainfall. The parameters produced by reduction of this data may be some of the weakest parameters in terms of accuracy.

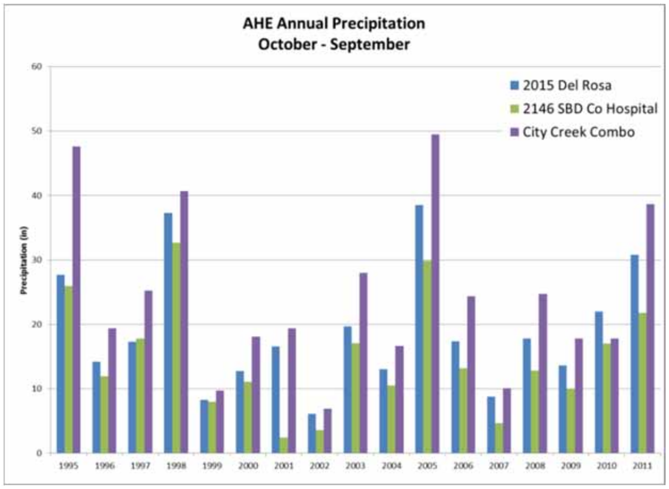


Figure 53. Comparative precipitation sites for AHE.

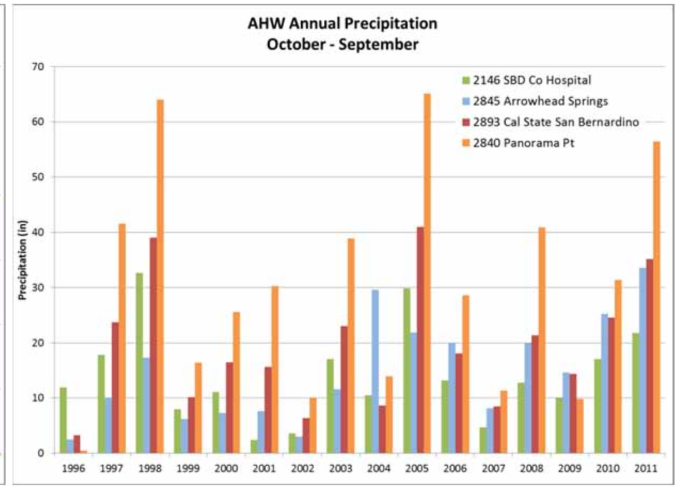


Figure 54. Comparative precipitation sites for AHW.

Conceptual Models

Conceptual models used in the analyses of potential tunnel construction impacts to groundwater and surface waters vary geographically and are generally described on a canyon by canyon scale. These models address the hydrogeologic system as a whole including the geology, groundwater, precipitation, groundwater dependent surface water and other hydrologic factors including sediment or bank storage and evapotranspiration. The bulk of the conceptual models will be detailed during the individual recovery analyses; however there are some broad generalizations that can be described.

Generally most non-intermittent streams within the project area are groundwater dependent to some extent. Most groundwater is stored in fractured rock aquifers. Groundwater movement is generally from north to south or down canyon throughout the project area. The shallow groundwater aquifer generally shadows topography although the gradient (difference in head between two points, slope of the head) can be orders of magnitude less. The exception is where water is constrained by a barrier such as a fault. Water moves in and out of these aquifers as evidenced by the change in head with time in each of the hydrographs. Outflows can be to another down-gradient groundwater aquifer or basin or to surface water expressions such as springs and seeps. Sometimes these sites can be easily quantified, such as from flow measurements of water pouring out of a spring or adit (horizontal well). Other times a vegetated channel with a sandy substrate in a gaining reach of the canyon is harder to identify as a specific point of exodus.

On Arrowhead East groundwater storage and permeability are primarily fault controlled. North-south oriented faults tend to be transmissive and east-west faults tend to be barriers. Springs are often found in stream bottoms near the faults, resulting from the ponding of water behind a barrier especially where an intersection is made with a north-south feature. Recharge from Sand Canyon, and maybe Little Sand Canyon, east has a significant component from precipitation at Mud Flats or above (higher elevation and further north). Borea Canyon receives more recharge locally and supplies springs and the stream in the mid-canyon, usually perennially. Groundwater tends to move vertically downward on Arrowhead East.

Faulting may control groundwater movement near the portal areas on Arrowhead West, but bedding planes and probable solution enhanced factures related to pre-Mesozoic marbles and gneisses are the primary conduits for groundwater in Sycamore, Badger and Ben Canyons. In these canyons fractures seen on the ground surface are discontinuous at depth and groundwater flow is sub-horizontal moving generally in a down canyon direction. Springs associated with marble beds in the canyons are often hydrologically separated from the deeper aquifer. The evidence for this separation is two-fold. First monitoring wells within the same borehole (different completions at different elevations) show very different recharge-recession behaviors. Additionally there is the obvious lack of impacted surface water in areas where groundwater impacts are severe. Recharge is generally local from Marshall and Cloud Peaks via conveyance associated with the Waterman Canyon fault to the north, but may have a component from the highlands above in the area of Lakes Gregory and Silverwood (especially deeper aquifers).

Impact Analyses

All surface and groundwater sites with data available to the Forest Service were evaluated for project related effects to groundwater dependent resources. Many of these sites were within the boundaries of the San Bernardino National Forest; others were not. The impact analyses were conducted during 2011 and all were completed by November 2011. Methodologies for impact determination and quantification varied by site but generally all went through a basic screening process with the same initial steps.

Methodologies - Groundwater

Impacts to groundwater were assessed a number of different ways but generally progressed canyon by canyon extending from the portal of initial construction. Initially presence or absence of an impact was determined at each monitoring well site. If an impact is perceived to exist, then an attempt is made to quantify that impact at some level. The quantification may be cursory for the benefit of the impact analysis and determination of the focus of further efforts or, as in some cases where project work required the attention, the quantification of impacts is more thorough on the order of a recovery analysis.

Initially presence or absence was assessed by looking for anomalous hydrograph inflection points or sudden steepening in the recession limb of the hydrograph during a time when tunneling could have had an influence. Regression techniques were used to determine the amount of change induced and a record of mining history was compiled using a variety of sources to determine the potential link (or lack thereof) between tunneling and impact.

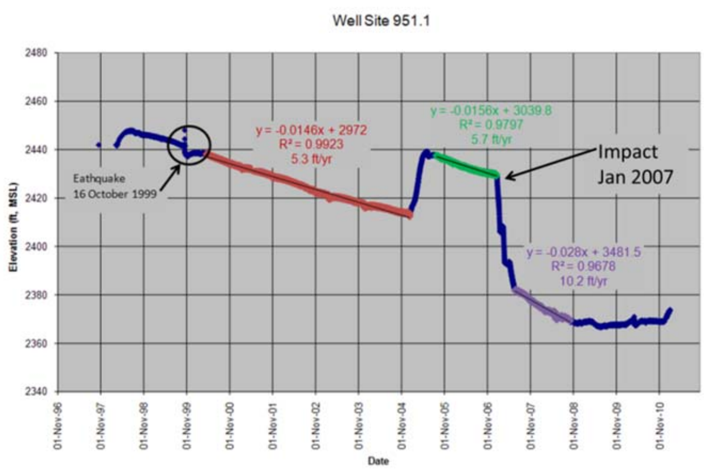


Figure 55. Groundwater hydrograph for Well 951.1 showing impact.

Using the hydrograph for the upper completion of Well 951 (Well 951.1) located on the divide between Badger and Ben Canyons as an example; a regression based recession analysis discloses that during the time of data acquisition, the general rate of decline in well head was between 5 and 6 feet per year. There are two exceptions to this. In mid-October of 1999 an earthquake of magnitude 7.1 occurred in a location approximately 47 miles to the east and southeast of Barstow, California. This event dubbed the Hector Mine Earthquake was responsible for anomalous perturbations in a number of wells within the project area. The second and most obvious exception is attributed to years of exceptionally heavy rainfall (El Niño years) when recharge related rebound occurred. After the 2004-2005 El Niño season the head was declining at a rate of approximately 5.5 feet per year when, in late January of 2007, the declination suddenly increased dramatically. This sudden decrease in head signifies water or pressure leaving the system. In the case of an impact water leaves the system from the rock fractures and flows into the tunnel. A review of the mining records and face maps show that the TBM was mining through a “very blocky to crushed” (Metropolitian Water District, 2007) section of ground associated with the Sycamore-1 fault. This fault runs sub-parallel to the alignment and possibly acted as a conduit to groundwater in the vicinity of well 951 almost 2,700 feet away. This site would be flagged as having a tunnel or construction related impact.

A cursory quantification of a determined impact might include the extension of a pre-impact recession limb across the impact period and to present or where it intersects the rebounding limb of the hydrograph. If the projection intersected the hydrograph once again before 2011 (the year when significant rebound occurred in a number of wells), the resource was generally considered to be likely recovered. If there was a decrement between the projection and the hydrograph, this was considered the remaining impact at that time. The limitations of this approach are several. First the approach can be un-conservative in that it does not account for periodic recharge to the system which would potentially decrease the rate of decline in the hydrograph or even show a rise in head. The result of this analysis would yield a smaller impact than would otherwise be realized if the recharge were added to the system. The approach however can be conservative if the rate of decline would have otherwise increased due to a persistent dry period. The findings would indicate a larger impact remaining than would actually have been if a more exact analysis was performed. Additionally rates of decline in some wells appear to be dependent on the elevation of the head, often times generally decreasing as the head elevation decreases.

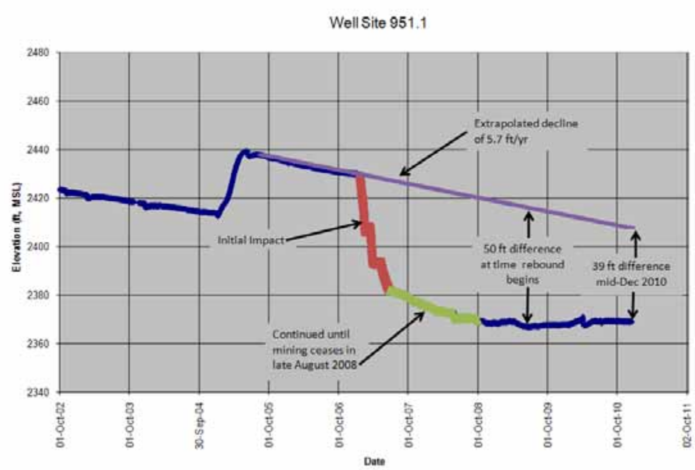


Figure 56. Groundwater hydrograph for Well 951.1 showing extrapolating continuation of pre-impact decline.

Again using Well 951.1 as an example, the last recession rate of -5.7 feet per year is extended beyond the impact point to December 2010. Using this approach an impact of about 40 feet would be assumed to exist at this point in time.

Although understanding time to recovery was outside the scope of the impact analysis, perspective on quantity was not. Recession and rebound are not uniform in all systems and are related to a number of factors some of which include whether or not the aquifer is confined or unconfined; factors relating to fracture geometry such as aperture, distribution and connectivity which in turn relates to storativity; and system flow dynamics such as proximity and behavior of groundwater sources and sinks. An impact of

20 feet in a system with an average recession of 15 feet per year may be a mild impact where it is fairly severe in a system that averages 2 feet per year. Well 951.1 had a maximum impact of approximately 50 feet with an average recession of 5.5 feet per year. Based on this information it would take approximately 9 years without rebound to lower the head in the associated aquifer under natural conditions.

Other methods for impact quantification have been employed which are not completely trivial, but do not follow the same rigor of a quantitative analysis. These are hybrids and have only been used on a small number of sites. No detail will be provided in this report, but specific information on each site may be found in the document *AHW Mining History w Groundwater & Surface Water Observations.docx* and will be included as an appendix to this report.

Some of the monitoring wells, especially those in use on the east tunnel, have been subjected to intensive scrutiny over the past several years. The primary motivations for this are the definitive impacts to surface water resources in these canyons and the need to understand the ties between the surface water and groundwater resources. The mitigation requirements imposed by the San Manuel Tribe and the Forest Service have imposed a higher standard for quantification of impacts to groundwater and their effects to surface water. The result is formulation of more complete conceptual and analytical models for three of the canyons on Arrowhead East. These canyons include Borea, Little Sand and Sand Canyons. The analyses include the groundwater monitoring wells and the associated surface water monitoring sites in these canyons and attempt to rigorously quantify impacts to these sites in quasi-real time.

Generally three methods or models have been employed in the analyses of these three canyons and all are regression based. Borea Canyon and Sand Canyon analyses are different but both employ a water budget approach to some degree. It is worth noting that the model for Sand Canyon was developed collaboratively by the San Manuel Tribe consultants, Metropolitan Water District and the US Forest Service with the goal of matching the mitigation water added to Sand Canyon to what would potentially be flowing without effects of tunnel impacts. Little Sand Canyon uses an un-impacted well in the lower canyon which has a good pre-impact correlation with other groundwater monitoring wells in the upper canyon to predict what the un-impacted hydrograph would look like for a particular well. This in turn can be used to predict the un-impacted flows for surface water sites. The results are more similar to recovery analyses as the involved parties attempted to more precisely quantify remaining impacts and potentially remaining time to full resource recovery. Methodologies for these sites will be included in the Recovery Analysis Section.

Methodologies – Surface Water

Surface water impacts were addressed using the local groundwater activity as screening criteria. If construction related impacts occurred to groundwater sites within or adjacent to a canyon, then the surface water within that canyon was scrutinized. The first step was to identify potential surface water sites proximal to the affected groundwater aquifer that had sufficient pre-construction monitoring data. Most of these sites had been established prior to tunnel construction in 1998 and many had some flow data prior to 1995.

The next step required analysis of the interaction (or lack of) between surface water data and groundwater during a baseline period. The baseline was taken as sometime before notable impacts to the groundwater and could potentially be extended as far back as there is sufficient and concurrent data for both sites. The well hydrograph is considered a proxy for the groundwater aquifer and a relationship using same day values for groundwater head and surface water flow was constructed. When developing these relationships it is important to keep the physical parameters in focus. At many surface water sites, particularly mid-channel sites with sandy substrate and lots of vegetation, groundwater (baseflow) may be only a small component of the overall flow measurement. Direct runoff from precipitation, bank and sediment storage, and evapotranspiration become major factors in flow quantity. Perched water stored in the sediment on a bedrock shelf above the bank may have no connection with deeper groundwater. Yet this source can potentially be recharged annually providing local augmentation to flow which can be depleted over a period of months, or longer. These physical parameters make the task of identifying connections between groundwater dependent resources very complex and in some instances very difficult to obtain.

After several years of investigating the relationships between these groundwater dependent resources and field monitoring of flows, it has generally been determined by technical staff with the Forest Service and MWD that predominately baseflow at most monitored sites occurs from July to October. There are some exceptions to this as when an extended precipitation season lasts into June or when summer storms augment monitored sites. Another occurrence happens when the precipitation from the next season (October through September) starts early. Normally seasonal rainfall begins in late November or December. An October heavily laden with precipitation will not affect baseflow in that month, but it will increase significantly the precipitation component of the measured surface flows. Generally these anomalies are identifiable and can be removed or accounted for but the effect can be a smaller than desirable dataset.

Spring sites, or particularly the adit sites (originally springs that were hollowed out to provide enhance flow), can be especially useful in developing relationships between groundwater and related surface water, as these sites have fewer non-groundwater derived components. In some cases a very good relationship was shown to exist between a well and a surface water site. For example, Spring Site 45 is actually an adit located in the mid reach of Borea Canyon. This site appears to have much less seasonal variability and has a good correlation with the hydrograph head values obtained from the well just to the north (Well 908). The baseline dataset was taken to be from 1997 through 2003 (impacts were potentially occurring in Well 908 as early as summer 2004) and the baseflow period is July through October of each year. A same day comparison between groundwater heads and monitored flow data yields an R^2 of 93% which, for this type of analysis, is a very good correlation. The determination of a linkage between the groundwater heads in the vicinity of the well and the water flowing from the adit or spring could be established for the baseline period.

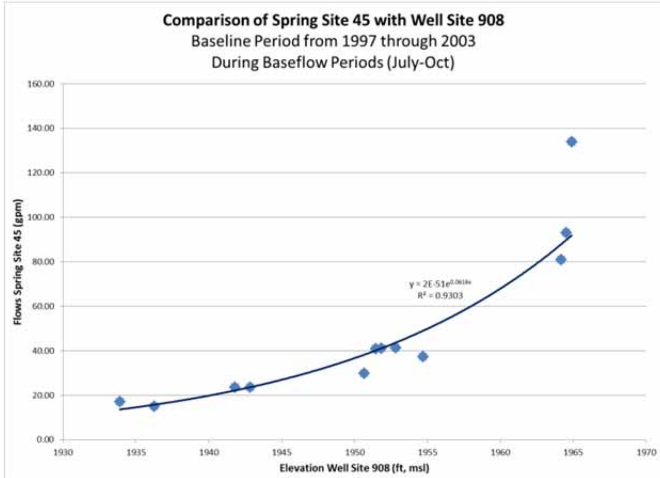


Figure 57. Spring 45 comparison with local groundwater well (baseline).

The next step was to examine the effects of construction impact on the relationship. Using the same method the post-impact data was added which would help determine the strength of the connection. If the relationship remained quantitatively similar or was similar until flow ceased, then the conclusion was that the groundwater and surface water were similarly impacted. Again looking at the relationship between Spring Site 45 and the groundwater head in Well 908, the post-impact relationship is very similar to the baseline. The R^2 is 94%, slightly improved with the density of data points. The temporal extent of the relationship has been limited to the end of the 2005 baseflow season as mitigation in the form of irrigation was added starting in 2006.

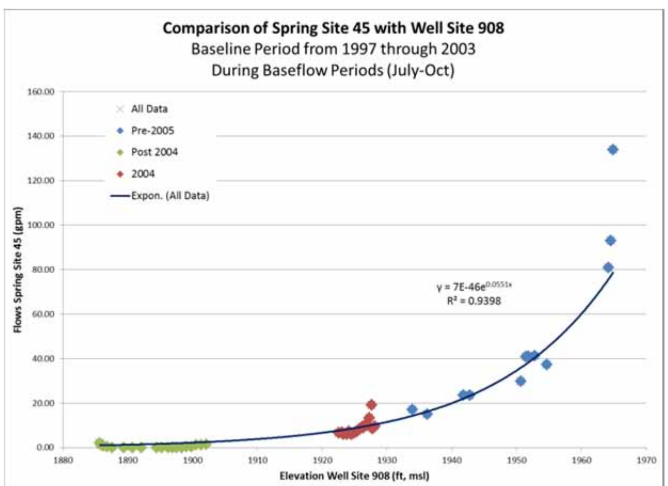


Figure 58. Spring 45 comparison with local groundwater well (all).

In cases where groundwater was indirectly tied to surface water, for example when there is a leaky barrier involved such as a fault or when the connection is more distal (as when the impacted groundwater is close to the alignment and the surface water site is half a mile or more down canyon), the surface water and groundwater may have a good baseline relationship that falters once the groundwater site is impacted. This type of relationship would show an upward shift between baseline data and post impact data resulting from the enhanced groundwater impact relative to the surface site. This type of relationship is useful as it shows a lack of impact or lack of intensity of impact to the surface water site.

In the example below Spring Site 213 flows in Badger Canyon (green dot) are compared with same day heads in Well 902.2 (red dot). Baseline data are red diamonds in the graph and give a R^2 of about 78%. Once post impact data is added (blue diamonds) the shift is up to the left. This is because the well was heavily impacted, yet the surface water was not. If all of the impacted groundwater in the area that had a reasonable baseline correlation exhibits a similar relationship, the conclusion would be that surface flows do not show definitive groundwater related impacts.

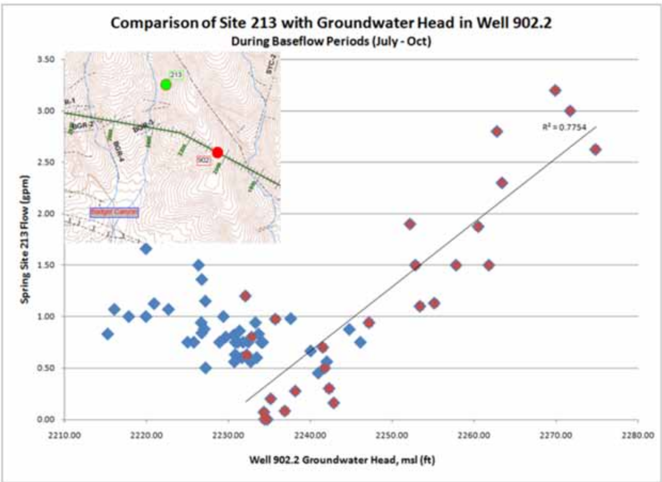


Figure 59. Spring 213 comparison with local groundwater well (all).

The obvious limitation would be having a monitoring well that has a good groundwater tie to the surface. In some areas, City Creek for example, there are decided surface water impacts but the affected groundwater that supplies these sites are not monitored. Therefore the relationships are indirect and nebulous at best.

Through this technique of correlation or negative correlation most of the surface water sites were compared with local monitoring well hydrographs in attempt to determine the potential of a groundwater connection and if affirmative, a qualitative assessment of the severity of the impact if possible. Some of the sites however were visually checked during the timeframe that groundwater was affected. If there was no pronounced apparent change or if flow appeared to be ephemeral, a more rigorous approach was not employed.

Most of the surface water sites were initially analyzed in this manner. It is recognized that, as mentioned previously, many sites have several flow components in addition to groundwater. For the sites in Borea Canyon, Little Sand Canyon and Sand Canyon, attempts were made to quantify these additional effects in order to better understand what natural conditions would be without mining related effects. The increased comprehension at these sites was necessitated by the need for mitigation of surface flows. The analytical models developed for these canyons will be included in the recovery section of the document.

Results

Impact analyses results are valid as of late 2011 and are estimates. Some sites which were initially impacted by tunnel construction appeared to have sufficiently recovered by this point. Sites which still presented impacts became the basis for the recovery analyses. The following tables summarize the results of the impact analyses.

Arrowhead West Wells

Canyon	Well	Impact	Apparent Impact Date	Estimated Remaining Impact September 2010	Remaining Relative Impact*
Devil's	900	Yes	February 2008	22 ft	2 to 10 times Typical Recession
Ben	901	No	N/A	N/A	N/A
	950	No	N/A	N/A	N/A
Badger	195	Yes	March 2007	1-2 ft	0.3 times Typical Recession
	196	Yes	March 2007	Potentially recovered by mid-2009	N/A
	902.1	Yes	January 2007	60 ft	8 to 9 times Typical Recession
	902.2	Yes	January 2007	Potentially recovered by late 2008.	N/A
	951.1	Yes	January 2007	40 ft	7 to 8 times Typical Recession
	951.2	Yes	January 2007	16 ft min.	3 times Typical Recession
Sycamore	952.1	No	N/A	N/A	N/A
	952.2	Yes	July 2005 & March 2006	22 ft	3 to 4 times Typical Recession
	903	Yes	July 2005	May have recovered this last year (2011).	N/A
Waterman	197	Yes	April 2004	Unknown	N/A

Canyon	Well	Impact	Apparent Impact Date	Estimated Remaining Impact September 2010	Remaining Relative Impact*
Waterman(cont)	905	Yes	November 2003	Mined through piezometer	N/A
	918	No	N/A	N/A	N/A
	923	Yes	April 2004	Unknown	N/A
	937	No	N/A	N/A	N/A
	946	No	N/A	N/A	N/A

*A Relative Impact of 3 times typical recession indicates that it would take approximately 3 years at the pre-impact typical rate of decline in groundwater head for the head to be at its current elevation.

Arrowhead West Surface Water

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
Devil's	Spring 08	No	N/A	N/A	Visual
	Horizontal Well 110	No	N/A	N/A	Regression Correlation w/Well 195
	Spring 153	No - Ephemeral	N/A	N/A	Visual
	Stream 193	Indeterminate – No baseflow data	N/A	N/A	N/A
	Stream 620	No	N/A	N/A	Regression Correlation – Poor Fit
Ben	Spring 09	No	N/A	N/A	Regression Correlation w/Well 901
	Stream 10	No	N/A	N/A	Regression Correlation w/Well 196
	Spring 11	No	N/A	N/A	Regression Correlation w/Well 196
	Spring 157	No - Ephemeral	N/A	N/A	Visual
Badger	Spring 21	Insufficient Data	N/A	N/A	N/A
	Spring 26	Insufficient Data	N/A	N/A	N/A
	Stream 27	No	N/A	N/A	Regression Correlation w/Well 902.2
	Stream 28	No - Ephemeral	N/A	N/A	Visual
	Stream 152	No	N/A	N/A	Regression Correlation w/Well 950
	Spring 213	No	N/A	N/A	Regression Correlation w/Well 902.2
	Spring 214	No	N/A	N/A	Regression Correlation

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
Badger(Cont)	Spring 214(cont)				w/Well 902.2
Sycamore	Spring 17	Yes	Early-Mid 2005	Indeterminate – Ceased Monitoring	Regression Correlation w/Well 923
	Spring 65	Yes	Early-Mid 2005	Indeterminate – Ceased Monitoring	Regression Correlation w/Well 903
	Stream 20	No	N/A	N/A	Visual
	Stream 30	No	N/A	N/A	Visual
	Stream 95	Indeterminate	2004 Water Diversion	N/A	N/A
	Stream 156	No	N/A	N/A	Regression Correlation w/Well 952.1
	Stream 182	Indeterminate	2004 Water Diversion	N/A	N/A
	Stream 205	No	N/A	N/A	Regression Correlation w/Well 952.1
	Stream 627	No - Ephemeral	N/A	N/A	N/A
Waterman	Stream 134	No	N/A	N/A	Visual
	Stream 191	No	N/A	N/A	Visual
	Spring 93	No - Ephemeral	N/A	N/A	N/A
	Horizontal Well 642	Maybe transient	February to April 2004	Probably not	Visual

Arrowhead East Wells

Canyon	Well	Impact	Apparent Impact Date	Estimated Remaining Impact September 2010	Remaining Relative Impact*
Strawberry	198	No	N/A	N/A	N/A
	906	No	N/A	N/A	N/A
Borea	907	Yes	February 2004	0-2 ft	0.3 times Typical Recession
	908	Yes	July 2004	2-3 ft	0.5 to 1 times Typical Recession
	953	Yes	May 2004	22 ft	3 times Typical Recession
Little Sand	954.1	Yes	January 2006	17 ft	1 to 2 times Typical Recession
	954.2	Yes	January 2006	17 ft	1 to 2 times Typical Recession
	909	Yes	December 2005	2 ft	0.5 times Typical Recession
	958.1	No	N/A	N/A	N/A
	958.2	No	N/A	N/A	N/A
	178	N/A	N/A	N/A	N/A
Sand	955.1	Yes	October 2006	Insufficient Data	N/A
	955.2	Yes	September 2006	Insufficient Data	N/A
	956.1	Yes	March 2006	19-23 ft	2 to 4 times Typical Recession
	956.2	Yes	February 2006	24 ft	2 to 4 times Typical Recession
	910	No	N/A	N/A	N/A

Canyon	Well	Impact	Apparent Impact Date	Estimated Remaining Impact September 2010	Remaining Relative Impact*
Sand(Cont)	959	Yes	September 2007	Insufficient Data	N/A
	957.1	No	N/A	N/A	N/A
	957.2	No	N/A	N/A	N/A
City Creek / Stubblefield	911	Yes	October 1998	130 ft	8 times Typical Recession
	912.1	Yes	October 1998	25 ft	25 times Typical Recession
	912.2	Yes	August 1998	18 ft	6 times Typical Recession
	913	Yes	July 1998	Unknown	N/A
	199	Insufficient Data	N/A	Insufficient Data	N/A

*A Relative Impact of 3 times typical recession indicates that it would take approximately 3 years at the pre-impact typical rate of decline in groundwater head for the head to be at its current elevation.

Arrowhead East Surface Water

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
Strawberry	Spring 201	No	N/A	N/A	Visual
	Stream 678	No	N/A	N/A	Visual
	Stream 38	No	N/A	N/A	Visual
	Stream 189	No	N/A	N/A	Visual
	Stream 624	No	N/A	N/A	Visual
	Stream 628	No	N/A	N/A	Visual
	Stream 629	No	N/A	N/A	Visual
	Stream 644	No	N/A	N/A	Visual
	Stream 645	No	N/A	N/A	Visual
	Stream 676	No	N/A	N/A	Visual
	Stream 677	No - Ephemeral	N/A	N/A	N/A
	Stream 679	No	N/A	N/A	Visual
	Spring 120	No	N/A	N/A	Visual
Borea	Spring 45	Yes	Mid-2004	No	Borea Model w/Well 908
	Stream 154	Yes	Mid-2004	No	Borea Model w/ Well 907
Little Sand	Stream 637	No - Ephemeral	N/A	N/A	N/A
	Spring 510	Yes	Early 2006	No	Little Sand Model w/Well 909
	Spring 44	Yes	2006	No	Little Sand Model w/Well 909

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
Little Sand[(Cont)]	Stream 509	Yes	2006	No	Little Sand Model w/Well 909
	Stream 155	Yes	By 2008	No	Little Sand Model w/Well 909
Sand	Stream 635	Indeterminate	N/A	N/A	N/A
	Spring 48	Yes	2007	Yes	Sand Canyon Model
	Stream 636	Yes	By 2007	No	Sand Canyon Model
	Spring 53	Yes	2006	Yes	Sand Canyon Model
	Spring 54	Yes	2007	No	Sand Canyon Model
	Spring 51	No	N/A	N/A	N/A
	Spring 185	No	N/A	N/A	N/A
	Stream 117	Yes	2007	No	Sand Canyon Model
	Stream 103	Yes	2007	N/A	Sand Canyon Model
City Creek / Stubblefield	Spring 55	No	N/A	N/A	
	Spring 56	Potentially Yes	Early 1999	No adequate Groundwater Correlations	Regression Correlation w/Well 911
	Spring 58	Yes	Early 1999	No adequate Groundwater Correlations	Regression Correlation w/Well 911
	Spring 59	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Spring 60	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
City Creek / Stubblefield	Stream 151	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 181	Yes	1999	No adequate Groundwater Correlations	Regression Correlation w/Well 913
	Spring 209	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 210	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 515	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 520	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 622	Potentially Yes	1998	Unknown	Visual – lacks pre-impact data for quantitative analysis
	Stream 625	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Horizontal Well 626	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 630	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 631	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A
	Stream 632	Indeterminate – Lacks	N/A	N/A	N/A

Canyon	Site	Impact	Apparent Impact Date	Remaining Impact September 2010	Method of Analysis
City Creek / Stubblefield	Stream 632(Cont)	adequate pre-impact data			
	Spring 633	Indeterminate – Lacks adequate pre-impact data	N/A	N/A	N/A

Recovery Analyses

Aquifer behavior in the project area is inferred using well hydrographs as a proxy. Study of many wells within the project area has shown that these hydrographs (and inferred aquifers) tend to exhibit fairly predictable behavior on a large scale. The hydrographs are typically a temporal depiction of groundwater head within a well. It is assumed that as the aquifer loses pressure or the water table elevation decreases (in an unconfined aquifer) the well data, in the aquifer surrounding the well, reflects this with a corresponding change in head. When the groundwater head decreases over time, the hydrograph shows a recession limb. If the head steadily rises, rebound is occurring. If rebound is related to precipitation, then it is recharge to the aquifer.

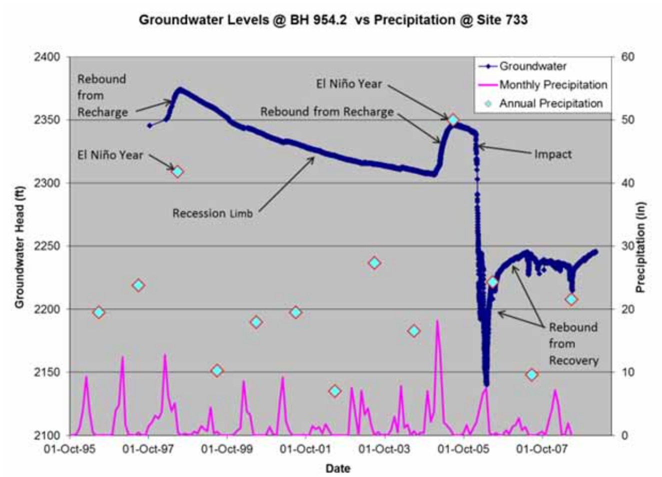


Figure 60. Groundwater head hydrograph for Well 954.21 showing precipitation at City Creek Ranger Station.

If rebound is related to a gradient produced by groundwater loss from the system resulting from construction activities, then the aquifer is undergoing recovery. *Hydrologic recovery* occurs when the impacted area returns to steady state resulting from these inflows or pressure adjustments and can be elastic or inelastic. Elastic recovery will bring the system back to its pre-impact state; inelastic recovery will result in a new steady state but the system will be short of its pre-impact state.

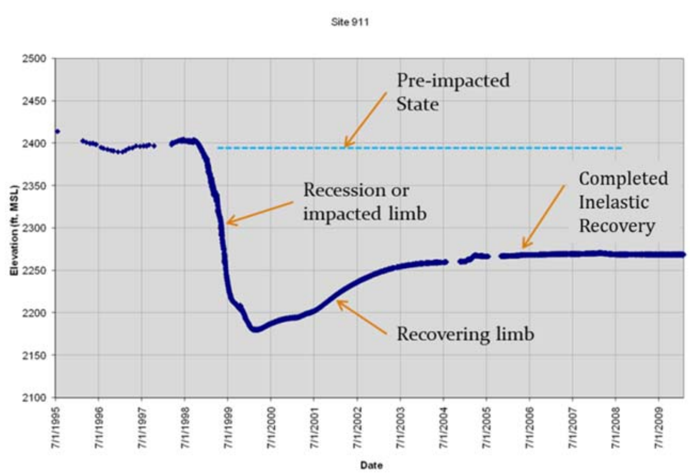


Figure 61. Groundwater head hydrograph for Well 911 depicting impact and recovery segments.

Ecological recovery occurs when the impacted groundwater dependent ecosystem (groundwater and surface water) hydrologically returns to a state of *ecological resiliency*, which happens when the ecosystem is able to adapt to multi-decadal environmental changes. Components of ecological recovery may include hydrologic recovery, recharge, inter-basin flow as well as other sources. Assuming the system was originally ecologically resilient prior to an impact (all other factors unchanged), ecological recovery should be achieved when the system reaches its pre-impacted state.

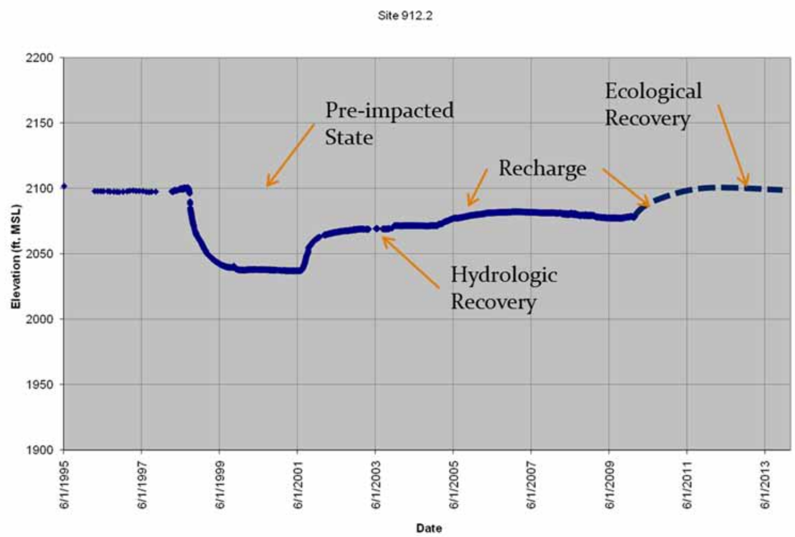


Figure 62. Groundwater head hydrograph for Well 912.2 depicting impact and recovery segments.

The Forest Service approach to recovery uses the ecological recovery criteria when evaluating whether recovery of an aquifer (and potentially associated surface water dependent resources) has taken place. It is therefore important to attempt to understand the natural behavior of the aquifer system in order to predict the natural state of the aquifer at a given time post-impact. This has been done in a variety of ways and is related to a number of factors including data availability and quality, apparent relationships (groundwater-surface water, groundwater-precipitation, groundwater-groundwater), apparent hydrogeologic ties and, very importantly, external drivers to quantify residual impact to groundwater dependent resources.

Within a given canyon several wells may indicate ongoing tunnel related effects during the initial impact analyses. Not all of these sites were chosen for recovery analyses. On Arrowhead East, the canyons of Borea, Little Sand and Sand had recovery analyses and modeling developed as a result of potential impacts to surface sites supporting biologically sensitive resources. The modeling was developed in an attempt to quantify the amount of augmentation to flow (. through irrigation) required to meet natural conditions within the channel. In considering the remaining impacted sites within the project area, it was decided that only sites that would have post project recovery monitoring would receive the more detailed analyses. Of these sites some would additionally go on to become important sites to the Seismic and Emergency Response Plan discussed in the next section.

The recovery analyses discussion will start with Arrowhead East as these analyses occurred first and formed the base for many of the others within the project area.

Borea Canyon

The Borea Canyon model was developed in 2010 as a response to questions concerning irrigation needs in Borea Canyon. This canyon had irrigation infrastructure installed in 2005 with a tank on Daley Spur Truck Trail above the mid to lower canyon. From here water was piped to just above Spring Site 45 at the upper end of flow and occasionally to a gaining section between Spring Site 45 and Stream Site 154. The tank has been filled manually with a water truck and by 2009 the question arose as to whether the surface water sites were still impacted, so a need to quantify surface water impacts based on the related groundwater arose.

Local Hydrogeology

This is a fractured rock aquifer with faulting as the primary control related to permeability providing conduits and barriers to flow. General groundwater gradient somewhat parallels topography with ridge flow toward canyon bottoms and down canyon to the south, parallel to several faults seen in the canyon bottom including the BC-1 fault. The Borea Canyon fault runs approximately southwest-northeast in the mid-canyon above Well 908. The N fault is a reverse fault that crosses at the lower end of what might be considered the mid-canyon just below Spring Site 45. This feature may be somewhat of an impediment to groundwater movement and responsible for ponding of water upstream to the point of interception with surface topography. Approximately 0.4 miles downstream lies the O fault, another compressive feature related to the east-west bend in the San Andreas fault.

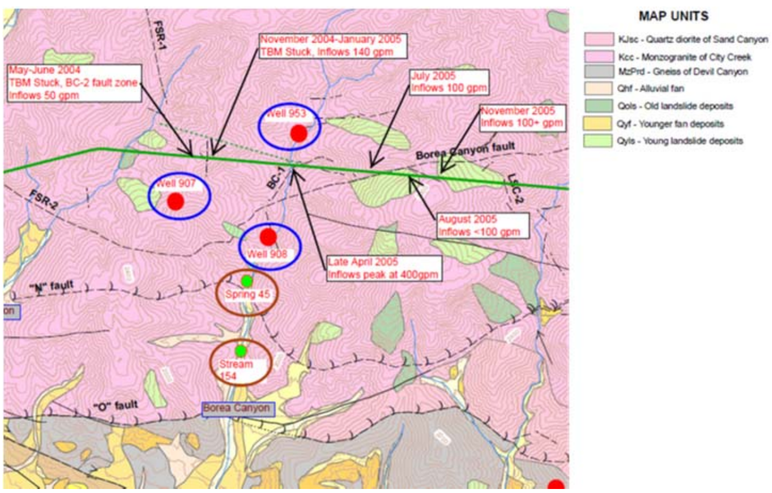


Figure 63. Borea Canyon geology map with monitoring sites and tunnel construction information.

Recharge originally was thought to come from the Mud Flats area to the northeast, but subsequent analyses don't bear this out. It may be that the Arrowhead Springs fault to the north is a significant impediment to groundwater movement this far west. Recharge is believed to come from precipitation proximal to the canyon and San Bernardino County Precipitation Gage 2015, which is located at US Forest Service Del Rosa workstation at the west mouth of the canyon, is used as a proxy for precipitation/recharge.

Groundwater Dependent Resources

Groundwater dependent resources within the canyon are represented by three groundwater monitoring wells and two surface water monitoring sites.

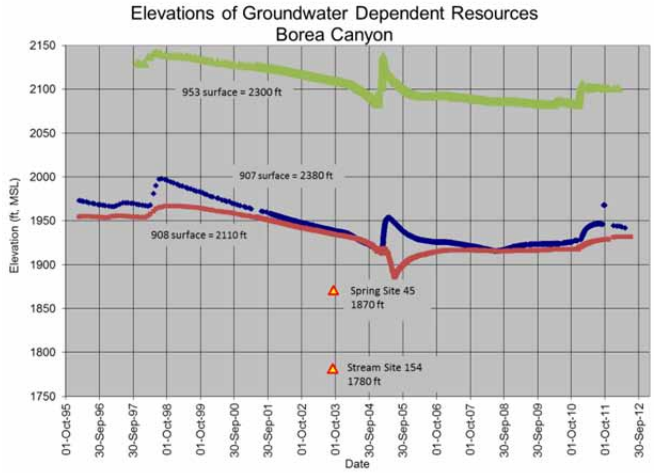


Figure 64. Comparison of Borea Canyon well hydrographs.

Well 907 is a single completion well that samples the aquifer directly below the west ridge adjacent to the mid-canyon. The hydrograph generally displays a slightly steeper annual recession than the other two wells in Borea Canyon (approximately 7-10 ft/yr. as compared to 2-7 ft/yr. for the other two) which may result from lower fracturing intensity (lower storage) and or faster drainage of the system related to a steeper initial gradient. Impact occurred in February of 2004 and decline ceased in February of 2005 in response to El Niño recharge. Groundwater then declined to the elevation of Well 908 in 2008. Since then rebound has brought the groundwater levels in the area back above Well 908. In 2011 the groundwater in the vicinity of Well 907 displayed a typical recharge response to above average rainfall.

Well 908 is located near the channel bottom and along a northwest trending splay off the Borea Canyon fault. The typical groundwater head recession in the vicinity of this well is more variable than the other wells but the pre-impact recession averaged approximately 8 ft/yr. When first impacts occurred in mid-2004, heads in wells 908 and 907 were near the same elevation. Well 908 is located about 0.3 miles down canyon from Well 953, but the head in Well 953 closely shadowed Well 908 with a fairly consistent gradient of 0.10 ft/ft until both wells were impacted by tunnel construction. Rebound started in July of 2005 and has been steady over time. Recharge from the 2011 precipitation year started in January of 2011.

Well 95 is located near the bottom of the upper canyon and north of the constructed tunnel. Pre-2004 behavior is similar to Well 908 but tunnel construction related impacts were apparent months earlier. El Niño related recharge behavior was similar to Well 907. Monitoring of this well discontinued in early 2012 due to equipment issues.

Spring Site 45 is one of several adits which were presumably springs and were excavated in the early 20th century for the purpose of increasing water production. This site is strongly groundwater based and much less reactive to individual precipitation events than most other surface water monitoring location within the project area. It is located just north of the N fault and may benefit from ponding of water upstream of this feature. If a 0.1 ft/ft gradient were extrapolated beyond Well 908 down canyon, the elevation of groundwater head at Site 45 would be 1835 ft when Well 908 head was at 1922 ft. The fact that Spring Site 45 is located at a fixed topographic elevation of 1870 ft helps to support the idea of the N fault as an aquitard. Additionally flow measurements at this site correlate very well with groundwater head elevations in Well 908 until the well head drops below an elevation of 1920 feet (which happened in mid-2004). At this point groundwater from Well 908 appears to have no influence on flow.

Stream Site 154 is a stream site located approximately 0.2 miles down canyon from Site 45. Surface water at this location supports a vegetation cluster in the vicinity and is tied to groundwater through a seep in the west bank of the canyon very proximal to the monitoring site. Additionally there may be surface flow contributions from what appears to be a gaining section of the stream which supports a vegetation cluster located between this site and Site 45 upstream. Analysis supports assumptions that Site 154 flow appears to be largely independent of Site 45 flow. The bedrock in this section is shallow and this reach has undergone extreme episodes of scour and siltation.

The Models

The canyon is broken down into two seemingly interdependent segments for the purpose of analyzing and predicting heads and flows. As mentioned earlier groundwater heads in the vicinity of Well 908 strongly correlate with flows at Spring Site 45. These resources are modeled initially and then the relationship between heads in Well 908 and Well 907 are used in a second model to predict Well 907 heads which in turn rely on a relationship between Well 907 heads and flows at Stream Site 154 for prediction of Site 154 flow.

The Upper Canyon Sites

The basic premise for the first model comes from the first law of thermodynamics which assumes conservation of mass (matter is neither created nor destroyed) which in hydrology is the water budget. Assuming a controlled volume (meaning the area volume does not shrink or expand), the amount of water entering the system in the area of Well 908 must be balanced by the amount of water leaving the system or the water level or pressure (head) of the system will change (a change in storage). The change in storage of this system is represented by the change in groundwater head in Well 908. An increase in head equates to a positive change in storage; conversely a decline in groundwater head signifies groundwater leaving the system or a negative storage change. Under natural conditions flow into the system can come from several sources including direct recharge through precipitation and recharge from areas of higher groundwater head. At this site, recharge is considered to be from predominately local precipitation sources, so recharge from other groundwater is neglected. In a natural system without anthropogenic influences water leaves through discharge to surface water sites (i.e. springs, seeps, fens, gaining reaches of streams and rivers) and to sinks such as another groundwater basin. Recovery occurs as groundwater moves in from other up-gradient sources after the aquifer has been unnaturally stressed. These stresses can include extraction of groundwater through discharge from a production well and in this case as a result of water transfer from the aquifer to the tunnel during mining.

Using the premise of conservation of matter, the modeling concept uses springs and recharge to understand changes in groundwater storage during the pre-impact or baseline period and then predict changes in storage after the aquifer has been impacted. If surface water resources fluctuate with groundwater head, then changes to these resources should reflect changes to the groundwater. Post impact prediction of groundwater head based on natural sources and sinks (contributions and extractions) without mining influence should in turn yield post-impact predictions of natural surface flows based on a scenario of a non-impacted aquifer. Once the groundwater rebound has occurred to the point where the observed groundwater heads and associated spring flows match the modeled (presumably non-impacted predictions) then ecological recovery is complete and the canyon should have obtained its original state of ecological resiliency.

The temporal span for analyzing baseline data has been taken to be from 1998 to 2003. Limitations exist to the Well 908 data set which precludes using an earlier start date. Additionally in the 2004 season two events happened which preclude use of the data. This is the probable time of initial effects to the groundwater in Borea Canyon and during October of 2003 the area experienced a large fire which burned through the canyon and denuded the surrounding hill slopes. The effects of the fire on the surface water resources were substantial in the years following the fire, especially when evapotranspiration and sediment transport dynamics are considered in the middle and lower canyon. Spring Site 45, being strongly groundwater based, was less affected by effects of the fire.

The proxy for recharge in this model is precipitation. Precipitation is the only truly independent variable in the model. Relationships with approximately 2 dozen rain gaging sites proximal to Borea Canyon and Mud Flats were examined. Data issues exist at all rain gage sites to some extent, but the site at Del Rosa Station (San Bernardino County Rain Gage 2015) had the best data quality and overall independent correlation with changes in the dependent groundwater data.

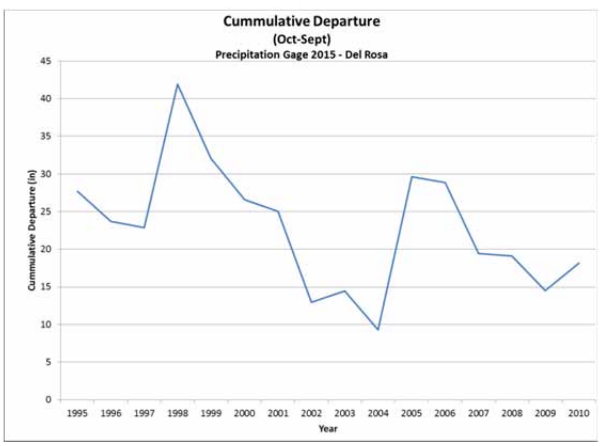


Figure 65. Cumulative departure from mean annual precipitation at Del Rosa gage.

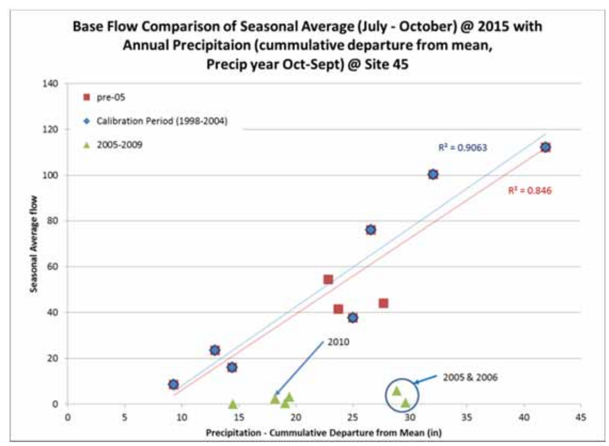


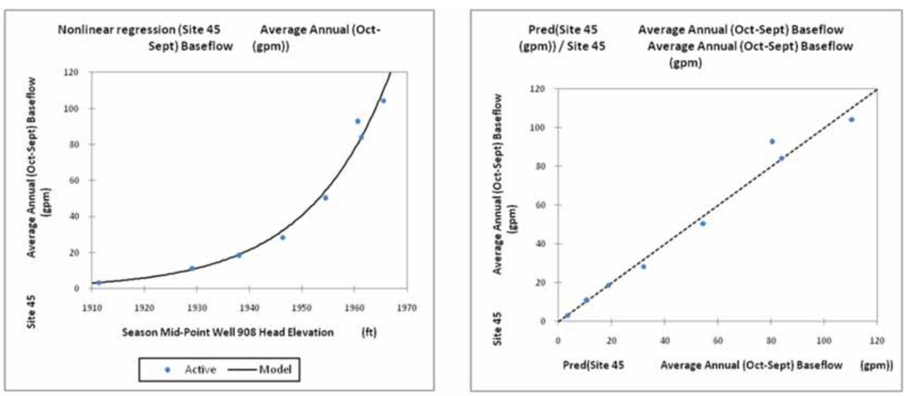
Figure 66. Comparison of Spring Site 45 baseflow and annual precipitation at Del Rosa rain gage.

In the data reduction process, daily rain gage data is converted to monthly totals and then monthly totals are summed to determine annual precipitation in inches. The months of October through September are used to construct the precipitation year. In order to understand long-term precipitation effects, cumulative departure from the mean annual precipitation was applied to the data starting from 1 October 1995. This was done for all rain gage sites considered in the analysis and a comparison was done between each rain gage site and each well hydrograph. It soon became apparent that wells responded more to relative differences in local precipitation versus sites that surrounded more distal recharge areas. A site located on the west ridge of the upper canyon Daley Spur (San Bernardino County Rain Gage 2962) was excluded because of some anomalous years.

Visual inspection showed the site installation to be very close to a knoll which potentially blocks rainfall coming in from the south or east and vegetation growth could block it from other directions as well if not maintained.

Figure 67. County Rain Gage 2962 shadowed by hill to east

Flow leaving this system is through surface water expression. Analysis done with Spring Site 45 determined that there was a good correlation between the flow rate at this site and the elevation head in Well 908 (at least until head dropped below an elevation of 1920 feet).



R^2 = .98

Site 45 = 2.04E-53 EXP (0.064 x mid-season elev)

Figure 68. Correlation Statistics showing fit of above expression with actual data.

Data reduction of the spring was done to allow use of an average seasonal flow and an average annual flow. The seasonal flow refers to the baseflow season (July through October) and is therefore out of sync with the precipitation year by one month. Since precipitation rarely occurs in October, it was decided that the benefit of the extra month of baseflow out weighted error introduced by the offset. The actual computation uses the recorded flows from July through October to get a cumulative flow for the season based on the flow rate in gpm calculated over a one day period and applied to the days between measurements. The number of days applied to a flow measurement is determined by interpolation between days with the exception of the first and last points. Half of the days between the first and second measurement are applied to the first in addition to all of the days from 1 July to the first measurement point. The last measurement point gets all days beyond that point until 1 October in addition to the days from halfway between the last and second to last points. In this way total cumulative baseflow in gallons from 1 July to 30 September are calculated. From this quantity an average baseflow in gpm for the baseflow season is determined. The average *Non-Seasonal* baseflow is the interpolated mid-point between the last year's average baseflow and the current year average baseflow.

During the baseline or validation period changes in groundwater storage result from precipitation recharge and spring flow. An increase or decline in the well hydrograph head is considered a proxy for storage changes within the aquifer. Of the three monitored wells in and adjacent to Borea Canyon, Well 908 is the most proximal to Spring Site 45 and directly up canyon by 850 feet. Additionally it has the best correlation with the surface water site and the precipitation site. For simplicity, changes in well head with time, or declination, coincides with the precipitation year (October to September). In reality there appears to generally be a three month lag between the start of the seasonal precipitation and the initial response to recharge in this well. The effects of precipitation are input as cumulative departure from the mean on an annual basis and there is generally no significant precipitation after June which provides recharge. The effect of the lag is therefore already incorporated into the annual declination. A positive value for declination indicates recharge. To obtain the overall annual declination the elevation of the hydrograph on 30 September of the previous year is subtracted from the elevation of the hydrograph of the current year. In the early years without continuous or daily readings, an interpolation was made to obtain the hydrograph elevation on 30 September. The mid-season value is simply half of the declination added to the previous year's value and not the actual value on 30 March.

A multivariable regression analysis with Well 908 as the dependent variable was selected as a starting point to determine the fit of the other variables. Spring Site 45 as an independent variable was used in conjunction with a variety of precipitation stations (also independent variable) to determine the best fit selection. As mentioned above the best overall correlation results from using Spring Site 45 and cumulative annual departure from mean annual precipitation at rain gage site 2015 as independent variables with annual head changes (declination) in Well 908 as the dependent variable.

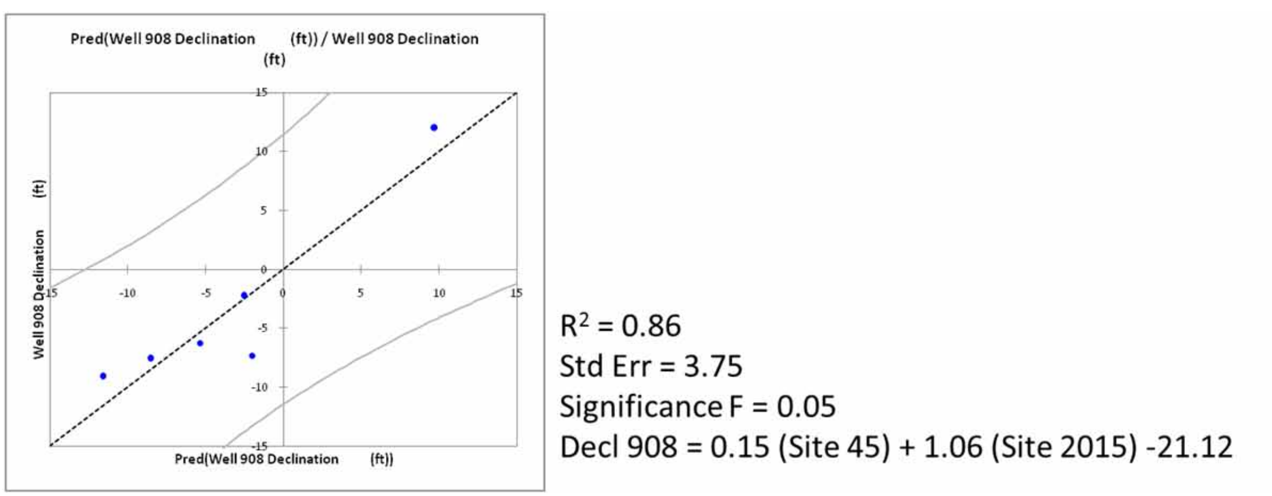
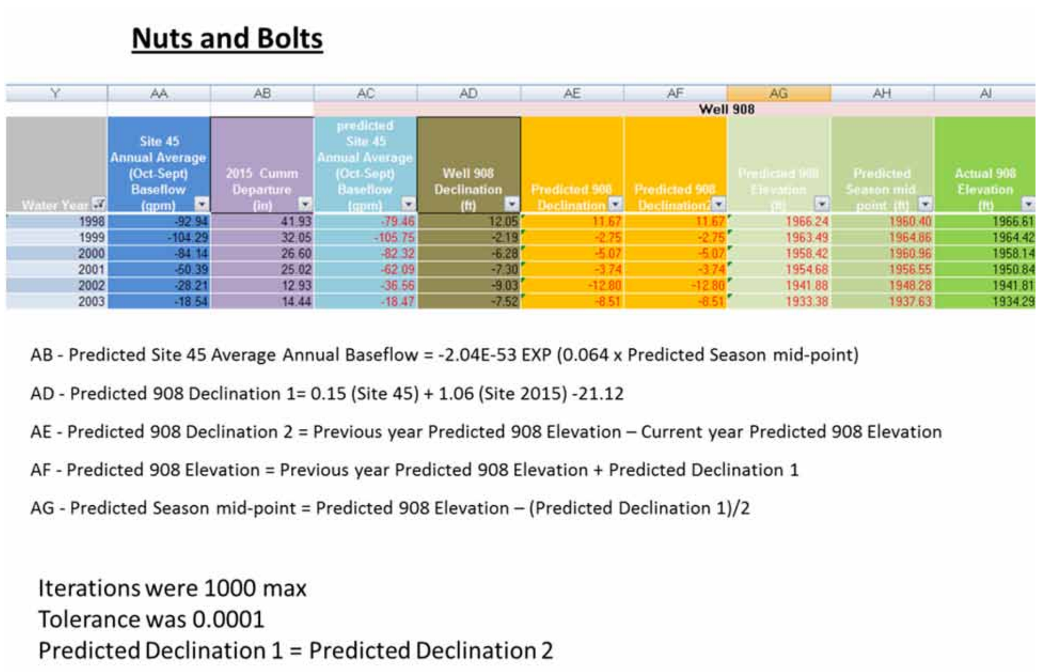


Figure 69. Correlation statistics and fit to real data using above predictive expression for Well 908 based on precipitation at Del Rosa rain gage.

At this point there are two relationships. Groundwater head declination is a function of precipitation at rain gage 2015 and of flow leaving Spring Site 45. Additionally the flow leaving Spring Site 45 is a function of groundwater head. In a predictive scenario there are two unknown variables (groundwater head and spring flow), but there two relationships as well.

Microsoft Excel is used as the platform for computations. Change in storage, or declination, is computed based on precipitation and spring flow as defined above. Declination is also computed based on the difference between prior year head and the current year head. The average annual flow at Site 45 is a function of the mid-year head in the well which is a function of prior year head and current year head. Excel is allowed to make iterative changes to the predicted current year head until the two different calculations for declination are within 0.0001 foot of each other.



Nuts and Bolts

Y	AA	AB	AC	AD	AE	AF	AG	AH	AI
			Well 908						
Water Year	Site 45 Annual Average (Oct-Sept) Baseflow (gpm)	2015 Cumm Departure (in)	predicted Site 45 Annual Average (Oct-Sept) Baseflow (gpm)	Well 908 Declination (ft)	Predicted 908 Declination	Predicted 908 Declination2	Predicted 908 Elevation (ft)	Predicted Season mid point (ft)	Actual 908 Elevation (ft)
1998	-92.94	41.93	-79.46	12.05	11.67	11.67	1966.24	1960.40	1966.61
1999	-104.29	32.05	-105.75	-2.19	-2.75	-2.75	1963.49	1964.86	1964.42
2000	-84.14	26.60	-82.32	-6.28	-5.07	-5.07	1958.42	1960.96	1958.14
2001	-50.39	25.02	-62.09	-7.30	-3.74	-3.74	1954.68	1956.55	1950.84
2002	-28.21	12.93	-36.56	-9.03	-12.80	-12.80	1941.88	1948.28	1941.81
2003	-18.54	14.44	-18.47	-7.52	-8.51	-8.51	1933.38	1937.63	1934.29

AB - Predicted Site 45 Average Annual Baseflow = -2.04E-53 EXP (0.064 x Predicted Season mid-point)

AD - Predicted 908 Declination 1= 0.15 (Site 45) + 1.06 (Site 2015) -21.12

AE - Predicted 908 Declination 2 = Previous year Predicted 908 Elevation – Current year Predicted 908 Elevation

AF - Predicted 908 Elevation = Previous year Predicted 908 Elevation + Predicted Declination 1

AG - Predicted Season mid-point = Predicted 908 Elevation – (Predicted Declination 1)/2

Iterations were 1000 max
Tolerance was 0.0001
Predicted Declination 1 = Predicted Declination 2

Figure 70. Modeled expressions and their values included in spreadsheet.

The model was seeded with an actual end season elevation in Well 908 from the year 1997 and the calculations were allowed to go forward to the end of 2003 in order to validate the model or compare the predicted values with the actual values for those years.

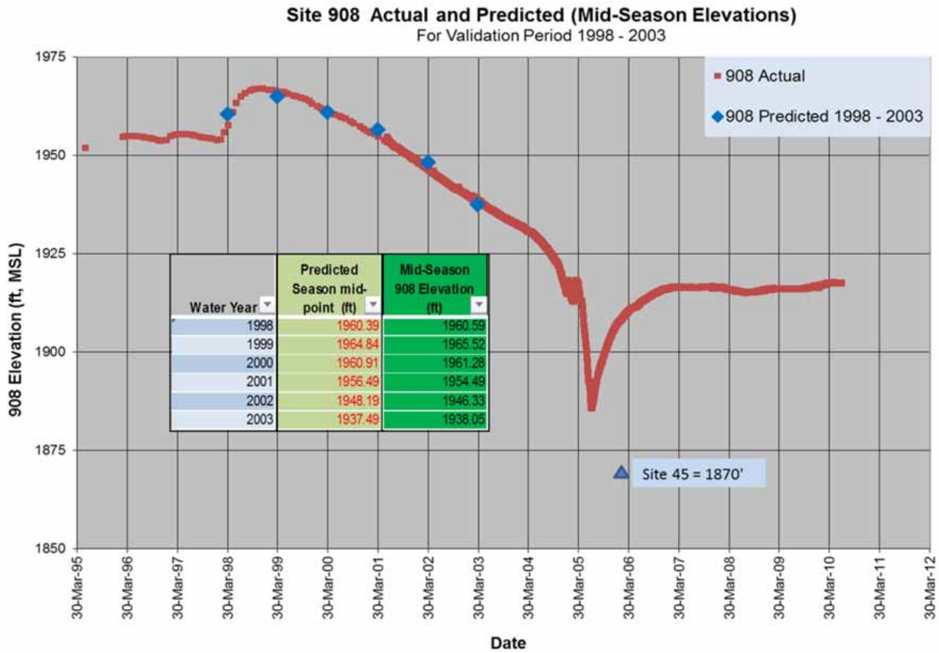


Figure 71. Groundwater hydrograph for Well 908 with actual and validation values.

Two significant deviations occurred in 2001 and 2002. In both years the calculated mid-season groundwater head value (which is actually an average head value for the year) was approximately 2 feet less than the predicted mid-season head value. In 2001 a predicted mid-season head of approximately 1956 ft resulted in a predicted flow at the spring of about 11 gpm higher than the actual flow of 50 gpm or an error of approximately 22 percent. The next year the predicted mid-season head was about 8 ft lower at 1948. This time the two foot deviation resulted in a flow difference of almost 8 gpm more than the actual measured base flow season average of 28 gpm or an error of almost 30 percent. Other errors in flow range from 1 to 15 percent.

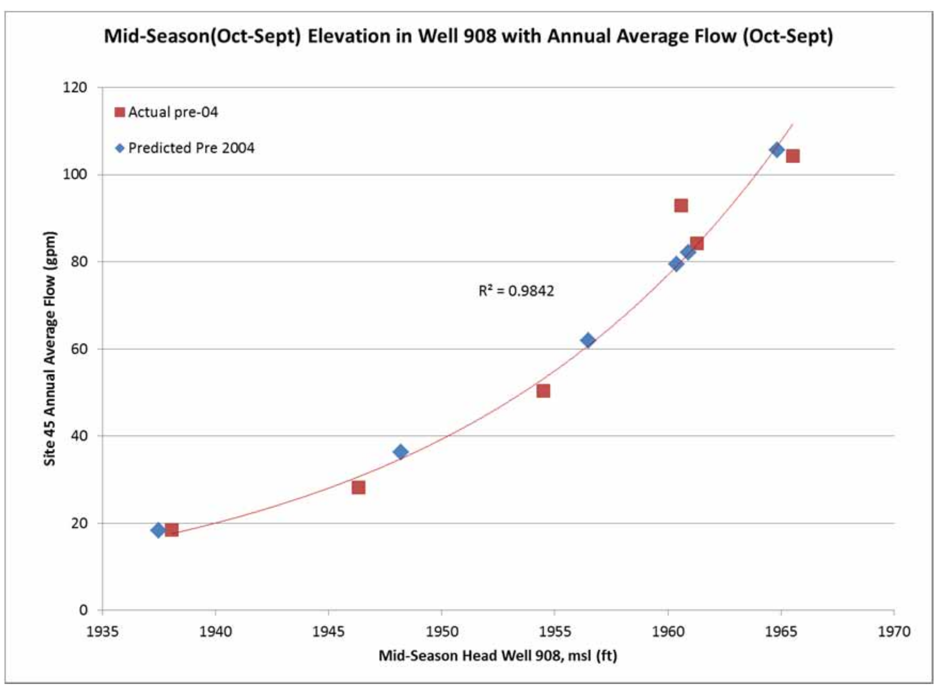
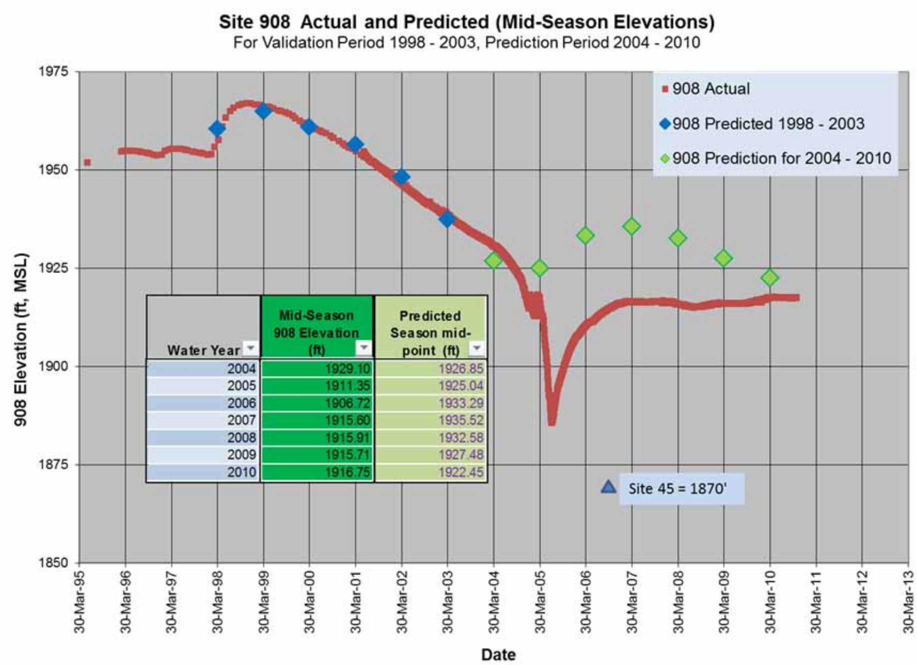


Figure 72. Predicted and actual value comparison between Well 908 heads and Spring 45 flows for baseline.

Next the model was allowed to run predictively from 2004 to 2010.



Water Year	Mid-Season 908 Elevation (ft)	Predicted Season mid-point (ft)
2004	1929.10	1926.85
2005	1911.35	1925.04
2006	1906.72	1933.29
2007	1915.60	1935.52
2008	1915.91	1932.58
2009	1915.71	1927.48
2010	1916.75	1922.45

Figure 73. Groundwater hydrograph for Well 908 with actual and predicted values.

The maximum modeled mid-season (seasonal average) impact at Well 908 occurred in 2006 with a drawdown of 26.5 feet. This equated to a predicted flow loss at Spring Site 45 of 10 gpm. During this season the modeled prediction would be about 14 gpm at the site. The measured flow was approximately 4 gpm for 2006 and declined to at or almost zero by 2008. In 2009 no water flowed from the adit. By 2010 groundwater had regained a foot of head and flows in the neighborhood of 1.5 gpm had returned to Site 45.

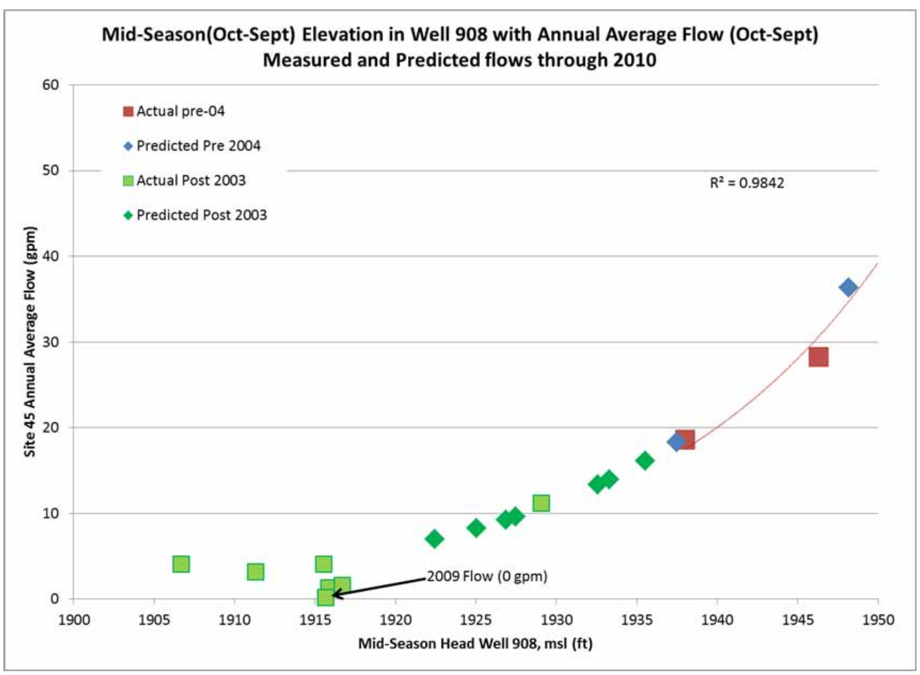
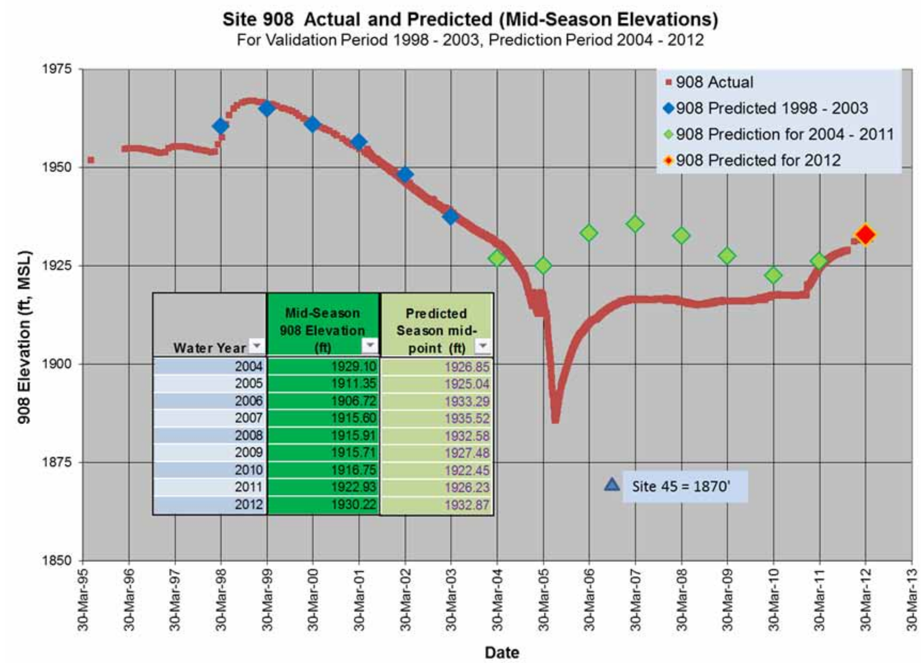


Figure 74. Predicted and actual value comparison between Well 908 heads and Spring 45 flows for post-impact period.

The 2011 season brought substantial precipitation, particularly in the month of December 2010. This rain provided recharge to the groundwater project wide and the Borea Canyon aquifers were no exception. The average head increase was 6 feet in 2011 and the gain is continuing in 2012. By the end of the year the final predicted mid-year head will be 1932.8 feet with the actual being in the neighborhood of 1931. The margin of error for the modeled groundwater head at this elevation is easily 1.5 feet, so this well would be considered to have reached ecological recovery.



Water Year	Mid-Season 908 Elevation (ft)	Predicted Season mid-point (ft)
2004	1929.10	1926.85
2005	1911.35	1925.04
2006	1906.72	1933.29
2007	1915.60	1935.52
2008	1915.91	1932.58
2009	1915.71	1927.48
2010	1916.75	1922.45
2011	1922.93	1926.23
2012	1930.22	1932.87

Figure 75. Groundwater hydrograph for Well 908 with actual and predicted values updated to 2012.

Indeed the measured surface water expression is in excess of the modeled flow at Spring Site 45 and has been for the two seasons post-2010. Monitoring will continue through the end of the 2012 season and it is anticipated that infrastructure removal will take place in the fall of 2012 or the winter of 2013.

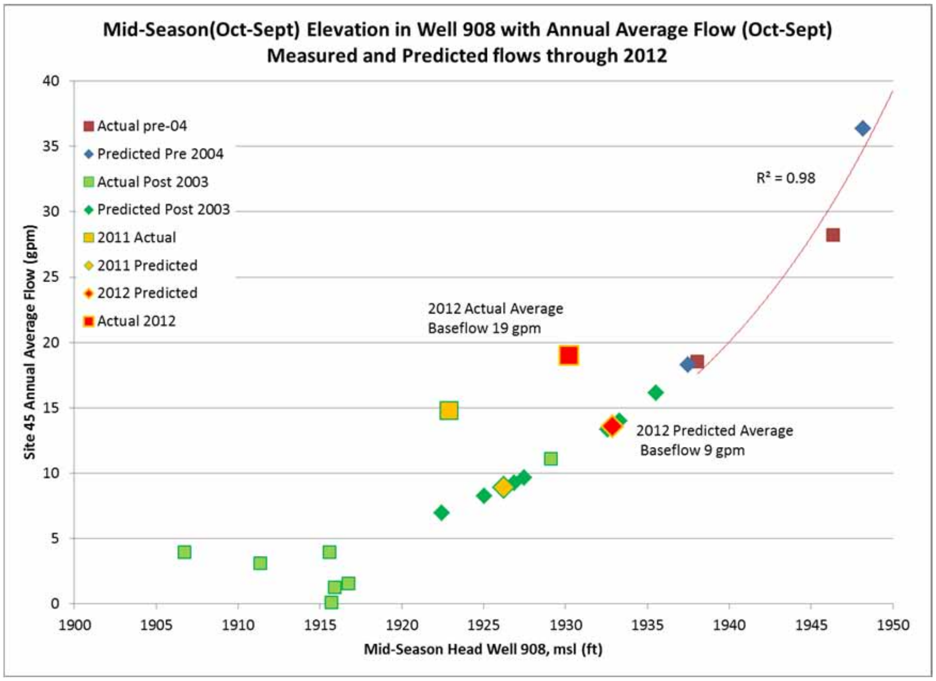


Figure 76. Predicted and actual value comparison between Well 908 heads and Spring 45 flows for post-impact period updated to 2012.

No model discussion is complete without pointing out the strengths and limitations. Amongst the assets of this analysis is the use of existing real data which has been obtained in the normal course of resource monitoring. No additional information requiring additional work and cost was required. Another advantage is that spring flow is directly tied to groundwater. Since it was groundwater that was directly impacted a bridge is made between the resources. Additionally the groundwater component of the model fits very well during validation and the surface water fit is okay with a variation between 1 and 28% of actual flow. The prediction results are reasonable. A mid-season head (season average) and an end of season head can be predicted. Since the groundwater change is fairly predictable over the short term, estimations of spring flow can be made in June to obtain an estimated prediction. This estimate can be used to target mitigation flows over the season, which was the original intent of the model.

There are some distinct shortcomings in this analysis. One obvious limitation is the size of the data set. It would be nice to have a longer baseline starting a good five to ten years earlier. Additionally the data was gathered throughout the course of the project by different individuals potentially resulting in monitoring error inherent in the sampling process. When considering proxy sites for inputs and extractions, the variables were chosen by best fit regression. These sites most likely do not fully represent all variables responsible for changes to storage within the system. Additionally groundwater is represented by proxy as well. Another significant issue is the move from predicted groundwater head to predicted baseflow at Spring Site 45. Predicted baseflows (July to October) are actually calculated on the average groundwater elevation over the October to September time period. In recession years this would tend to associate flows with a higher groundwater head during the baseline period. In recharge years baseline flows may be higher in the summer because this is when the groundwater typically peaks and then recedes. This drop is not represented in the averaging calculation only the mid-point between the beginning and end of the season. So here the flow may be high with respect to the groundwater. The proper method would be to actually use a mid-year flow calculation or a base season well calculation during the model validation.

Despite the model deficiencies, it became a useful tool for the Forest Service in flow prediction. Although it may tend to under predict flows in the lower range it helped to provide justification for continuation of minimal mitigation when the flows in Borea Canyon were extremely low. Additionally it appears the canyon may have returned to some ecological balance which is sustainable by the natural system.

The Lower Canyon Sites

The upper canyon model used a basin scale approach. At this level surface water was only one of the variables responsible for storage changes. This next analysis considers only the relationship between a surface water site and an associated groundwater site (Well 907 and Stream Site 154, respectively). This model uses the baseline groundwater head relationship between Well 907 on the ridge to the west of Borea Canyon and Well 908 in the bottom of the canyon. This relationship is used to predict groundwater head elevations at Well 907 based on predicted elevations at Well 908 with no other independent validation. Once a groundwater head is obtained the baseline relationship between Well 907 head and Stream Site 154 is used to predict flow at the surface water site.

The association between Well 908 and Well 907 heads is problematic because storage changes in Well 907 are more dramatic than those in Well 908, potentially because of differences in aquifer structure (fracture size, density and connectivity; parameters which can influence groundwater storage capacity). The aquifer around Well 907 potentially drains into the canyon in the area of Well 908.

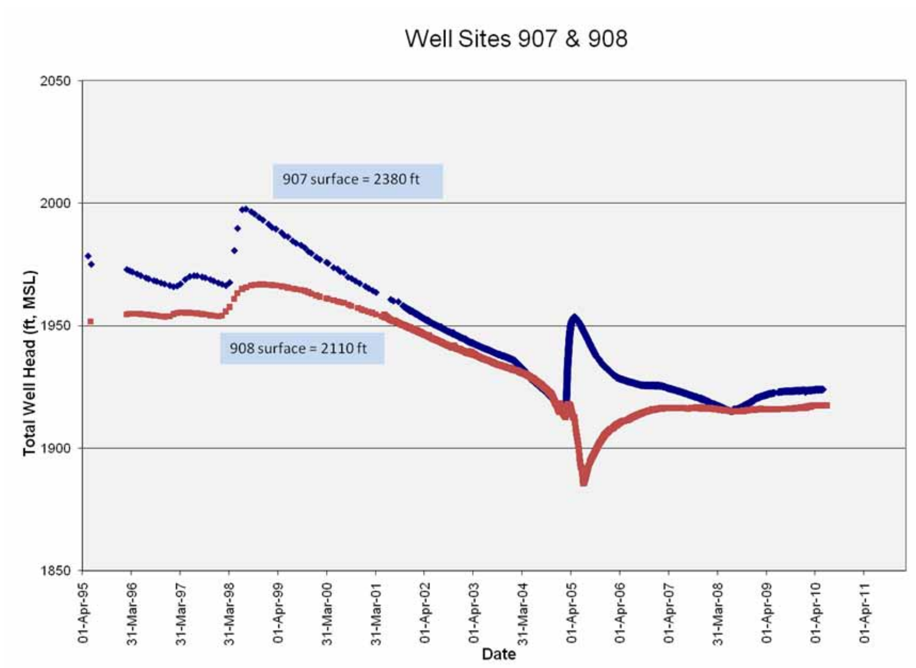
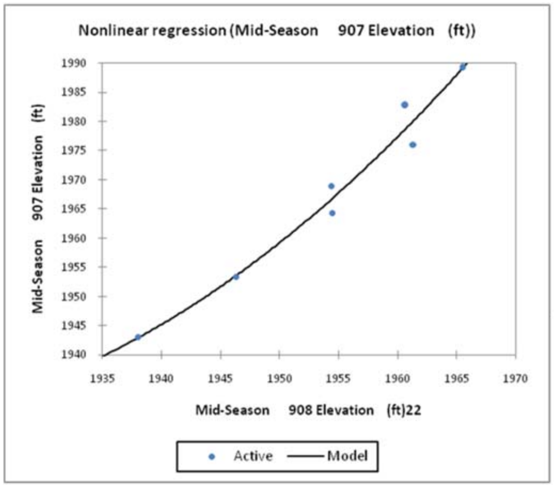


Figure 77. Comparison of Wells 907 & 908 groundwater head.

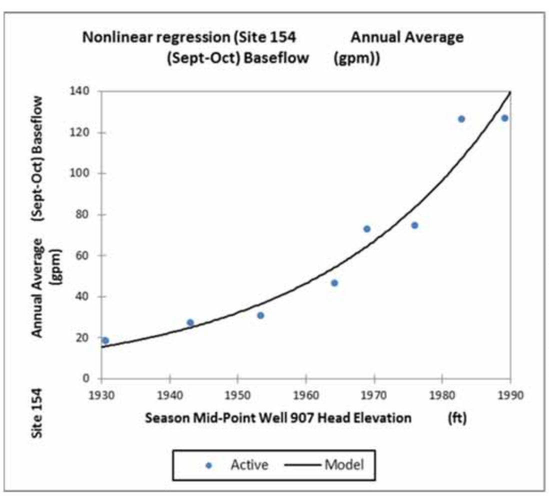


Non-Linear Relationship from 1997 - 2004
R2 = 0.97

Head Well 907=77912.9 - 79.5099 x Head Well 908 + 2.0800 x Head Well 908^2

Figure 78. Comparison of actual and modeled values using above expression for relationship between Wells 907 & 908.

In this analysis, similar to the previous upper canyon analysis, the surface water site is assumed to be directly and solely influenced by the groundwater. There are a number of concerns with this supposition as there are other factors which were not prevalent in the previous analysis. First Stream Site 154 is a surface water site and subject to the effects of evapotranspiration. These effects are not directly accounted for in the model. Additionally variation in substrate can be somewhat significant at this site. Well 907 correlates best with the surface flow at Stream Site 154, but Site 154 is probably not the only site influenced by Well 907. Furthermore some of the flow at the monitoring site may occur subsurface and that amount may not be trivial depending on the amount of aggradation in the stream. In the summer surface flow in the canyon is not necessarily continuous. Flow from Site 45 doesn't appear to always find its way as far as Site 154. In fact there is usually a dry section and then a vegetated reach which may or may not contain surface flow. It appears that this is a gaining reach that may on occasion contribute to site 154 downstream. If this happens, the assumption that flow at the stream site is derived from the proximal bank seep is only partially true. This said, the correlation between Site 154 and Well 907 is fairly good and thus is considered reasonable for use in the analysis.



Non-Linear Relationship from 1997 - 2004
$R^2 = 0.95$

Flow 154=3.3124E-30*Exp(3.6592E-02*Head Well 907

Figure 79. Predictive relationship between Well 907 & Stream Site 154 using above expression.

As in the previous analysis, excel is the computational platform. The predicted value of mid-season head in Well 908 (average value for the season) for the validation period is used to predict a mid-season head value for Well 907. This in turn predicts flow at Stream Site 154. The validation period runs from 1997 through 2004 in this analysis. The largest deviations occurred in 1998 and 2000 with heads over predicted by four feet and under predicted by 4 feet respectively.

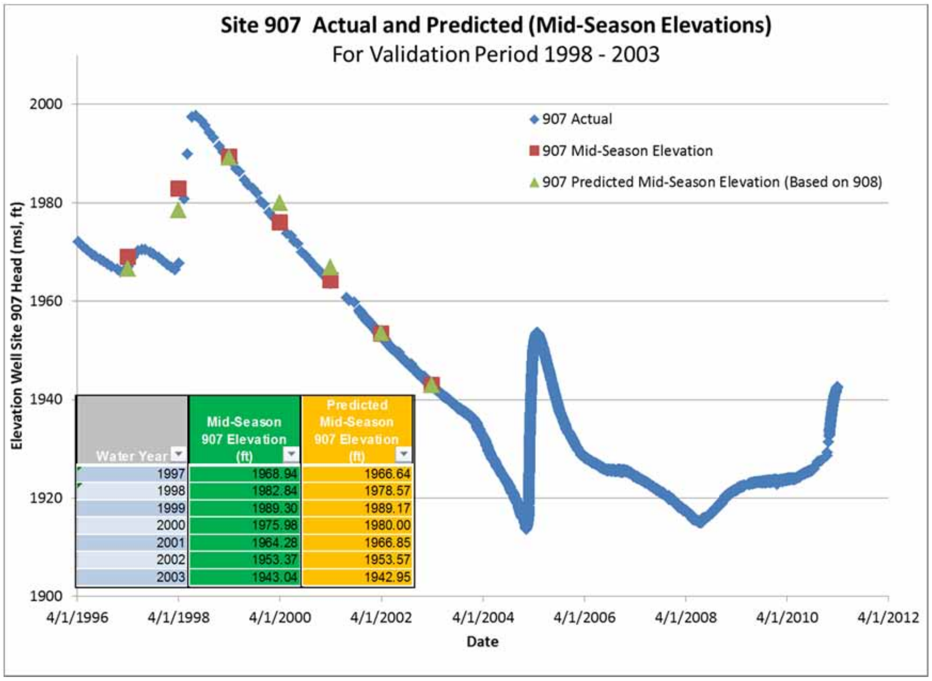


Figure 80. Groundwater hydrograph for Well 907 with actual and predicted baseline values.

These head deviations lead to flow differences of around 27 and 30 percent (of actual flow) between actual and predicted values for this temporal span. Another large deviation in flow prediction of 29 percent occurred in 2001 with a less significant groundwater head deviation (approximately 2.5 feet).

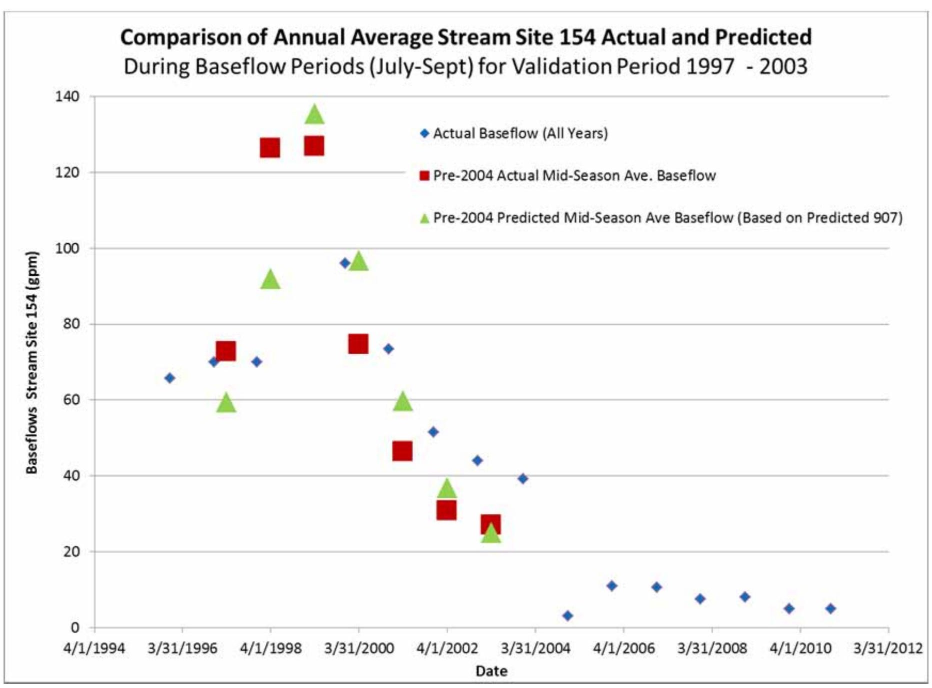
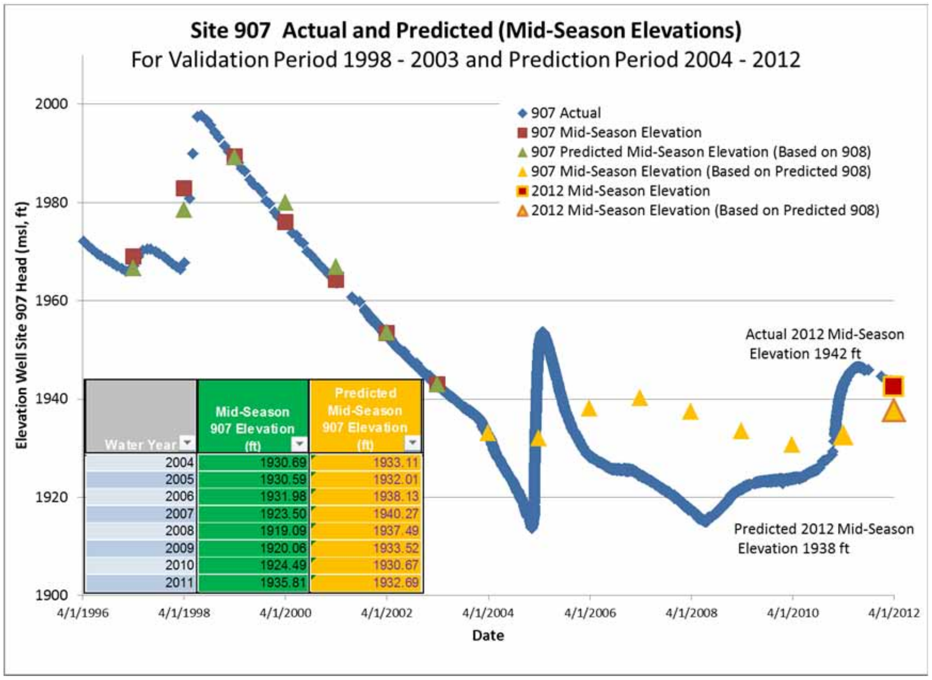


Figure 81. Modeled and actual flows for Stream Site 154 during baseline period.

Moving forward in a predictive mode, the predicted head in Well 908 is used to predict head in Well 907 from 2004 through 2011.



Water Year	Mid-Season 907 Elevation (ft)	Predicted Mid-Season 907 Elevation (ft)
2004	1930.69	1933.11
2005	1930.59	1932.01
2006	1931.98	1938.13
2007	1923.50	1940.27
2008	1919.09	1937.49
2009	1920.06	1933.52
2010	1924.49	1930.67
2011	1935.81	1932.69

Figure 82. Modeled and actual flows for Stream Site 154.

And in turn the surface water monitoring site is predicted from 2004 to 2012.

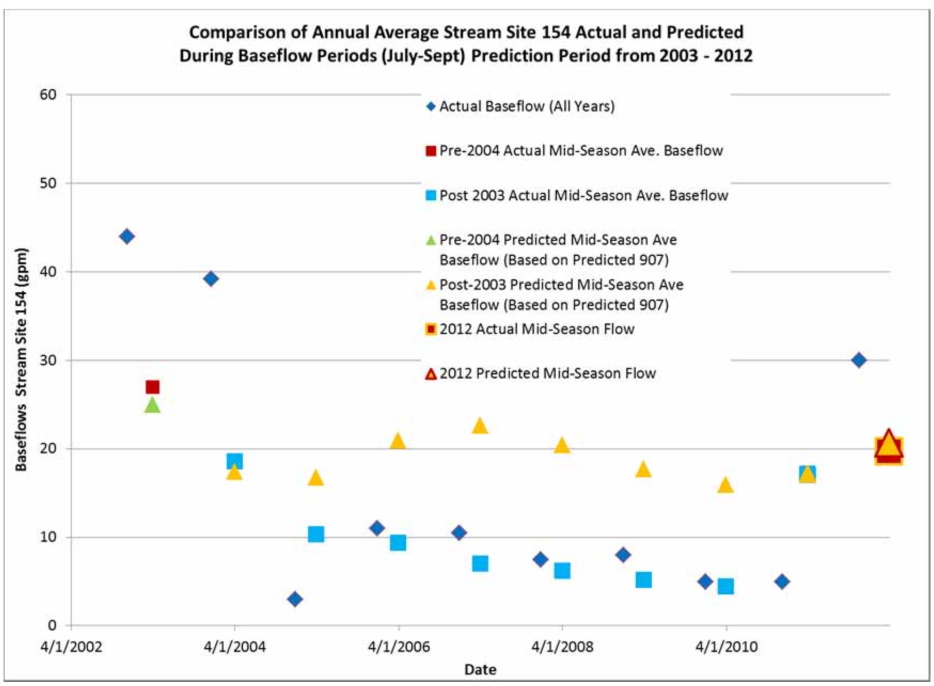


Figure 83. Modeled and actual flows for Stream Site 154 during post-impact period.

As with the upper Borea Canyon model, the results indicate a return of the canyon's groundwater dependent resources to condition of ecological recovery. The three foot deviation in groundwater head is well within the range of error for this model.

Many of the model assets are similar to those mentioned earlier when evaluating the upper canyon analysis such as the use of existing data and direct ties between surface flow and groundwater head. During the discussions above some of the limitations were also mentioned but others also exist. One of these is the fact that the groundwater relationship between Wells 908 and 907 is a polynomial regression. The boundary conditions on this type of relationship can be much narrower than some of the others. In this case the association is not valid when the average head elevation in Well 908 drops below 1925 feet. This occurred once in 2010 when the elevation dipped down to 1922 feet.

As of 2011 it appears that the resources in Borea Canyon have stabilized. MWD and the Forest Service agreed that there was value in an additional year of resource monitoring, so it will continue until the end of the 2012 monitoring season. After this point all surface water mitigation infrastructure will be removed from the canyon and monitoring of surface water sites will cease. Well 908 observations will continue as part of a Seismic Event Response Plan discussed later in this document.

Little Sand Canyon

By early 2008 the Forest Service Inland Feeder Project management team along with MWD agreed with the premise that there was some degree of impact to groundwater resources in the upper end of Little Sand Canyon. The FS staff had long suspected that these impacts may have extended to surface water sites in the canyon as well. During the spring of 2008 it appeared to the Forest Service that the surface water resources in the canyon may be manifesting effects of these impacts through reduced flows. The lower reach of this canyon contains habit for sensitive and Threatened and Endangered (T&E) species managed by the US Fish and Wildlife Service (FWS). An agreement had been made between these two agencies which allowed a zero take (i.e. no listed species would be harmed), therefore the possibility of an impact to surface resources was of major concern for the Forest Service. As a result both MWD and the FS opted for a collaborative approach to impact analyses in Little Sand Canyon. Each party would perform their own independent analyses and present findings with full peer review on each side. Two workshops took place in June and July of 2009 and the proceedings are documented in a memorandum entitled *Assessment of Ground and Surface Water Impacts from Arrowhead Tunnel Mining in Lower Little Sand Canyon* (Berg & Bearmar, 2009). What is included below is a condensed version of this document with additional information specific to the groundwater dependent resource analyses.

Ground and Surface Water Impact Assessment

Data sources in the Little Sand Canyon area include four wells (954, 909, 958 & 178) and five surface water monitoring sites (637, 510, 509, 44 & 155). Information from all the wells was included in the assessment. The surface water assessment focused on sites 44, 509 and 155. Flow at 637 is very intermittent and this site supports little or no riparian habitat. Impacts at 510 were less relevant to the discussion because 510 is distant from the downstream T&E Species habitat and flow at 510 is also intermittent.

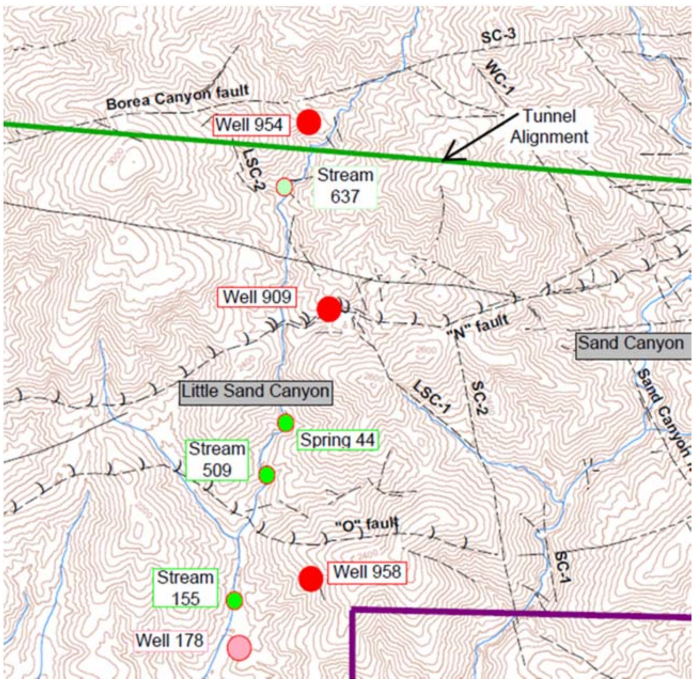


Figure 84. Little Sand Canyon map with monitoring sites.

Both MWD and FS specialists identified groundwater impacts to wells 954 (both upper and lower intervals) and 909. Neither party identified an impact to either interval of well 958. Data at well 178 were insufficient to complete an impact assessment although on balance both parties suspected that no impact occurred at 178. The figure below illustrates a groundwater impact staring in late-January/early February 2006 at the lower interval of well 954.

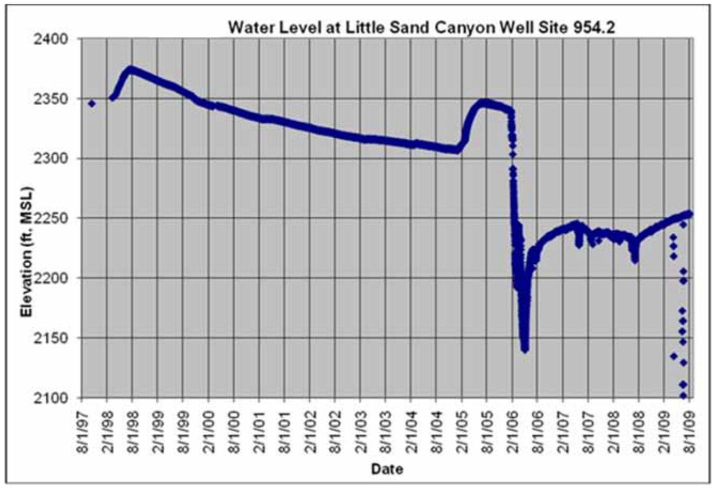


Figure 85. Groundwater hydrograph for Well 954.2.

<u>Hydrogeological Context</u>

Groundwater feeding surface flows can come from a perched groundwater reservoir or the upper portion of a deeper aquifer. Either way this groundwater is more responsive to local precipitation events and also often may show a higher rate of water table change than deeper groundwater. The deeper groundwater may be physically separated from the shallow aquifer by means of an impermeable layer or it may be connected through fractures to the surface but have a slower rate of response. This water can travel long distances and recharge may come from many miles away. As a result, precipitation response is somewhat or sometimes completely attenuated. In systems with connectivity, the response of one aquifer to changes in state prompts some type of stress on the other aquifer. A lower aquifer that has lost piezometric pressure will create an increase in gradient between the upper and lower and a drawdown in water table surface will occur as a result. Conversely, a rise in the water table due to precipitation or from some other source will exert hydraulic pressure on the lower aquifer and increase the piezometric surface. This can be done by very little addition of water to the lower system.

Groundwater-dependent resources in lower Little Sand Canyon most certainly are influenced by both upper and lower aquifers. The general direction of flow is southward and down canyon. The shallower aquifer system most likely shadows the topography although the gradient of flow would be orders of magnitude less. An exception to this generality is where water movement is constrained by a barrier such as a fault.

In a bedrock-dominated system such as Little Sand Canyon, the primary conduits allowing groundwater movement are geologic. These geologic controls include the interception of faults and joints with the surface topography. Confining beds and contacts of different rock units can also intersect with the surface. These contacts can have different in-situ stresses on either side of the contact and induce fracturing as a result. All of these fractures or joints can store water, but will not allow flow unless there is some degree of connectivity. The degree of fracturing, fracture aperture, connectivity, and pervasiveness--both vertically and horizontal--of fractures and their orientation, along with weathering, mineralization, and gouge and precipitate formation control the flow potential along the groundwater-surface water conveyance and determine the preferential pathways of flow. In some cases those pathways are intercepted by surface sediments, and the properties of those sediments also influence spring flow characteristics.

The surface water resources in lower Little Sand Canyon are discharge points for the aquifer and depend on the aquifer for their water supply during the dry months. Surface water flow in lower Little Sand Canyon from the beginning of record in the early 1990's has always been perennial. Site 44, located at the upper end of the lower canyon, is potentially influenced by the O Fault or a splay off the O Fault. The recorded low flow at site 44 is 2.5 gpm in the mid-1990's. Site 509, located on a section with bedrock substrate about 350 feet down canyon from site 44, is in a gaining reach on the O Fault and has had a recorded low flow of about 20 gpm. The lowest monitoring point in the canyon, site 155, is located in a fairly wide section of the channel with varying substrate. Site 155 had a low flow documented in 1990 of 5gpm and on 8/5/09 a secondary low flow of 8 gpm. Much of the water in this section moves below the channel surface in the summer baseflow months, but there has always been some amount of flow recorded. The fact that these streams are perennial, with no zero flows and lush vegetation during prolonged periods without precipitation, attests to the groundwater dependency of these features.

With respect to the location of the tunnel in upper Little Sand Canyon, three known major geologic features might provide barriers or conduits to flow. The upper most is a section of the little Sand Canyon Fault. This northwest-southeast trending feature in the upper canyon most probably connected well 909 to the tunnel bore before inflows to the tunnel dropped the piezometric pressures in well 954 in early 2006. This feature appears to be fairly transmissive longitudinally and may provide some resistance to flow down canyon. The intersection of this feature with the surface in the upper canyon is probably responsible for the expression of water at spring site 510. Down canyon from the Little Sand Canyon Fault is the N Fault. This is an east-west trending reverse fault with a moderate dip and is thought to be an impediment to groundwater flow. South of this fault the channel drops off fairly rapidly until above the adit at site 44. There are no known or monitored groundwater-dependent surface water sites in this reach of the canyon.

The next documented primary feature down canyon is the O Fault. This is also an east-west trending (at least in the Little Sand Canyon area) reverse fault. The dip of this feature is poorly constrained and is usually inferred. Sites 44 and 509 are located on the north side of this fault with site 155 being to the south. Many different geologic features or contacts are observable through this area and many sub-features are mapped between the major features. Any of these features and likely many provide connectivity from the upper canyon aquifer to the lower canyon. Additionally, below the O fault the groundwater appears un-impacted from tunneling. It is likely that the surface features have direct connectivity to the upper canyon through some of the geologic features discussed and potentially via inflows laterally from interflow. The lowest monitored site in the canyon, site 155, is probably connected indirectly to the upper canyon through surface water from above the O fault and receives groundwater flow directly from the lower canyon below the O fault.

Confounding Effects

Potential construction-related impacts to surface waters are more difficult to identify than groundwater effects in the project area for a variety of reasons, one being the influence of rainfall on surface flows. Tunnel construction does not affect rainfall but can clearly affect surface flows through changes in groundwater dynamics. The confounding influence of rainfall is most noticeable during November through April when rainfall is likely in the project area. Consequently assessment of the groundwater-surface water linkage is restricted to the May through October period. Because some significant rain events can occur throughout the summer, but primarily in late spring (e.g., May) and early autumn (e.g. October) decisions on the actual base period for the analyses need to be made. In practice, we used periods ranging from May through October to July through October and assessed the sensitivity of the results to the differing analysis periods.

Another confounding effect on surface water impact assessment is the flow regime at the monitoring locations. Site 44, for instance, is an enhanced spring (adit) similar to Site 45 in Borea Canyon. At the Site 44 location flow is measured at the confluence with the channel and only a short distance from the water expression out of the adit; thus there is little chance for evapotranspiration to reduce the measured flow and there is little chance for water to infiltrate channel sediment (and be un-measurable). Sites 509, and in particular 155, are in alluvium and experience flow reduction due to upstream evapotranspiration.

A final confounding effect is the potential influence of reduced precipitation on streamflow. Both reduced precipitation and tunnel mining potentially reduce streamflow magnitude; identifying the cause of any reduced flow can be easier said than done.

Impact Assessment

A primary question, asked by both MWD and FS staff, was what surface water flows "should" be presuming no construction impact. To answer this question a two-step approach would make sense: (1) derive a "baseline" pre-impact relationship, ideally by regressing water level at an un-impacted well against streamflow before any possibility of a construction impact, and (2) after passage of the TBM the regression would be repeated with deviation from the baseline regression signaling a surface water impact.

Groundwater

Unfortunately, the length of record for the only relevant un-impacted well (Well 958) wasn't long enough prior to TBM passage to generate a reliable regression with surface flows. This complicated the situation and necessitated the use of data from wells that were eventually impacted. In this approach the pre-impact/baseline regression fit (between well water level and surface flow) was initially established for impacted wells (but before impact). However, because Well 954 was eventually impacted (e.g., the drastic drop in water level) regressing post-impact well water level directly with surface flow wasn't appropriate. Instead both MWD and FS staff agreed that the next step required estimating (or projecting/simulating) groundwater levels at impacted wells from the time of impact to the present. MWD and FS staff used different techniques to generate these synthetic/projected groundwater level curves. The post-impact/synthetic water level curves were then regressed against surface flow. Last, the post-impact regressed flows were compared against the pre-impact/baseline flows to see if the post-impact surface flows were outside the envelope of the baseline relationship. If they were, both MWD and FS staff agreed a construction effect would be evident.

Two methods were used by FS staff to develop the post-impact synthetic groundwater curves. The first was an analog groundwater decrement – annual precipitation comparison. In this analysis 3 years of groundwater hydrograph data (2005-2008) and the associated precipitation at the rain gage 733 (near City Creek Ranger Station) were qualitatively analyzed. The precipitation pattern in terms of average, high average, and low average was compared to another analog period, 2001-2004. The slope of the graph of groundwater head versus time for this period was superimposed on the same graph starting at the time of impact. If, at some point after impact, the decrement appeared to return to a pre-impact decrement, this was superimposed at the end of the synthetic non-impact prediction.

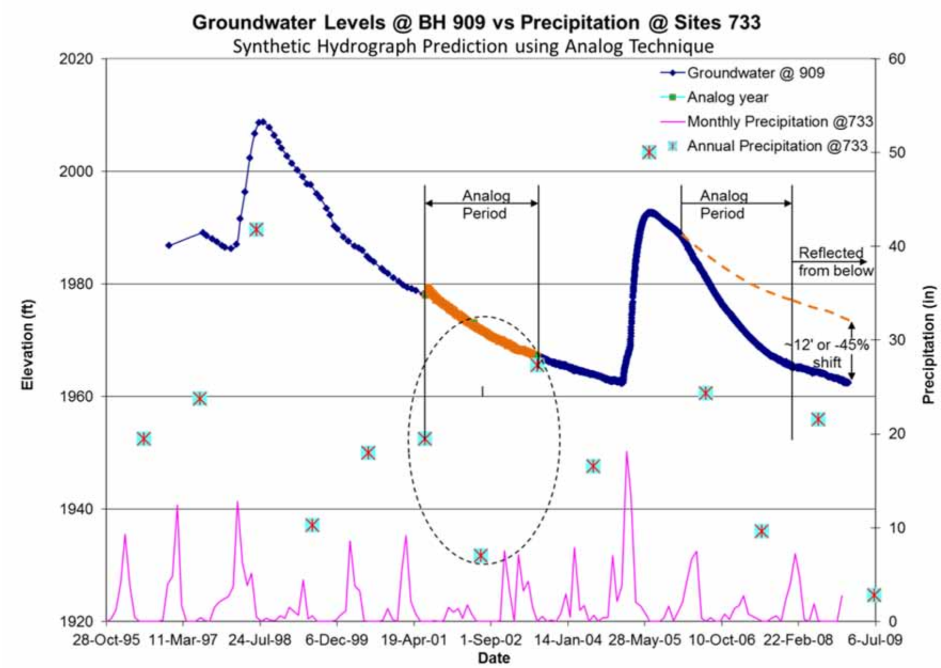


Figure 86. Groundwater hydrograph for Well 909 showing post-impact projection using the analog rain year technique.

In January of 2009 two wells were analyzed using this method, Well 954.1 and Well 909. The results revealed an impact of approximately 60 feet and 12 feet of head for Wells 954.1 and 909 respectively. MWD staff used a similar method but with a longer pre-impact period (2000-2004).

The second method employed by FS staff was applied only to Well 909. In this second method a tight relationship was identified between groundwater head in the lower completion of un-impacted Well 958 and impacted Well 909 prior to impact at 909 (R^2 of better than 99%). Well 909 was regressed against Well 958.2 and two relationships were developed; one for the rebounding or recharge limb and one for the receding limb.

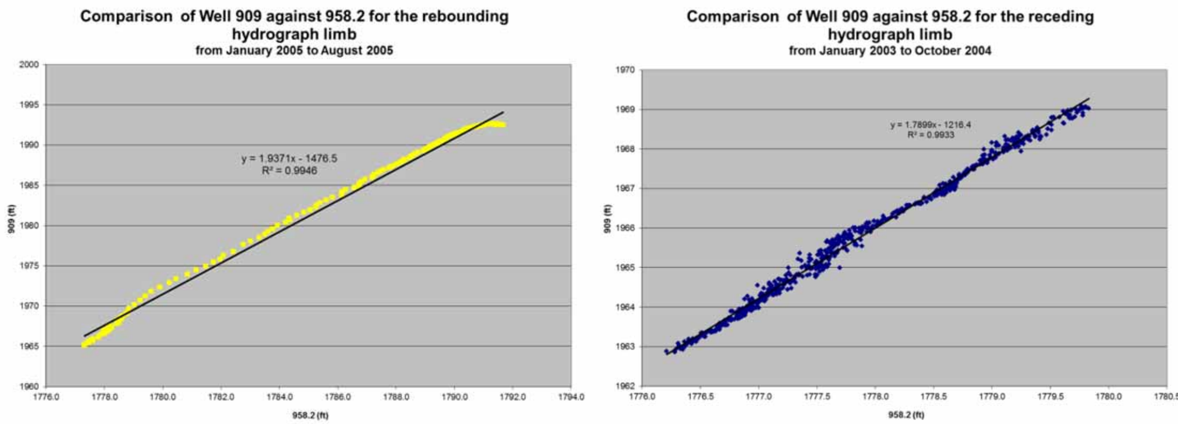


Figure 87. Comparison of same day groundwater heads between Well 909 and Well 958.2 for rebounding and receding limbs.

The pre-impact relationship was presumed to apply post-impact to Well 909 and was used to project a simulated (non-impact) groundwater hydrograph for Well 909 using Well 958.2.

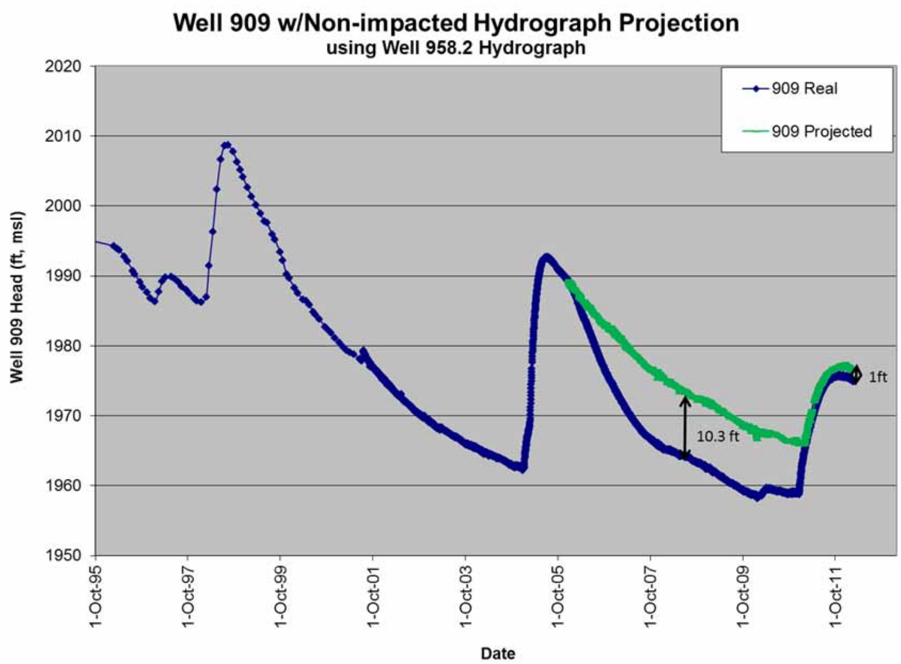
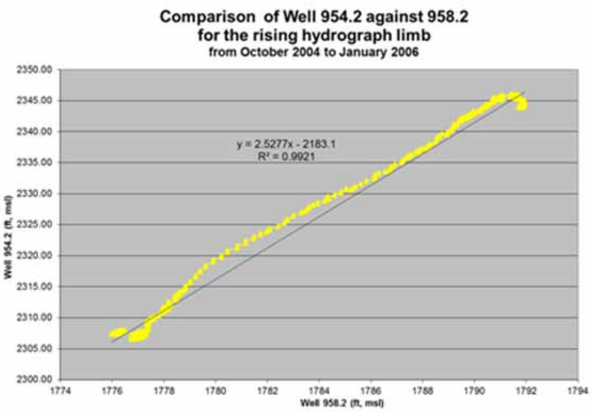


Figure 88. Groundwater hydrograph for Well 909 showing modeled non-impact projection.

The analysis using this technique displayed a maximum impact at Well 909 occurring in December of 2007 of a little over 10 feet. By February of 2012 the recovering aquifer reduced this impact to approximately a foot. This site has obtained ecological recovery.

The lower completion of Well 954 was examined in a similar manner. Same day head values in Well 954.2 were regressed with head values in Well 958.2 for a recharge and recession limb. Both regressions correlated very well (R^2 of 0.99 and 0.96 respectively).



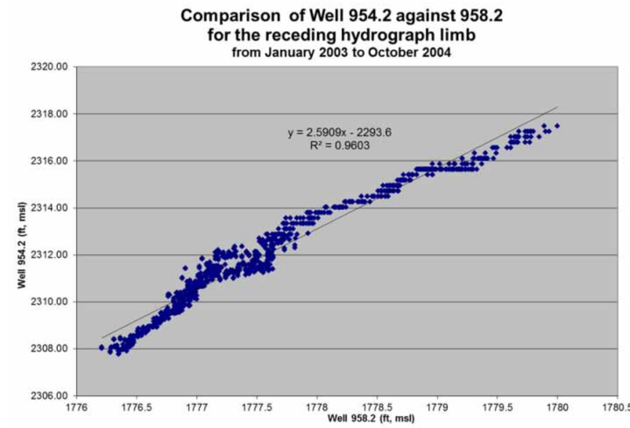


Figure 89. Comparison of same day groundwater heads between Well 954.2 and Well 958.2 for rebounding and receding limbs.

Again a non-impacted post 2006 hydrograph was constructed using the two regressions and the real head values in Well 958.2.

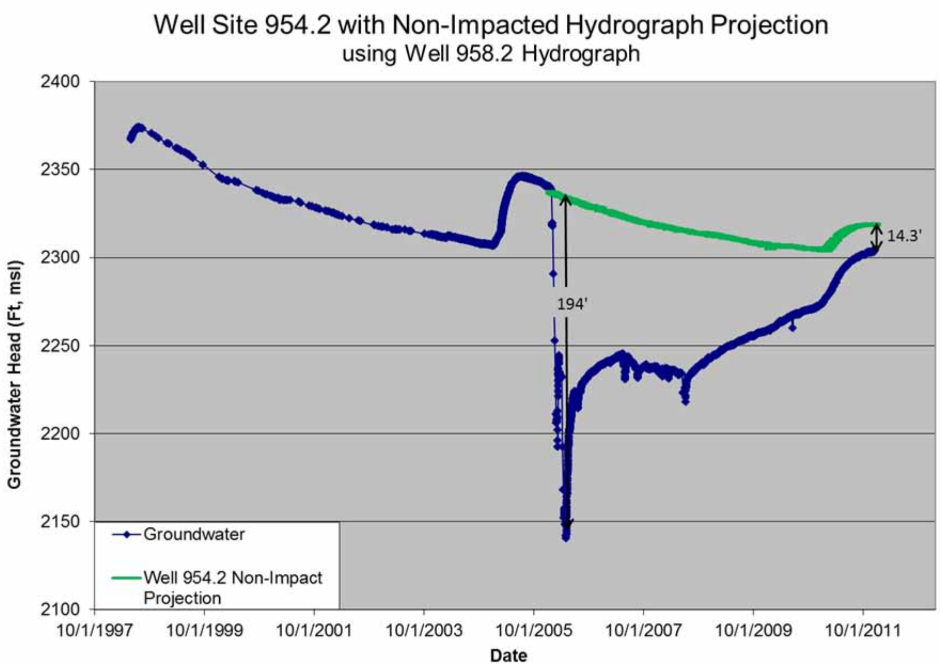


Figure 90. Groundwater hydrograph for Well 954.2 showing modeled non-impact projection.

From this analysis we obtain a maximum impact in Well 954.2 of approximately 193 feet in May of 2006. As of December 2011 this impact was reduced to approximately 14 feet.

The upper completion in this well uses the groundwater head relationship between the two wells to predict heads in Well 954.1 post 2006. This is an area where groundwater appears to travel vertically downward. Head differences had been fairly predictable prior to tunnel construction with a difference of roughly 50 feet of head during recession years and approximately 75 to 85 feet during the height of recharge. In 2006 when Well 954.2 responded to impacts the increased gradient between the upper and lower sections of the aquifer resulted in a pressure loss in the upper level of the aquifer and a maximum gradient between the two of 235 feet. As of October 2011 this gradient has been reduced to approximately 100 feet during a recharge cycle.

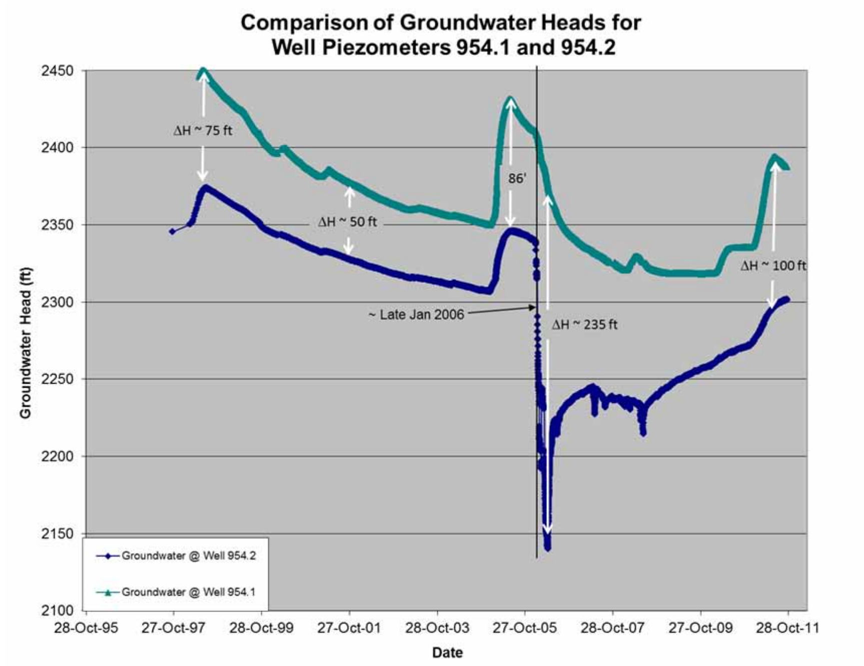


Figure 91. Comparison of groundwater hydrographs for different intervals in Well 954.

Once the lower section of the aquifer, indicated by Well 954.2, has reached ecological recovery and the baseline gradient trend has been re-established between the two well completions it is anticipated that the groundwater in the vicinity of the upper completion of this well will have recovered as well.

As of summer 2012 not further data has been retrieved from this well due to equipment issues. This site is being fitted with new equipment and will be monitored for the next 5 years or until recovery, whichever arrives first.

Impact Assessment – Surface Water

Up canyon surface water sites exhibited fair to good correlations with groundwater sites during the pre-impact or baseline period. The surface sites were regressed against the groundwater sites on roughly a same day comparison. Since surface water monitoring in this canyon commonly pre-dates groundwater monitoring the amount of baseline data is dependent on commencement of the well monitoring for each well. The general technique for assessing surface water impact was to compare flows from a surface site with a head from a well during the baseline and then again during the post-impact (post 2006) period using a non-impacted hydrograph. This hydrograph can be from a non-impacted well such as Well 958 or from a non-impact projection obtained from an impacted well. If the surface water has no impact, then there should be no change in relationship. If the surface water shows an impact, a downward shift of the flow data relative to the well data will occur.

In the case of the surface water site Well 909 was chosen for comparison. First a baseline comparison was made and the lower bound was determined. Next the subsequent years from 2006 on were matched with the non-impacted synthetic hydrograph constructed for Well 909. Flows at Site 45 correlate much more strongly to groundwater heads when compared with the other surface water sites in the canyon and it is a little more proximal to the point of groundwater discharge.

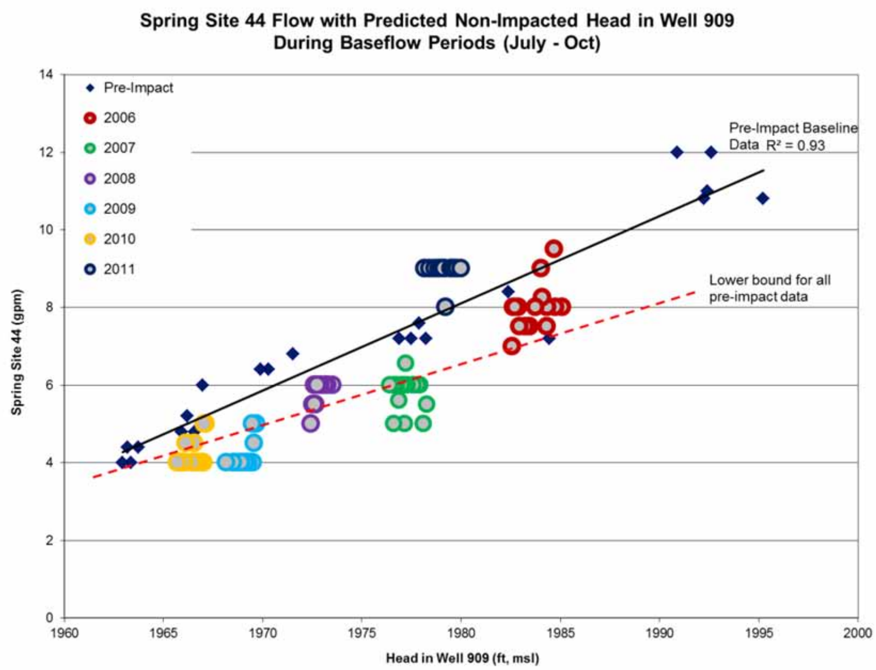


Figure 92. Comparison of Spring 44 flows versus groundwater heads in Well 909 for baseline and post-impact flows (using modeled non-impact projection in Well 909).

The above graph indicates that a downward shift appears to have occurred in approximately 2007 that may have extended through 2010. By 2011, when significant gains were made in terms of rebound in the Little Sand Canyon aquifers, it appeared that effects had reversed themselves. Currently the data is not available to obtain comparative values for 2012.

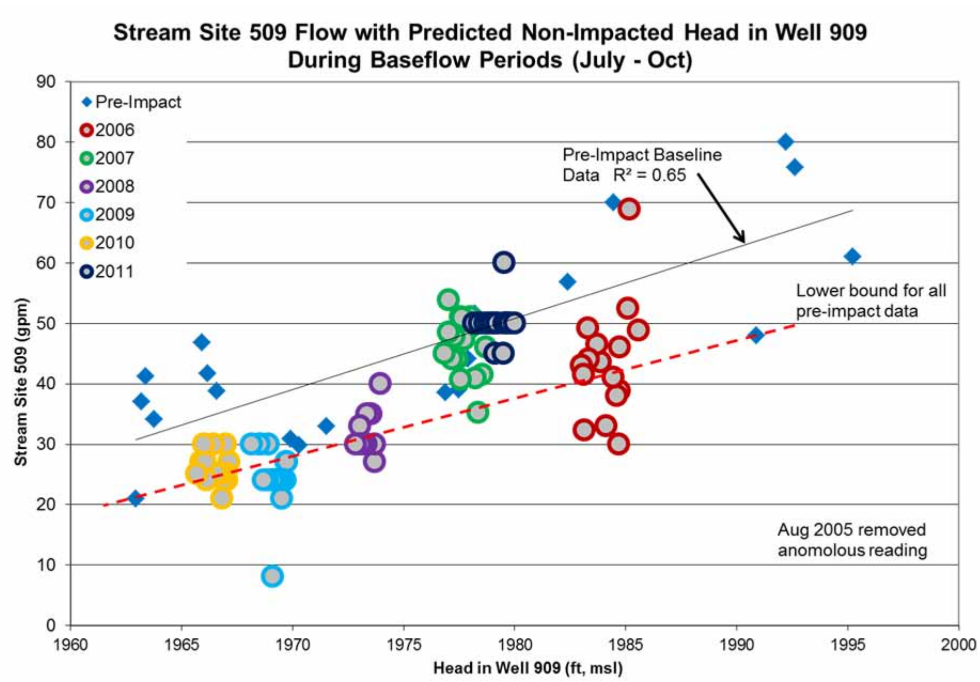


Figure 93. Comparison of Stream Site 509 flows versus groundwater heads in Well 909 for baseline and post-impact flows (using modeled non-impact projection in Well 909).

The trend for Stream Site 509 is somewhat similar to Site 44. This site is located in what is probably a gaining stretch of the canyon above the O fault. Impacts to this site which appeared to occur in

2007 were probably from groundwater directly as opposed to surface flow from the vicinity of Site 44. Again it appears that Site 509 has recovered by 2011.

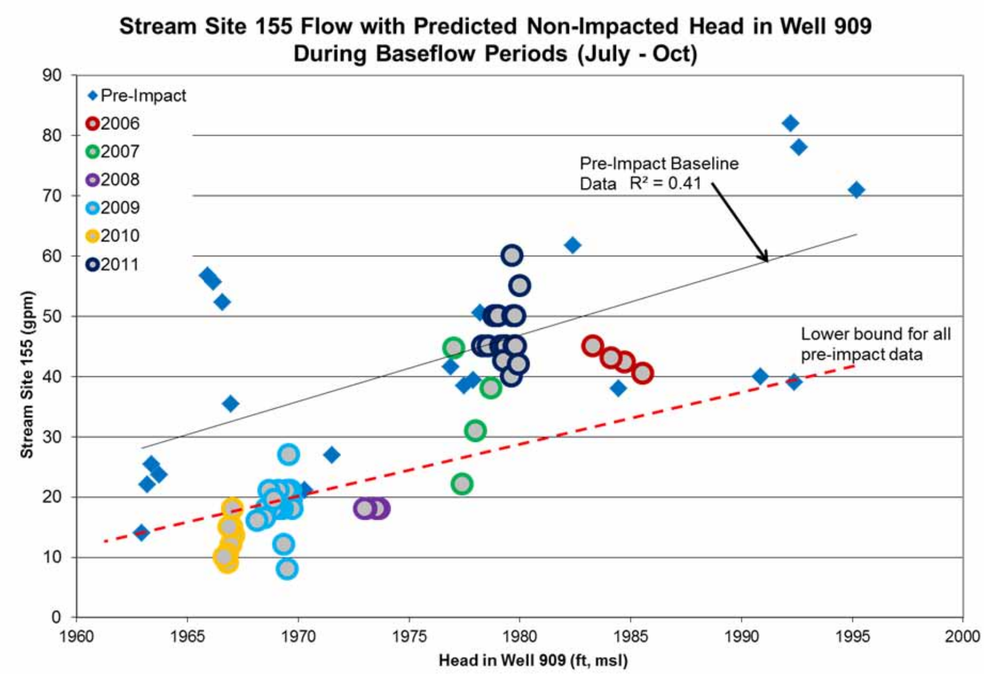


Figure 94. Comparison of Stream Site 155 flows versus groundwater heads in Well 909 for baseline and post-impact flows (using modeled non-impact projection in Well 909).

Stream Site 155 is located in a broad reach below the O fault. This reach meanders some from year to year and it actual location is much more variable than either of the other two sites up canyon. Much of groundwater ingress to this site is probably derived from the area south of the O fault so any impact would be as a result of flow reduction from the upper portion of the canyon. Well 958 would probably be a more appropriate comparison; however the limited duration of the baseline period makes correlation less reliable. Using Well 909 provides consistency with the other two sites. In this case the results are similar, with mild impacts potentially presenting as early as 2007. By 2011 a strong case can be made for recovery at this site as well.

<u>Conclusion</u>

An initial question was whether flows at the Little Sand surface water monitoring sites appeared to be below normal. 2008 baseflow medians at many sites in the Arrowhead West area, and at USGS gages in lower City Creek and East Twin Creek, were relatively high compared to earlier years. 2008 baseflow medians at Little Sand Canyon sites 509 and 155 were however, the lowest on record. Although the low 2008 baseflows in lower Little Sand were anomalous, and potentially due to tunnel construction, no alternative cause for the low medians was identified. This begged the question as to the cause of the low 2008 flows--in particular in comparison to other project area locations that definitely weren't impacted by tunnel mining and that presumably experienced the same climatic conditions as the lower Little Sand sites.

The linkage from ground to surface water was a critical part of an answer to the cause of the 2008 low flows. The veracity of the groundwater projections is a critical part of both the MWD and FS analyses because it directly drives conclusions about any surface water impacts. The projected water levels were relatively close between the MWD and FS analyses but were not identical. By summer of 2008 water level differences currently between observed and the non-impacted projected were in the 50-60 ft range for the both intervals of Well 954 and in the 6-12 ft range for Well 909. In other words differences in projected groundwater levels between the MWD and FS approaches were up to 10 ft.

MWD and FS specialists both identified tunnel-related groundwater impacts to two wells in the Little Sand Canyon area. The FS identified surface water impacts on the basis of projected stream flows that are outside the range of historical variation. MWD did not identify projected flows outside the range of historical variation. Both parties, however, agreed that the surface water techniques used by each party were legitimate, technically sound and had no "fatal flaws".

Differences in the surface water results appeared to be based on reasonable differences in assumptions and slightly different applications of similar techniques. Also unfortunately surface water response in lower Little Sand Canyon appears to be very sensitive to minor groundwater changes. Differences in projected groundwater levels by MWD and the FS were very small, less than 10 feet in absolute change in water level elevation, but were large enough to generate relatively larger differences in streamflow projections.

In the summer of 2009 MWD and the FS had stepped up surface water and resource monitoring of the canyon. Although the two entities didn't agree on the status of construction related effects to Little Sand Canyon, both groups recognized the potential risk to biologic resources downstream, especially with T&E species involvement, and felt additional attention was prudent. In the three succeeding years groundwater resources have displayed significant rebound, especially on the heels of the 2011 precipitation season. Well 909 which tracks groundwater changes in the middle reach of Little Sand Canyon has reached the point of ecological recovery and it appears the surface water resources have re-established their baseline relationships with the groundwater as well. Only Well 954 in the upper canyon still has some residual effects of mining although they are relatively mild in comparison to the initial effect. This well will continue to be monitored by the Forest Service to ensure even the upper reaches of the canyon have fully recovered and Little Sand Canyon is once again ecologically resilient.

Sand Canyon

Background

Bordered by McKinley Mountain to the east, Mud Flats to the north and the Little Sand Canyon watershed to the west, the Sand Canyon watershed encompasses over 2000 acres. The canyon itself contains documented perennial springs which contribute flow into the main channel and provide habitat for amphibians, reptiles, bird and larger mammals. The San Manuel Band of Serrano Mission Indians owns and occupies the land in the lower portion of the canyon. In addition to casino operations on this property, they have in past years managed a water bottling plant near the canyon outlet.

Water resource monitoring within Sand Canyon includes four channel sites, 5 springs and 5 groundwater monitoring wells. Two of these Wells, Well 957 and Well 959 bound the San Manuel Reservation on the east and north respectively and were installed in the early 2000's with the intent of providing an early warning for mining effects that may be nearing the reservation lands. Well 958 in Little Sand Canyon completes this set, bordering the reservation to the west.

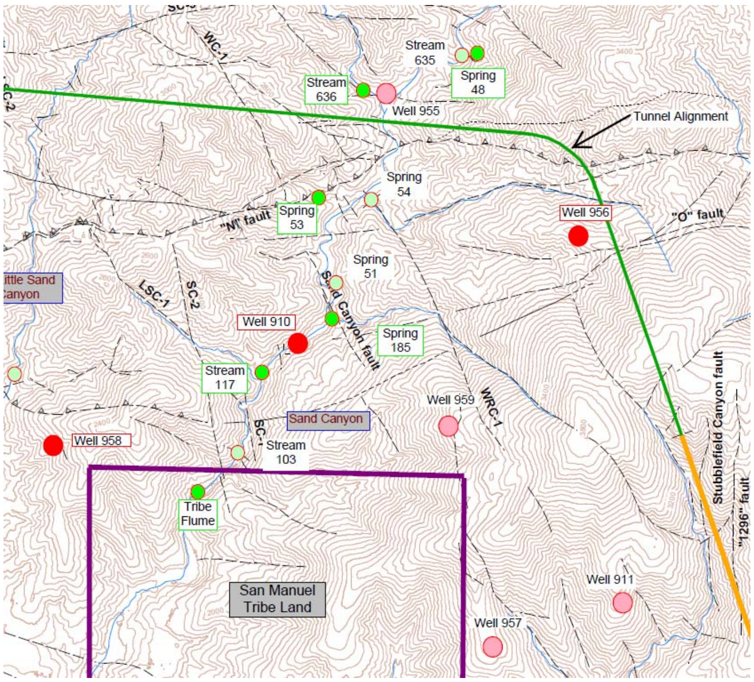


Figure 95. Water monitoring sites in Sand Canyon. Note: Lighter red and green were not used in the recovery analyses.

Recharge to Sand Canyon groundwater is probably both local, entering the system through the many faults within the canyon, but also and predominately from higher elevation contributions. Mud Flat is a broad plateau directly north of Sand Canyon. No rain gages are known to exist in this area so precipitation data for use with quantification of ground and surface water changes is provided from other sites, namely the gage located in City Creek at the Forest Service City Creek fire station and at the San Bernardino County Hospital. Based on the USGS modeling efforts it has also been suggested that significant portions of deep groundwater recharge occur from higher elevations potentially in the neighborhood of Lake Arrowhead to the north (Anna, Fahy, Mckeown, Bianchi, & Chatoian, 2003).

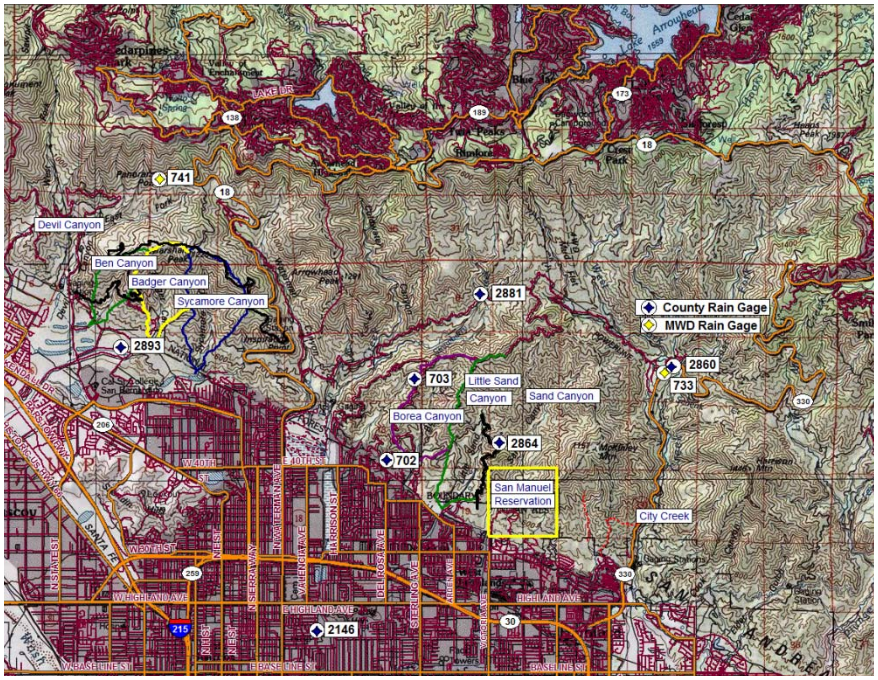


Figure 96. Local MWD and San Bernardino County Precipitation Gages.

Impacts to water resources resulting from tunnel construction likely came in several waves. The initial effects to surface water may have started as early as mid-2006 as the TBM encountered and mined through the Waterfall Canyon-1 (WC-1) fault. The southeastern terminus of this feature intersects the N fault very close to where Spring Site 53 is monitored. Based on analyses with 2 groundwater wells (Wells 910 and 956) this site may have displayed effects from impacted groundwater late in the 2006 monitoring season. No other sites appeared to have had these effects so early. By October of that year the TBM was below the bottom of Sand Canyon and Well 955 was affected. By February and March of 2007 the lower and upper completion respectively, of Well 956 located on the east slope of the upper canyon were declining rapidly from tunnel related effects. Also by March surface water impacts to other sites within the canyon were evident and mitigation of impacts to surface water sites began in early April 2007.

Background

Of the 5 well sites in Sand Canyon only Well 957 appears to be definitively un-impacted by tunnel construction. This well is located far down canyon and is actually located to the east of the McKinley Mountain ridge and therefore not in the canyon at all. Well 910 is generally considered to have remained without impact and has therefore been used in analyses for impacted sites. Well 959 near the northeastern corner of the San Manuel Reservation may have sustained a tunnel related impact, but this well didn't become operational until 2004 so pre-impact baseline data is of inadequate duration to help in the analysis. The two remaining wells in the upper canyon, Wells 956 and 955 did sustain definitive impacts from tunneling.

Well 955 is located near the canyon bottom as it bifurcates into west and east branches. This well has two completions and likely penetrates the N fault with the lower completion representative of the higher head groundwater to the south. The result is an artesian condition giving the lower aquifer a greater head than the upper aquifer. This well would most likely have been a long-term representation of the aquifers; however circumstances have rendered the information from these piezometers of little use to current impact and recovery analyses. In 2004 the upper completion standpipe was capped. This act shifted the head upward by approximately 8 feet and may have changed the behavior of well hydraulics and/or the information collection equipment. At any rate the amount of consistent baseline data has been reduced to the point that a good analysis is difficult. The lower completion of Well 955has a good baseline record which appears similar in character to other deeper wells on AHE (Wells 954.2 and 956.2). Impact to groundwater in this area is very evident in September of 2006 and a rebound period appeared to follow. In early 2008, well before full recovery occurred, the transducer failed. As this piece of equipment was grouted into the borehole over 400 feet below the ground surface a failed transducer is a death blow to further data acquisition.

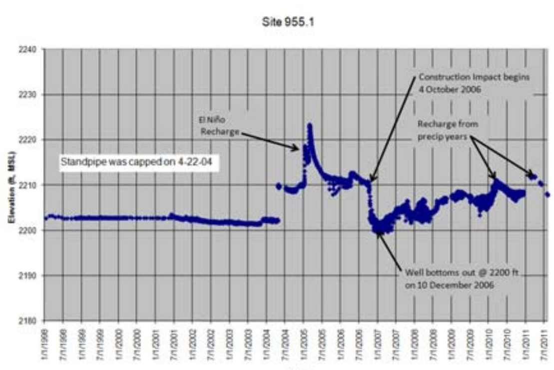


Figure 97. Hydrograph for upper completion Well 955.

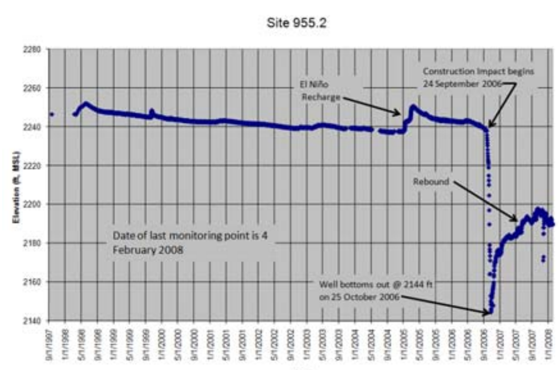


Figure 98. Hydrograph for lower completion Well 955.

The remaining well in Sand Canyon, Well 956 has two completions which display very similar hydrographs indicating placement within the same aquifer. The upper completion (Well 956.1) is slightly more reactive to some seasonal recharge whereas this is much more subtle at depth. This aquifer is likely the source of springs and seeps on the east slope of the canyon and as the groundwater in this area rebounds the surface water resources also appear to move toward recovery from tunnel construction effects. Well 956 has been selected for groundwater recovery monitoring in the mid to upper Sand Canyon.

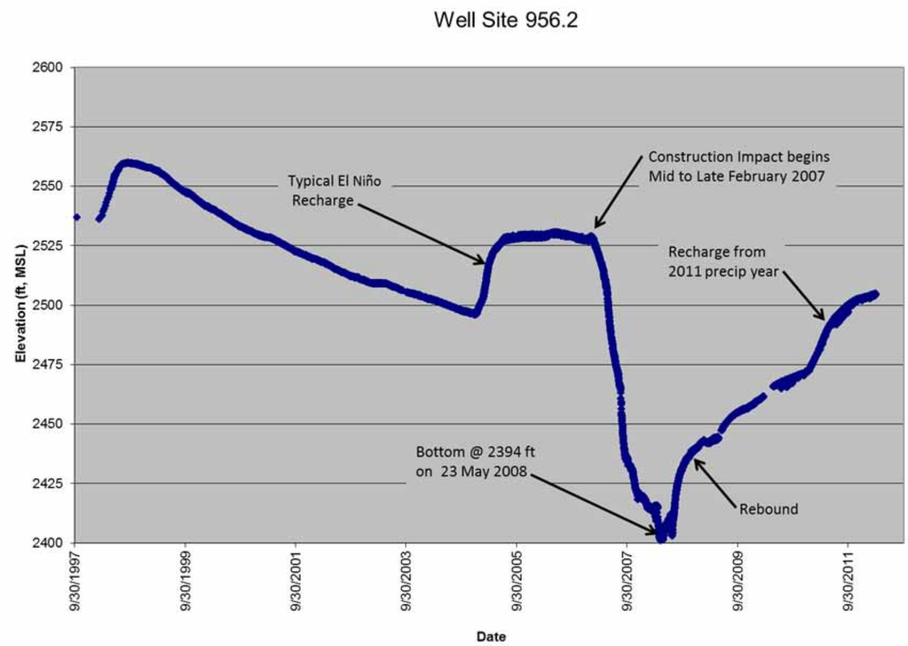


Figure 99. Hydrograph for lower completion Well 956.2.

Methodology

The approach to developing a hydrograph which displays a prediction of groundwater conditions without tunnel effects uses a method very similar to the one employed for Well 909 in Little Sand Canyon. This technique uses an un-impacted well, with a good pre-impact relationship to the impacted well, to simulate a non-impacted hydrograph for the affected well. As the upper canyon aquifers in the Sand and Little Sand Canyons display hydrographs with very similar behaviors, it is not surprising that the same control well used to construct the other modeled hydrograph might also provide good correlation with Well 956. While not quite as good as the relationship with Well 954 (Well 956 is more distal) the relationship between 958.2 and 956 has an acceptable declining relationship (R^2 is 96%) and an excellent correlation with the rising limb (R^2 of 99%).

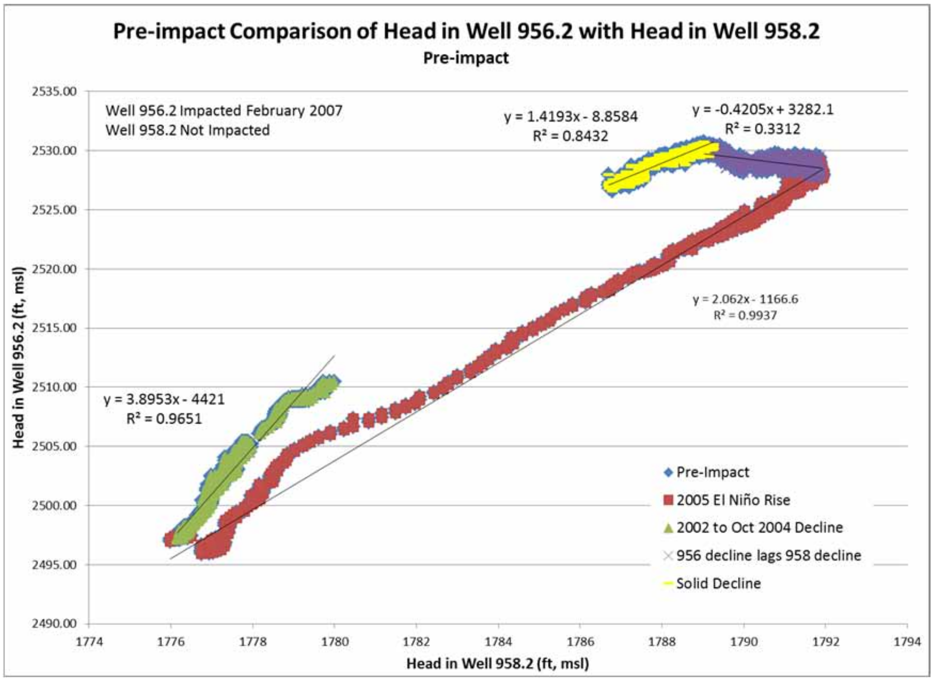
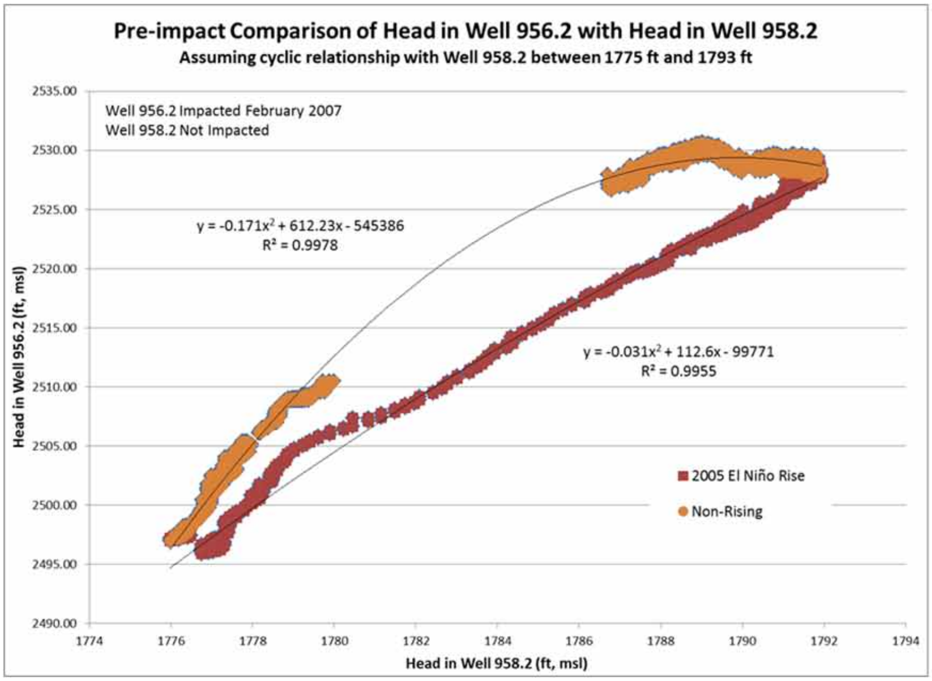


Figure 100. Same day comparison between head in Well 956.2 with head in Well 958.2. graph shows equation of regression and coefficient of determination for rising and non-rising hydrograph limbs.

The declining limb consists of comparative same day data from 2002 through the initiation of rebound in late 2004. In order to enhance and extend this relationship, the data from late 2005, when Well 958.2 initiated decline, until impact to Well 956.2 in late February of 2007 was added to the declining data set. Although both wells completed the initial rebound from the 2005 El Niño year precipitation at approximately the same time, the hydrograph for Well 958 starts to recede almost immediately whereas the hydrograph for Well 956.2 levels off for a period of about 8 months before initiating a definitive decline. The lag period displays a terrible correlation as there is almost no change in Well 956 head and is potentially an artifact of the distance between the two wells. It can be assumed that if the groundwater impact from tunneling had not propagated to the aquifer near Well 956.2 and if the hydrograph recessions continued, the post 2005 receding limb might intercept the pre-2005 receding limb. In such a case a predictive relationship could be developed for the non-rising limb in Well 956.2 (which incorporates the recession and the "level" portion of the hydrograph) based on the receding limb in Well 958.2. The two relationships for the rising and non-rising limbs might look like the graph below.



Nonlinear regression of variable 956.2:
For Non-Rising Limb
Goodness of fit statistics:

Observations	1818.000
DF	1815.000
R^2	0.998
SSE	698.827
MSE	0.385
RMSE	0.621

Nonlinear regression of variable 956.2:
For Rising Limb
Goodness of fit statistics:

Observations	587.000
DF	584.000
R^2	0.996
SSE	429.837
MSE	0.736
RMSE	0.858

Figure 101. Same day comparison between head in Well 956.2 with head in Well 958.2. Graph extrapolates equation of regression for the full non-rising hydrograph limb.

The result of the regression analyses for the rising and non-rising limbs provide the following expressions for use in simulating non-impact head in Well 956.2 based on the head in Well 958.2.

$H_R = -0.031*(H_{958.2R})^2 + 112.6* H_{958.2R} - 99771$

$H_{NR} = -0.171*(H_{958.2NR})^2 + 612.23* H_{958.2NR} - 545386$

Where:

H_R = Simulated same day head in Well 956.2 without presumed tunnel effects for $H_{958.2R}$

H_{NR} = Simulated same day head in Well 956.2 without presumed tunnel effects for $H_{958.2NR}$

$H_{958.2R}$ = Daily Head in Well 958.2 during rising limb

$H_{958.2NR}$ = Daily Head in Well 958.2 during receding limb

Note
Constants in each equation shifts the resultant head and is re-calculated each time an inflection point is reached and the direction of head changes. For instance the first head value for the rising limb is matched to the final value for the non-rising limb.

As aquifer behavior can change with depth (i.e. permeability with fracture density, faulting, rock type, etc.), great care must be used when predicting these behaviors; this is especially true when regressive relationships are used to extrapolate beyond the baseline date set. In the case of the expression above, the simulation is presumed valid if the head in Well 958.2 is roughly between 1775 feet 1793 feet.

Using these expressions to model un-impacted heads in Well 956.2 several predictions can be made. By projecting the simulated hydrograph on the actual hydrograph, which displays measured data, maximum drawdown as a result of mining can be approximately estimated along with a suggested timeframe for occurrence. Additionally the recovery progress and current impact status is determined.

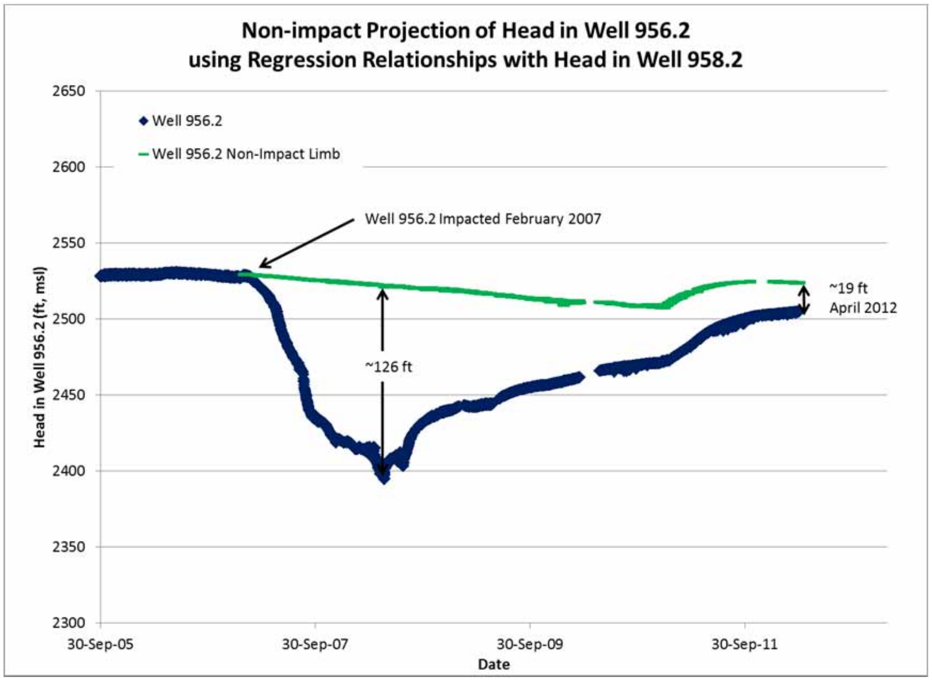


Figure 102. Well 956.2 hydrograph with predicted head (green) and actual head (blue) after tunnel effects in 2007.

Based on this analysis a maximum impact of approximately 125 feet occurred around mid-May 2008 and rebound has been occurring fairly steadily since. As most unaffected wells in the project area show a recession in head from around 2006 or 2007 to 2010, it can be surmised that most of the rebound is not recharge based, but due to movement of water or increasing pressure from up gradient areas in an attempt to equilibrate or "fill the trough". As the impacted area reaches equilibrium with the larger system, the groundwater in the area moves toward ecological recovery. As of April 2012 (the date of the most recent data during the writing of this report) another 20 feet is needed for full recovery and the head in this area is still increasing.

In addition to the current impact status, it is commonly desired to estimate time to full recovery. In the case of 956.2, recovery has been steadily occurring over the previous 4 years. Using this data a trend can be established to predict the diminishing impact over the course of the next few years. Remaining impact is simply the difference between the projected un-impacted head in Well 956.2 and the measured head in the well at the end of each water year (30 September). These values through the end of 2011 are regressed against time from point of impact using an exponential regression of the form:

$$Y = pr1*Exp(pr2*X)$$

Where:

Y = Remaining Impact,

X = Time From Start of Recovery in years

pr1, pr2 = Regression parameters

The following expression was generated:

Remaining Impact (ft) = 102.048 * Exp(-0.407 * Δ Time from Start of Recovery)

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

Recovery Prediction Curve

Based on current recovery rate At Well 956.2

Date	Water Year	Δtime from Start of Recovery (years)	Remaining Impact (ft)	Predicted Impact (ft)
9/30/2008	2008	0.36	88.32	
9/30/2009	2009	1.36	58.39	
9/30/2010	2010	2.36	38.26	
9/30/2011	2011	3.36	26.97	
9/30/2012	2012	4.36		17.31
9/30/2013	2013	5.36		11.52
9/30/2014	2014	6.36		7.67
9/30/2015	2015	7.36		5.11
9/30/2016	2016	8.36		3.40
9/30/2017	2017	9.36		2.26
9/30/2018	2018	10.36		1.51
9/30/2019	2019	11.36		1.00
9/30/2020	2020	12.36		0.67
9/30/2021	2021	13.36		0.44
9/30/2022	2022	14.36		0.30
9/30/2023	2023	15.36		0.20

Goodness of fit statistics:	
Observations	4.000
DF	2.000
R^2	0.999
SSE	1.682
MSE	0.841
RMSE	0.917
Iterations	12.000

If we assume, based on maximum residuals in the model of 2 feet and RMSE of around 1 foot, that there is an accuracy of ± 2 feet we can predict a time to ecological recovery. Based on the *Recovery Prediction Curve*, this would occur by the end of 2018 or in approximately 6-years.

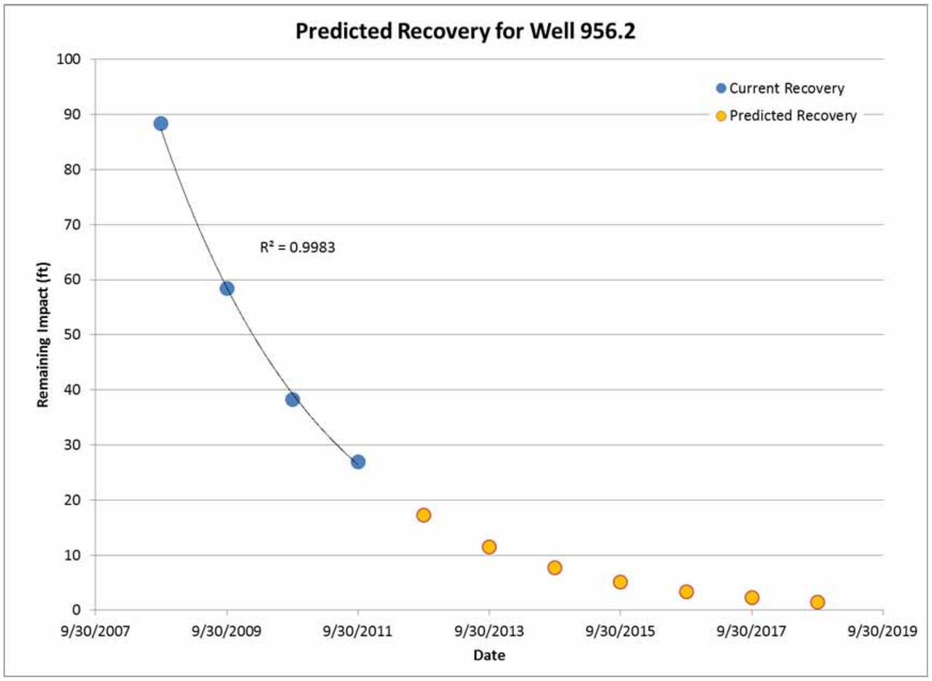


Figure 103. Predicted recovery curve for groundwater in the vicinity of Well 956.2.

The upper piezometer in the monitoring well (Well 956.1) is presumed to be within the same aquifer but approximately 500 feet higher in the borehole and slightly more reactive to smaller annual precipitation events. However a general comparison of Well 956.1 with the same control well, Well 958.2, yields good initial results.

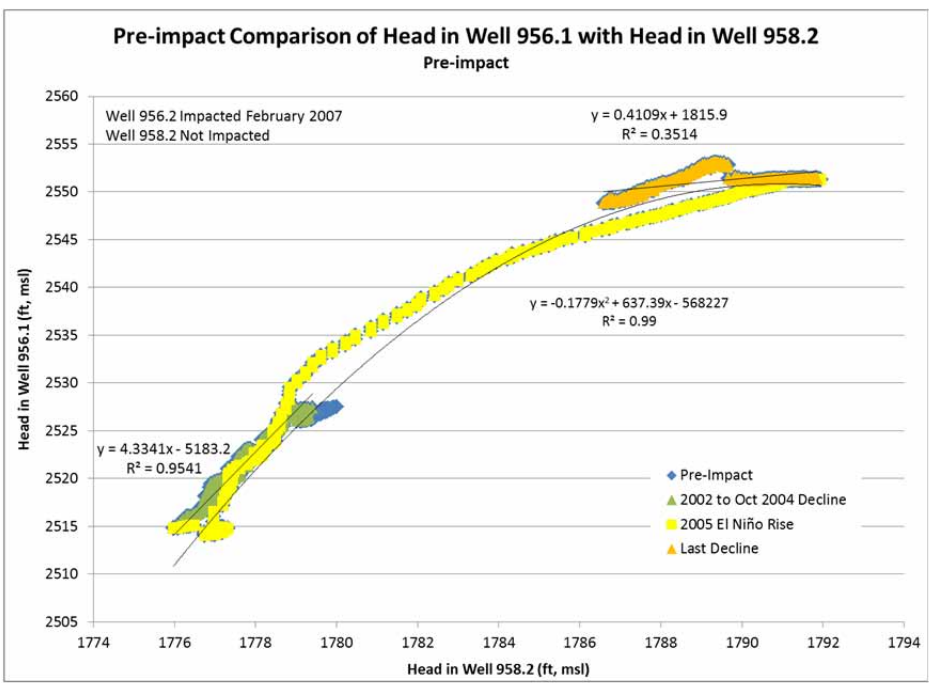
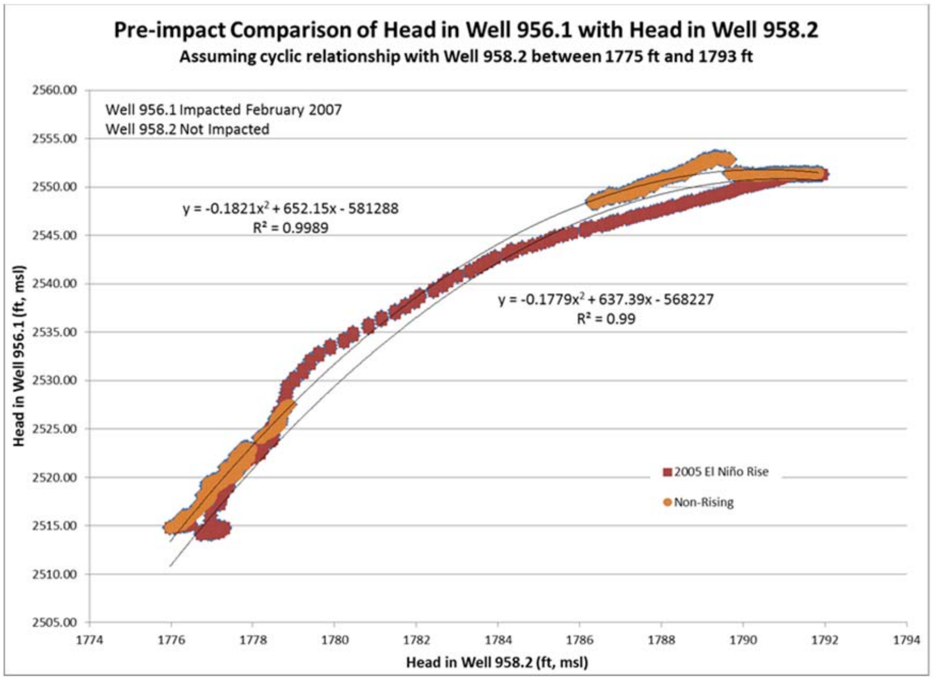


Figure 104. Same day comparison between head in Well 956.1 with head in Well 958.2. Graph shows equation of regression and coefficient of determination for rising and non-rising hydrograph limbs.

Again the recession legs are combined using declining data for Well 958.1 to yield two relationships, one to be used for the control well's rising limb and one for the non-rising limb which incorporates the lag with Well 956.1.



Non-Rising Limb	
Goodness of fit statistics:	
Observations	1685.000
DF	1682.000
R^2	0.999
SSE	463.629
MSE	0.276
RMSE	0.525

Rising Limb	
Goodness of fit statistics:	
Observations	648.000
DF	645.000
R^2	0.990
SSE	1580.317
MSE	2.450
RMSE	1.565

Figure 105. Same day comparison between head in Well 956.1 with head in Well 958.2. Graph extrapolates equation of regression for the full non-rising hydrograph limb.

The result of the regression analyses for the rising and non-rising limbs provide the following expressions for use in simulating non-impact head in Well 956.1 based on the head in Well 958.2.

$$H_R = -0.178*(H_{958.2R})^2 + 637.393* H_{958.2R} - 568227.283$$

$$H_{NR} = -0.182*(H_{958.2NR})^2 + 652.150* H_{958.2NR} - 581287.582$$

Where:

H_R = Simulated same day head in Well 956.1 without presumed tunnel effects for $H_{958.2R}$

H_{NR} = Simulated same day head in Well 956.1without presumed tunnel effects for $H_{958.2NR}$

$H_{958.2R}$ = Daily Head in Well 958.2 during rising limb

$H_{958.2NR}$ = Daily Head in Well 958.2 during receding limb

Subject to the constraint:

1775 feet < Head in Well 958.2 < 1793 feet

Superimposing the simulated data on the Well 956.1 hydrograph provides a snapshot of presumed impacts and groundwater recovery.

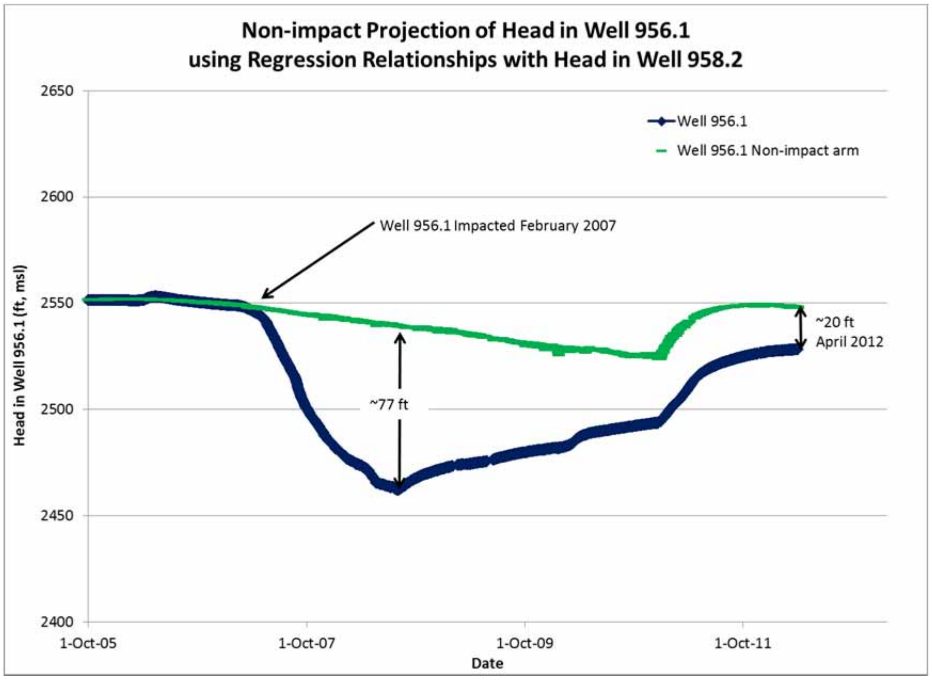


Figure 106. Well 956.1 hydrograph with predicted head (green) and actual head (blue) after tunnel effects in 2007.

As with the lower interval simulation both quantitative and qualitative assessments can be made. At Well 956.1 maximum impact of approximately 77 feet occurred around late June 2008 which indicates that there is approximately a month lag between effects in the upper and lower aquifers. Rebound has been fairly steady but slightly more attenuated over time, however a larger proportion resulted from the 2011 precipitation in the upper versus lower portion of the aquifer. As of April 2012 (the date of the most recent data obtained from Well 956 as of the writing of this report) approximately 20 feet is needed for full recovery and again, the head in this area is still increasing.

Estimated recovery was determined using the same exponential function used with the lower interval above. The following expression was generated:

Remaining Impact (ft) = 99.5013 * Exp(-0.3889 * Δ Time from Start of Recovery)

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

Recovery Prediction Curve

Based on current recovery rate At Well 956.1

Date	Water Year	Δtime from Start of Recovery (years)	Remaining Impact (ft)	Predicted Impact (ft)
9/30/2008	2008	1.66	70.80	
9/30/2009	2009	2.66	51.09	
9/30/2010	2010	3.66	32.66	
9/30/2011	2011	4.66	23.96	
9/30/2012	2012	5.66		16.39
9/30/2013	2013	6.66		11.34
9/30/2014	2014	7.66		7.85
9/30/2015	2015	8.66		5.44
9/30/2016	2016	9.66		3.76
9/30/2017	2017	10.66		2.61
9/30/2018	2018	11.66		1.80
9/30/2019	2019	12.66		1.25
9/30/2020	2020	13.66		0.86

Goodness of fit statistics:

Observation	4.000
DF	2.000
R^2	0.996
SSE	5.630
MSE	2.815
RMSE	1.678
Iterations	18.000

The rising limb of this model had some significantly higher residuals of 4 to 5 feet which could under-predict rise in the non-impact hydrograph and potentially under estimate the remaining impact. The same expression had negative residuals of almost three which would over predict the rise and over-estimate impact. If we assume, based on these residuals and the rising limb RMSE of around 1.5 feet, that there is an accuracy of ± 3 feet we can predict a time to ecological recovery. Based on the *Recovery Prediction Curve*, this would occur by the end of 2017 or in approximately 5-years.

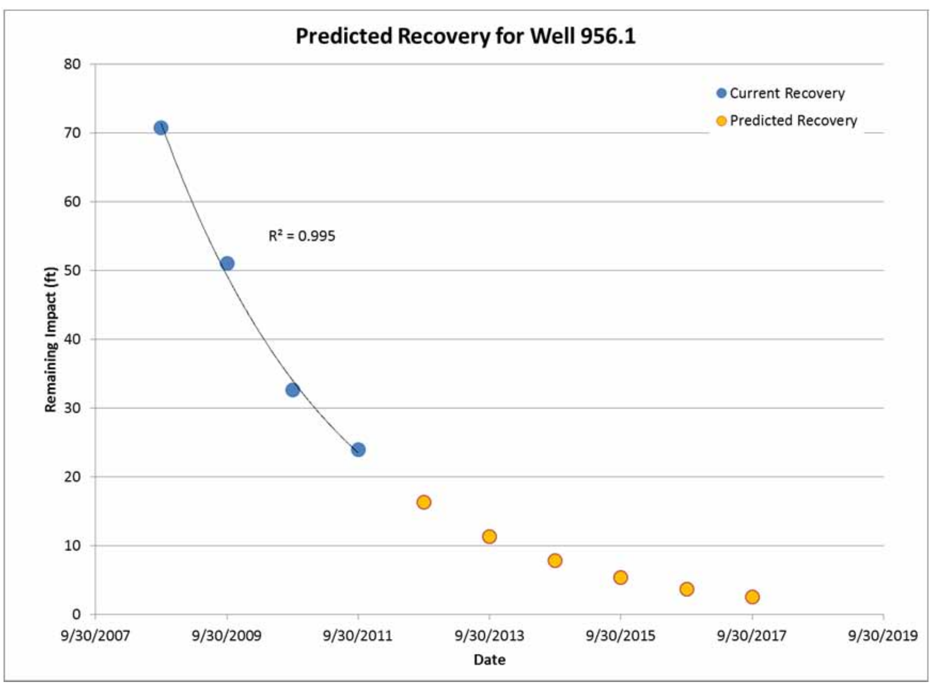


Figure 107. Predicted recovery curve for groundwater in the vicinity of Well 956.1.

Background

As the eastern most watershed encompassed within the Arrowhead Tunnels project area, at over 2000 acres Sand Canyon is also by far the largest. The continuity and range of the riparian vegetation, the multiple documented spring source inputs to the main channel and the variety and abundance of wildlife are a few of the factors which engender the importance of this watershed not only to the Forest Service, but also to the San Manuel Tribe in the lower end of the canyon.

Thus in 2007 as the TBM pushed its way under Sand Canyon and the first of the surface water effects were beginning to manifest, concern arose from all parties (MWD, SMT and FS) pertaining to potential impacts to the biologic resources. In order to prevent negative effects to these resources, MWD installed an extensive mitigation system which allowed application of irrigation water throughout the canyon. A water storage tank was installed in a saddle on the ridge west of Sand Canyon and to the north of the San Manuel Reservation boundary. Access to the tank was by Little Sand Canyon Truck Trail along this ridge dividing Sand and Little Sand Canyons. Initially water was trucked into the tank, however by fall of 2007 a 6-inch diameter hard line was buried in the roadbed leading up to the tank. This line supplied on demand water from the East Valley Water District tank at the lower end of the road. Using a helicopter, MWD draped a main water supply line over ridge and drainage until it intersected the main channel in Sand Canyon. From here the line continued northward until reaching Spring Site 48 located in the mid-reach of the east fork. Off of this main supply line, laterals were dispersed which could supply water to a number of in channel and side canyon sites. Additionally some laterals were used to feed terraces located on the banks above the canyon. In these places groundwater seeps provided moisture to a number of non-riparian vegetative species. Another supply line was extended from the tank down to a site located just north of the San Manuel Reservation boundary.

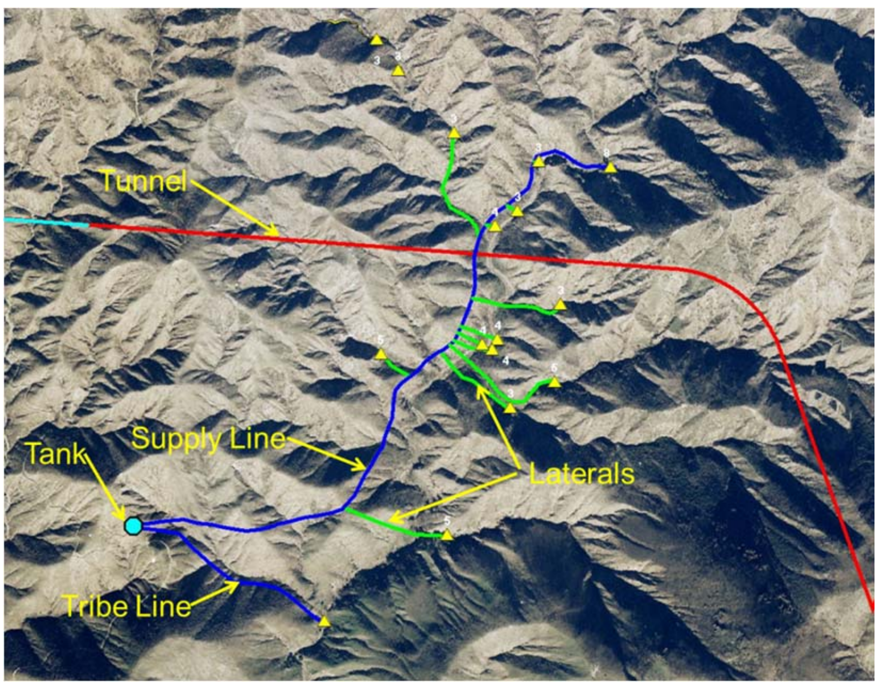


Figure 108. Conceptual layout of mitigation lines in Sand Canyon. Triangles are water application sites.

Initially all parties were concerned with providing ample water supply to the biologic resources in the canyon. San Manuel had its own monitoring network on tribal lands and had been keeping track of canyon flows for the better part of a decade prior to 2007. Their hydrogeology consultant Mark Shaffer of Aspect Consulting had developed an analog year model which used precipitation and groundwater levels to relate the current year to a similar pre-impact year. Based on these observations and the determined minimal water needs to maintain a series of biologically diverse pools flow criteria was established. The criteria included minimal flows at a flume located just above the northern pool and was graduated based on the seasonal growth. During the early part of the season when plant growth is at its peak and many organisms are in the aquatic phase of life there is need for abundant and consistent water in the pools. During this phase the tribe's biologic consultant, Bruce Palmer, determined that a minimum daily flow of 15 gpm would be sufficient to amply supply the pools. This condition was applied from the spring growth season through July. During August and September as the vegetative growth decreased and riparian animals such as toads became more terrestrial the minimum measured flow requirement eased to 10 gpm. As the growing season waned and vegetation experienced the annual die back, evapotranspiration requirements diminished. From this point until the spring growth, the acceptable measured daily minimum flow at the tribe's flume was determined to be 5 gpm. If flow did not meet the prescribed conditions, additional mitigation water was applied. As it has been generally determined that surface water impact to tribal lands is a result of deficit flow in the upper and middle canyons, most water application was via upper canyon supply lines. In some instances this proved to be inadequate and the lower canyon supply line located at the reservation boundary was activated. Initially the tribe's consultants communicated the flow deficits and requested mitigation water as they were not a liberty to disclose any of the flume data. Eventually the Forest Service consulting hydrologist, Neil Berg (formally FS research hydrologist and project surface resource technical lead), signed a confidentiality agreement with San Manuel Tribe in order to obtain the flume data. Collaborative attempts were made between Dr. Berg and Mark Shaffer to relate tribe flume flows to a weir located at Stream Site 117. Both sites were monitored using flow meters and data recorders. The attempts were largely unsuccessful however large diurnal variations of over 50 gpm were noted at both sites.

By 2008, four years after the Old Fire, as vegetation recovered and corresponding water needs increased, MWD was becoming skeptical of what they considered an arbitrary and unscientific approach to water application in Sand Canyon, especially in the lower canyon. They felt that through over-irrigation they were potentially creating habitat in the canyon that they would be responsible for maintaining into perpetuity. On the other hand the Forest Service did not want to manage to a biologic minimum as they were doing in Borea Canyon. Sand Canyon is a much larger watershed with more diverse and complex riparian habitat. The Forest Service biologists Steve Loe and Angelica Mendoza indicated that water rich years were necessary to add resiliency and allow recovery of the ecosystem from the effects of drier years. Dr. Berg had developed several approaches, both qualitative and quantitative, which had been used to determine the existence of surface water impacts project-wide (Berg, 2012). All of his approaches used existing pre-impact surface water data and indicated significant impacts within the canyon in 2008. Additionally MWD's hydrogeologist, Tom Hibner, developed a groundwater based correlation with a number of surface water sites in the canyon. His approach indicated a much smaller remaining impact to surface resources. It was evident that a new approach needed to be developed that would assist in the real-time quantification of existing surface water impacts within Sand Canyon. This approach would need to have buy in from all three parties in order to be useful in determining quantities of mitigation water applied, or even if it was still needed. The result was a collaborative effort amongst all three parties which would take almost a year to develop. The next section which documents that effort was originally drafted by Dr. Neil Berg and has had contributions from most other team members (Berg, Bearmar, & Shaffer, 2010). It has been substantially edited for the current document.

Sand Canyon Surface Water Procedure Documentation

<u>Introduction/Objectives</u>

Staff of the three agencies involved in the Arrowhead Tunnel Project (ATP) jointly decided to develop a procedure to systematically predict, or estimate, natural flow rates at selected surface water monitoring sites in Sand Canyon. A number of sites in the canyon had been impacted by ATP tunnel construction since 2007 and have periodically received mitigation water. A critical question is how much mitigation water to apply. When mitigation water is applied there's uncertainty about the magnitude of natural flow rates because evapotranspiration and other factors mask the contribution of natural flow to the total (natural plus irrigation) flow rates that are measured at most monitoring sites. The approach taken seeks to determine what natural flows would be—without hydrologic impacts related to tunneling and absent any mitigation water—to optimize decisions on the timing and amount of mitigation water needed. In practice, on a weekly basis irrigation flows are adjusted (as needed) to match predicted, or targeted, natural flows.

The intent with this methodology is to mimic as closely as possible what would be the natural flow regime. Corollaries to this objective are (1) if flow would naturally be un-measurable then irrigation should not "artificially" augment flows—in other words irrigation would not create unnecessary flow, and (2) the Sand Canyon ecosystem would not be managed "to the minimum", presumably allowing resilience in wetter years to compensate for degraded conditions in drier years.

The methodology was developed by an interdisciplinary technical team with input and buy-off by biologists, hydrologists, and hydro-geologists from the San Manuel Tribe, Metropolitan Water District of Southern California, and the USDA Forest Service. Project managers from all three organizations have accepted the methodology on the recommendation of the technical team.

One objective was to be as quantitative as possible, realizing the limitations of both our collective knowledge of the hydrologic, geologic, and biologic processes within Sand Canyon, and the limitations of available quantitative tools. Models do not exactly duplicate real world dynamics; there is variability and "error" inherent in model simulations. To address this variability, and to achieve a basic philosophical theme followed throughout the evolution of the ATP—that of conservative management of ecosystem resources—conservatism was explicitly incorporated into the methodology. Conservatism is particularly critical when predicted flows are low or zero. The methodology incorporates intensified time- and site-specific investigation when predicted flows go below certain triggering magnitudes. A "bottom line" perspective is that predicted low flows need to be doubly verified before acceptance of the predicted values as mimicking natural conditions.

The statistical models developed are deterministic expressions incorporating measurements of spring and stream flow, groundwater levels, and precipitation. Although the measurements are made to high levels of professional standards, a variety of sources of variability (e.g., measurement and observer “error”, differences in measurement time of day, etc.) contribute to variability in both independent and dependent model variables.

This document summarizes the approach used to develop the procedure.

Overview of Major Events Occurring During the ATP That Affect the Methodology

In terms of modeling surface water flow timing and magnitude several events occurring during the ATP need to be acknowledged and described. The massive Old wildfire in autumn 2003 resulted in significant changes to the landscape. In particular the almost complete removal of surface vegetation over many acres of the project area drastically changed evapotranspiration rates, with consequent changes to surface flows (simply stated, the removal of vegetation reduced plant water uptake and consequently provided more water for stream flow). As plants grew back, evapotranspiration (ET) rates slowly returned to normal. The rate of ET “recovery” is not completely known and without local ET measurements the post-fire effect of ET changes can only be approximated. The fire-induced removal of hillside and riparian vegetation also accelerated erosion and caused massive influxes of sediment to some of the project area canyons. These fluvial geomorphic changes complicate quantification of surface water hydrologic processes to the extent that pre-fire bedrock scoured channel reaches changed overnight to sediment-laden channels; in some locations water that had flowed over bedrock surfaces—and that could therefore be readily measured—flowed through the sediment after the fire, and could not be measured with the same precision and accuracy as before the fire. The Old wildfire therefore marked a critical juncture in the flow dynamics of the ATP project area. Spanning the period before and after the fire would clearly add significant variability to the datasets.

Impacts to groundwater from tunnel construction were detectible in the Sand Canyon monitoring wells starting in mid to late 2006. By early 2007 impacts had propagated to the surface flows in Sand Canyon, and mitigation water was initially applied in upper Sand Canyon early in April 2007. (Earlier impacts to the City Creek watershed are not considered relevant to the methodology.) Mitigation water has been applied from 2007 through 2011. Spanning the period before and after tunnel impact would also clearly add significant variability to the datasets and significantly complicate model development.

A third “event” in the history of the ATP is the “300-year” drought that occurred between 1999 and 2002. The climatology of the ATP project area includes relatively infrequent high precipitation “El Nino” years superimposed over a general arid climatic regime. The 1999 to 2002 period was the driest four-year period on record.

Although the Sand Canyon ecosystem has historically experienced wildfire and dry periods—with consequent adaptation by biota to a range of environmental variability--the combination of the Old fire, the 300-year drought, and the construction impact to ground and surface waters is unprecedented historically.

Conceptual and Analytical Modeling

Surface water flow dynamics in Sand Canyon are driven by a variety of inter-related factors. These factors “wax and wane” over time as environmental conditions vary. Three primary drivers of surface flow in the canyon are (1) groundwater—as a significant source of surface flow from springs and seeps, particularly during dry summer months; (2) precipitation, both directly as a contributor to surface runoff and stream flow, primarily during non-summer periods, and indirectly as the source of groundwater and the near surface processes; and (3) surface/near-surface processes like ET and interflow/perched water/bank storage, that influence surface flows over relatively short time frames.

Flow at Stream Site 117 was affected by tunnel construction early in 2007. The site is located in the middle reach of Sand Canyon, approximately 800 feet down canyon from a monitored well which remains un –impacted by tunnel construction and approximately 2,500 feet down canyon from the nearest monitored spring sites. These spring sites were impacted by tunnel construction. Between these monitored surface water sites a gaining section exists in the main channel—i.e. groundwater enters the channel and provides contribution to flow. As Site 117 overlays a portion of the aquifer without detected impacts and gets a large portion of its flow from upstream sources with groundwater impacts, the site has been considered a representative for mid-canyon hydrologic health. If the surface water at this site is recovered, then we anticipate there can be no more effects down canyon. However if this site does still show pronounced effects, then it is probable that at least some of these effects propagate downstream, potentially as far as the reservation and the tribe’s pools. There has been an extensive effort by members of the Forest Service team and by tribe consultants to develop a relationship that would predict flows downstream given flow at Site 117. Success has been marginal and any such work and corresponding data is proprietary and has not been disclosed by the San Manuel Tribe. Because of the importance of Site 117 and because the stream site appeared to embody at least the environmental constituents of all the other monitored surface flow sites, all modeling efforts were initially focused on Site 117. Once a solid analytical tool had been developed for this site, the methodology was applied to four other surface water monitoring sites in Sand Canyon equipped to provide irrigation water to the canyon.

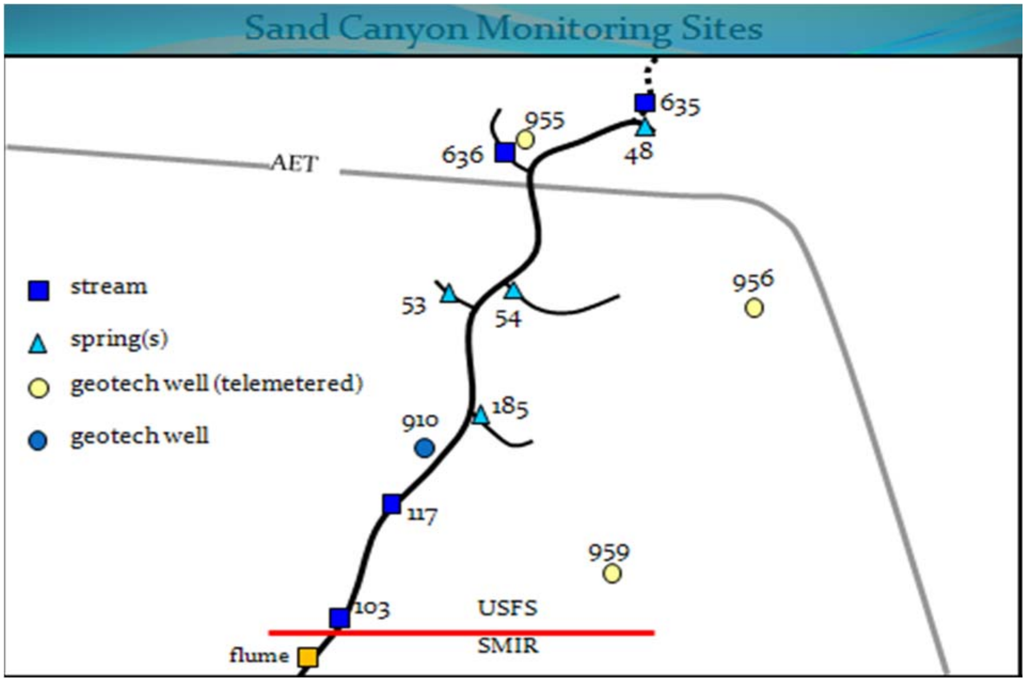


Figure 109. Schematic of Monitoring Locations, Sand Canyon, and the Alignment of the Arrowhead East Tunnel.

Datasets were generated for three independent variables representing the three surface flow drivers. These variables were then regressed—in a linear multiple variable framework—against flow at Stream Site 117. Ultimately five separate equations were developed, each having three independent variables. The regressions incorporated a baseline period that was eventually used to help validate the models. Because of the 1999-2002 drought, the Old wildfire, and tunnel construction impacts, choice of a baseline period was complicated. Ultimately the period 1999 through 2003 was selected, to include both relatively high and low precipitation years, and to assure adequate data availability (e.g., water level data from a critical well was problematic for use in the regressions before 1999).

Model Variables

Although the ATP incorporates a broad spectrum of field monitoring, information is not available for all the factors conceptually deemed important and as typical with modeling efforts, a variety of imperfections reduce the precision and accuracy of modeled outputs. ATP monitoring does include ground, surface water, and precipitation monitoring at a variety of relevant locations in and adjacent to Sand Canyon. The methodology directly incorporates groundwater information, from an un-impacted well located in the upper portion of the canyon, and precipitation data, from a long-duration gage sited west of the ATP project area. Near surface effects such as interflow and ET information is not directly monitored in the ATP. However Site 185, an un-impacted spring site in Sand Canyon, was selected as a proxy for these effects as it is believed this site is fairly representative of many other impacted sites in Sand Canyon with regard to these effects.

Extensive assessment was conducted, particularly on the choice of monitoring well and precipitation gages, because more than one alternative gage (or well) was available. Limitations in data record length and continuity were a consideration, and the desire to use only directly measured data (i.e. not extrapolated or otherwise constructed data) put sideboards on options for variable selection and construction. Additionally only data for which all variables, independent and dependent, were measured on the same date were used.

Precipitation

Precipitation timing and amount can affect surface water flows in several ways. Precipitation is the source of groundwater. It is also the source of direct runoff. Less obviously, precipitation influences the amount and timing of interflow—infiltrated water contained within the soil above the water table which moves slowly down to the channel, bank storage, and other surface/near-surface processes that have secondary effects on surface flows. The timing of precipitation effects varies with the differing water sources. Precipitation falling during any given year may take months or years to infiltrate and augment groundwater aquifers. On the other hand, precipitation can drive surface runoff on temporal scales of minutes and hours. Because the focus the methodology is the summer baseflow period, when short-term precipitation influences are not relevant, we concentrated on the longer term precipitation inputs to groundwater. Additionally it has been determined throughout the project area that before notable recharge can occur, a threshold of annual precipitation must be met. This threshold varies based on location, but is above what is required to replenish soil moisture and meet the needs of local vegetation during its peak growth season. Since general vegetation growth, type and density, is partially based on general reoccurring precipitation patterns, the threshold was selected as one-half the median annual precipitation; which , as of 2012, amounts to approximately 6.5 inches. The analyses then assessed the number of years that antecedent precipitation appears to influence groundwater dynamics. These regression analyses identified a three year antecedent period as relevant. Separate regression analyses, one for each site, directed solely at antecedent precipitation, identified weightings that were applied to each of the three antecedent years. These weightings are site specific as recorded flow at the individual monitoring sites were used as the dependent variables in this part of the analysis. The main regression for each monitoring site therefore includes a precipitation variable weighting the previous year as xx% of the total precipitation component, the second prior year as yy% of the precipitation variable, and the third prior year as zz% of the precipitation variable. The threshold is then subtracted from the sum of the weighted components resulting in the precipitation variable used in the main regression for each respective year. A negative value defaults to zero and indicates the results of the previous three years of rainfall did not contribute significantly to flow during the current year at the monitoring site. The 3-year contributions to any particular rainfall year for modeling purposes are as follows:

Three Year Contribution Coefficeints for Rain Gage 2146

Summary Table

Monitoring Site	Percentage of Contribution		
	Current Year	Last Year	2-Years Prior
Stream Site 117	81%	18%	2%
Spring Site 53	64%	30%	5%
Spring Site 54	69%	24%	7%
Stream Site 636	-2%	84%	19%
Spring Site 48	8%	58%	34%

Precipitation records from two sites, one at the Metropolitan Water District maintained gage at City Creek Ranger Station (Gage 733), and the second at the San Bernardino County maintained gage at San Bernardino Hospital (Rain Gage2146), were found to equally represent precipitation in terms of model parameters. The Hospital site record was selected because of its longer duration and the perceived future robustness of the data. At the time of the original modeling effort in 2010 technical difficulties arose with Gage 733 that would render the data starting in 2009 unobtainable. Using the county's gage at San Bernardino Hospital, the net applied rainfall to each year (in green) can be seen in the graph below alongside the actual measured precipitation for that year (in red).

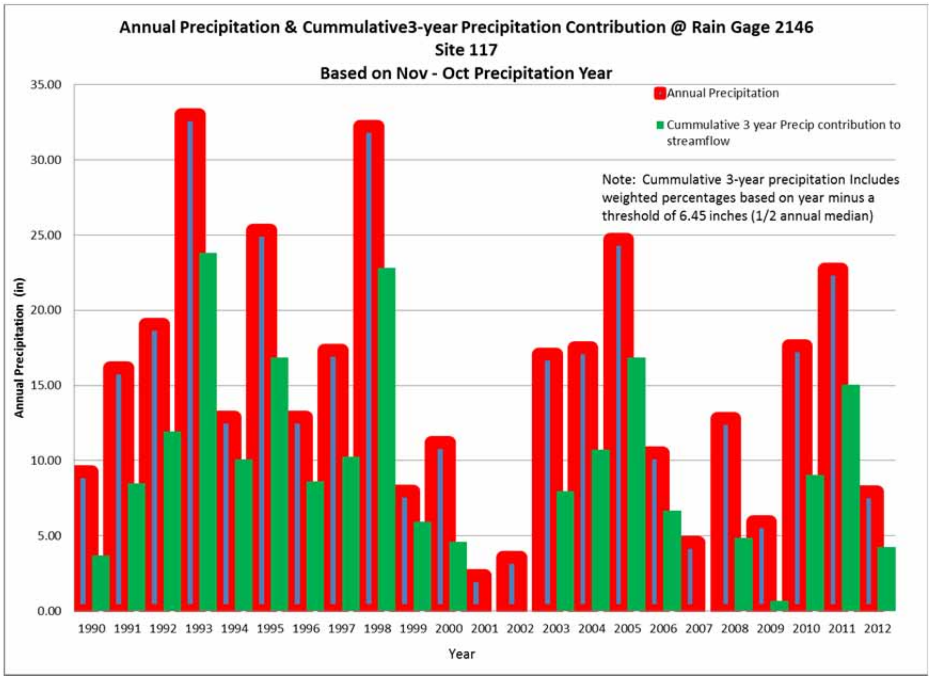


Figure 110. Annual precipitation and annual precipitation contribution for San Bernardino Hospital rain gage.

Groundwater

Monitoring Well 910 is located in an area that appears to have remained free of tunnel construction related impacts. This may result from fault barriers, such as the N fault, up canyon and the differing lithologic unit the well resides in or it may be that the groundwater loss was insufficient to propagate effects so far down canyon. The fact that it presents a record of data without mining effects makes it useful. Additionally the other surface water sites correlate reasonably well to this site prior to 2007. Well 956, located to the north west of the canyon bottom, correlates slightly better to some upper canyon sites but the impact to groundwater in this area renders the data undesirable for this predictive analysis.

The record use from Well 910 is limited, however, to the period after July 20, 1999. Before this time the water level in the borehole was often high enough to flow under artesian conditions into the nearby channel and therefor the hydrograph has an upper bound. The well would have little correlation with flows at this point.

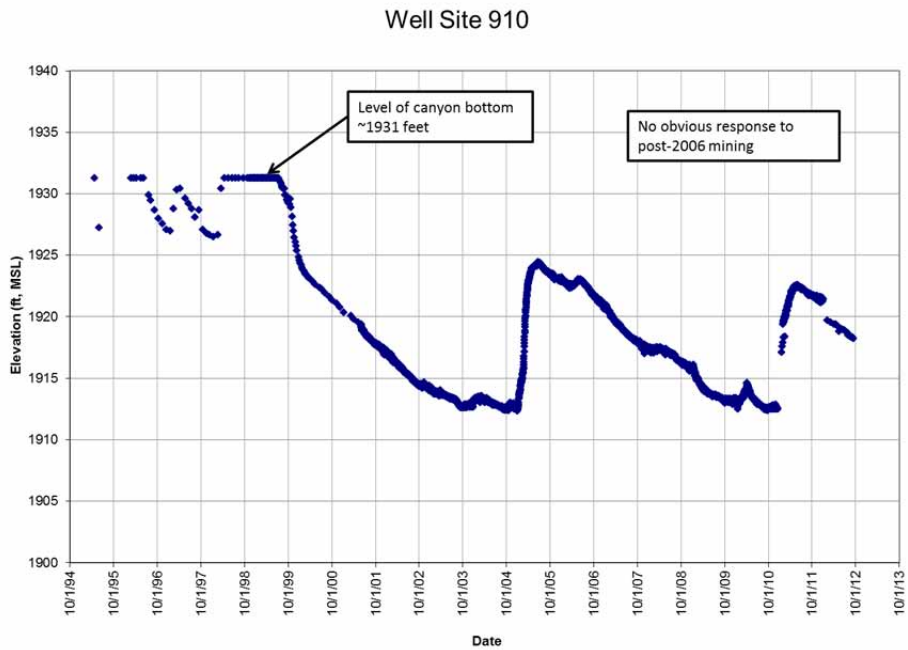


Figure 111. Hydrograph for Monitoring Well 910 in Sand Canyon.

Surface and Near-surface Processes

Although Site 185 is labeled a spring site, it is actually measured at the confluence of its tributary with the main channel. Like Spring Site 54 approximately 2000 feet to the north, this is a fairly significant tributary in Sand Canyon. Unlike Site 54, this site is much more distal to the tunnel alignment and it overlies the same, apparently un-impacted, lithologic unit as Site 117. As a result, this is the only surface water monitoring site in Sand Canyon insignificantly impacted by tunnel construction. Because water from this spring travels some distance through the tributary before it reaches the monitoring point it is subject to, albeit to a smaller degree, the same environmental effects of other surface water sites in the canyon. The tributary channel above the monitoring site periodically flows and contributes primarily rain-induced flows to Site 185. Like many other sites of interest in Sand Canyon, the channel above Spring Site 185 is well vegetated and as such experiences the effects of evapotranspiration. Site 185's location, in particular close to surface site 117, is an advantage, and Site 185 is believed to generally experience the same general climatic conditions as surface sites of interest in Sand Canyon. Although flows at Site 185 are of lower magnitude than other sites in the canyon, particularly Site 117, it is the variability of the site that best represents the near surface effects. This variability is then scaled up or down according to the dependent variable in the regression. The graph below shows the relationship between Sites 185 and 117 during the baseflow timeframe for the baseline data sets.

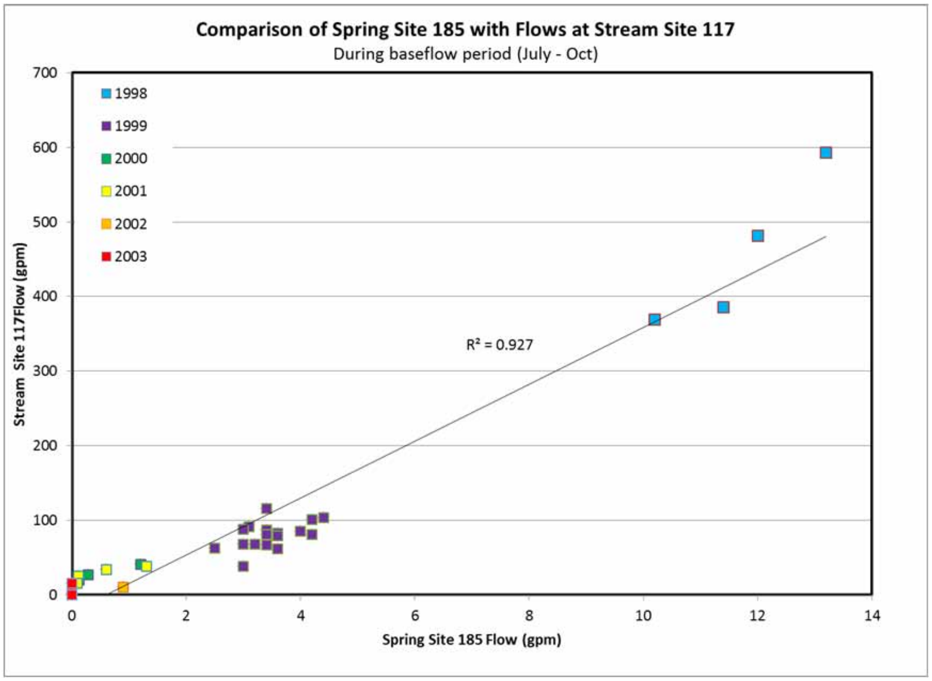


Figure 112. Stream Site 117 versus the control Spring Site 185 for the baseline data set.

Dataset Selection

Monitoring of surface flows began in the early 1990’s in the ATP project area. Weekly monitoring of the Sand Canyon surface water sites began in summer of 2006 and has continued through October 2012 (in the latter years from March to October); therefore “weekly” is the timeframe for each of the regression models. The climate of the San Bernardino Mountains is dominated by Mediterranean influences with almost all precipitation falling in the later-autumn to late-spring period. Summer precipitation occurs only very sporadically, largely as thunderstorms coming from the south and east. Stream and spring flows in the ATP project area are therefore primarily conditioned in the dry summer months by a combination of groundwater, near-surface channel dynamics like interflow and flow from channel banks, and ET. Summer stream flows are generally much less variable than winter flows which are typically influenced by precipitation events. A subset of the baseline data was extracted which includes only data points from July through October. This subset corresponds to the baseflow period and is the primary period for model development because (1) this period experiences relatively little flow variation (compared to winter and spring), (2) this is the period when tunnel impacts are most pronounced in the watershed (as much of this “baseflow” is supplied by groundwater) and (3) mitigation water can be critically needed during these months—recall the primary purpose of this effort is to “predict” what flows would naturally be and match mitigation.

Low Predicted Flows

Rain events in late 2009 created high flows in Sand Canyon before the weir was removed. This resulted in destruction of the data recording system at Site 117 which allowed almost continual flow monitoring at the site during the baseflow period. MWD chose not to replace this equipment so near continual measurements were reduced to weekly as at the other Sand Canyon sites. As mentioned earlier, this site was important to the tribe’s consultants as a result of attempts to correlate the mid canyon flows to the flow above the tribe pools. To incorporate consistency in the data, flow at Site

117 was measured between the hours of 0900 and 1000. However, this timeframe does not correspond to the diurnal lows. At 1000 the flow is still relatively high as temperatures are still on the cooler side and plants have not yet started the daily uptake of water which, when combined with sunlight and carbon, is used to produce carbohydrates and further growth. Flow reduction resulting from this evapotranspiration process tends to peak in the hours before or after midnight—that is the low flow is often in the early morning hours. Although attempts at correlating the two sites were largely unsuccessful, it was determined that flows in the 30 to 40 gpm range at Site 117 during the monitoring time—peak flows for the canyon—would result in very low or zero flow down canyon at the tribe's flume during their low flow time period. This was a major concern. Low flows are a special case in that biological considerations can be more acute when flows near 0—in the case of the tribe's pools down canyon, they tended to dry up. At a critical time during the season this drying could result in a loss of biota such as tadpoles. Therefore it was important to be particularly sure that the models do not predict 0 flow when non-0 flow would be the natural occurrence. To help assure the accuracy and precision of low-flow predictions specialists from each organization closely review environmental conditions and the predicted flows when either of two "triggering" conditions are met: (1) predicted flows at site 117 are less than or equal to 40 gpm, or (2) daily minimum measured flows at the tribal flume are less than or equal to 5 gpm in September or later, less than or equal to 10 gpm in August, or less than or equal to 15 gpm in July or earlier. Tools for this intensive review include (but are not limited to) the FS's flow "ranking" procedure (Berg, Arrowhead Tunnels Surface Water Impact Assessment, 2012), analog year well hydrographs, and the use of analog year flume flow data as a comparison—performed by Dr. Berg and the tribe's consultants. Results of any biological monitoring, and conditions at five pools near the tribal flume on the reservation have also been factored into the intensive assessment.

Validation

Models must be validated to demonstrate the scope of their utility. For deterministic models like the multiple regression models developed here, imprecision in modeled outputs is inherent for a variety of reasons. Beyond those mentioned above, sources of "error" in both independent and dependent variables include measurement and observer variability, and natural variability in the physical phenomena modeled. Validation helps quantify the scope and scale of the "error envelope" of the modeled outputs and provides a means to add conservatism to the operational use of the model results.

The results of the multiple regressions generally under-predicted flows in the middle range at some sites, but at site 117 this middle range falls within the less than 40 gpm criteria for "Low Flows" mentioned above. This under-prediction is a manifestation of (1) the limitations of the regression and inability to incorporate all variables and (2) variability and error inherent in the combined datasets that form the foundation of the models. Because of the under-prediction, the predicted values were augmented by an additional flow amount which equates to the standard error of the regression; basically the standard deviation of the actual flow values around the predicted regression line. This addition attempts to incorporate the error into predictive flows in a way which is conservative. This conservatism follows the agreed-upon philosophy of the tribe, MWD, and the FS to err on the side of conservatism. The figure below compares the predicted (with the one standard error added in) and measured flows for both the baseline period (1999-2003) and recent years with irrigation.

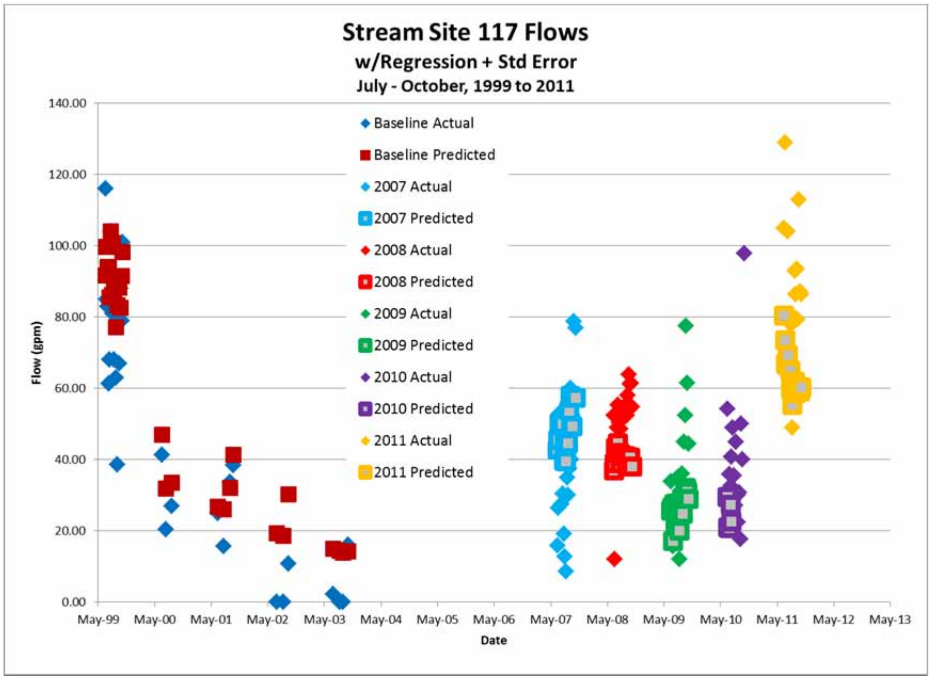


Figure 113. Measured and modeled flows at Site 117 for July through October time period. Note that most of the measured (or actual) flows post-2007 have mitigation water added.

May-June Time Period

Although the July through October period (considered the baseflow period) is preferred from an analytical standpoint (specifically the relatively low flow variability), irrigation at some sites may be required earlier than July. The July through October period is considered a baseflow period when much of the water comes from stored water, either as groundwater or as near surface storage, which is released steadily throughout this temporal span. The model in its current configuration did not address any direct effects of precipitation that were likely to occur outside this July-October time period. Consequently the main July-October (or baseflow) models were augmented by a procedure to address the additional precipitation induced flows experienced during the May and June time periods (also called the “differential flows”). Conceptually this approach realizes that recent precipitation is a major driver of surface water flows for the May-June period; winter and spring rains generate surface runoff, and consequently streamflow. Additionally ET may be higher during this period in support of new plant growth, especially during warmer days. For May and June, flows predicted by the July-October models (the base prediction without the one standard error “buffer”) were augmented by an amount determined by a function of three additional precipitation variables, each as the cumulative precipitation falling (1) 0-30 days prior to flow calculation, (2) 31-60 days prior to flow calculation, and (3) 61-90 days prior to flow calculation. Because ET has been shown to be at times a significant driver of flows, air temperature, as a proxy for ET, was added as a fourth independent variable (as the average of the maximum for each of five days prior to the flow prediction date). As with the main July-October methodology, the May-June augmentation or “differential” procedure is a multiple regression.

The figure below illustrates the "fit" between the measured differential flows at site 117 and the predicted differential flows (based on the May-June differential procedure) at site 117 during the baseline period (e.g., the May 2000 actual flow was 90 gpm greater than the flow predicted by the July-October procedure, therefore the actual May-June differential is considered to be 90 gpm or 90 gpm higher than baseflow). The figure also plots the results of the May-June differential methodology (e.g., the May 2000 predicted flow differential per the May-June procedure was approximately 85 gpm) and compares the actual to predicted differential flow magnitudes.

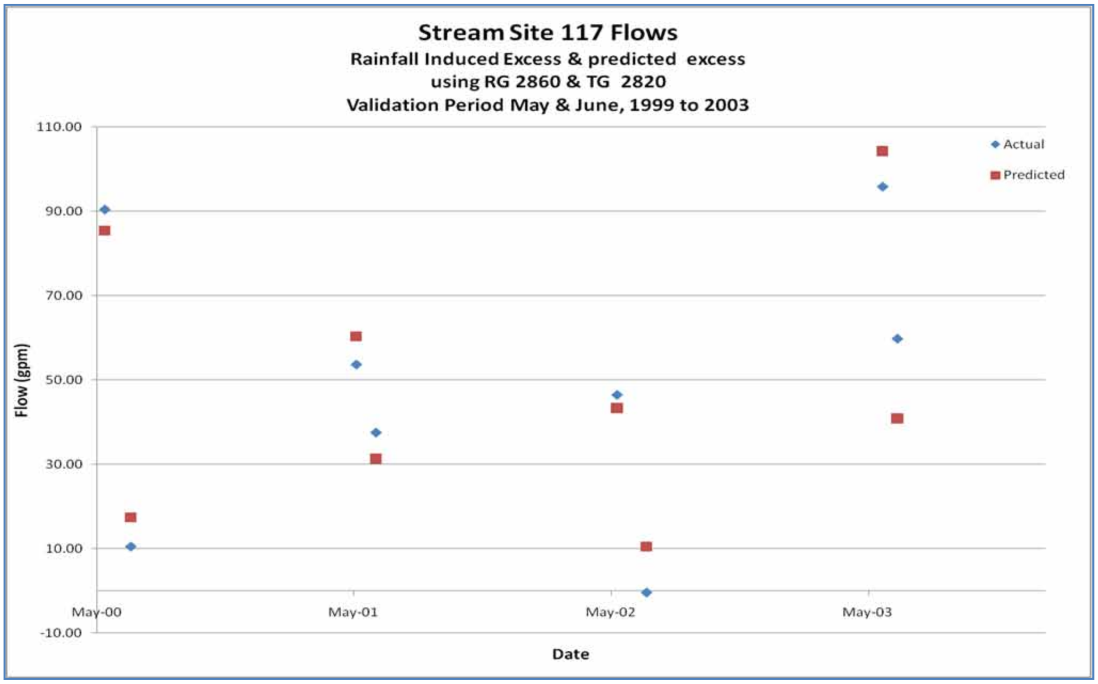


Figure 114. Measured and Modeled Flows at Site 117 for May through June Time Period. RG 2860 is the City Creek precipitation gage and TG 2820 is the San Bernardino County air temperature gage.

To complete the methodology the predicted May-June differential is added to the base value predicted by the July-October (Baseflow) Procedure for an overall value on the respective date in the May-June time period. Although normally the July-October procedure under-predicted May-June flows, there is the potential that a negative differential could be predicted by the May-June differential methodology. If such a value occurs the methodology result defaults to 0 (i.e. the base—no standard error—value predicted by the July-October procedure alone).

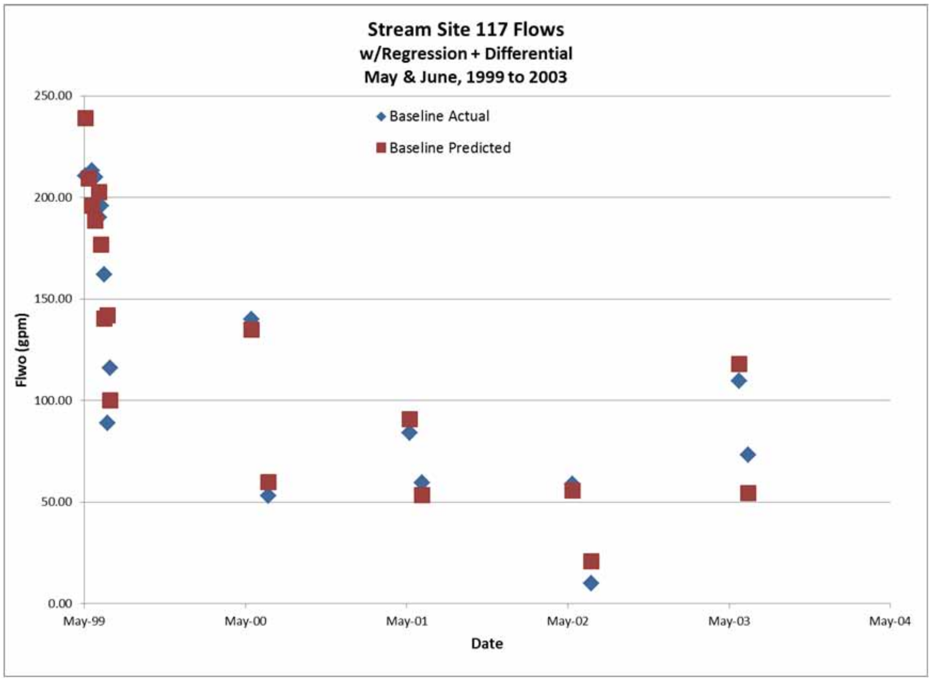


Figure 115. Measured and Modeled Flows at Site 117 for May through June Time Period with the Differential added to account for increased precipitation and ET.

<u>Operational Usage</u>

The models have been applied weekly during the period May through October in the following manner:

- Tabulated, predicted flow values are determined on the basis of the models. Only Site 185, which incorporates ET, changes daily (or even hourly). The well head changes very slowly and very little precipitation actually occurs during the monitoring season. Therefore a table can be printed which matches various values of Spring Site 185 flows to corresponding flows at other sites. An example is shown below.

Sand Canyon Flow Predictions

Date: 6/21/2011 Well 910 Elevation (ft): 1922.50
Apply Flow Differtial? Yes

	Site 185 Flow (gpm)	Site 48 Flow (gpm)	Site 636 Flow (gpm)	Site 54 Flow (gpm)	Site 53 Flow (gpm)	Site 117 Flow (gpm)
Differential		0.33	2.13	0.90	0.02	25.37
Precip Contribution		7.51	8.97	12.66	12.69	13.59
	0.10	5.42	4.02	6.30	1.53	46.60
	0.20	5.42	4.09	6.36	1.57	47.94
	2.10	5.37	5.33	7.37	2.38	73.44
	2.20	5.37	5.39	7.42	2.42	74.78
	2.30	5.36	5.46	7.47	2.46	76.12
	2.40	5.36	5.52	7.52	2.51	77.46
	2.50	5.36	5.59	7.58	2.55	78.80
	2.60	5.36	5.65	7.63	2.59	80.15
	2.70	5.35	5.72	7.68	2.63	81.49
	2.80	5.35	5.78	7.74	2.68	82.83
	2.90	5.35	5.85	7.79	2.72	84.17
	3.00	5.35	5.91	7.84	2.76	85.51
	3.10	5.34	5.98	7.90	2.80	86.86
	3.20	5.34	6.05	7.95	2.85	88.20
	3.30	5.34	6.11	8.00	2.89	89.54
	3.40	5.34	6.18	8.06	2.93	90.88
	3.50	5.33	6.24	8.11	2.98	92.22
	3.60	5.33	6.31	8.16	3.02	93.57
	3.70	5.33	6.37	8.21	3.06	94.91
	3.80	5.32	6.44	8.27	3.10	96.25
	3.90	5.32	6.50	8.32	3.15	97.59
	4.00	5.32	6.57	8.37	3.19	98.93
	4.10	5.32	6.63	8.43	3.23	100.28
	4.20	5.31	6.70	8.48	3.27	101.62
	4.30	5.31	6.76	8.53	3.32	102.96
	4.40	5.31	6.83	8.59	3.36	104.30
	4.50	5.31	6.89	8.64	3.40	105.65
Measured	4.3	2.7	36	12	2.3	193

- The MWD field crew measures flow at Site 185 to obtain comparable flow predictions at each Sand Canyon surface water site. The crew compares the measured and predicted flows.

- If the measured flow is lower than the predicted flow at any site the field crew will adjust the irrigation rate so that the combined natural plus irrigation water mimics the predicted flow. Predicted flows at each site will be met so that if flows are adequate at site 117 but low at an upper tributary site, irrigation will be increased at the upper tributary.

- Conversely if flows at the upper sites are adequate but low at site 117, one or more of the upper sites will be adjusted to bring flows at site 117 to within the appropriate range based on model predictions. This methodology recognizes that the upper canyon has some gaining sections of which only specific points are monitored, yet contribution to the downstream is in more than just these locations.

<u>Specifics of the Models</u>

Regression models were developed for Sand Canyon monitoring sites 117, 53, 54, 636, and 48. In the following algorithms:

- Site 117: Q_{117} = (13.32**Site 185*)+(-0.0124**Precip 2146*)+(1.716**910 Head*)-3277.5.
  Standard Error of Regression = 9.99 gpm

- Site 53: Q_{53} = (0.483**Site 185*)+(-0.025* *Precip 2146*)+(0.113**910 Head*)-215.54.
  Standard Error of Regression = 0.37 gpm

- Site 54: Q_{54} = (0.546* *Site 185*)+(0.057* *Precip 2146*)+(0.442**910 Head*)-845.54.
  Standard Error of Regression = 0.686 gpm

- Site 636. Q_{636} = (0.741* *Site 185*)+(-0.004* *Precip 2146*)+(0.122**910 Head*)-232.85.
  Standard Error of Regression = 0.913 gpm

- Site 48. Q_{48} = (-0.028* *Site 185*)+(0.018* *Precip 2146*)+(0.175**910 Head*)-331.69.
  Standard Error of Regression = 0.28 gpm

Where:

Q_x = predicted flow at the corresponding monitoring site (gpm)

Site 185 = flow measured (gpm) at Sand Canyon monitoring Spring Site 185 on the date the model is applied.

Precip 2146 = the weighted precipitation value (inches), from the San Bernardino County Rain Gage 2146 located at the San Bernardino Hospital, incorporating precipitation from the three years prior to the date the model is applied.

910 Head = the head or water level in well 910 (feet) for the date the model is applied.

<u>Sand Canyon Surface Water Model Implementation and Resource Recovery</u>

Application of the Sand Canyon Surface Water Model and the mitigation water adjustment procedures began early in the 2010 monitoring season with buy-in from all parties. It was agreed to “test” the model for the season and carefully monitor results. The model has always been perceived as a tool to help with mitigation water and recovery status quantification. Typically MWD operates the analyses and supplies their field crews and the Forest Service a copy of the results. The Forest Service verifies the results and discusses mitigation needs and results with both MWD and with the San Manuel Tribe consultants.

As the canyon continued to recover the model results have always been the topic of conversation. The predictions from 2007 through 2009 do indeed lend credence to the claim that MWD has “over mitigated” the canyon as measured flows often exceeded predictions. It must be noted however, that water has not been applied uniformly throughout the canyon at all points of groundwater entry. To do so would be extremely onerous and costly. Instead, a handful of sites have been outfitted with mitigation lines and monitoring. Water has been applied at these sites in such a way as to ensure adequate water in the middle and especially the lower canyon. The result being that it appears that these relatively few sites are “over mitigated”. Early in the 2011 monitoring season all three parties decided that substantial recovery had occurred to many of the surface water sites and the extra “buffer” designed into the model to provide conservatism was no longer needed. Therefore starting in 2011 the standard error of the regression was no longer added in to the model’s predictive values. However close watch on both Forest Service and Tribe resources ensued and several conference calls were convened to discuss the modeled and measured results on both Forest Service and Tribal properties. In late August of 2011 following some particularly hot weather and low flows, the Forest Service requested application of mitigation water from MWD. Mitigation flow, which until this point had not been utilized, commenced and continued for the next several weeks. By the end of the 2011 monitoring season, it appeared that the Sand Canyon Model was predicting that recovery of surface water resources was close, however because of the sensitive nature of the riparian resource on Forest Service and Tribe lands there was a general desire to provide an additional year of monitoring before formally assessing recovery status.

During the 2012 monitoring season, the Forest Service continued to carefully watch the Sand Canyon surface resources. It was generally accepted by Forest Service field personnel that have been monitoring flows and vegetation growth over the past several years that the canyon contains significantly higher levels of biomass than in previous years and that it was quite healthy during the 2012 baseflow season. Higher early season growth presumably resulted in sudden drop in surface water flows seen in stream sites. This drop is typically seen in mid to late July and is seen in the Tribe’s flume as well. This year the drop occurred in July as Site 117 dropped to about half. This year however flow on the Tribe land was largely unaffected as the flume continued to flow and pools remained healthy. As the season wore on, temperatures dropped somewhat and vegetation growth slowed; flows increased significantly. Site 117, while valued for its mid-canyon location and representation of general hydrologic health, presents some complications with response to evapotranspiration and with the sandy substrate which is present in some years. This in channel variability can make a comparative flow analysis troublesome.

Current Status

In late September of 2012 the Forest Service and Tribe consultants discussed the results of the measured flows in Sand Canyon (Spring Site 48, Stream Site 636, Spring Site 53and Stream Site 117) and compared those to the model predicted flows and to Dr. Berg’s methodologies.

Additionally groundwater levels in Well 910 were used to predict an "analog water year" with respect to pre-impact conditions. From a groundwater perspective an analog water year, based on Well 910 water levels would be approximately 2001.

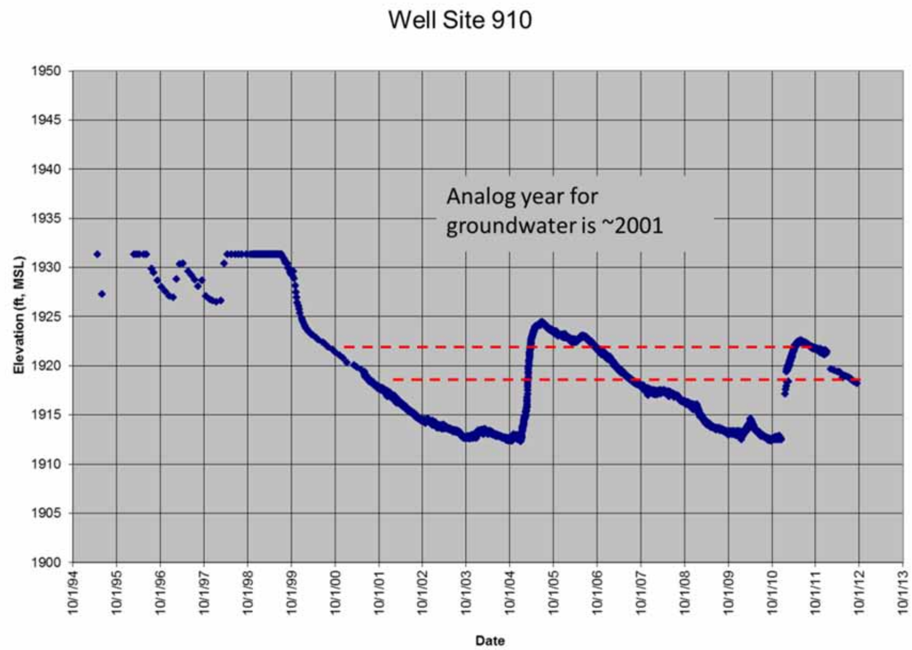


Figure 116. Well 910 Hydrograph comparing water levels for 2012 and pre-impact 2001.

Based on these discussions the Forest Service technical staff determined that upper Sand Canyon still shows about a 50 percent reduction in flow denoted by Spring Site 48 and continued impact at Well Site 956 (which has been steadily recovering).

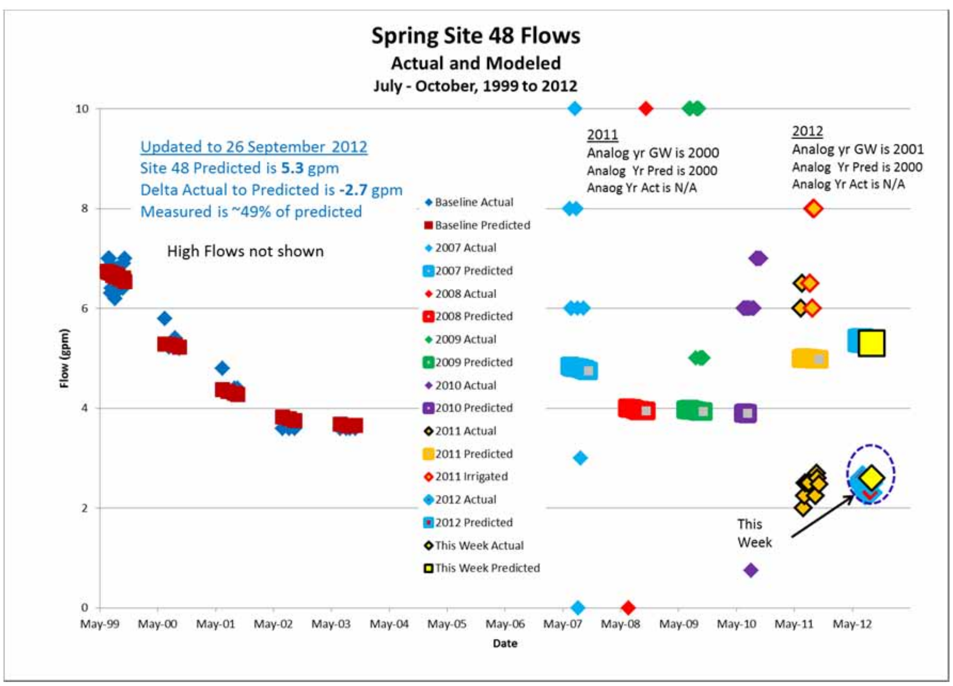


Figure 117. Actual and Modeled flows at Spring Site 48 up through late September 2012. Note that flows are fairly consistent which is typical of a site based largely on groundwater.

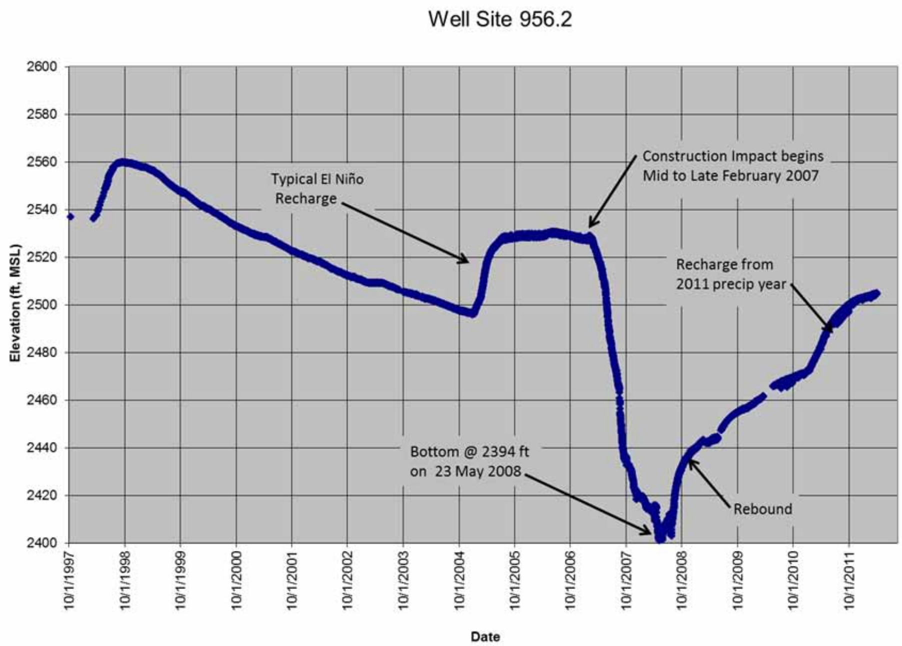


Figure 118. Hydrograph for the lower interval of Well 956 in upper Sand Canyon. Recovery has been occurring steadily but is not yet complete.

Because this spring supports relatively little habitat and contribution to channel flow is insignificant, and because flows have been consistently increasing, it was decided by the Forest Service that monitoring by MWD could conclude at the end of this season. Monitoring will occur up to twice next season by the Forest Service Geotechnical Engineer during regular site visits to monitoring wells (provided for in Section 3 of this document).

Site 53 is a spring in a small side canyon to the east and somewhat demarcates the boundary between the upper and middle canyon. This site is subject to the effects of evapotranspiration but not generally to the same extent as the main channel sites. In 2011 Site 53 appeared to be within 30 percent of recovery. The baseline analog flow year for 2011 would be approximately 2001 whereas the groundwater and baseline prediction analogs are in the neighborhood of the year 2000. As flows generally decreased in Sand Canyon between 1998 and 2005, a measured analog of 2001 denotes somewhat lower flows than would be expected at this site. Measured flows in 2012 have generally been much lower, with a 2002 to 2003 analog year instead of the anticipated 2001 analog year. However during September flows have increased significantly and appear to be in the lower 2001 range. Recovery at this site is more nebulous than at the previous spring site (Site 48). With no clear and definitive tunnel effects still present from a flow perspective and with consideration of the health and vigor of the riparian habitat, the Forest Service ATP team concluded that this site appeared sufficiently recovered to warrant discontinuation of monitoring at the conclusion of the 2012 season.

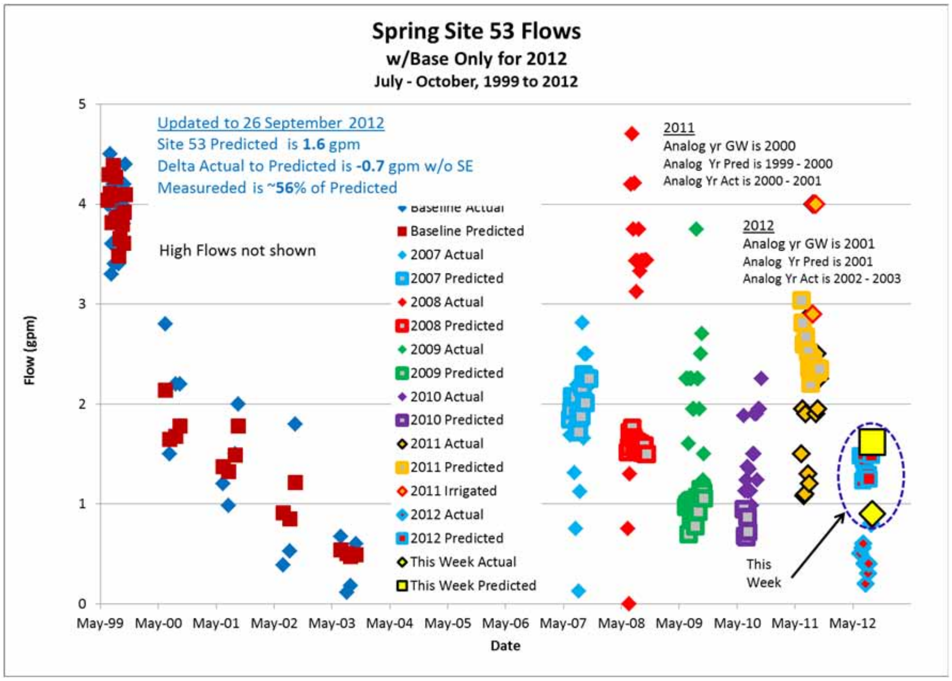


Figure 119. Actual and Modeled flows at Spring Site 53 up through late September 2012. Note that the last measurement/prediction (yellow) better match those of 2001. This is true of several September flows (located behind the enlarged yellow).

The two in channel sites, Stream Site 636 and Stream Site 117 are typical of other sites with heavy influences from evapotranspiration and changes in substrate. Both of these site exhibit lush riparian vegetation this year in abundance of what has been seen in the past. The result is a large flow variation not only from week to week, but also diurnally. Time of day becomes critical to consistent measurements.

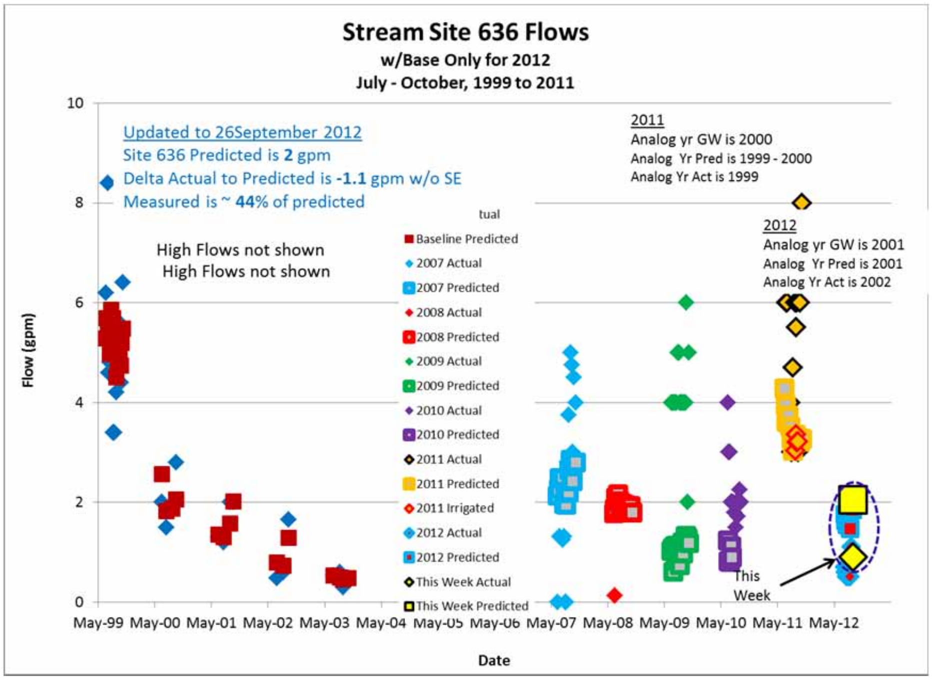


Figure 120. Actual and Modeled flows at Stream Site 636 through late September 2012.

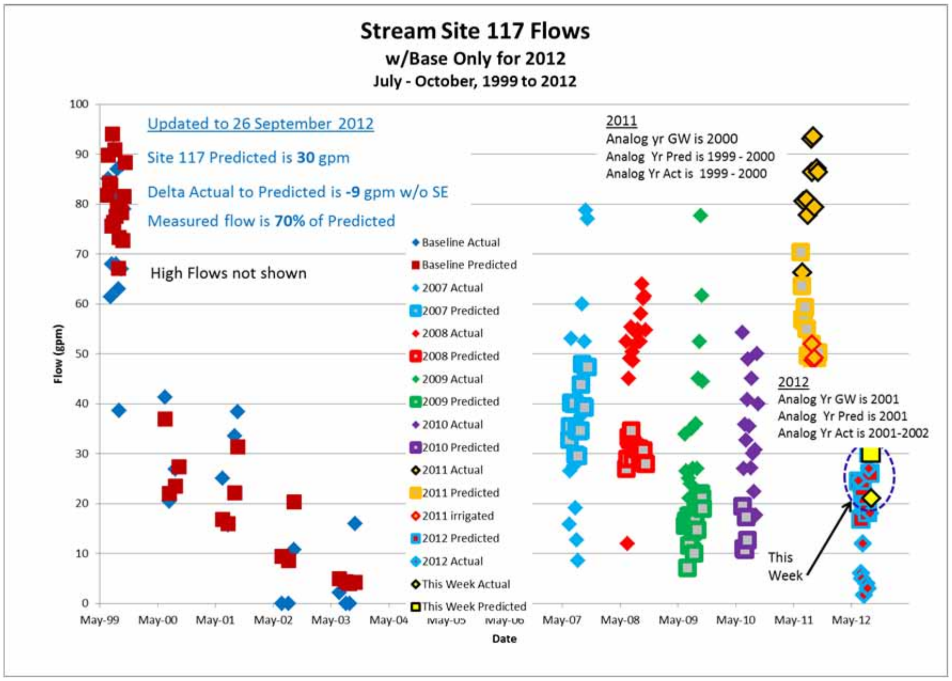


Figure 121. Actual and Modeled flows at Stream Site 117 through late September 2012. Note that the last measurement/prediction (yellow) better match those of 2001.

As with other sites, baseline analog predictions for the year 2011 are approximately in line with the year 2000. Measured flows at these sites for the un-mitigated flows are directly in line with this comparison or are even a little high. Part of the reason for the disparity between the higher measured flows and the lower predicted flow lies with the lack of El Niño data in the original model calibration. This aside, it appeared that channel flow in the mid-canyon was very close to reaching ecological recovery in 2011. Comparison of predicted flows this year (2012) with the baseline predictions yield 2001 as an analog prediction year. For much of the season, the analog year for actual flows is in the neighborhood of 2002 which displayed generally lower flows at all Sand Canyon surface water monitoring sites. However, the final third of the 2012 monitoring season flows have increased as vegetation requirements have decreased resulting in measured flows which more approximate the 2001 analog year. Additionally the flume above the Tribe's pools has continued to flow and the pools have been healthy. Given the apparent health of the mid and lower canyon ecosystems along with the fact that flows seem to have returned to what would be expected when factoring in ET variability, the Forest Service, in concurrence with the Tribe's representatives, determined that monitoring could discontinue at the end of this year and that the mitigation infrastructure can be removed at the conclusion of the season.

In conclusion, it must be noted that the Sand Canyon surface water resource mitigation management effort, while sometimes contentious, was one of the best examples of true collaboration that existed in conjunction with the Arrowhead Tunnels Project. The Sand Canyon Surface Water Prediction model was jointly inspired by, contributed to and constructed by technical representatives from all three parties; the Forest Service, Metropolitan Water District and the consultants for the San Manuel Tribe. The model itself is far from perfect and was only developed to be a tool, not a substitute for other analyses and technical proficiency. As such it has served as a basis for additional evaluations, discussions and collaboration in the management of the valuable surface resources in Sand Canyon.

Sycamore Canyon

Well 903 Recovery Analysis - Reserved

<u>Background</u>

Located on the lower half of a spur ridge above a north east fork of Sycamore Canyon and approximately 1000 feet north of the tunnel alignment, this is a double completion monitoring well.

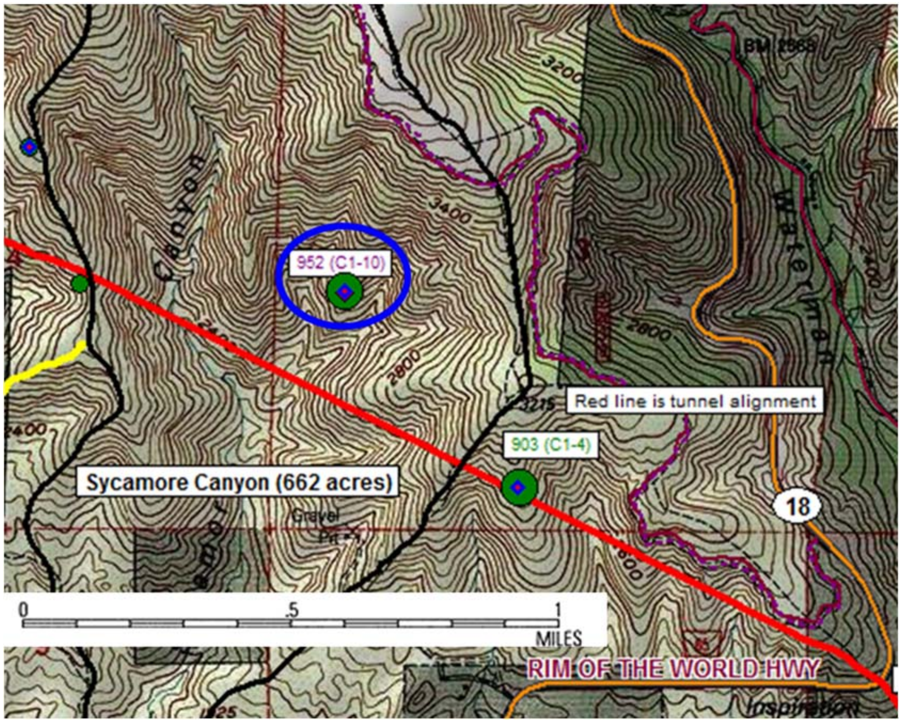


Figure 122. Map showing location of Well 952 in Sycamore Canyon.

The borehole is located near the intersection of the Sycamore-4 and Sycamore-5 faults and initially penetrates gneiss but likely also extends through the marble layers which can be seen as an outcrop in the canyon below.

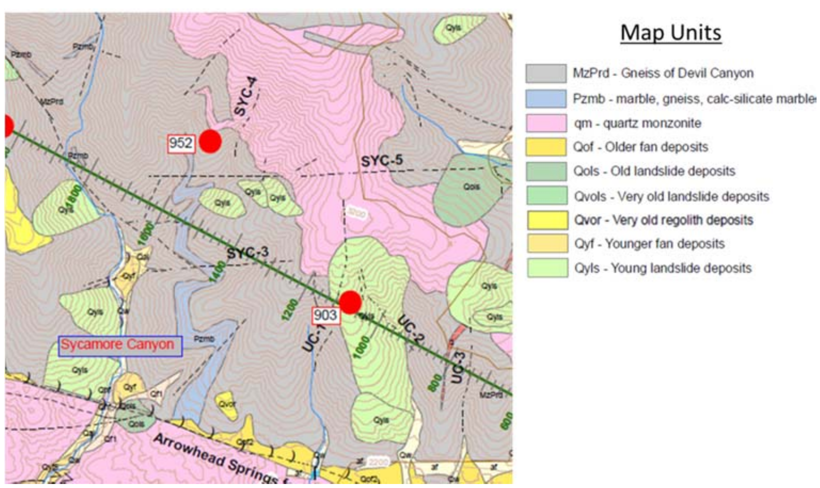


Figure 123. Geology Map showing Sycamore Canyon area.

The gneiss potentially acts as an aquitard, shielding the upper groundwater aquifer from the effects of the tunnel. Monitoring of the borehole extends back to mid-1998 and comparison of head data between the upper completion, which is a standpipe, and the lower piezometer (located at a depth of

820 feet bgs) demonstrates diversity in response to the typical recessional and recharge cycles. The upper completion is much more responsive to annual recharge and behavior typifies an upper or perched groundwater aquifer. Indeed, both completions responded very differently to the 1998 Hector Mine Earthquake. The upper aquifer responded by an increase in pressure while the lower completion lost pressure. Once impacts to groundwater occurred in the vicinity of this borehole, the lower completion response was evident, while the upper completion demonstrated no effects; in fact recharge was occurring at this elevation. The permeability separation between the affected aquifer and the upper groundwater may have shielded local surface water from tunnel construction effects.

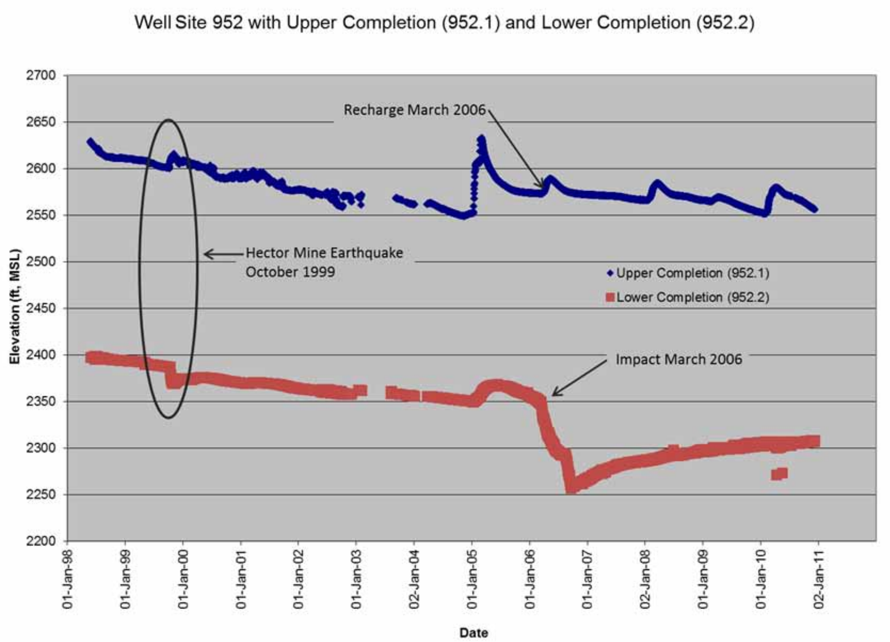


Figure 124. Comparative groundwater hydrograph for upper and lower intervals in Well 952.

The lower interval of Well 952 is considered a proxy for the impacted aquifer in that area. Generally prior to mid-2005 it experienced a moderate recession rate of approximately 7 feet per year. Recharge occurs only during above average precipitation years, for instance when the county rain gage located at Cal State San Bernardino (Gage 2893) registers more than 25 inches for the October to September precipitation year. Originally recharge was thought to come from a combination of local and regional sources with groundwater flow from Lake Silverwood area. Analysis doesn't quite support this and the Waterman Springs fault may provide some barrier to flow. A more in depth analysis would need to be performed to verify.

The first indication of impact to groundwater surrounding the lower interval of Well 952 may have occurred in July of 2005 just after Well 903 to the east was impacted. Two weeks after the response of Well 903 to mining, the rate of recession in Well 952.2 suddenly increased by a rate 4 to 5 times anything on record for this site. A definitive impact to groundwater occurred in March of 2006. The lowest point was reached by the end of that year, showing almost 100 ft (Well 952.2) below natural decline. It would take about 14 years of typical recession (at 7 ft per year) to reach this point naturally. The aquifer surrounding the upper piezometer remained unaffected. The following year the TBM was under Badger Canyon to the west and groundwater in the vicinity of Well 952.2 displayed a rebound of 30 feet and was progressing well.

Recovery Analysis

Conservation of matter is the basis for this analysis. Change in storage is the result of the difference between what enters and what leaves the system. If more water comes in as recharge than what leaves, the pressure in the aquifer increases and head increases with time. Conversely if there is little recharge to the area, then discharge dominates and the typical recession arm is seen in the hydrograph.

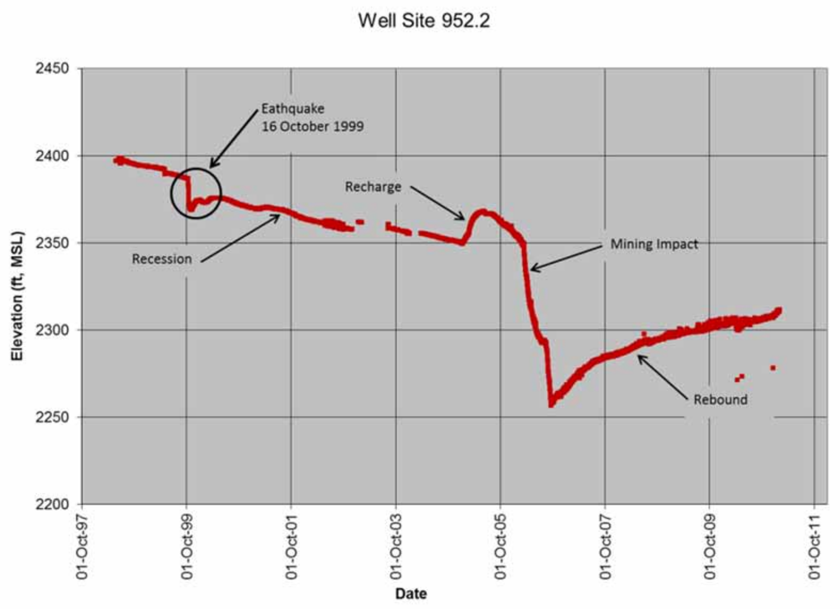


Figure 125. Groundwater hydrograph displaying head over time in Well 952.2.

The Hector Mine Earthquake of 1999 created a significant pressure drop at this site but stabilization had occurred by the spring of 2000. The post-earthquake hydrograph appears to behave in a manner similar to the years prior. For this reason the years 1998 to 2005 have been included in the baseline data set, with the water year 2000 excluded. Although impact to surrounding groundwater may have occurred as early as July of 2005, these first impacts were mild and toward the end of the water year. Additionally a recharge year needs to be included in the analysis, therefore 2005 is the last year included in the baseline data set.

Storage

During the Baseline or Validation period changes in storage are believed to result from precipitation, groundwater flow into the system and natural groundwater flows out through discharge to surface water sites or areas of lower groundwater head. Changes to groundwater storage can be seen in the Well hydrograph elevation changes over time. In this analysis changes to head in Well 952.2 (the lower completion of Well 952) are considered a surrogate for pressure changes in the surrounding aquifer. Well 952.2 is likely a confined aquifer with a definitive upper physical boundary. As the actual "water table" cannot move, the piezometric surface represents potential within the system. Accordingly, more head or pressure from recharge on the system than loss of pressure resulting from discharge leaving increases the system potential or pressure or head.

System Discharge

Negative groundwater head or pressure changes to a groundwater aquifer system without anthropogenic influences are generally the result of discharge to surface water sites or groundwater dependent resources or groundwater movement to down gradient groundwater sites (such as basins). Surface water sites generally have a fixed elevation while down gradient groundwater basin heads can fluctuate just as the up gradient head can. The magnitude of the flux from the system often times varies with overall gradient and therefore the way it relates to storage changes is often not linear. In the case of groundwater represented by Well 952.2 there are no know associations with surface water sites within the project area and inter-basin flow is very difficult to quantify. However, as the head in this well does change over time, the discharge term does exist. Analysis has shown that the amount of recession or negative change in storage over the year at this site does vary with the groundwater head for that year. The variation occurs in a way that is similar to the relationship between storage changes and surface water discharge at other sites. A proxy for this flux out of the system has been developed and this term is labeled *Average Annual Groundwater Head in Well 952.2*. This variable is simply the arithmetic average between the groundwater head on the last day of the current year and the groundwater head on the last day of the preceding year. The water year ends on 30 September and the hydrograph for this site is fairly uniform for the recession years, so this method of calculation well represents the variable. The actual relationship between the variable and storage changes is more of a general trend and demonstrates only a partial tie. The complete assessment requires additional variables.

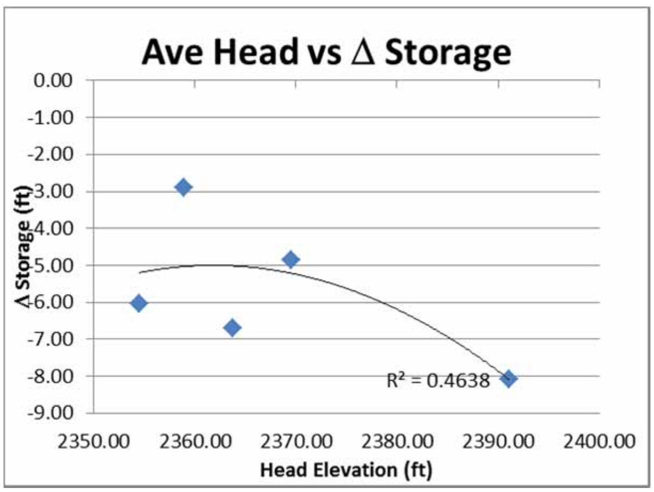


Figure 126. Groundwater head versus change in storage for Well 952.2.

System Recharge

As with many of the analyses, this is the only truly independent variable in the system and represents flux into or increased potential on the aquifer surrounding the piezometer in the lower completion of Well 952. As mentioned earlier, it is perceived that groundwater recharge in this area may be more influenced by local precipitation than regional. The San Bernardino County Precipitation Gage 2893 located at Cal State San Bernardino is used in this analysis. In addition to being proximal to the groundwater site, this particular gage has the most consistent data set with the fewest errors when comparing the other two gages in the area (Arrowhead Springs gage 2854 & San Bernardino Co Hospital gage 2146). Gage 2893 appeared to have the best quality data as well as the best overall fit with the dependent variables. Data is cumulative over the year and is presented in total inches starting from 1 October and ending on 30 September for a given water year.

As recharge appears to be influenced locally, the relationship with precipitation is included directly as annual indicating that the aquifer is more responsive to smaller resolution changes. The analysis with precipitation indicates a strong correlation between precipitation and recharge or a lack of precipitation and a decline in groundwater head.

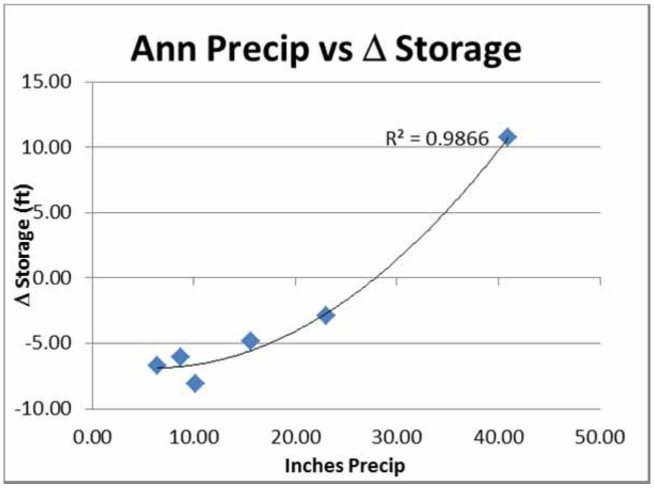


Figure 127. Annual precipitation at rain gage 2893 versus change in storage for Well 952.2.

Conceptual Groundwater Model

Changes in pressure detected by the transducer in Well 952.2 are converted into changes in feet of head which represents the variable potentiometric surface in the confined aquifer around the well. This variation is driven by the disparity between water moving into and out of a system. In the case of a confined aquifer, very little water moving in or out of storage can cause large changes in pressure. No attempt has been made to quantify the amount of water, only to predict changes in head using general trends as variables. In the case of this analysis *Annual Precipitation at Gage 2893* is the variable which represents inputs to the system. Recession or negative storage changes dominate except when precipitation is significant. Extractions are more nebulous. *Average Annual Groundwater Head in Well 952.2* infers an increasing gradient between the aquifer sampled by Well 952.2 and an indeterminate down gradient sink as the value in the variable increases. The implication being that as the gradient increases the flux out of the system increases and the influence on storage changes appropriately. It should be mentioned that this variable is not a strong predictor by itself.

Analytical Model Calibration

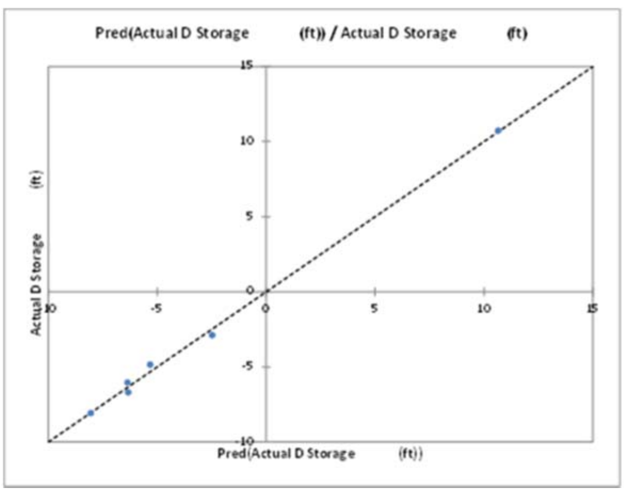
The analytical model was developed using the basic premise of the conceptual model. Inflows and extractions are variables used to predict natural (non-mining related) changes in storage in Well 952.2 and this is in turn used to predict annual net changes to the groundwater head. The model uses a multivariate second order polynomial regression with *Average Annual Groundwater Head in Well 952.2* and *Annual Precipitation at Rain Gage 2963* as independent predictors. For calibrating the equation the actual Average Annual Head is used. This yields the expression:

ΔS = -11878.7671 + 10.0563 * Actual Average Head - 0.1958*Annual Precipitation at 2893 - 2.1294E-03*(Actual Average Head)^2 + 1.4532E-02*(Annual Precipitation at 2893)^2

Where:

ΔS = Change in storage at Well 952.2
ΔS & Actual Average Head are in feet
Annual Precipitation at 2893 is in inches

The model was calibrated to data from 1999 to 2005 (excluding 2000) and fit well. The largest deviations occurred in 2001 and 2003 with residuals of 0.46 feet and -0.42 feet respectively.



Goodness of fit statistics:	
Observations	6.000
DF	1.000
R²	0.997
SSE	0.642
MSE	0.642
RMSE	0.801

Figure 128. Predicted versus actual Change in Storage values for Well 952.2 along with related statistics.

The model has two basic constraints:

- *Average Annual Groundwater Head in Well 952.2* is a good predictor when it is above 2360 feet. The error when it is between 2340 feet and 2360 feet is one foot or less.

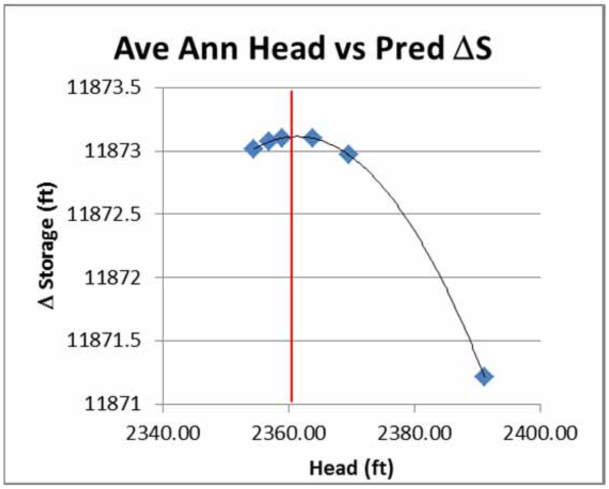


Figure 129. Change in Storage for Well 952.2 based on the modeled expression including only the Average Annual Groundwater Head component.

- *Annual Precipitation at Rain Gage 2963* works well when the variable value is above 7 inches for the year.

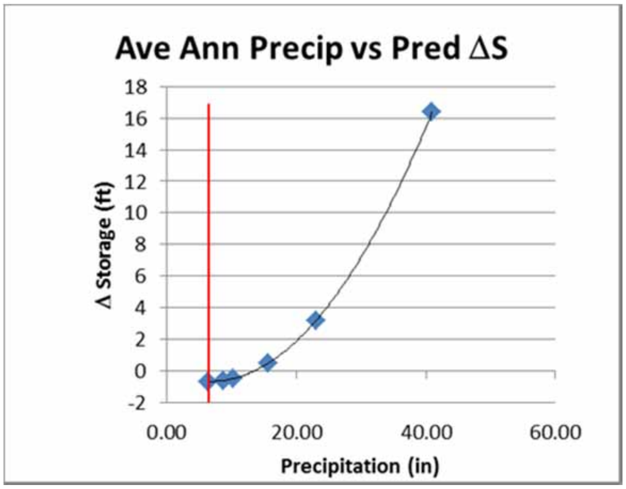


Figure 130. Change in Storage for Well 952.2 based on the modeled expression including only the Average Annual Precipitation @ 2963 component.

The calibrated results look like this:

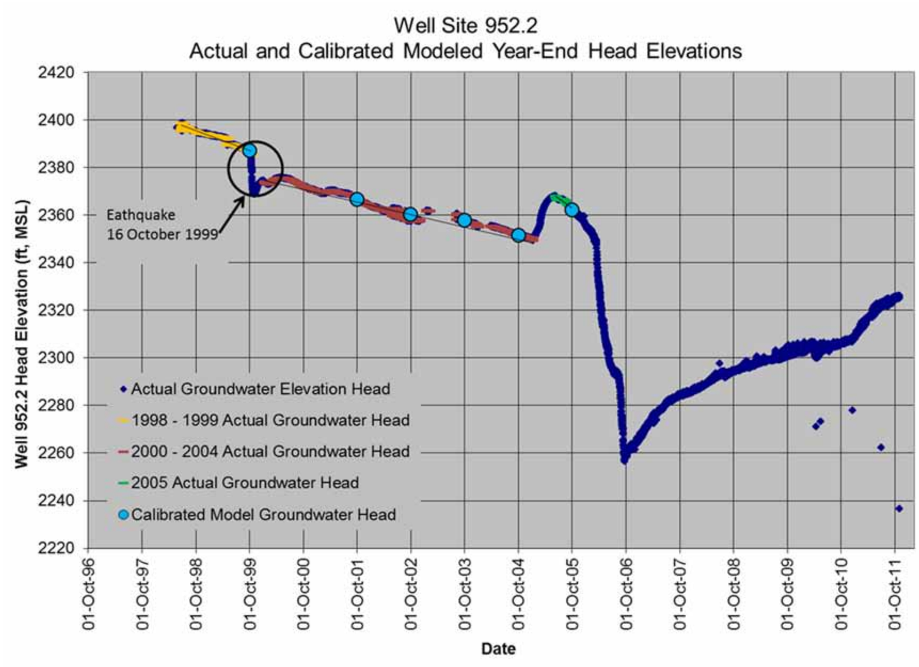


Figure 131. Groundwater hydrograph showing modeled baseline data for Well 952.2.

Model Validation

When trying to predict what the hydrograph will do after the impact period, there will be basically two dependent variables in the relationship, Change in Storage and Average Well Head. There are two relationships as well.

Changes in Groundwater Storage f(Annual Precipitation, Average Annual Head**)**

Changes in Groundwater Storage f(Initial Groundwater Head, Average Annual Head**)**

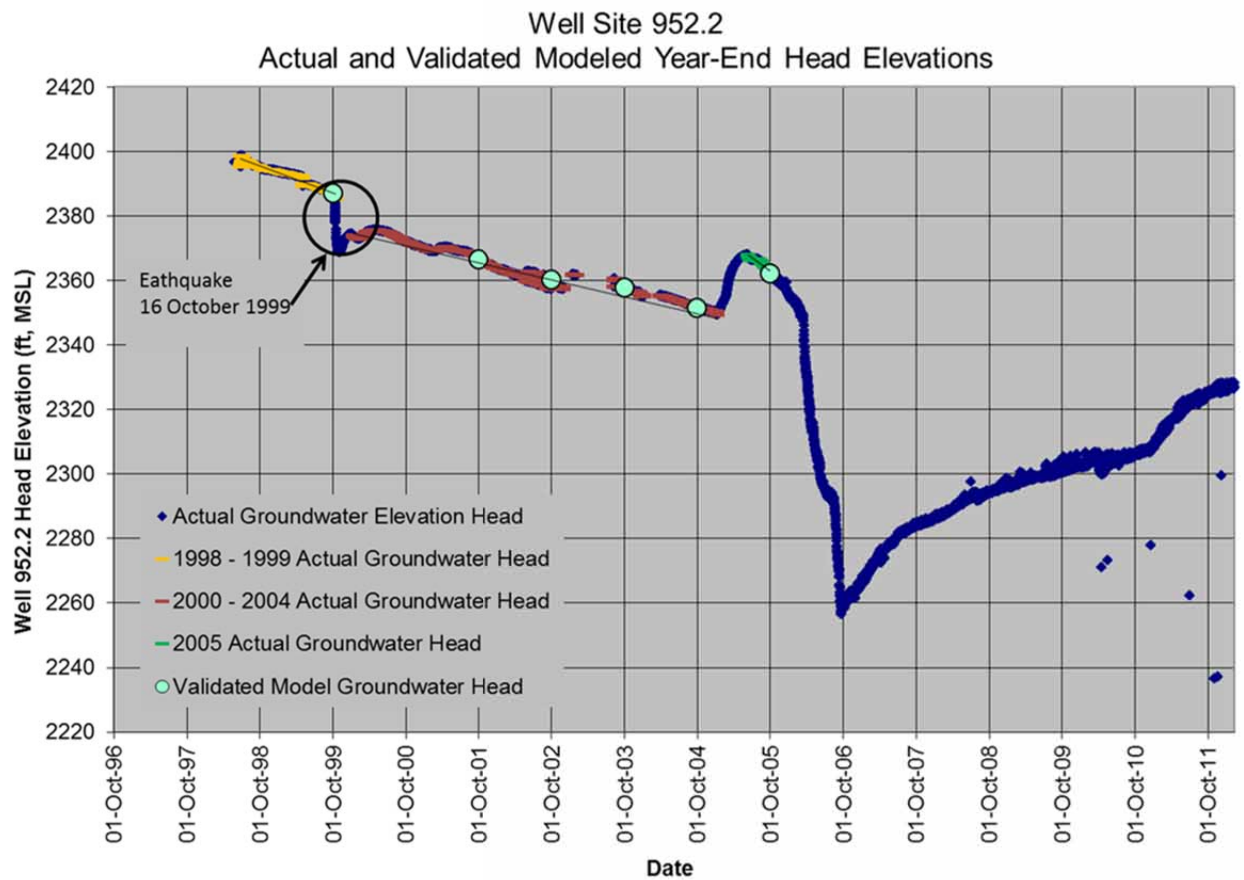
The solution involved varying Average Annual Head until Changes in groundwater storage for both expressions were equal. This was done using Excel solver with a tolerance of 0.005 feet of Storage. Additional constraints included maintaining Average Annual Head between 2340 and 2400 feet.

The model was run from 1999 to 2005 with Average Head, Change in Storage and Year End Groundwater Elevation in Well 952.2 predictive. The Year End Groundwater Elevation for the year 2000 was added manually due to the downward shift created by the earthquake.

The predicted results are shown in the table below in blue text. The red text is not calculated but actual values. Note that the maximum deviation between predicted and actual groundwater head at Well 952.2 occurred in 2007 at approximately 0.1 feet.

Validation Results

Note that here Average Head is also predictive. The results are still very close to the calibration results.



Time Domain		Well 951.1			SB Co Rain Gage	Variable	Regression Based Predictions			Prediction Based on Initial Conditions			Information		
Water Year End Date	Water Year (Oct - Sept)	Actual Year End Head Well 951.1 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Precipitation at 2893 (in)	Predicted Average Head (ft)	Predicted Year End Head	Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)	Δ^2 Storage (Actual-Predict)	Comments
30-Sep-99	1999	2386.99	2391.15	-8.09	10.17	2391.06	2387.05	-8.03	-8.03	-8.03	2387.05	2391.06	-0.06	-0.06	
30-Sep-00	2000	2371.98		-15.01	16.44		2371.98				2371.98				Remove - Eqarthquake
30-Sep-01	2001	2367.13	2369.56	-4.85	15.61	2369.33	2366.67	-5.31	-5.31	-5.31	2366.67	2369.33	0.46	0.46	
30-Sep-02	2002	2360.43	2363.78	-6.70	6.42	2363.51	2360.35	-6.32	-6.32	-6.32	2360.35	2363.51	0.08	-0.38	
30-Sep-03	2003	2357.54	2358.99	-2.89	23.03	2359.12	2357.89	-2.47	-2.47	-2.47	2357.89	2359.12	-0.35	-0.42	
30-Sep-04	2004	2351.50	2354.52	-6.04	8.69	2354.71	2351.53	-6.35	-6.35	-6.35	2351.53	2354.71	-0.03	0.31	
30-Sep-05	2005	2362.23	2356.87	10.73	40.96	2356.87	2362.20	10.66	10.66	10.66	2362.20	2356.87	0.03	0.06	Potentially beginning of impact

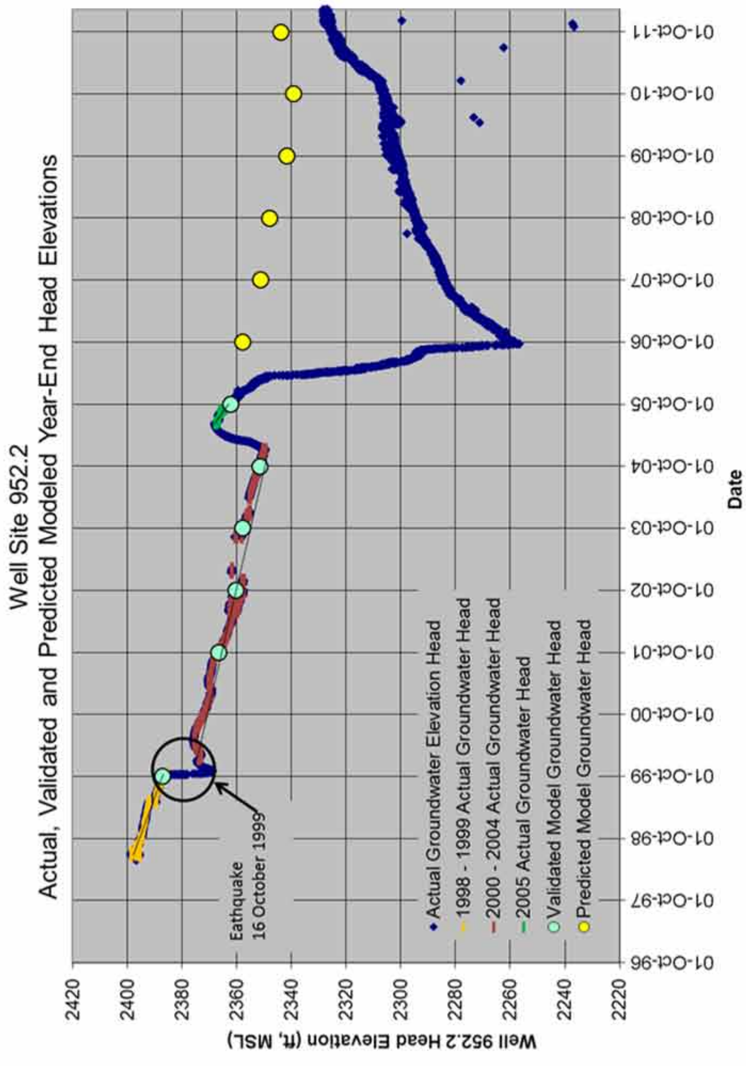
Red text denotes typed and not calculated values

Figure 132. Groundwater hydrograph with modeled and actual baseline data; tabulated and calculated spreadsheet values.

Model Prediction

Now that the model predicted baseline information fairly accurately, the next step was to run it predictively from 2006 through 2011.

Prediction Results



Time Domain		Well 951.1			SB Co Rain Gage	Variable	Regression Based Predictions			Prediction Based on Initial Conditions			Information	
Water Year End Date	Water Year (Oct - Sept)	Actual Year End Head Well 951.1 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Precipitation at 2893 (in)	Predicted Average Head (ft)	Predicted Year End Head	Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)	Δ^2 Storage (Actual-Predict)
30-Sep-99	1999	2386.99	2391.15	-8.09	10.17	2391.06	2387.05	-8.03	-8.03	-8.03	2387.05	2391.06	-0.06	-0.06
30-Sep-00	2000	2371.98		-15.01	16.44		2371.98				2371.98			
30-Sep-01	2001	2367.13	2369.56	-4.85	15.61	2369.33	2366.67	-5.31	-5.31	-5.31	2366.67	2369.33	0.46	0.46
30-Sep-02	2002	2360.43	2363.78	-6.70	6.42	2363.51	2360.35	-6.32	-6.32	-6.32	2360.35	2363.51	0.08	-0.38
30-Sep-03	2003	2357.54	2358.99	-2.89	23.03	2359.12	2357.89	-2.47	-2.47	-2.47	2357.89	2359.12	-0.35	-0.42
30-Sep-04	2004	2351.50	2354.52	-6.04	8.69	2354.71	2351.53	-6.35	-6.35	-6.35	2351.53	2354.71	-0.03	0.31
30-Sep-05	2005	2362.23	2356.87	10.73	40.96	2356.87	2362.20	10.66	10.66	10.66	2362.20	2356.87	0.03	0.06
30-Sep-06	2006	2259.53	2310.88	-102.70	18.04	2359.97	2357.74	-4.46	-4.46	-4.46	2357.74	2359.97	-98.21	-98.24
30-Sep-07	2007	2283.99		24.46	8.51	2354.55	2351.37	-6.37	-6.37	-6.37	2351.37	2354.55	-67.38	30.83
30-Sep-08	2008	2294.18		10.19	21.34	2349.62	2347.87	-3.51	-3.51	-3.51	2347.87	2349.62	-53.69	13.69
30-Sep-09	2009	2300.34		6.17	14.34	2344.84	2341.81	-6.05	-6.05	-6.05	2341.81	2344.84	-41.47	12.22
30-Sep-10	2010	2305.63		5.29	24.56	2340.50	2339.19	-2.62	-2.62	-2.62	2339.19	2340.50	-33.56	7.91
30-Sep-11	2011	2325.22		19.59	35.15	2341.48	2343.77	4.58	4.58	4.58	2343.77	2341.48	-18.55	15.01
30-Sep-12	2012													

Red text denotes typed and not calculated values

Figure 133. Groundwater hydrograph with modeled and actual post-impact data; tabulated and calculated spreadsheet values.

Several inferences can be made from the modeling results. At the least a trend toward recession or recharge is predicted and an actual quantitative value is given for the annual net storage change and ending head in feet. These values are based entirely on a model calibrated to the data set encompassing the years 1999 and 2001 through 2005 and may not be relevant to a future where Average Annual Head in Well 952.2 drops below 2340 feet. Additionally a year end maximum impact can be determined from looking at the predicted head versus the actual head in Well 952.2. This maximum occurred in 2006 (30 September) at a differential of approximately 100 feet with a resolution of 1 year. Comparison with the simple extension of the pre-impact recession to the point of maximum impact yields a similar value. The resolution in this analysis is 12 hours and the maximum impact is interpolated at approximately 103 feet on 23 September 2006.

By the end of the last water year, 30 September 2011, it appears the remaining impact is less than 20 feet. This indicates an overall recovery of about 80 feet from maximum. An attempt has been made to project recovery and determine the number of years to ecological recovery. This was done using the current recovery trend and projecting that trend into the future. For this rather simple analysis the *Predicted Year-End Head in Well 952.2* was compared with the *Actual Year-End Head in Well 952.2* from the point of impact to the last year of full data, 2011. Using an exponential regression of the form:

Y = pr1*Exp(pr2*X)

Where:

Y = Remaining Impact,
X = Time From Start of Recovery in years
pr1, pr2 = Regression parameters

The following expression was generated:

Remaining Impact (ft) = 111.2012*Exp(-0.2946*Δ Time from Start of Recovery (yrs))

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

	Recovery Curve Prediction					
	Based on current recovery rate					
Date	(Oct - Sept)	Start of	Δ Year End	Impact -	Impact -	Year End
9/30/2006	2006	0.49	-98.21	98.21		
9/30/2007	2007	1.49	-67.38	67.38		
9/30/2008	2008	2.49	-53.69	53.69		
9/30/2009	2009	3.49	-41.47	41.47		
9/30/2010	2010	4.49	-33.56	33.56		
9/30/2011	2011	5.49	-18.55	18.55		2325.22
9/30/2012	2012	6.49			16.44	2327.33
9/30/2013	2013	7.49			12.25	2331.53
9/30/2014	2014	8.49			9.12	2334.65
9/30/2015	2015	9.49			6.79	2336.98
9/30/2016	2016	10.49			5.06	2338.71
9/30/2017	2017	11.49			3.77	2340.00
9/30/2018	2018	12.49			2.81	2340.96
9/30/2019	2019	13.49			2.09	2341.68
9/30/2020	2020	14.49			1.56	2342.21

Goodness of fit statistics:	
Observations	6.000
DF	4.000
R^2	0.987
SSE	53.209
MSE	13.302
RMSE	3.647
Iterations	12.000

The analysis yields an ecological recovery time of approximately 9 years from the end of 2011 or to the end of year 2020. By this point it is predicted that recovery will be within 2 feet.

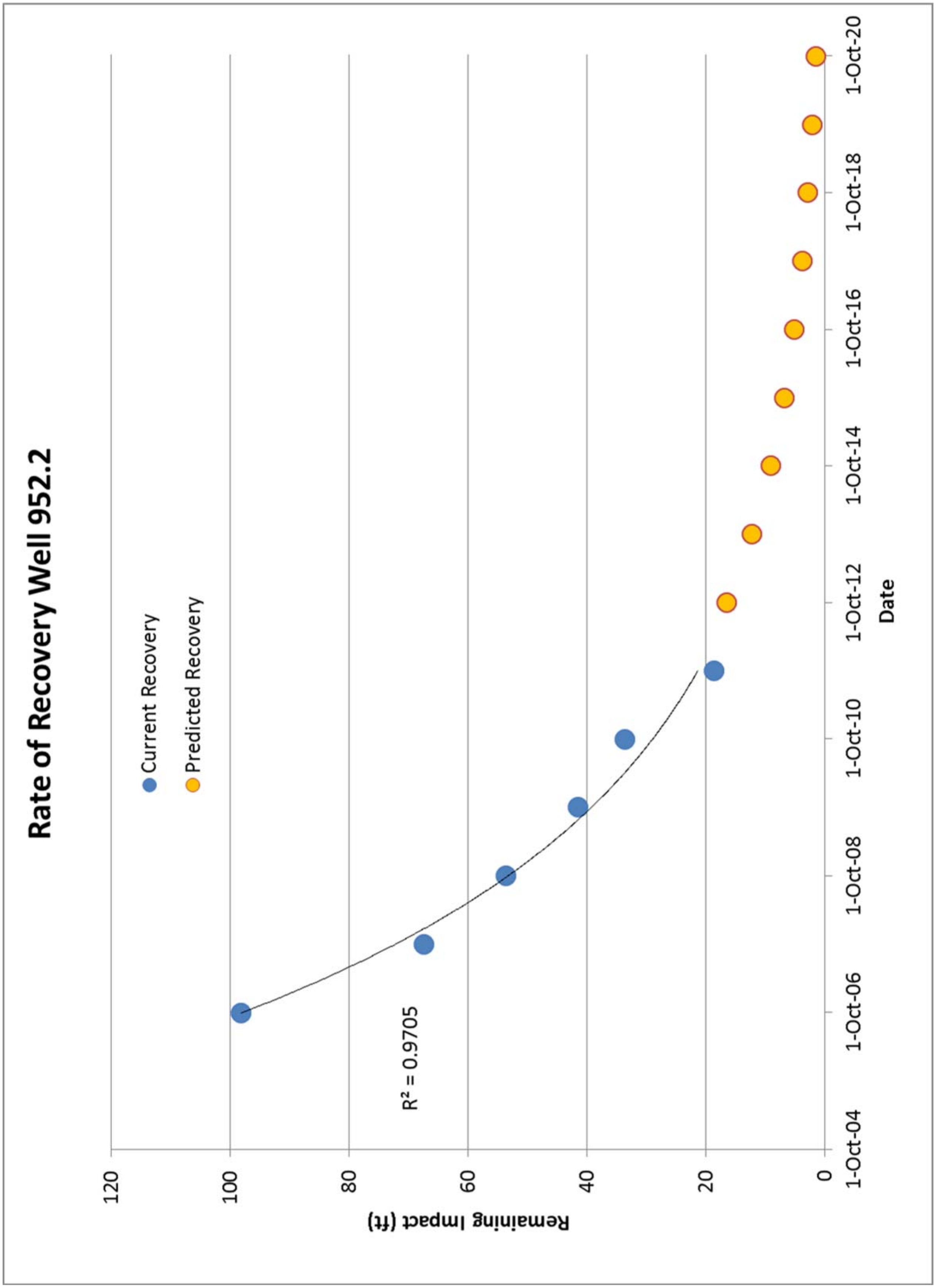


Figure 134. Groundwater recovery prediction for Well 952.2 using the difference between modeled and actual data.

It is worth making a few comments about the analytical model itself. The model is intended to be a tool for impact prediction but is not definitive and is not a substitute for technical knowledge and experience and use of good judgment. The model takes a relatively complicated system and reduces it into a few variables with apparent relationships. The analysis is deterministic, meaning it attempts to describe the physical setting in terms of real variables but also set constraints on the values of those variables and their behavior.

The model has both advantages and limitations, most of which have been discussed in the text of this analysis or listed at the back end of the other analyses and so will not be repeated again. These factors will have to be considered as it will be up to the user to evaluate these at the time of use to determine if the analysis still has validity in the physical world.

Badger Canyon

Background Information

The borehole for the double completion monitoring well representing the impacted groundwater aquifer around Badger Canyon is actually located on the spur ridge which travels south from Marshall Peak between Badger Canyon to the west and Sycamore Canyon to the east. Two other wells located in the canyon bottom closer to the mouth. These wells were affected when the TBM moved through but have since recovered. Therefore the only monitored aquifer currently displaying construction related impacts is that in the vicinity of Well 951.

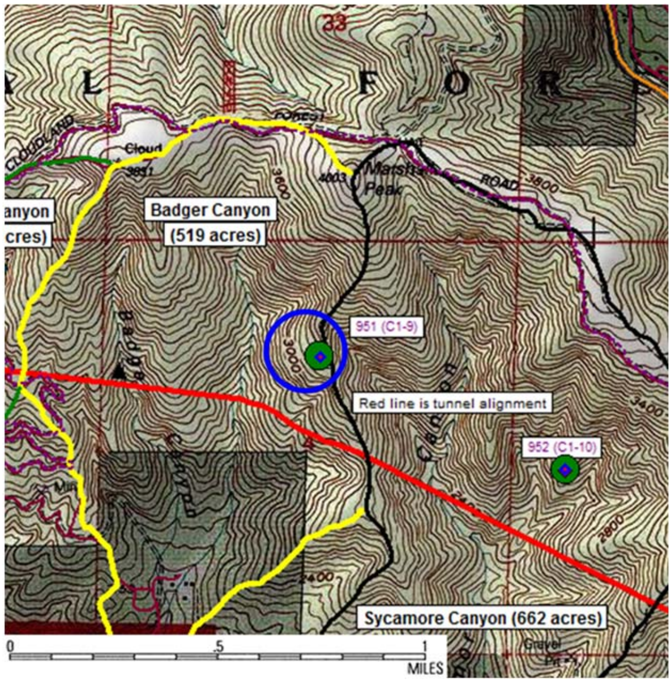


Figure 135. Map showing location of Well 951 in Badger Canyon.

Lithologically this area is similar to Sycamore Canyon with intervals of Mesozoic gneiss displaced by marble. The borehole is located at approximately 3200 feet with the upper completion transducer located approximately 900 feet below that. The lower completion transducer is located at an elevation of approximately 1800 feet. It may well be that the wells have penetrated the marble layers and extend into the gneiss below. At any rate, it appears that there exists some type of shielding of surface waters from the deeper groundwater, for although the deeper groundwater in the vicinity of Badger Canyon experienced affects from tunnel construction, the surface water system appears to have remained unaltered.

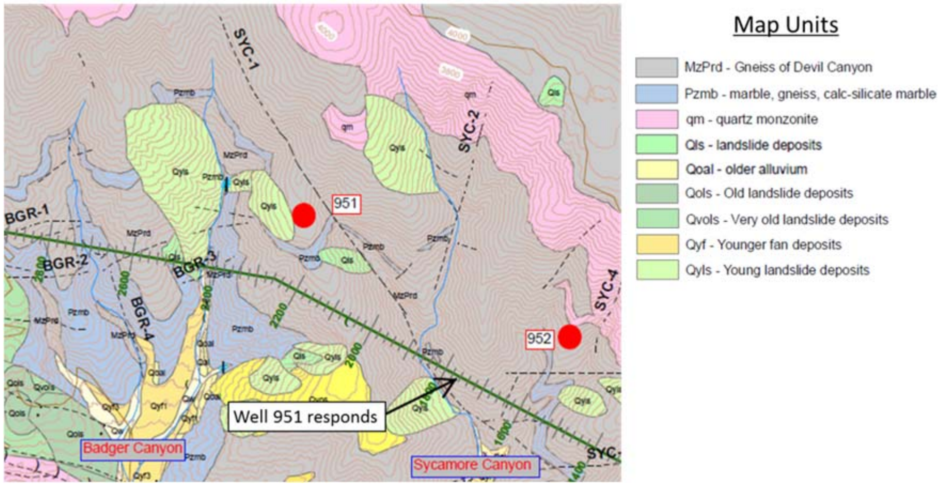


Figure 136. Geology Map showing Badger Canyon area.

This well is approximately 1000 feet up ridge from the tunnel alignment; but more importantly it is proximal to the Sycamore-1 fault. The TBM was mining sub-parallel to this fault and through difficult ground in January of 2007 when the groundwater in the vicinity of Well 951 (at that time 2700 feet to the west of the TBM) was initially affected. Both upper and lower completions responded with a steep drop in head.

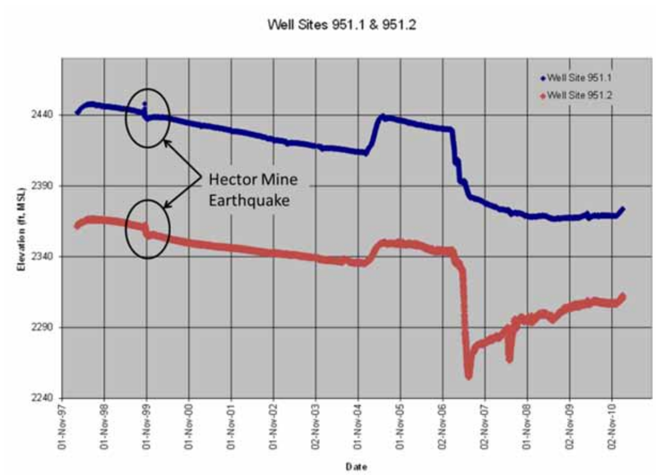


Figure 137. Comparative groundwater hydrograph for upper and lower intervals in Well 951.

It is likely both completions are in parts of the same aquifer as they appear to have similar characteristics, especially prior to January of 2007. The upper completion is in a slightly more reactive area as response to recharge is a bit quicker and intensified and the typical recession has a slightly steeper slope (5.5 and 3.5 feet per year for upper and lower respectively). Both wells reacted similarly to the Hector Mine Earthquake in October of 1999 with an initial pressure spike (more pronounced in the upper section) followed by a drop. After the January 2007 impact however, the lower part of the aquifer started to rebound about 5 months later whereas the upper portion continued to drop over the course of the next 2 years. This sustained decline may have been the result of the pressure loss in the lower area and the creation of an increased gradient between the two areas. At some point it may be that sufficient recovery occurred for the effects to propagate upward and allow recovery to finally begin in the area sampled by Well 951.1. Interestingly the decline in this upper completion levels off in November of 2008 which is several months after the completion of mining.

The low point is reached in June of 2009 after the installation of the steel liner and all groundwater ceases flowing into the tunnel.

Well 951.1 Recovery Analysis

The ultimate objective of this analysis entails the production of an analytical model which will predict a natural non-impacted groundwater head in Well 951.1 after the time when impacts have occurred to groundwater in this area. This information can then be used to determine a number of things such as recovery progression, current recovery status and predicted time to ecological recovery. It is the goal that this model be deterministic and replicates the physical characteristics of the system using real data. The use of the data relationships in the analysis must support physical expectations. For example a relationship between groundwater head and annual precipitation should not be inversely proportional as increasing precipitation should not cause the groundwater to decline in the aquifer.

To accomplish the objective, the concept of conservation of matter is utilized using the aquifer in the vicinity of the transducer as a control volume. Following this concept, groundwater flux into the system must equal groundwater flux out of the system or the amount of groundwater stored within this system (or volume) will change. This is basically the water budget approach and utilizes change in groundwater storage as a dependent variable with inflows to the system and outflows from the system as two other groups of independent variables.

The crux of the task requires obtaining variables which describe inputs and extractions to the system such that the system responds appropriately. The variables must be developed from real, accessible and quantifiable data sets in order to be used predictively. For instance if a variable for flow leaving the system in the form of surface water expression uses stream flow as a proxy then this may only be a viable variable as long as flows continue to be measured in the manner they were during model construction.

In order to develop and validate a model, adequate baseline data must be available. This is especially true of regression based models as the extremes within the data set can skew the model. The smaller the data set, the more emphasis the extremes have on the outcome. At the same time the range of the natural cycles need to be included in the sample or the model may be invalid for certain conditions which are outside the initial calibration phase. For example assume precipitation is used as a variable in model development. If the calibration data set includes only lower values of precipitation then the predictive behavior of the model may be very inaccurate with high value precipitation inputs (especially during El Niño years). This is especially true of non-linear relationships.

The baseline data set used to develop and calibrate the predictive model for Well 951.1 spans the water years from 1998 to 2006. However due to anomalous pressure readings resulting from the Hector Mine Earthquake the year 2000 has been removed. Furthermore tunneling effects to groundwater in this area occurred in 2007 so this marks the start of the predictive period.

Storage

As inferred by the section title, the upper interval in the groundwater monitoring Well 951 (Well 951.1) is the dependent variable representing change in storage. For simplicity, changes in well head with time or declination were taken to coincide with precipitation year or October to September. In reality, there appears to be approximately a 3 month lag between precipitation and groundwater recharge in this area. However with generally no significant rainfall after June the system has completed its response to the input and the effects of the lag are already incorporated into the annual recession. Change in storage is a net effects variable and does not incorporate a minimum or maximum change for the year. A positive value for change in storage is an increase in groundwater head.

System Discharge

Natural outflows from the control volume usually come in the form of discharge to surface water sites and/or discharge to down-gradient groundwater sites or sinks. In this case there are no known surface water sites within the project area which are associated with the groundwater in the vicinity of Well 951.1. The storage does decline with time, so there is flow leaving the area at least in the form of flux to other groundwater. There may also be flow to other off project down canyon surface water sources, but this is unconfirmed. Therefore a proxy has been established for groundwater flux leaving the system, *Average Annual Groundwater Head Well 951.1*. This variable has been used before in other models and describes the rate at which the head declines based on the current head in the well. Often times the rate of change decreases with decreasing overall head. In this case that change is a fairly poor predictor by itself, but improves the model accuracy when used in conjunction with the recharge variables.

System Recharge

The system behavior resulting from recharge is more complex. After substantial analyses, it became apparent that recharge is only partially dependent on infiltration of annual precipitation. It also appeared that another component tied more distally to precipitation was affecting storage during the average recession year. The variable that appears to represent this recharge component is *Cumulative Departure from the Average Annual Precipitation*. The reduction of precipitation to this form better characterizes hydrologic trends over time versus direct annual precipitation which can display large variations from one year to the next. As many groundwater systems tend to respond to larger resolution changes because of the indirect connectivity to precipitation sources, a term that incorporates a trend becomes more applicable to recharge comparison. The San Bernardino County rain gage 2893 located at Cal State San Bernardino displays the best overall correlation with groundwater behavior at this site.

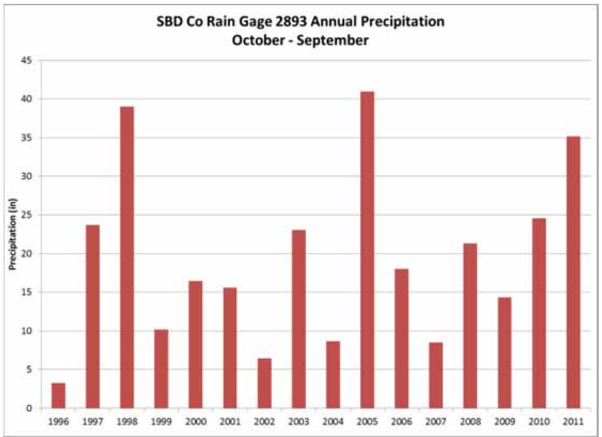


Figure 138. Annual Precipitation at Cal State San Bernardino.

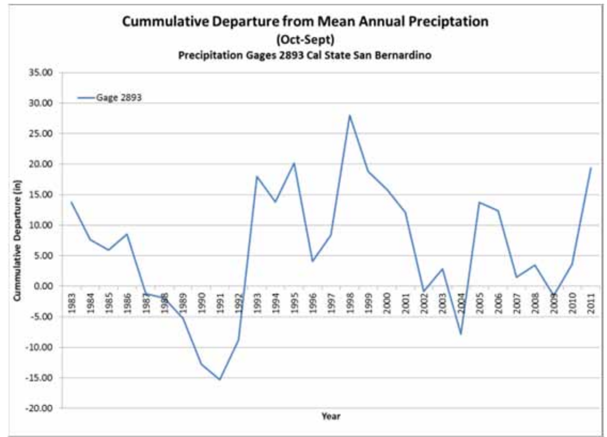


Figure 139. Cumulative Departure from Mean Annual Precipitation at Cal State San Bernardino.

Analysis shows that when the Annual Precipitation at Rain Gage 2893 is below 25 inches, recessional behavior generally dominates the hydrograph and annual storage changes are tied to the cumulative departure variable. If precipitation at this gage exceeds the 25 inches, the opposite appears to be true and that year's change in storage is at least partially tied to direct precipitation from that year.

Analytical Model Construction and Calibration

Conceptually flow leaving the control volume generally governs, that is groundwater flux leaving the system usually exceeds flux entering. Groundwater flow in during this time has a heavier long-term precipitation bias which is generally decreasing. Outflow quantity is dependent on overall groundwater head and decreases with decreasing heads but still usually exceeds supply.

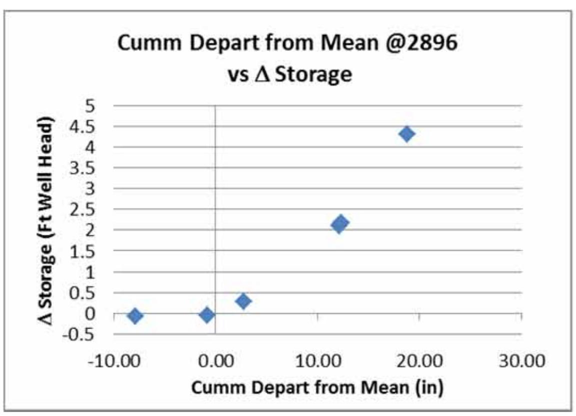


Figure 140. Change in Storage for Well 951.1 based on the modeled expression including only the Cumulative Departure from the Mean Annual Precipitation component (normal precipitation years).

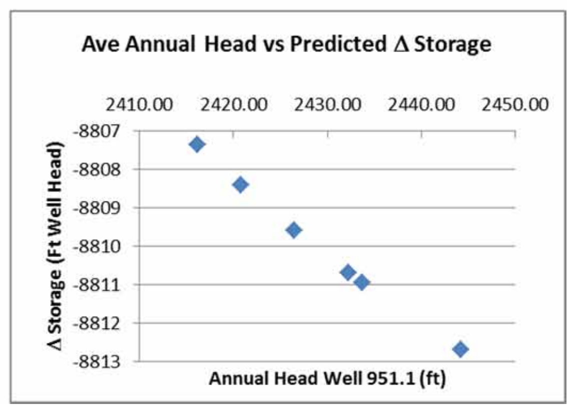


Figure 141. Change in Storage for Well 951.1 based on the modeled expression including only the Annual Groundwater Head component. (normal precipitation years).

If *Cumulative Departure from Mean Annual Precipitation* were to drop much below -10 inches, the relationship with this variable ceases to be valid, as additional drop would cause an increase in storage changes (which is not realistic). In this case a default value set the change in storage to the average recession value over the 2001 – 2004 time period.

During years of high annual precipitation the system changes some. At this time recharge from local precipitation drive storage changes and causes the hydrograph to rebound. Therefore in this case storage changes as a function of precipitation (which is probably more local and in terms of increased groundwater flux in), as well as groundwater moving in and feeds to down gradient resources.

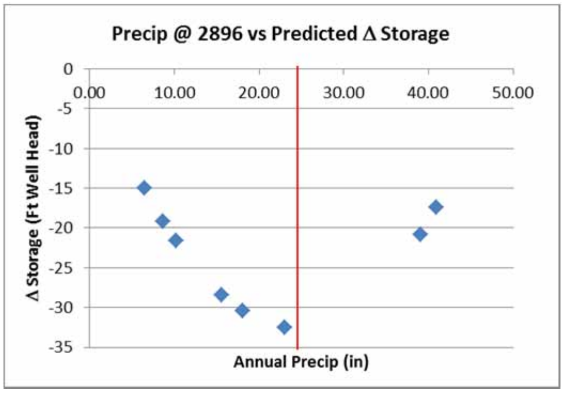


Figure 142. Change in Storage for Well 951.1 based on the modeled expression including only the Annual Precipitation component (high precipitation year).

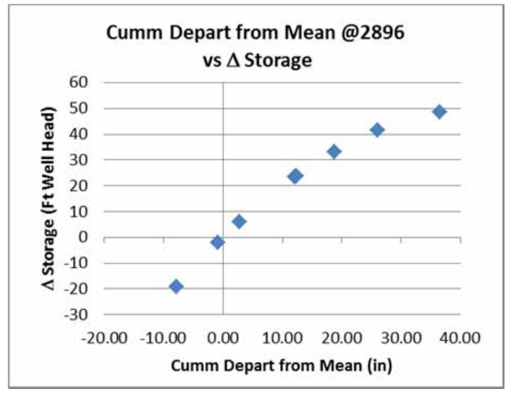


Figure 143. Change in Storage for Well 951.1 based on the modeled expression including only the Cumulative Departure from the Mean Annual Precipitation component (high precipitation year).

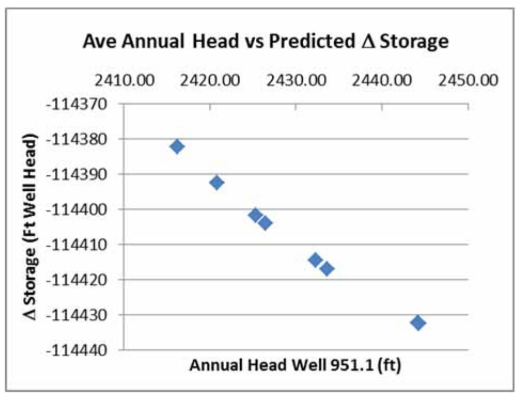


Figure 144. Change in Storage for Well 951.1 based on the modeled expression including only the Average Annual Groundwater Head component (high precipitation year).

The conceptual model leads to three analytical scenarios. When precipitation at SBD Co Rain Gage 2893 is greater than 25 inches then recharge the equation governs. The Recharge Equation was calibrated using the entire data set from 1998 to 2006 (excluding 2000 - the year of the earthquake which caused a downward shift in well head) and consists of a polynomial regression with

$$\text{Change in Storage } (\Delta S) = f\,(\text{precip, cum. dep., ave ann. Head})$$

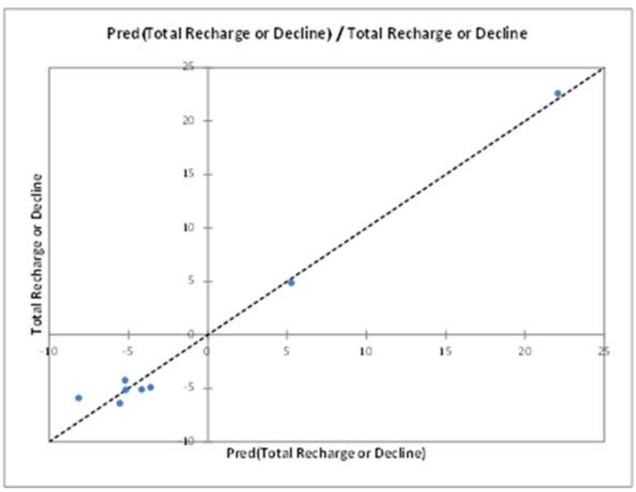
The analytical expression reduces to:

ΔS = 114415.2818 - 2.6817**Annual Precipitation at 2893* - 92.3684**Average Annual Head, Well 951.1* + 2.2387**Cumulative Departure from Mean 2893* + 5.5054E-02*(*Annual Precipitation at 2893*)^2 + 1.8636E-02*(*Average Annual Head, Well 951.1*)^2 - 2.4884E-02* (*Cumulative Departure from Mean 2893*)^2

Where:

ΔS = Change in storage at Well 951.1
ΔS & Average Annual Head are in feet
Annual Precipitation at 2893 and Cumulative Departure is in inches

The calibrated model fits the calibration data very well. The largest deviations occurred in 2003 and 2006 with residuals of -1.3 feet and 2.2 feet respectively. Both of these are during years in which rebound does not occur on the hydrograph. The recharge equation would not be used to predict these years. The two years that would be predicted by this equation, 1998 and 2005, have residuals of -0.4 and 0.5 respectively.



Goodness of fit statistics:	
Observations	8.000
DF	1.000
R^2	0.986
SSE	9.606
MSE	9.606
RMSE	3.099

Figure 145. Predicted versus actual Change in Storage values for Well 951.1 along with related statistics (high precipitation years).

The second scenario occurs when precipitation at SBD Co Rain Gage 2893 is less than 25 inches but *Cumulative Departure from Mean 2893* is greater than -10 inches. In this case an expression (the Recession Equation) that generally predicts recession of the groundwater head over time appears to best fit the baseline data. The Recession Equation was calibrated using only declining hydrograph data corresponding to the years from 1999 to 2006 (excluding 2000 for the earthquake and 2005 as it was a recharge year). Again this expression is a 2nd order polynomial regression with:

$$\Delta S = f\text{ (cum. dep., ave ann. Head)}$$

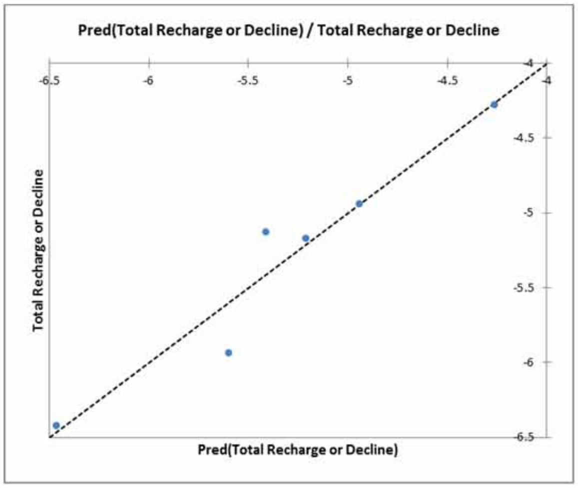
The analytical expression for the Recession Equation is:

$$\Delta S = 8803.1760 - 7.0597 * \textit{Average Annual Head, Well 951.1} + 0.07461 * \textit{Cumulative Departure from Mean 2893} + 1.4132\text{E-}03 * (\textit{Average Annual Head, Well 951.1})^2 + 8.2326\text{E-}03 * (\textit{Cumulative Departure from Mean 2893})^2$$

Where:

ΔS = Change in storage at Well 951.1
ΔS & Average Annual Head are in feet
Cumulative Departure is in inches

With this expression the calibrated equation fits the data fairly well, especially at the ends. The largest deviations occur in the center of the ΔS range with the years 2001 and 2006. The residuals for each are both in the neighborhood of 0.3 with 2001 predicted 0.3 feet higher than measured and 2006 predicted low.



Goodness of fit statistics:	
Observations	6.000
DF	1.000
R^2	0.931
SSE	0.197
MSE	0.197
RMSE	0.444

Figure 146. Predicted versus actual Change in Storage values for Well 951.1 along with related statistics (normal precipitation years).

The final scenario is the extreme of the first. It occurs when *Annual Precipitation at 2893* is less than 25 inches and *Cumulative Departure from Mean 2893* is less than -10 inches. This is a very dry period. During this time inputs to the system are low. The default value for this is a storage change of -5.3 feet per year and was derived from the average slope of the hydrograph during the 2001 through 2003years.

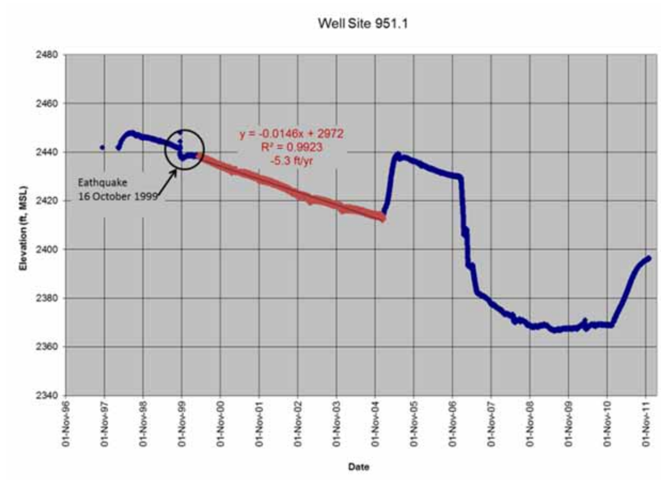


Figure 147. Groundwater hydrograph for Well 951.1 displaying default recession (steepest for baseline period) for very low precipitation periods.

The calibrated model looks like this:

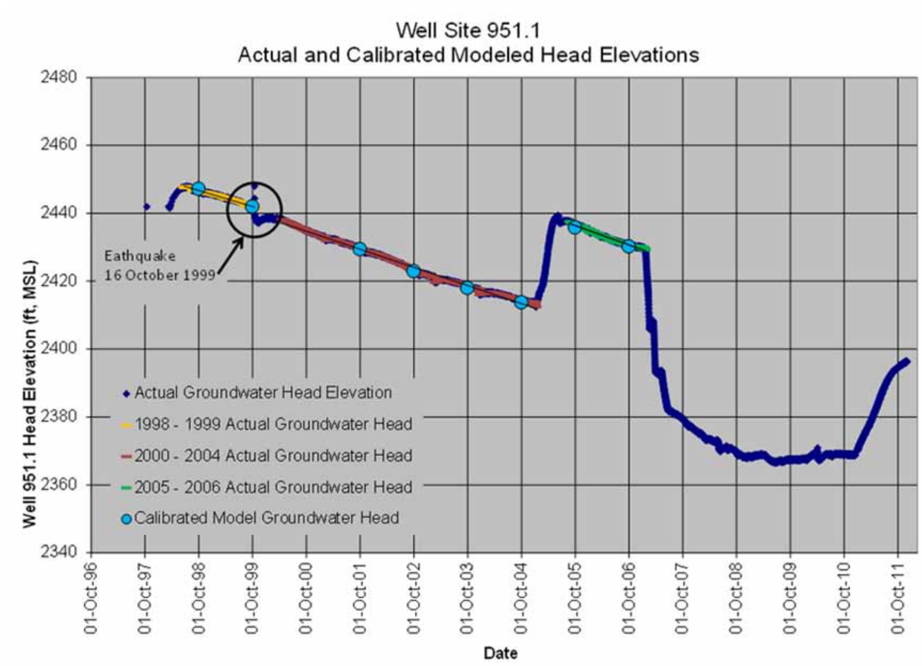


Figure 148. Groundwater hydrograph showing modeled baseline data for Well 951.1.

Validation Results

When trying to predict what the hydrograph will do after the impact period there will be two dependent variables in the relationship, *Change in Storage at Well 951.1* and *Average Annual Head Well 951.1*, as well as two independent variables, *Cumulative Departure from Mean Annual Precipitation at 2893* and *Annual Precipitation at 2893.* Both of the independent variables relay on the same precipitation data downloaded from the San Bernardino County website (SB Co). In addition to the variables, there are two relationships as well.

Changes in Groundwater Storage f(Cum Precip, Average Head, maybe Precip**)**

Changes in Groundwater Storage f(Initial Groundwater Head, Average Head**)**

The solution varies *Average Annual Head Well 951.1* until *Change in Storage at Well 951.1* for both expressions are equal. This is done using solver in Excel with a tolerance of 0.005 ft of Change in Storage and subject to the following constraints:

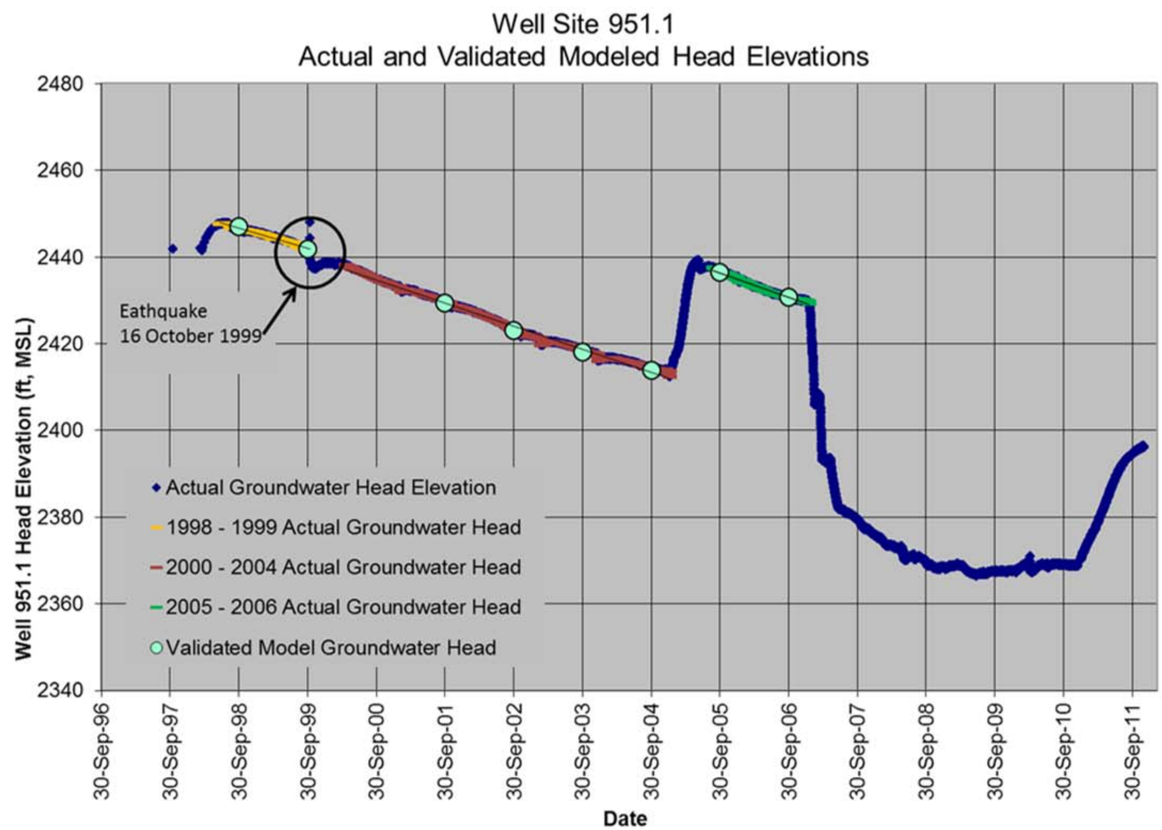
$$2400 \text{ feet} < \text{Average Head} < 2500 \text{ feet}$$

The model was run from 1998 to 2006 with Average Head, Change in Storage and Year End Groundwater Elevation in Well 951.1 predictive. The Year End Groundwater Elevation for the year 2000 was added manually due to the downward shift created by the earthquake.

The predicted results are shown in the table below. The blue text identifies the Recharge Equation value used in the model. The brown text displays the Recession Equation value used. Cumulative Precipitation has not yet fallen below -10 inches, so the default value for Change in storage has not emerged to date. The red text is not calculated but actual values. The average deviation between predicted and actual groundwater head at Well 952.1 during the baseline period is approximately ± 0.2 feet.

Validation Results

Note that here Average Head is also predictive. The results are still very close to the calibration results.



Time Domain	Well 951.1			SB Co Rain Gage 2893		Adjusted Variable	Regression Based Predictions				Prediction Based on Initial Conditions			Information
Water Year (Oct - Sept)	Actual Year End Head Well 951.1 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Annual Precipitation at 2893 (in)	Cummulative Departure from Mean (in)	Predicted Average Head (ft)	Predicted Year End Head	Predicted Decline - Recession Equation (ft)	Predicted Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)
1998	2446.77	2444.35	4.85	39.02	28.02	2444.47	2447.03	-1.02	5.11	5.11	5.11	2447.03	2444.47	-0.26
1999	2441.60	2444.18	-5.17	10.17	18.81	2444.41	2441.79	-5.24	-5.45	-5.24	-5.24	2441.79	2444.41	-0.19
2000	2434.85		-6.75	16.44	15.87		2434.85					2434.85		
2001	2429.72	2432.29	-5.13	15.61	12.11	2432.16	2429.46	-5.39	-3.94	-5.39	-5.39	2429.46	2432.16	0.26
2002	2423.30	2426.51	-6.42	6.42	-0.85	2426.26	2423.05	-6.41	-5.04	-6.41	-6.41	2423.05	2426.26	0.25
2003	2418.36	2420.83	-4.94	23.03	2.80	2420.60	2418.16	-4.89	-3.12	-4.89	-4.89	2418.16	2420.60	0.20
2004	2414.08	2416.22	-4.28	8.69	-7.88	2416.05	2413.94	-4.22	-4.81	-4.22	-4.22	2413.94	2416.05	0.14
2005	2436.66	2425.37	22.58	40.96	13.70	2425.17	2436.41	-3.57	22.47	22.47	22.47	2436.41	2425.17	0.25
2006	2430.72	2433.69	-5.94	18.04	12.36	2433.61	2430.82	-5.58	-8.00	-5.58	-5.58	2430.82	2433.61	-0.10

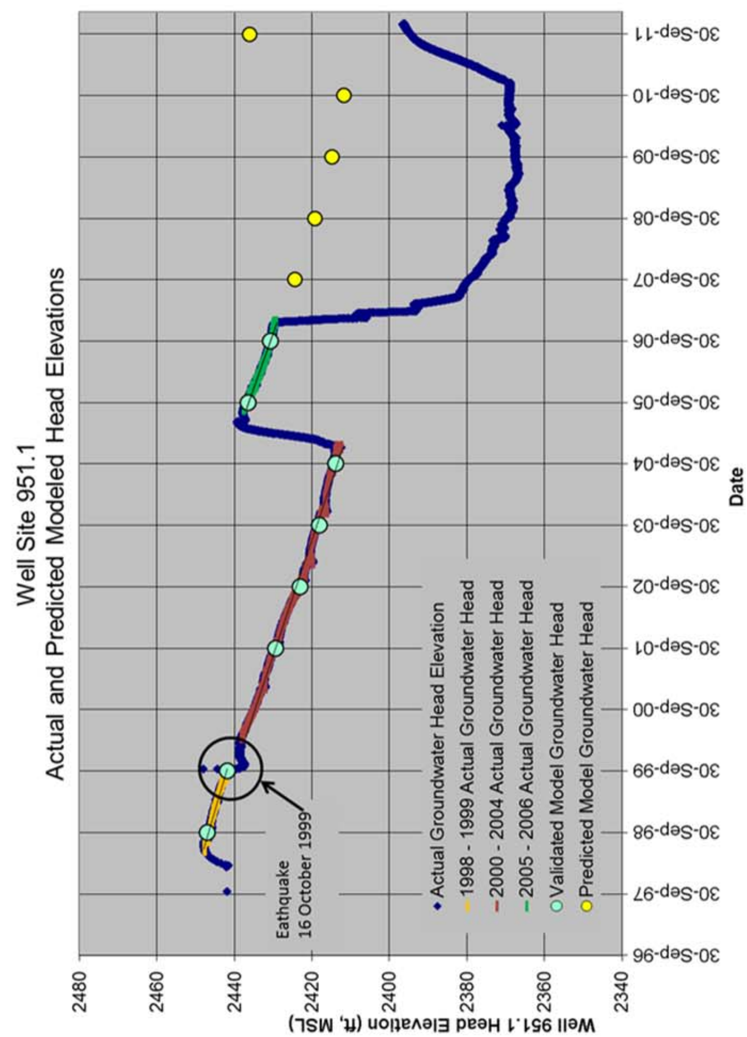
Red text denotes typed and not calculated values

Figure 149. Groundwater hydrograph with modeled and actual baseline data; tabulated and calculated spreadsheet values.

Model Prediction

Now that the model predicted baseline information fairly accurately, the next step was to run it predictively from 2006 through 2011.

Prediction Results



Time Domain	Well 951.1			SB Co Rain Gage 2893		Adjusted Variable	Regression Based Predictions				Prediction Based on Initial Conditions			Information
Water Year (Oct - Sept)	Actual Year End Head Well 951.1 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Annual Precipitation at 2893 (in)	Cummulative Departure from Mean (in)	Predicted Average Head (ft)	Predicted Year End Head	Predicted Decline - Recession Equation (ft)	Predicted Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)
1998	2446.77	2444.35	4.85	39.02	28.02	2444.47	2447.03	-1.02	5.11	5.11	5.11	2447.03	2444.47	-0.26
1999	2441.60	2444.18	-5.17	10.17	18.81	2444.41	2441.79	-5.24	-5.45	-5.24	-5.24	2441.79	2444.41	-0.19
2000	2434.85		-6.75	16.44	15.87		2434.85					2434.85		
2001	2429.72	2432.29	-5.13	15.61	12.11	2432.16	2429.46	-5.39	-3.94	-5.39	-5.39	2429.46	2432.16	0.26
2002	2423.30	2426.51	-6.42	6.42	-0.85	2426.26	2423.05	-6.41	-5.04	-6.41	-6.41	2423.05	2426.26	0.25
2003	2418.36	2420.83	-4.94	23.03	2.80	2420.60	2418.16	-4.89	-3.12	-4.89	-4.89	2418.16	2420.60	0.20
2004	2414.08	2416.22	-4.28	8.69	-7.88	2416.05	2413.94	-4.22	-4.81	-4.22	-4.22	2413.94	2416.05	0.14
2005	2436.66	2425.37	22.58	40.96	13.70	2425.17	2436.41	-3.57	22.47	22.47	22.47	2436.41	2425.17	0.25
2006	2430.72	2433.69	-5.94	18.04	12.36	2433.61	2430.82	-5.58	-8.00	-5.58	-5.58	2430.82	2433.61	-0.10
2007	2379.44		-51.28	8.51	1.49	2427.58	2424.33	-6.49	-6.24	-6.49	-6.49	2424.33	2427.58	-44.89
2008	2369.84		-9.61	21.34	3.46	2421.80	2419.26	-5.07	-3.88	-5.07	-5.07	2419.26	2421.80	-49.43
2009	2367.38		-2.46	14.34	-1.58	2417.03	2414.80	-4.47	0.54	-4.47	-4.47	2414.80	2417.03	-47.42
2010	2368.96		1.58	24.56	3.60	2413.24	2411.69	-3.11	15.27	-3.11	-3.11	2411.69	2413.24	-42.73
2011	2394.47		25.51	35.15	19.38	2423.86	2436.04	-1.33	24.36	24.36	24.35	2436.04	2423.86	-41.57
2012														

Red text denotes typed and not calculated values

Figure 150. Groundwater hydrograph with modeled and actual post-impact data; tabulated and calculated spreadsheet values.

Several inferences can be made from the modeled predictions. The model indicates that a normal recession pattern would have developed after the 2005 recharge followed by another recharge in 2011. This is similar to what has been seen in other un-impacted wells within the project area. The resolution of this data is one year and therefore shows the results on 30 September of each year. The model results also indicate a maximum impact of 50 feet occurring in 2008. The current rate of rebound or recovery can also be assessed by comparing actual and modeled data and indicates that groundwater head has been slow to rebound in the vicinity of the monitoring well. By the end of 2011 only eight feet of recovery has occurred. This may be a result of the impact to the lower portion of the aquifer (which will be described in the analysis for Well 951.2) similar to the effects of Well 954 on Arrowhead East in Little Sand Canyon. Once the lower aquifer has had enough recovery, perhaps the upper aquifer recovery will proceed at a quicker pace.

The anomalously slow recovery makes the attempt at projecting recovery into the future somewhat dubious. Still the attempt has been made to project recovery and determine the number of years to ecological recovery. Based on the minimal data available, the recovery trend can be looked at as either linear or exponential. Either is equally applicable to the data having an R^2 of 0.95. The linear data projects the minimum time to ecological recovery, while the other shows recovery decades away. For both analyses the *Predicted Year-End Head in Well 952.2* was compared with the *Actual Year-End Head in Well 952.2* from the point of impact to the last year of full data, 2011. The linear expression was:

Remaining Impact (ft) = 54.3084 - 2.8265*Δ Time from Start of Recovery (yrs)

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

The exponential regression is of the form:

Y = pr1*Exp(pr2*X)

Where:

Y = Remaining Impact,
X = Time From Start of Recovery in years
pr1, pr2 = Regression parameters

The following expression was generated:

Remaining Impact (ft) = 111.2012*Exp(-0.2946*Δ Time from Start of Recovery (yrs))

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

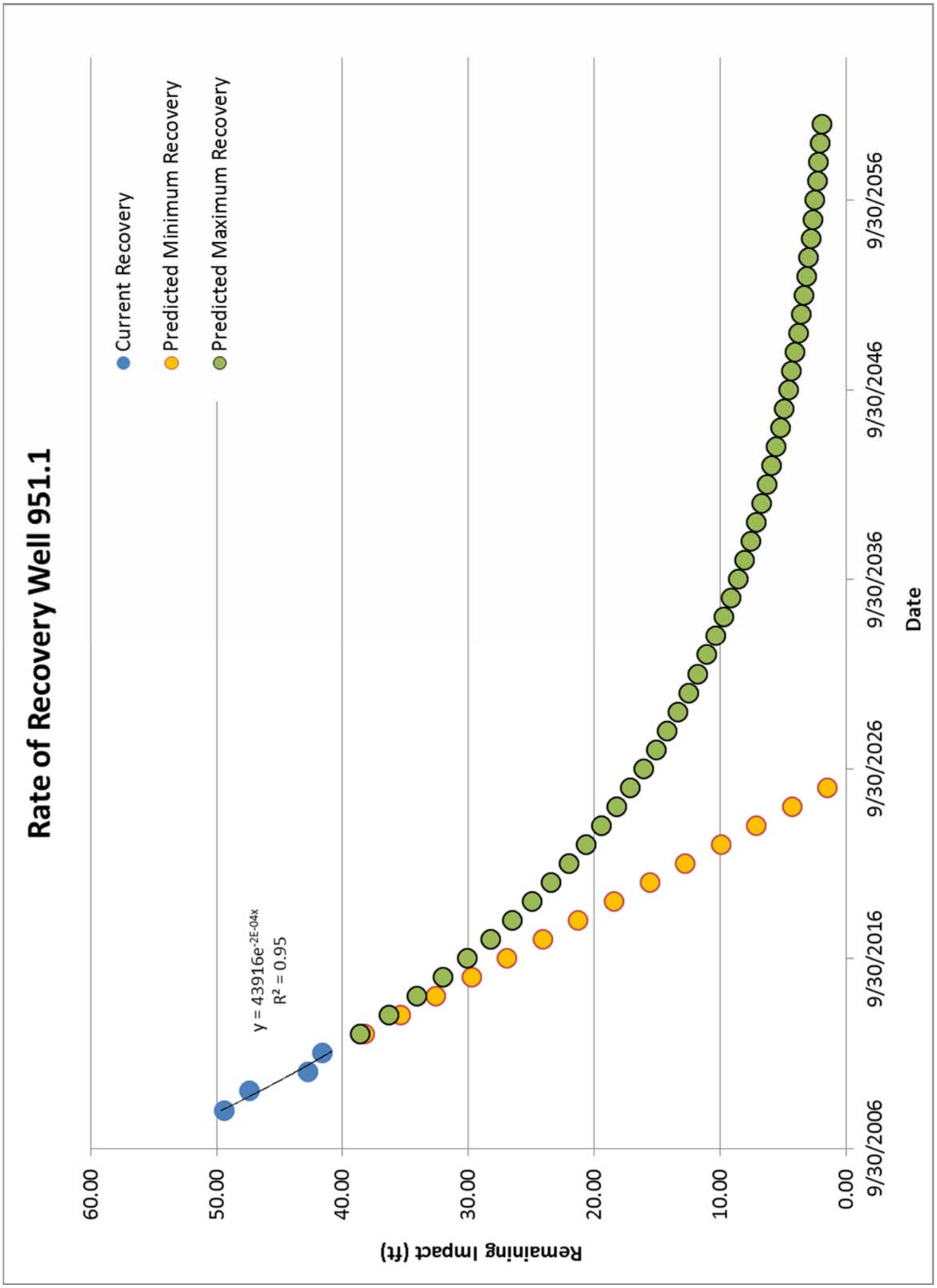


Figure 151. Groundwater recovery prediction for Well 951.1 using the difference between modeled and actual data.

The subsequent analyses indicate that ecological recovery could occur sometime 2026 and 2060. These analyses will have to be re-visited in the ensuing years as the lower aquifer recovers and presumably the upper one increases its rate of recovery.

Well 951.2Recovery Analysis

The lower piezometer in Well 951 displays similar behavior to the upper, but is separated by a vertical distance of 400 feet and therefore may have different influences. The upper aquifer (or upper portion of the same aquifer) appears to respond to stress in the lower. When the lower aquifer was affected by tunnel construction, the gradient produced between the two piezometers appeared to create a response in the upper. However even as the lower aquifer started to rebound or recover from tunnel effects, the upper took many months to initiate recovery and it is occurring at a much slower rate. It may be that some vertical permeability differences exist causing the delayed or attenuated response above. Therefore when analyzing the lower aquifer for recovery, the conceptual model is similar to the upper aquifer, but the variables and their constraints may be somewhat different.

Storage

The head in Well 951.2 is the target of prediction therefore net annual change in head describes the change in system storage from year to year.

System Discharge

The variable representing flux leaving the system is similar to that of the upper aquifer. As there are no monitored surface water discharge sites associated with this groundwater system, flow leaving the system will be indirectly accounted for based on a gradient difference assumed with a fixed elevation down canyon site. The proxy for this unknown gradient is the head in Well 951.2. This variable will consist of the average head for the year determined from the average difference between the current year's head and the previous year's head, both taken on 30 September. This variable will be labeled *Average Annual Head in Well 951.2* and is taken in feet above sea level.

System Recharge

As with the upper aquifer, recharge is a bit complex. This area appears to be dominated more by general precipitation trends which suggest a groundwater influence. Analysis demonstrates this aquifer has a better relationship with precipitation trends in the area of San Bernardino County Gage 2840 Panorama Point, a higher elevation location off of Highway 18 and above the east fork of Devil's Canyon. The mean of the annual rainfall at this site is approximately 34 inches but this can be misleading as the data actually displays more of a bimodal distribution with most of the data below 45 inches and about 20 percent above 53 inches.

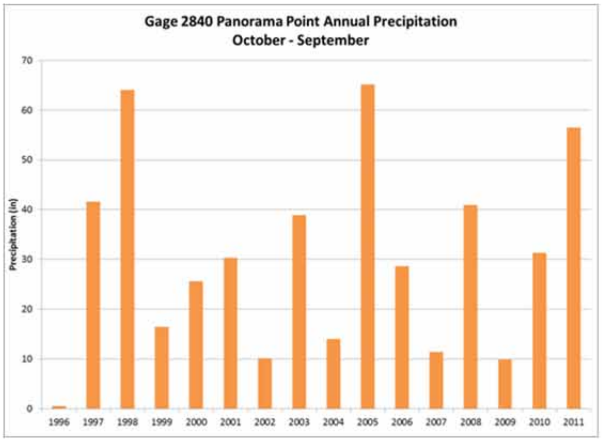


Figure 152. Annual Precipitation at Panorama Point.

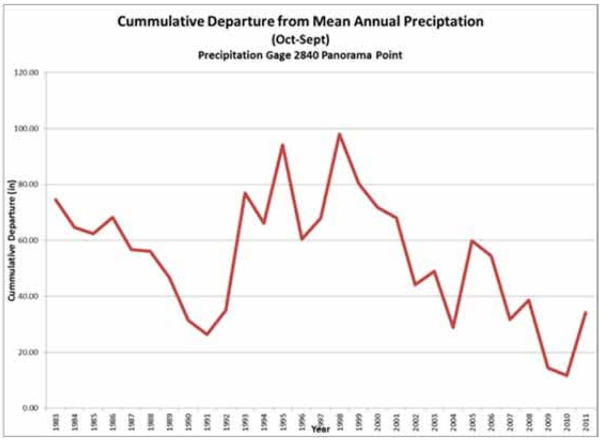


Figure 153. Cumulative Departure from Mean Annual Precipitation at Panorama Point.

The concept governing flow into the system is similar to the upper piezometer groundwater where recession of head over time generally dominates the hydrograph. During most years *Cumulative Departure from Mean Annual Precipitation at Gage 2840* appears to be a driver for storage changes. As this variable increases (representing higher up-gradient groundwater head), recession decreases. This variable adds significantly to storage changes when it is less than 76 inches. When over 85 the increase in contribution becomes negligible, but can still be used. After this additional increases in cum departure result in decreased storage changes which does make sense physically and may under predict recharge. Therefore caution is advised in this case. When precipitation is high enough another inflow component is added to the system and recharging of the aquifer occurs. This component appears to be tied directly to the current year's precipitation and *Annual Precipitation at Gage 2840* becomes a proxy for this direct recharge and is effective when the precipitation is at or above 40 inches for the year.

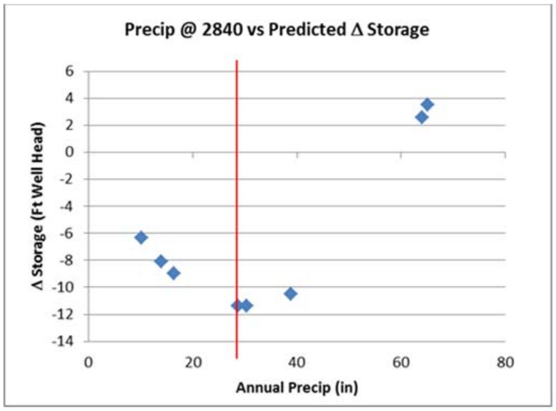


Figure 154. Change in Storage for Well 951.2 based on the modeled expression including only the Annual Precipitation component (high precipitation year).

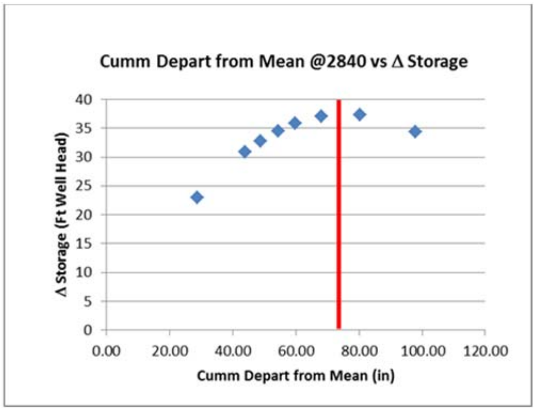


Figure 155. Change in Storage for Well 951.2 based on the modeled expression including only the Cumulative Departure from the Mean Annual Precipitation component (high precipitation year).

Model Construction and Calibration

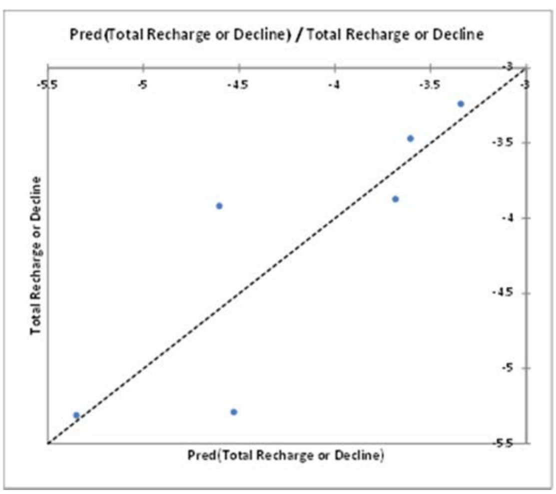
As mentioned before, in this system recession of groundwater head over time generally governs unless significant rainfall occurs over the course of the season. This concept leads to two different scenarios. The first describes the system during most years and uses the variables *Average Annual Head at Well 951.2* as a discharge variable and *Cumulative Departure from Mean Annual Precipitation at Gage 2840* as the representative of flux into the system. *Change in Storage at Well 951.2* is predicted by the relationship. The expression for this condition is:

ΔS = 14341.0264 - 11.9914 * *Average Annual Head at Well 951.2* + 3.6118E-02 * *Cumulative Departure from Mean Annual Precipitation at Gage 2840* + 2.5044E-03 * (*Average Annual Head at Well 951.2*)^2 + 3.7794E-04 * (*Cumulative Departure from Mean Annual Precipitation at Gage 2840*)^2

Where:

ΔS = *Change in Storage at Well 951.2*
ΔS & Average Annual Head are in feet
Cumulative Departure is in inches

The data set corresponding to the years of hydrograph recession was used to construct and calibrate the above expression. This equates to the years 1999 through 2006 (excluding 2000 for the earthquake and 2005 as it was a recharge year). The fit is less than ideal. The largest deviations in predicted storage change occur in 2002 and 2006 with differences (predicted minus actual) of 0.7 feet low and 0.8 feet high, respectively.



Goodness of fit statistics:	
Observations	6.000
DF	1.000
R^2	0.726
SSE	1.114
MSE	1.114
RMSE	1.056

Figure 156. Predicted versus actual Change in Storage values for Well 951.2 along with related statistics (high precipitation years).

However the expression is good for the full range of the variables.

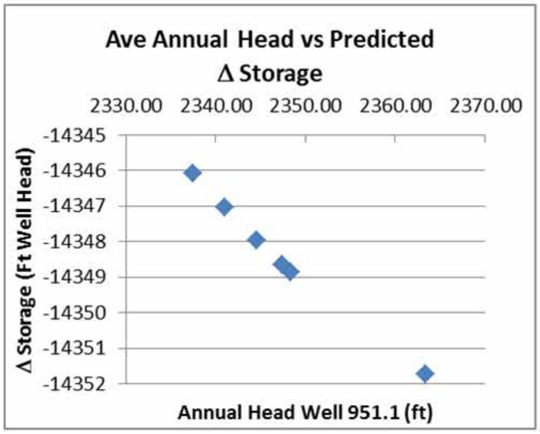


Figure 157. Change in Storage for Well 951.2 based on the modeled expression including only the Annual Groundwater Head component (normal precipitation years).

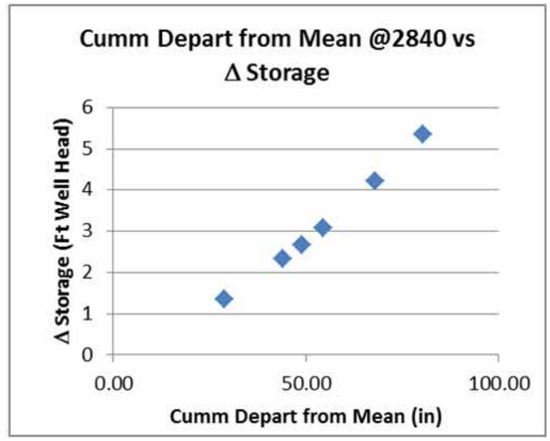


Figure 158. Change in Storage for Well 951.2 based on the modeled expression including only the Cumulative Departure from the Mean Annual Precipitation component (normal precipitation years).

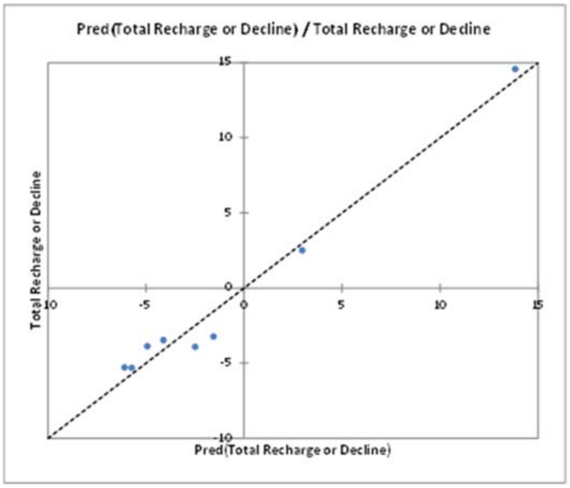
The second scenario is the exception and is driven by annual precipitation at Panorama Point in excess of 40 inches. In this case the current year's precipitation is significant enough to make an immediate contribution to incoming flux. Therefore *Annual Precipitation at 2840* is an added variable and a new expression is generated which usually predicts a positive change or increase in groundwater storage in the vicinity of Well 951.2.

ΔS = 134789.3911 - 0.7500 * *Annual Precipitation at 2840* - 114.1709 * *Average Annual Head at Well 951.2* + 0.9865 * *Cumulative Departure from Mean Annual Precipitation at Gage 2840* + 1.2339E-02 *(*Annual Precipitation at 2840*)^2 + 2.4170E-02 * (*Average Annual Head at Well 951.2*)^2 - 6.4918E-03 * (*Cumulative Departure from Mean Annual Precipitation at Gage 2840*)^2

Where:

ΔS = *Change in Storage at Well 951.2*
ΔS & Average Annual Head are in feet
Annual Precipitation and Cumulative Departure are in inches

The full range of the data set from 1998 through 2006 (again excluding 2000 for the earthquake) was used to construct and calibrate this part of the model. The fit is quite good with 2002 and 2003 presenting the largest deviations between expected and predicted. The predicted observations were 1.4 and 1.7 feet high, respectively. The target values were the recharge years of 1998 and 2005. These predicted values were about 0.5 feet high and 0.7 feet low.



Goodness of fit statistics:	
Observations	8.000
DF	1.000
R^2	0.975
SSE	7.980
MSE	7.980
RMSE	2.825

Figure 159. Predicted versus actual Change in Storage values for Well 951.2 along with related statistics (high precipitation years).

Although the overall fit is generally very good for the range of values, the physical characteristics of the environment place limitations on the use of the expression. Plugging the range of precipitation values back into the associated part of the expression produces:

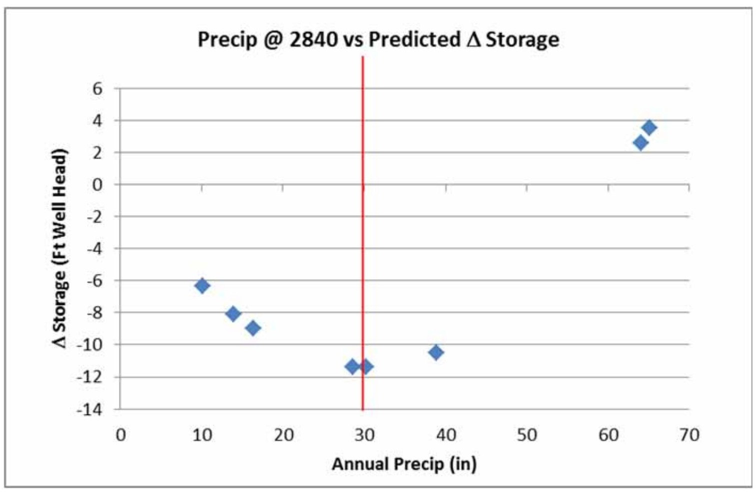


Figure 160. Change in Storage for Well 951.2 based on the modeled expression including only the Annual Precipitation component (high precipitation year).

The values increase storage once precipitation drops below 30 inches. Root mean square deviation (RMSD) is a measure of the deviation between predicted and actual values. Generally the lower RMSD value indicates a better the fit of the regression to the actual data. Normalization over the range of predicted values allows comparison of one set of data to another set of data. Further analysis demonstrates that at a threshold of about 40 inches the normalized RMSD (NRMSD) drops to about half of what it is using 30 inches for the precipitation threshold. Therefore 40 inches is chosen as the lower bound for using this expression.

The two other variables in the expression additionally have constraints. When the *Average Annual Head at Well 951.2*, the proxy for gradient between the aquifer and a down canyon sink, is greater than 2363 feet, increasing head causes increases in storage. This is unrealistic in the physical sense and does not support a deterministic approach to modeling. The error induced by extending the parameters to 2370 is less than 1.5 feet however, and this is deemed acceptable in order to extend the useful range of the model.

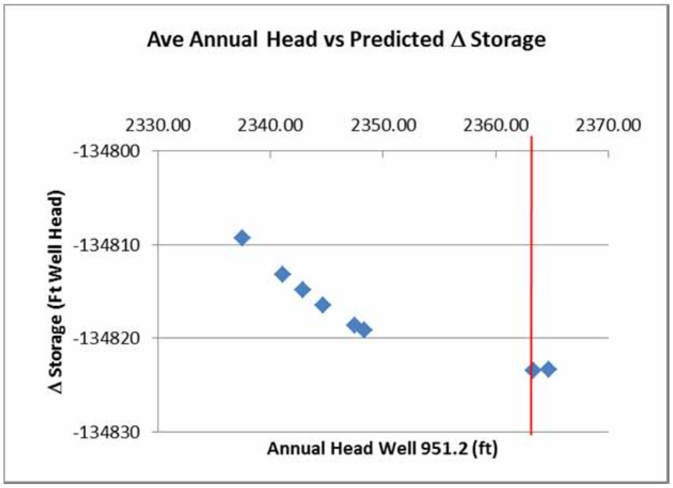


Figure 161. Change in Storage for Well 951.2 based on the modeled expression including only the Average Annual Head component (high precipitation year).

Additionally *Cumulative Departure from Mean Annual Precipitation at Gage 2840* presents a problem when its value rises above 76 inches for the same reasons described above. Increased values decrease input into the system when the opposite should be true. However a value of 85 inches induces an error of less than one foot, so 85 inches has been set as the upper bound for this variable. This higher value occurred once in the early data and has been used in the validated data set. However caution is advised when approaching the limits of the variables. It is necessary to determine if the results are realistic and whether the system behaves as expected.

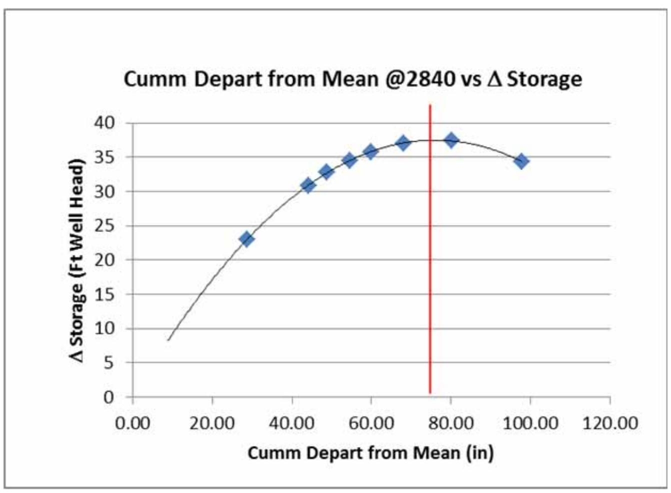


Figure 162. Change in Storage for Well 951.2 based on the modeled expression including only the Cumulative Departure from Mean Annual Precipitation component (high precipitation year).

Another issue arises at the lower end of the curve when cumulative precipitation is low, less than 20 inches, and annual precipitation is below 40 inches. Changes to storage decline much more quickly and this decline produces big drops in the hydrograph using this expression. No such drops have been observed to data in the baseline data set. The remedy is to use an annual precipitation lower bound of 40 inches for this expression.

Using each expression within the constraints described a calibrated model is constructed.

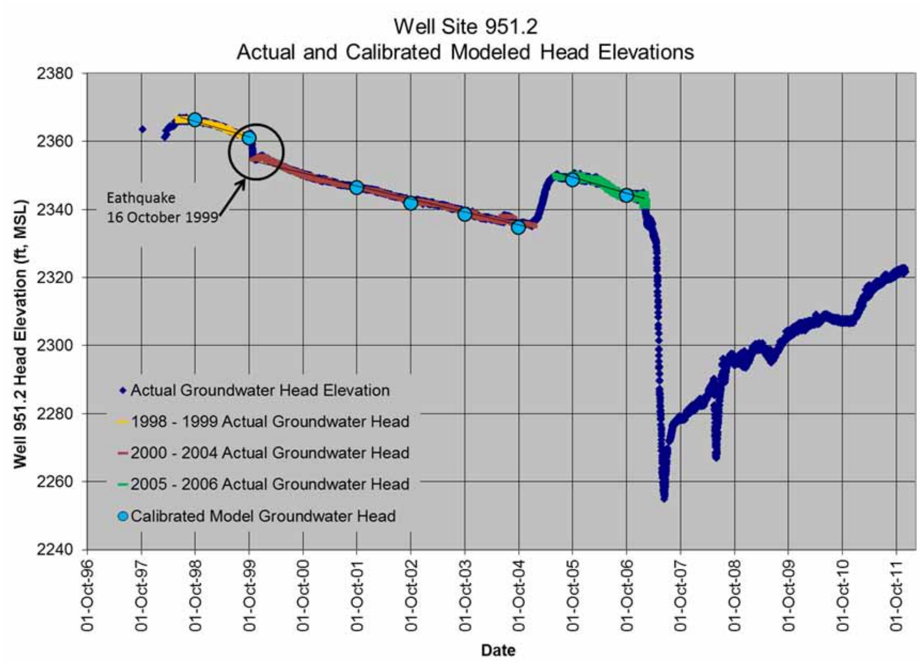


Figure 163. Groundwater hydrograph showing modeled baseline data for Well 951.2.

Validation Results

Validation of the model is similar to the others. It is constructed using multiple expressions with a common variable which must equilibrate for each expression. Again change in groundwater storage is the equilibrated variable and the relationships are thus:

Changes in Groundwater Storage f(Cum Precip, Average Head, maybe Precip**)**

Changes in Groundwater Storage f(Initial Groundwater Head, Average Head**)**

The solution varies *Average Annual Head Well 951.2* until *Change in Storage at Well 951.2* for both expressions equilibrate. This is done using solver in Excel with a tolerance of 0.005 foot of Change in Storage and subject to the following constraints:

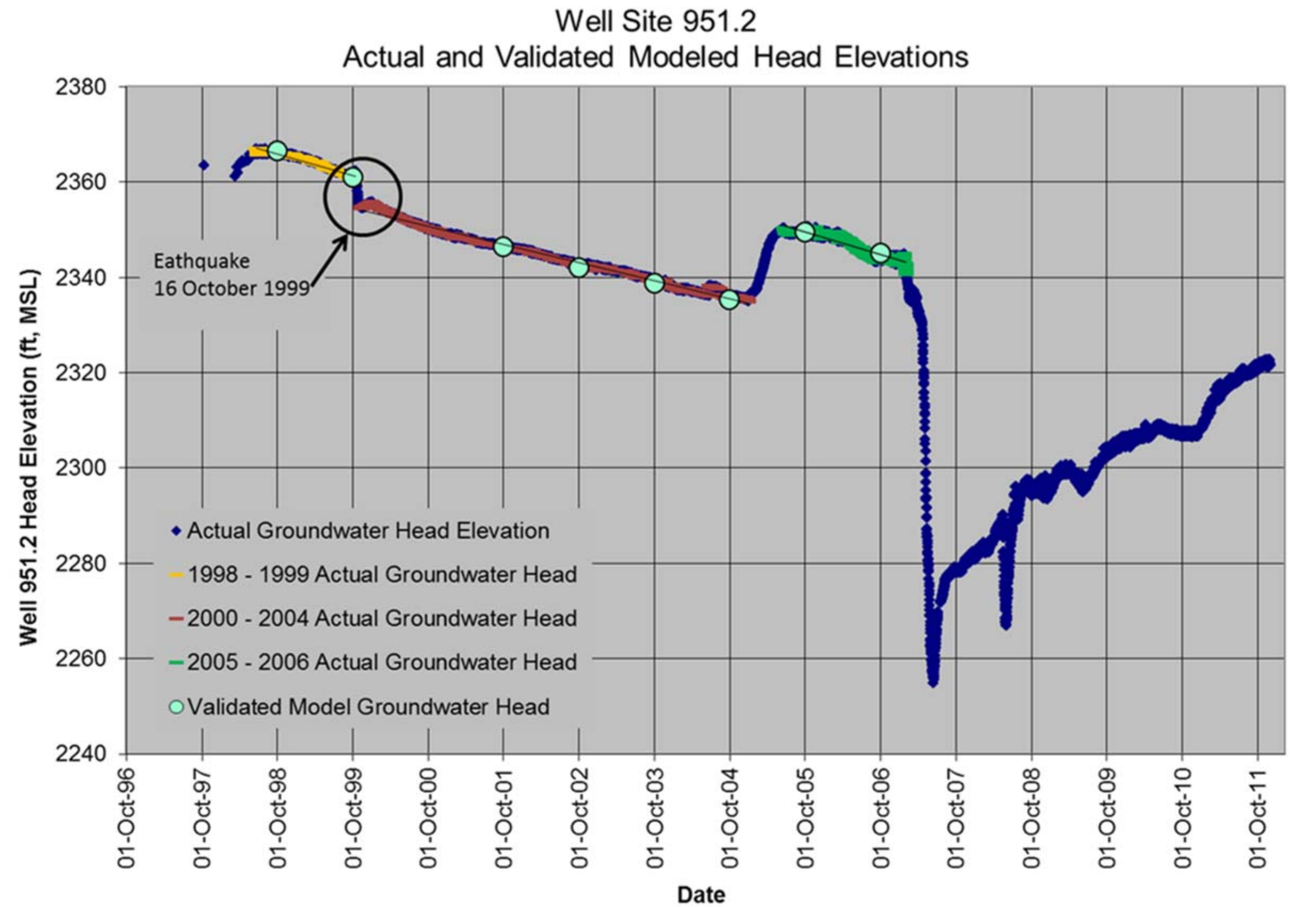
2300 feet < Average Head < 2370 feet

The model was run from 1998 to 2006 with Average Head, Change in Storage and Year End Groundwater Elevation in Well 951.2 predictive. The Year End Groundwater Elevation for the year 2000 was added manually due to the downward shift created by the earthquake.

The predicted results are shown in the table below. The blue text identifies the expression used when precipitation is greater than the threshold value of 40 inches. The brown text displays the lower value expression used and generally shows a decrease in storage. The red text is not calculated but actual values. The average deviation between predicted and actual groundwater head at Well 952.2 during the baseline period is approximately ± 0.5 feet.

Validation Results

Note that here Average Head is also predictive. The results are still very close to the calibration results.



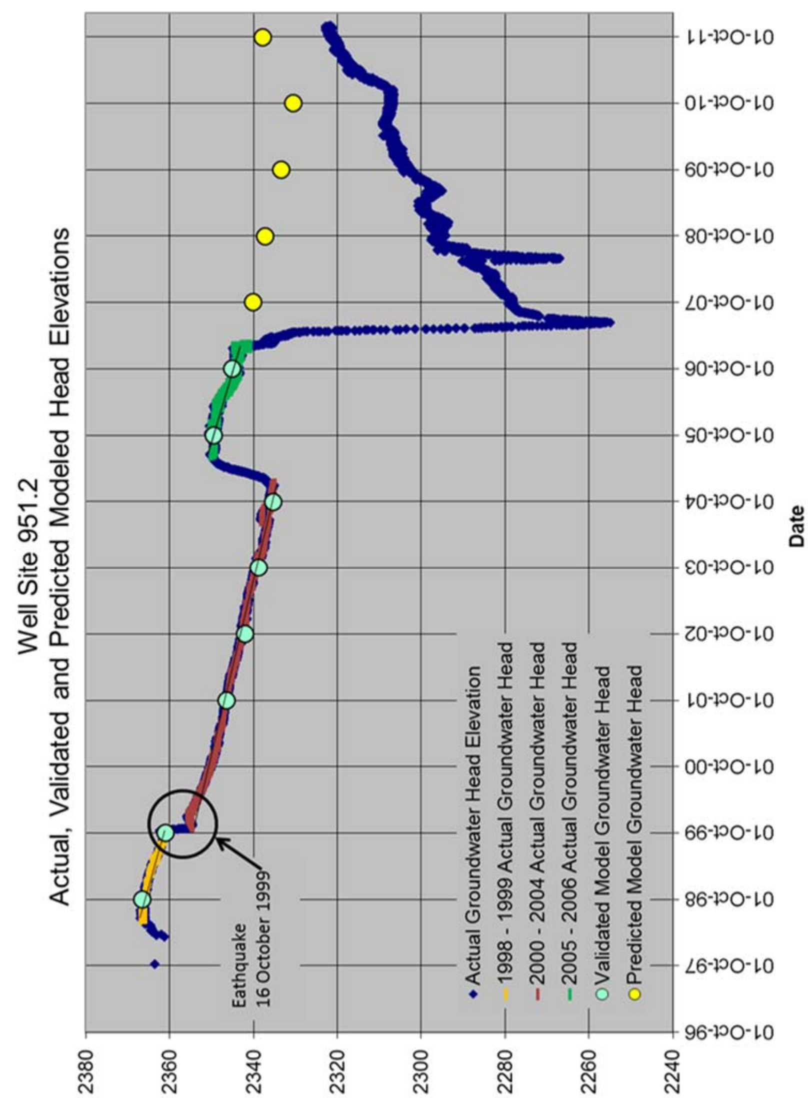
Time Domain	Well 951.2			SB Co Rain Gage 2840		Adjusted Variable	Regression Based Predictions				Prediction Based on Initial Conditions			Information
Water Year (Oct - Sept)	Actual Year End Head Well 951.2 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Annual Precipitation at 2840 (in)	Cummulative Departure from Mean (in)	Predicted Average Head (ft)	Predicted Year End Head	Predicted Decline - Recession Equation (ft)	Predicted Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)
1998	2366.00	2364.74	2.51	64.04	97.96	2365.00	2366.50	-3.77	3.01	3.01	3.01	2366.50	2365.00	-0.51
1999	2360.68	2363.34	-5.31	16.4	80.29	2363.79	2361.09	-5.42	-5.68	-5.42	-5.42	2361.08	2363.79	-0.40
2000	2350.06		-10.62	25.6	71.83		2350.06					2350.06		
2001	2346.59	2348.33	-3.47	30.28	68.05	2348.27	2346.47	-3.59	-4.06	-3.59	-3.59	2346.47	2348.27	0.12
2002	2342.67	2344.63	-3.92	10.12	44.10	2344.22	2341.97	-4.50	-2.14	-4.50	-4.50	2341.97	2344.22	0.70
2003	2339.43	2341.05	-3.24	38.88	48.92	2340.39	2338.81	-3.16	-0.87	-3.16	-3.16	2338.81	2340.39	0.62
2004	2335.56	2337.49	-3.87	13.96	28.81	2337.03	2335.26	-3.55	-4.37	-3.55	-3.55	2335.26	2337.03	0.30
2005	2350.13	2342.84	14.57	65.16	59.91	2342.39	2349.52	-2.84	14.26	14.26	14.26	2349.52	2342.39	0.61
2006	2344.84	2347.48	-5.29	28.64	54.48	2347.28	2345.04	-4.48	-5.95	-4.48	-4.48	2345.04	2347.28	-0.20
2012														

Figure 164. Groundwater hydrograph with modeled and actual baseline data; tabulated and calculated spreadsheet values.

Model Prediction

Now that the model predicted baseline information fairly accurately, the next step was to run it predictively from 2007 through 2011.

Prediction Results



Time Domain	Well 951.2			SB Co Rain Gage 2840		Adjusted Variable	Regression Based Predictions				Prediction Based on Initial Conditions			Information
Water Year (Oct - Sept)	Actual Year End Head Well 951.2 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Annual Precipitation at 2840 (in)	Cummulative Departure from Mean (in)	Predicted Average Head (ft)	Predicted Year End Head	Predicted Decline - Recession Equation (ft)	Predicted Recharge - Recharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)
1998	2366.00	2364.74	2.51	64.04	97.96	2365.00	2366.50	-3.77	3.01	3.01	3.01	2366.50	2365.00	-0.51
1999	2360.68	2363.34	-5.31	16.4	80.29	2363.79	2361.09	-5.42	-5.68	-5.42	-5.42	2361.08	2363.79	-0.40
2000	2350.06		-10.62	25.6	71.83		2350.06					2350.06		
2001	2346.59	2348.33	-3.47	30.28	68.05	2348.27	2346.47	-3.59	-4.06	-3.59	-3.59	2346.47	2348.27	0.12
2002	2342.67	2344.63	-3.92	10.12	44.10	2344.22	2341.97	-4.50	-2.14	-4.50	-4.50	2341.97	2344.22	0.70
2003	2339.43	2341.05	-3.24	38.88	48.92	2340.39	2338.81	-3.16	-0.87	-3.16	-3.16	2338.81	2340.39	0.62
2004	2335.56	2337.49	-3.87	13.96	28.81	2337.03	2335.26	-3.55	-4.37	-3.55	-3.55	2335.26	2337.03	0.30
2005	2350.13	2342.84	14.57	65.16	59.91	2342.39	2349.52	-2.84	14.26	14.26	14.26	2349.52	2342.39	0.61
2006	2344.84	2347.48	-5.29	28.64	54.48	2347.28	2345.04	-4.48	-5.95	-4.48	-4.48	2345.04	2347.28	-0.20
2007	2278.29		-66.55	11.36	31.78	2342.60	2340.15	-4.89	-7.38	-4.89	-4.89	2340.15	2342.60	-61.87
2008	2294.46		16.17	40.91	38.63	2338.71	2337.26	-3.42	-2.89	-2.89	-2.89	2337.26	2338.71	-42.81
2009	2302.70		8.25	9.84	14.40	2335.35	2333.44	-3.82	-10.59	-3.82	-3.82	2333.44	2335.35	-30.74
2010	2306.61		3.90	31.35	11.69	2331.98	2330.52	-2.92	-13.42	-2.92	-2.92	2330.52	2331.98	-23.91
2011	2320.31		13.70	56.44	34.06	2334.18	2337.84	-2.40	7.32	7.32	7.32	2337.84	2334.18	-17.53

Figure 165. Groundwater hydrograph with modeled and actual post-impact data; tabulated and calculated spreadsheet values.

Several determinations can be made based on the model results. The first is the maximum impact to the groundwater resulting from tunnel construction. In this case a drawdown of 62 feet was evident by the end of September 2007. Based on a projection of the recession slope out from the point of impact, a maximum impact of 85 feet would have actually occurred in mid-June. This was short-lived however as a rebound of over 20 feet occurred within the next two months. By late September the impact based on the cursory projection is in line with the model prediction. Results also indicate the groundwater is rebounding toward ecological recovery at a steady rate. Recharge of the modeled aquifer and of the actual groundwater occurred as a result of high precipitation in 2011and remaining impact as of late September was approximately 18 feet.

An attempt at analyzing projected recovery was undertaken and is similar to the analyses at other groundwater sites. The current recovery trend is projected into the future. In this case the difference between *Predicted Year-End Head in Well 951.2* and the *Actual Year-End Head in Well 951.2* from the point of impact through the end of 2011 is regressed against time from point of impact using an exponential regression of the form:

Y = pr1*Exp(pr2*X)

Where:

Y = Remaining Impact,
X = Time From Start of Recovery in years

pr1, pr2 = Regression parameters

The following expression was generated:

Remaining Impact (ft) = 75.4617 * Exp(-0.3252 * Δ Time from Start of Recovery)

Where:

Δ Time from Start of Recovery = difference in years from current year to year recovery started to occur.

	Recovery Curve Prediction				
		Based on current recovery rate			
Date	Water Year (Oct - Sept)	Δ Time from Start of Recovery (yrs)	Δ Year End Head (Actual-Predict)	Remaining Impact - Actual (ft)	Remaining Impact - Predict (ft)
9/30/2007	2007	0.65	-61.87	61.87	
9/30/2008	2008	1.65	-42.81	42.81	
9/30/2009	2009	2.65	-30.74	30.74	
9/30/2010	2010	3.65	-23.91	23.91	
9/30/2011	2011	4.65	-17.53	17.53	
9/30/2012	2012	5.65			12.00
9/30/2013	2013	6.65			8.67
9/30/2014	2014	7.65			6.26
9/30/2015	2015	8.65			4.52
9/30/2016	2016	9.65			3.27
9/30/2017	2017	10.65			2.36
9/30/2018	2018	11.65			1.71
9/30/2019	2019	12.65			1.23
9/30/2020	2020	13.65			0.89

Goodness of fit statistics:	
Observations	5.000
DF	3.000
R^2	0.996
SSE	5.216
MSE	1.739
RMSE	1.319
Iterations	11.000

The analysis yields an ecological recovery time of approximately 7 years from the end of 2011 or to the end of year 2018. By this point it is predicted that recovery will be within 2 feet.

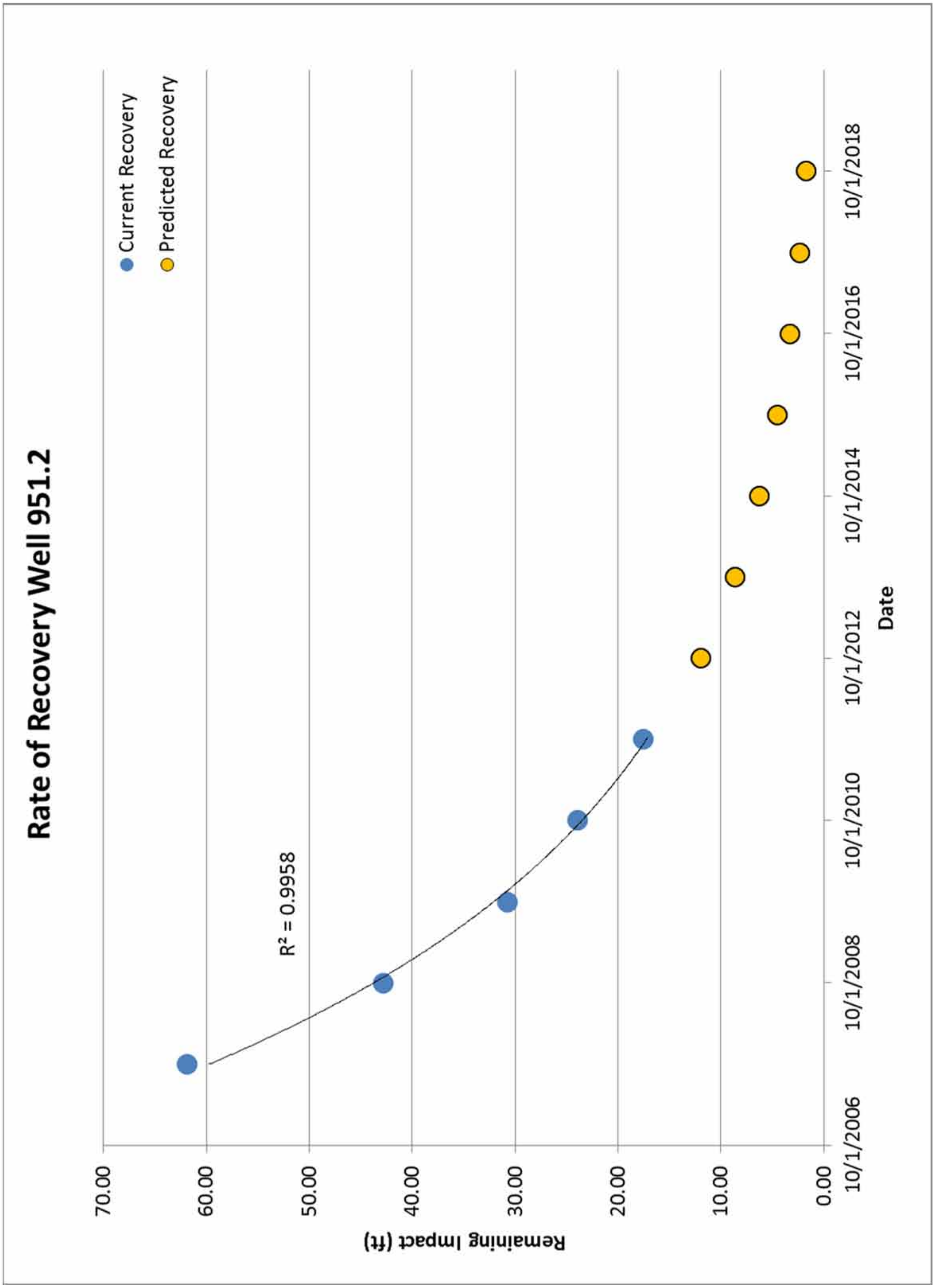


Figure 166. Groundwater recovery prediction for Well 951.2 using the difference between modeled and actual data.

Model Inaccuracies and Use

All modeling efforts are inherently flawed. Modeling is at best, an attempt to understand and perhaps recreate variations in the physical world. It starts with a conceptual model which qualitatively describes the system. Concepts may be inaccurate as many different scenarios may describe system effects. When moving from concept to analytical model the quantitative description becomes even more inaccurate. Hydrologic systems are very complex and most of the variables are lumped and inferred. For instance groundwater recharge from precipitation is dependent many factors, some of which include precipitation duration, intensity, event spacing, infiltration versus runoff and evapotranspiration, depth to groundwater, substrate, recharge path and potential geologic conduits/barriers. All of these factors in turn have many of their own variables. Yet all of this has been lumped into a single precipitation recharge variable for which there is an adequate (hopefully) data set. Yet other sources of recharge which are not described may exist but are difficult to quantify. The models are limited to variables which can be described using physical data.

Even if data is available, adequate datasets can be difficult to obtain. Adequacy refers not only to temporal span, but also to quality. Both of these can be difficult to achieve over the long term as equipment maintenance, crew turn over and other issues arise.

Mathematical expressions used to drive the models are generated using curve fitting regressions. The regressions themselves have a certain amount of error. The real data is not completely described by the expression even with high correlation values. An increased range can make curve-fitting appear better than it actually is. Statistical values can be misleading.

All of the modeling effort is directed at attempting to predict the system response over time beyond the baseline period. In the case of the models included in this report, there is no additional validation data beyond baseline because of changes to the natural system resulting from impacts. Therefore it is important to use caution when considering the modeled results. It is important to periodically re-evaluate the physical characteristics of the system and decide whether the conceptual model is still appropriate. If so, consider the quantitative analysis. Ensure the variables are still within the parameter ranges used to develop the model. Compare the behavior of the results to their behavior during model development. The model is not a substitute for sound technical knowledge, but a tool to be used with discretion by an individual with the appropriate technical understanding of the science and the project.

Devil's Canyon

Well 900 Recovery Analysis

Background Information

Well 900 is a single completion monitoring well which sits on the main ridge aligned to the southwest from Cloud Peak.

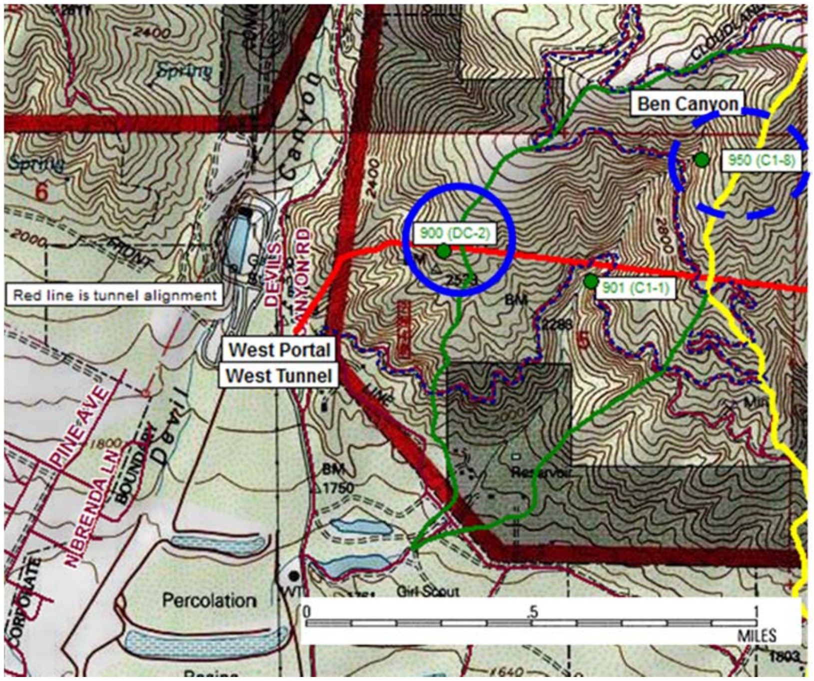


Figure 167. Map showing location of Well 900 on the east slope of Devil's Canyon and control Well 950 in Ben Canyon.

This ridge is the divide between Devil's and Ben Canyons and is crisscrossed by splays of the North Branch of the San Andreas fault and by Ben Canyon faults. The borehole at Well 900 potentially penetrates marble and gneiss layers and additionally may bisect one or more faults. This borehole is located within a couple hundred horizontal feet of the tunnel alignment and was impacted dramatically in February of 2008.

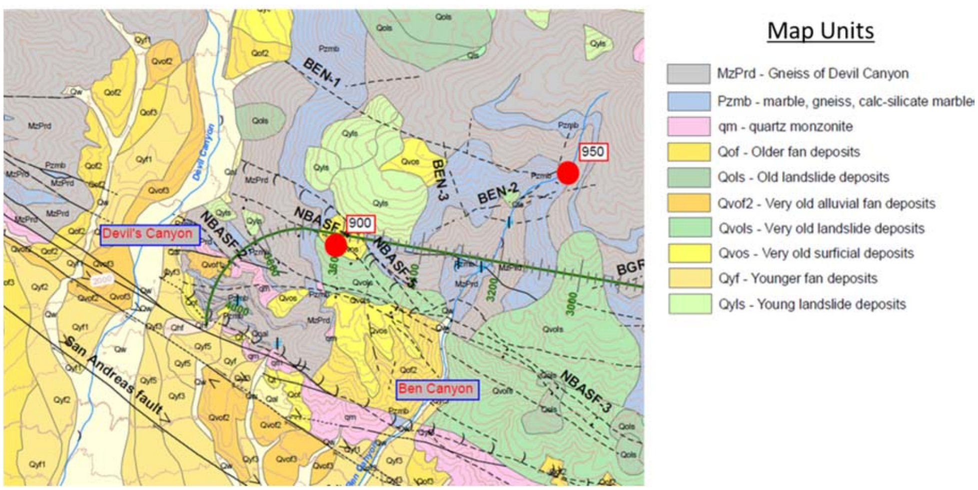


Figure 168. Geology Map showing Lower Devil's Canyon and Ben Canyon area.

Recharge is at this well site is variable. Prior to the year 2000, groundwater recharge followed an annual pattern with most recharge occurring by June and most recessional changes in head complete by January or February. Head variations were on the order of 20 feet with total head generally between 2260 and 2280 feet. In 1999 two things happened. The most notable was the beginning of what is believed to be an extremely low precipitation period (300 yr return cycle) and on 16 October 1999 the Hector Mine Earthquake (magnitude 7.1) which caused pressure fluctuations in this well along with many other wells in the area. From the years 2000 to 2006 the hydrograph is characterized by a general recession which averages -10 ft/yr. The pressure changed again abruptly in June 2001 when the data recorder was automated.

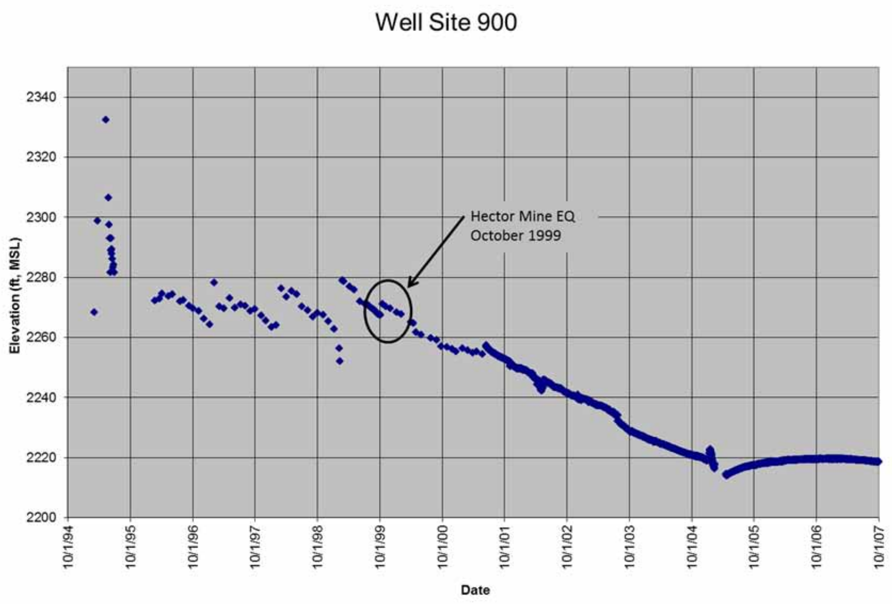


Figure 169. Groundwater hydrograph for Well 900 displaying behavior in the first decade of monitoring.

The recharge to this area is thought to be groundwater based as analysis does not show direct correlation with precipitation but shows better correlation with an adjacent aquifer. Additionally the post impact rebound curve shape appears to be very typical of a system under exclusive groundwater influence.

Construction related impact occurred during mid-February of 2008 (well head 2217 ft with a natural recession of approx. 2 ft/yr) as the TBM entered into this heavily faulted ridge. The well head bottomed out 2 months later at 1956 ft (an overall loss of 216 ft). Within a few days rebound commenced and has been ongoing steadily since. By the end of the 2008 water year (30 September) the head in Well 900 had gained 137 feet of its original loss which would put it roughly 80 feet below its natural elevation. It would take between 8 and 40 years typical recession (based on it highly variable past) to reach this point naturally. There are no known surface water sites directly associated with this groundwater site on or near Forest Service lands.

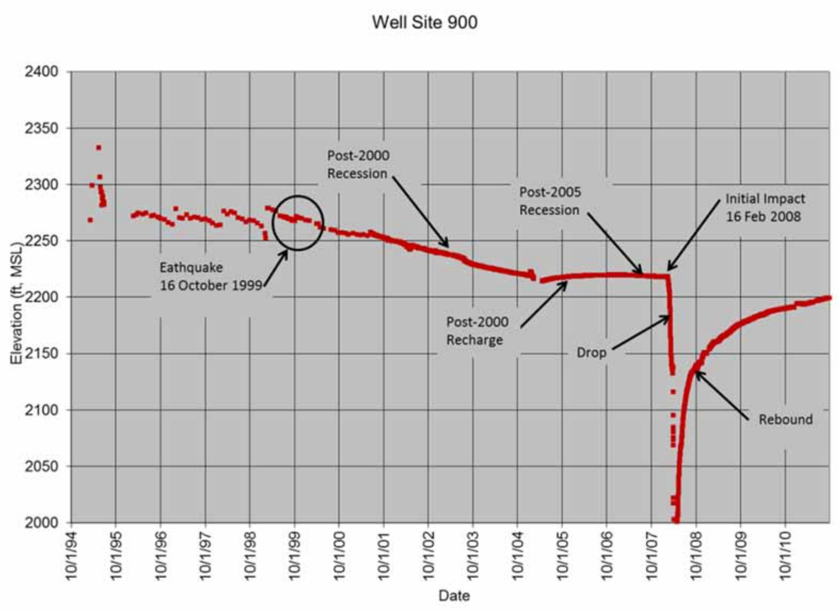


Figure 170. Groundwater hydrograph for Well 900 depicting general behavior and significant events/features.

Recovery Analysis

As with the other groundwater sites on AHW, conservation of matter is used as the basis for the analysis. Changes in storage, exemplified by changes in hydrograph head, are a result of water moving through the aquifer. A positive change in storage results from recharge (from precipitation and up gradient parts of the aquifer) and recovery. A decrease in storage generally results from surface water expression, movement to down gradient aquifers or groundwater extractions; in this case impacts from tunnel construction.

As mentioned previously the Hector Mine Earthquake caused a downward shift in the Well 900 hydrograph. A couple of years later in June of 2001 automation of the data acquisition system caused a three foot jump in the hydrograph head. The first incident may have caused changes to the behavior of the hydrograph. The second could possibly be adjusted for by manually shifting hydrograph values prior to automation however it was decided not to tamper with the hydrograph data. Since it is desirable to use a baseline data set which helps to characterize the aquifer under its current conditions for model construction and validation purposes, the years 2002 through 2007 have been chosen for selecting baseline information. This amounts to the time from well automation to mining impact.

Storage

The hydrograph data for Well 900 is considered the proxy for aquifer storage in this area. For simplicity, changes in well head with time, or declination, was taken to coincide with precipitation year or October to September. In reality, the timeline is more arbitrary during the recession period as it is dependent on groundwater head at that time. The recharge period adds complexity. Increases in storage are more likely to correspond to increases in up-gradient sources which in turn respond to other up-gradient sources or to precipitation, presumably with a lag in time. Change in storage is a net effects variable and does not incorporate a minimum or maximum change for the year. A positive value for change in storage is an increase in groundwater head.

System Discharge

Outflows from the system in terms of discharge to surface sites or as groundwater movement to down-gradient sites are both a function of gradient between the observation site (in this case Well 900) and the discharge site. Surface water sites generally have a fixed elevation while down-gradient groundwater basin heads can fluctuate just as the up-gradient heads can. The magnitude of the flux from the system often times varies with overall gradient and therefore the way it relates to storage changes is often not linear. In the case of Well 900, discharge seems generally to dominate the hydrograph.

There are no known associated surface water sites in the project area and groundwater inter-basin flow is very difficult to quantify. As the system is dynamic, with recession over time, the term does exist. A proxy for this flux out of the system has been used through a term called “Average Annual Groundwater Head”. The assumption is that the gradient between the monitored groundwater site and the discharge site varies with the up-gradient head. The lack of a direct tie between the well head and a definitive quantifiable discharge site is a limitation of this analysis. Never the less a very good relationship does exist between this variable and the value of storage changes for the recession years.

The actual variable *Average Annual Groundwater Head at Well 900* is calculated using an October to September baseflow year. The hydrograph is fairly uniform and the groundwater head elevation for 30 September of the previous year is averaged with the same date for the current year. This variable was regressed against *Change in Storage* (at Well 900) for the baseline data set. The comparison is very good, but departs from expected deterministic values when the value of *Average Annual Groundwater Head at Well 900* is above 2240 feet.

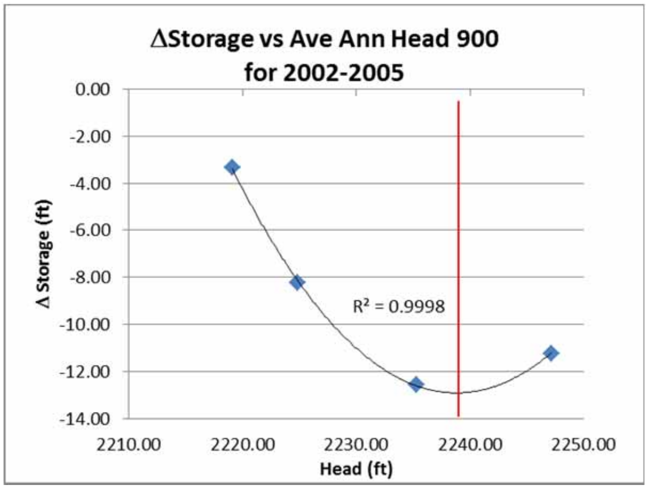


Figure 171. Average Annual Groundwater head versus change in storage for Well 900.

System Recharge

In this case no sufficient ties to precipitation sites were apparent based on any techniques used in previous analyses at other sites. Well 950 is a single completion monitoring well located in the upper reaches of Ben Canyon which potentially exhorts a gradient pressure of 300 to 400 feet on the aquifer sampled by Well 900. This well is considered to be un-impacted and could have direct connectivity through the Ben-2 fault.

Figure 172. Comparative groundwater hydrograph for the impacted Well 900 and the control Well 950 during the same time period.

The head in well 950 was analyzed with storage changes in Well 900. The variable proxy for gradient between groundwater heads at Well 950 and 900 is *Average Annual Head at Well 950* and the process for calculation was similar to the *Average Annual Head at Well 900* data reduction.

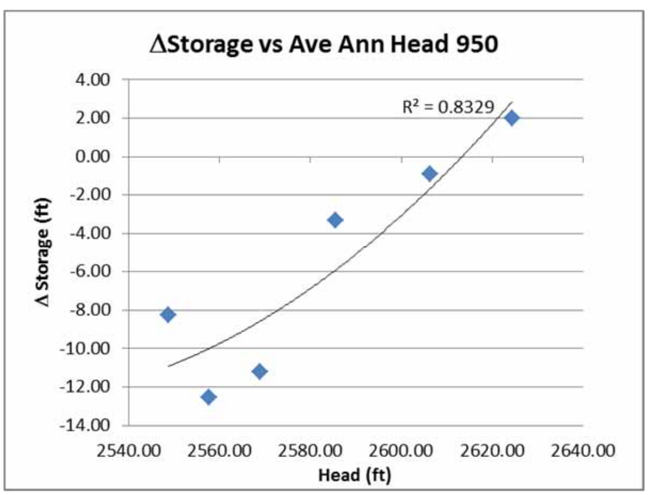


Figure 173. Average Annual Groundwater head versus change in storage for Well 950.

Conceptual Groundwater Model

Change in groundwater storage is seen by fluctuations in the well hydrograph. The general trend is water moving out of the system by flow to down-gradient areas, as described previously. This flow is represented by *Average Annual Head at Well 900* and is valid for heads below 2240 ft, but can loosely apply below 2245 ft.

Inflows to the system, probably tied to up-gradient groundwater, are small and only serve to decrease the net flux out unless the up-gradient head is high enough. Data modeling shows the relationship increases flow when head at Well 950 is approximately 2560 ft or higher.

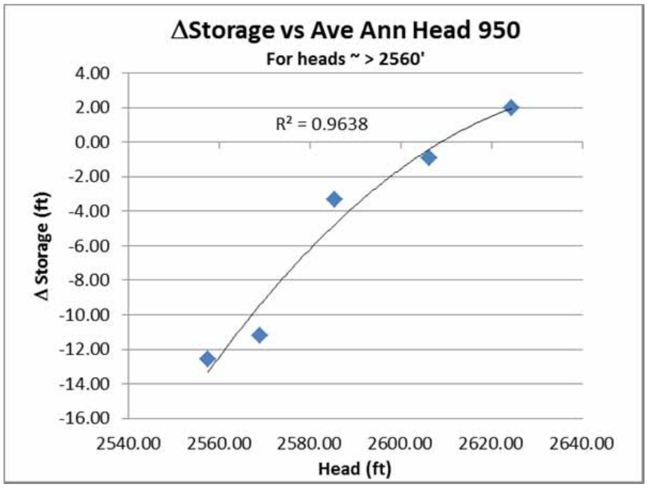


Figure 174. Average Annual Groundwater head versus change in storage for Well 950 for head greater than 2560 feet.

When inflows to the aquifer system in the vicinity of Well 900 are high enough the rate of recession decreases. With a much more significant input the change in storage is a positive value which is seen through a rising hydrograph limb.

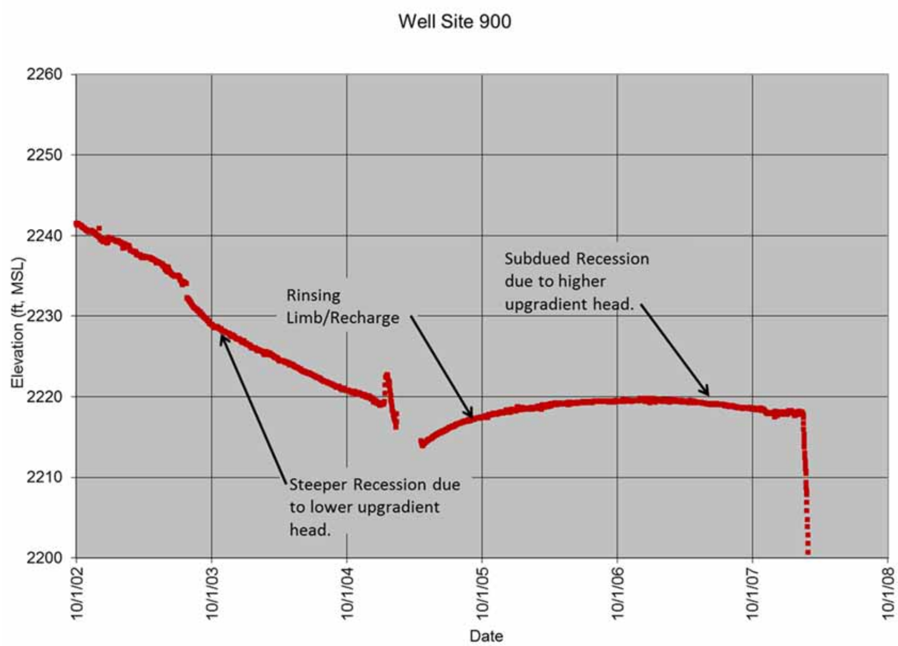


Figure 175. Groundwater hydrograph for Well 900 depicting changing storage trends.

Model Calibration

A model is developed which uses the described inflow and outflow variables to predict changes to groundwater storage and in turn annual net changes to the groundwater head in Well 900 under natural (non-mining related) conditions. A second-order polynomial regression is chosen as a best-fit using *Average Annual Groundwater Head in Well 950* and *Average Annual Groundwater Head in Well 900 as independent predictors*. The model is calibrated using the actual Change in Storage values for each year from 2002 through 2007. This yields the following general equation:

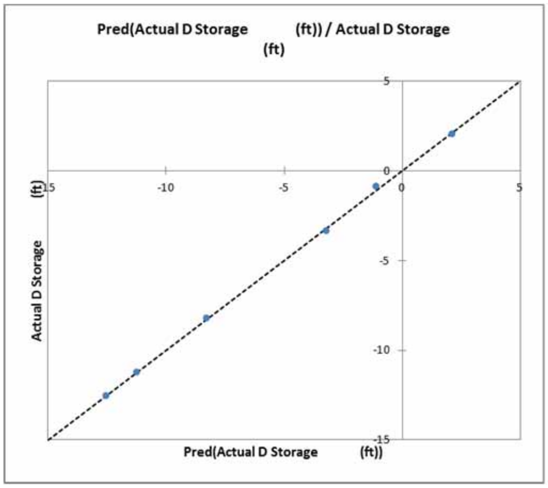
ΔS = 119198.1022 - 98.6834*Actual Average Head 900 - 6.8264*Actual Average Head 950 + 2.2038E-02*Actual Average Head 900^2 + 1.3335E-03*Actual Average Head 950^2

Where:

ΔS = Change in storage at Well 900

And all units are in feet

The predicted values are very close to the actual values for the above relationship with the largest deviation occurring in 2005 and 2007.



Goodness of fit statistics:	
Observations	6.000
DF	1.000
R^2	1.000
SSE	0.074
MSE	0.074
RMSE	0.272

Figure 176. Predicted versus actual Change in Storage values for Well 900 along with related statistics.

This model has two general constraints:

- Head in Well 900 must be below 2245 feet or the model is not valid.
- Head in Well 950 must be above 2560 feet or there is generally no significant influence from up-gradient pressure on the aquifer in the vicinity of Well 900. This does not preclude use of the model however. There is simply no flow in and all storage change is based on flux out alone.

Based on the above criteria the year 2002 was used for model calibration in order to provide the minimum data set needed for the regression, but was not used predictively during the pre-impact period for model validation.

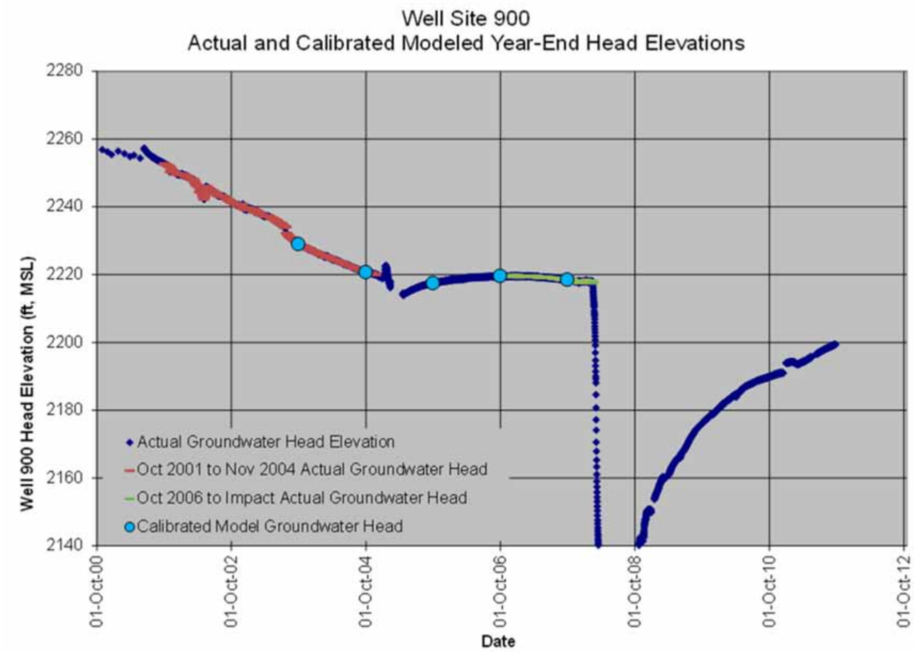


Figure 177. Groundwater hydrograph showing modeled baseline data for Well 900.

Model Validation

Attempting to predict what the groundwater will do after the initiation of construction impacts involves basically two dependent variables, *Change in Storage at Well 900* and *Average Annual Head in Well 900*. There are two relationships as well.

Changes in Groundwater Storage f(Average Annual Head 900, Average Annual Head 950**)**

Changes in Groundwater Storage f(Initial Groundwater Head 900, Average Annual Head 900**)**

In this analysis Annual Average Head in Well 950 is the only truly independent variable.

The solution results from varying *Average Annual Head in Well 900* until *Changes in Storage* for both expressions are equal. This was done using solver in Excel with a tolerance of 0.005 ft of Storage. Additional parameters included constraining *Average Annual Head in Well 900* between 2200 feet and 2300 feet.

The model was run from 2003 to 2007 with *Average Annual Head in Well 900*, *Change in Storage at Well 900* and *Year End Groundwater Elevation in Well 900* predictive. The *Year End Groundwater Elevation* for the year 2002 was added manually due to the *Average Annual Head at Well 900* being outside the model constraints. The predicted results are shown in the table below in blue text. The red text is not calculated but actual values. Note that the maximum deviation between predicted and actual groundwater head at Well 900 occurred in 2007 at approximately 0.1 feet.

Validation Results

Time Domain		Well 900			Well 950	Regression Based Predictions			Information		
Water Year End Date	Water Year (Oct - Sept)	Actual Year End Head Well 900 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Actual Average Head 950 (ft)	Predicted Year End Head 900 (ft)	Predicted Recharge (ft)	Δ Storage (ft)	Δ Year End Head (Actual-Predict)	Δ^2 Storage (Actual-Predict)	Comments
30-Sep-97	1997	2269.45	2269.52	-0.13		2269.45		-0.13	0.00	0.00	
30-Sep-98	1998	2268.21	2268.83	-1.24	2651.43	2268.21		-1.24	0.00	0.00	
30-Sep-99	1999	2267.50	2267.86	-0.71	2649.36	2267.50		-0.71	0.00	0.00	
30-Sep-00	2000	2256.90	2262.20	-10.60	2633.70	2256.90		-10.60	0.00	0.00	Remove - Earthquake
30-Sep-01	2001	2252.76	2254.83	-4.14	2600.43	2252.76		-4.14	0.00	0.00	Shift in hydrograph - Due to automation??
30-Sep-02	2002	2241.53	2247.15	-11.23	2568.94	2241.53	Well 900 > 2245' - Model N/A	-11.23	0.00	0.00	
30-Sep-03	2003	2228.97	2235.25	-12.56	2557.58	2229.01	-12.52	-12.52	-0.04	-0.04	
30-Sep-04	2004	2220.74	2224.85	-8.23	2548.70	2220.73	-8.28	-8.28	0.01	0.05	
30-Sep-05	2005	2217.39	2219.07	-3.34	2585.49	2217.52	-3.20	-3.20	-0.13	-0.14	
30-Sep-06	2006	2219.41	2218.40	2.01	2624.39	2219.62	2.10	2.10	-0.22	-0.09	
30-Sep-07	2007	2218.52	2218.96	-0.89	2606.32	2218.53	-1.09	-1.09	-0.01	0.21	
30-Sep-08	2008	2138.09	2178.30	-80.43	2580.84						Impacted this year
30-Sep-09	2009	2176.04	2157.07	37.95	2565.22						
30-Sep-10	2010	2189.76	2182.90		2556.31						
30-Sep-11	2011	2199.40	2194.58		2587.74						

Red text denotes typed and not calculated values

Note that here Average Head is also predictive. The results are still very close to the calibration results.

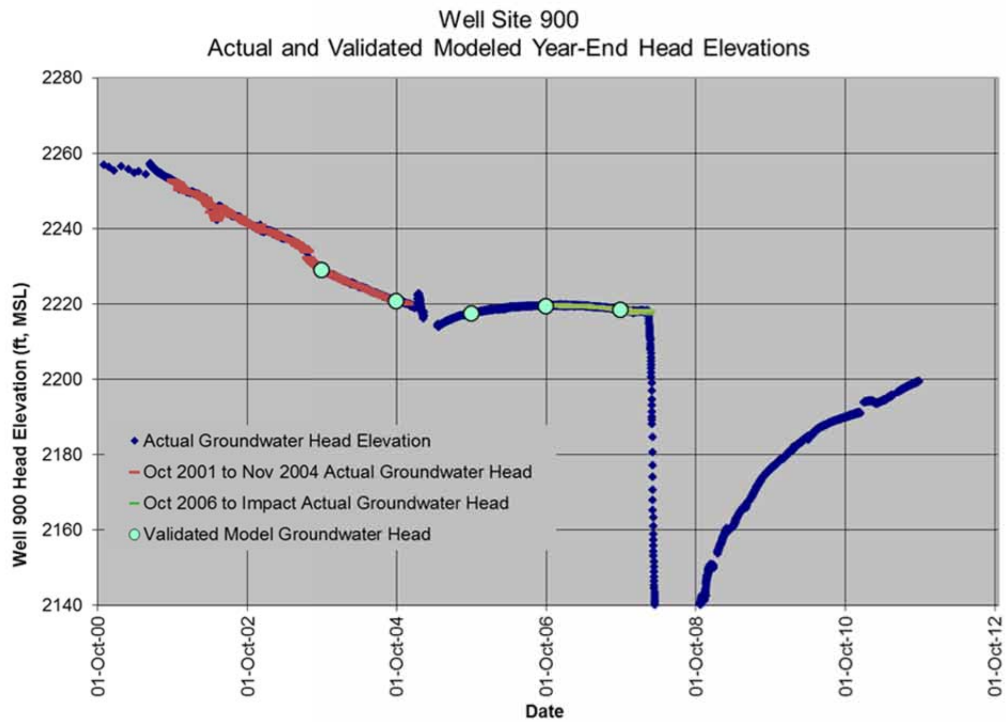


Figure 178. Groundwater hydrograph with modeled and actual baseline data; tabulated and calculated spreadsheet values.

Model Prediction

With the margin between the actual and validated results acceptably small, the final step was to run the model predictively from 2008 to 2011.

Prediction Results

Time Domain		Well 900			Well 950	Variable	Regression Based Predictions			Prediction Based on Initial Conditions			Information
Water Year End Date	Water Year (Oct - Sept)	Actual Year End Head Well 900 (ft)	Actual Average Head (ft)	Actual Δ Storage (ft)	Actual Average Head 950 (ft)	Predicted Average Head 900 (ft)	Predicted Year End Head 900 (ft)	Recharge - Discharge Equation (ft)	Δ Storage (ft)	Δ Storage (ft)	Predicted Year End Head	Predicted Average Head (ft)	Δ Year End Head (Actual-Predict)
30-Sep-97	1997	2269.45	2269.52	-0.13			2269.45		-0.13			0.00	0.00
30-Sep-98	1998	2268.21	2268.83	-1.24	2651.43		2268.21		-1.24				
30-Sep-99	1999	2267.50	2267.86	-0.71	2649.36		2267.50		-0.71			0.00	0.00
30-Sep-00	2000	2256.90	2262.20	-10.60	2633.70		2256.90		-10.60			0.00	0.00
30-Sep-01	2001	2252.76	2254.83	-4.14	2600.43		2252.76		-4.14		2252.76	0.00	0.00
30-Sep-02	2002	2241.53	2247.15	-11.23	2568.94	2247.15	2241.52	-11.24	Well 900 > 2245 - Model N/A	-11.23	2241.53	2247.15	0.01
30-Sep-03	2003	2228.97	2235.25	-12.56	2557.58	2235.27	2229.00	-12.52	-12.52	-12.52	2229.01	2235.27	-0.03
30-Sep-04	2004	2220.74	2224.85	-8.23	2548.70	2224.86	2220.71	-8.29	-8.29	-8.29	2220.72	2224.86	0.03
30-Sep-05	2005	2217.39	2219.07	-3.34	2585.49	2219.10	2217.47	-3.23	-3.23	-3.23	2217.48	2219.10	-0.08
30-Sep-06	2006	2219.41	2218.40	2.01	2624.39	2218.49	2219.49	2.02	2.02	2.02	2219.50	2218.49	-0.08
30-Sep-07	2007	2218.52	2218.96	-0.89	2606.32	2218.96	2218.40	-1.09	-1.09	-1.09	2218.41	2218.96	0.12
30-Sep-08	2008	2138.09		-80.43	2580.84	2217.42	2216.41	-1.99	-1.99	-1.99	2216.42	2217.42	-78.32
30-Sep-09	2009	2176.04		37.95	2565.22	2215.90	2215.36	-1.05	-1.05	-1.05	2215.37	2215.90	-39.32
30-Sep-10	2010	2189.76		13.72	2556.31	2215.19	2215.00	-0.36	-0.36	-0.36	2215.01	2215.19	-25.24
30-Sep-11	2011	2199.40		9.63	2587.74	2215.30	2215.58	0.58	0.58	0.58	2215.59	2215.30	-16.18

Red text denotes typed and not calculated values

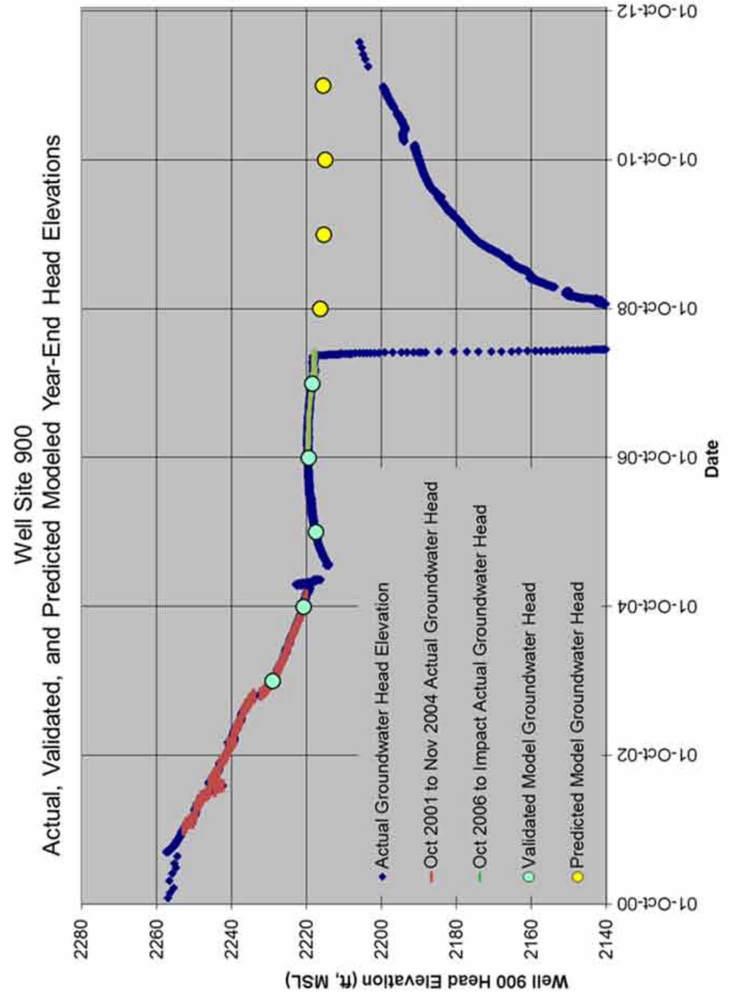


Figure 179. Groundwater hydrograph with modeled and actual post-impact data; tabulated and calculated spreadsheet values.

Several inferences can be made from the modeling results. At the least a trend toward recession or recharge is predicted and an actual quantitative value is given for the annual net storage change and ending head in feet. These values are based entirely on the years 2002 through 2006 and may not be relevant to a future where heads exceed 2240 feet in Well 900 or the head in Well 950 drops below 2560 feet. Additionally a year end maximum impact can be determined from looking at the predicted head versus the actual head in Well 900. This maximum occurred in 2008 (30 September) at a differential of approximately 80 feet with a resolution of 1 year. Compare this with the simple extension of the pre-impact recession to the point of maximum impact. The resolution in this analysis is 12 hours and the maximum impact is interpolated at approximately 261 feet on 5 April 2008.

By the end of the last water year, 30 September 2011, it appears the remaining impact is less than 20 feet. This indicates an overall recovery of more than 140 feet from maximum impact and over 60 feet net derived from an annual resolution. An attempt has been made to project recovery and determine the number of years to ecological recovery. This was done using the current recovery trend and projecting that trend into the future. For this rather simple analysis the *Predicted Year-End Head in Well 900* was compared with the *Actual Year-End Head in Well 900* from the point of impact to the last year of full data, 2011. Using an exponential regression of the form Y = pr1*Exp(pr2*X); where Y = Remaining Impact, X = Time From Start of Recovery in years; the following expression was generated.

Remaining Impact (ft) = 102.3838*Exp(-0.5807*Δ Time from Start of Recovery (yrs))

Recovery Curve Prediction Based on current recovery rate					
Water Year (Oct - Sept)	Δ Time from Start of Recovery (yrs)	Δ Year End Head (Actual-Predict)	Remaining Impact - Actual (ft)	Remaining Impact -Predict Min (ft)	Remaining Impact -Predict Max (ft)
2008	0.49	-78.32	78.32		
2009	1.49	-39.32	39.32		
2010	2.49	-25.24	25.24		
2011	3.49	-16.18	16.18		
2012	4.49			7.55	10.39
2013	5.49			4.22	6.67
2014	6.49			2.36	4.28
2015	7.49			1.32	2.74
2016	8.49			0.74	1.76
2017	9.49			0.41	1.13
2018	10.49			0.23	0.73

Goodness of fit statistics:	
Observations	4.000
DF	2.000
R^2	0.990
SSE	24.485
MSE	12.242
RMSE	3.499
Iterations	18.000

As the rate of groundwater recovery appears to be strongly groundwater related it is therefore fairly predictable. Based on the rebound analysis and using the worst case scenario *Remaining Impact-Prediction Max*, impacts to the groundwater aquifer in the vicinity of Well 900 are anticipated to diminish to within a foot by 2017 or in 5 years. It is anticipated that ecological recovery occurs before or during this time.

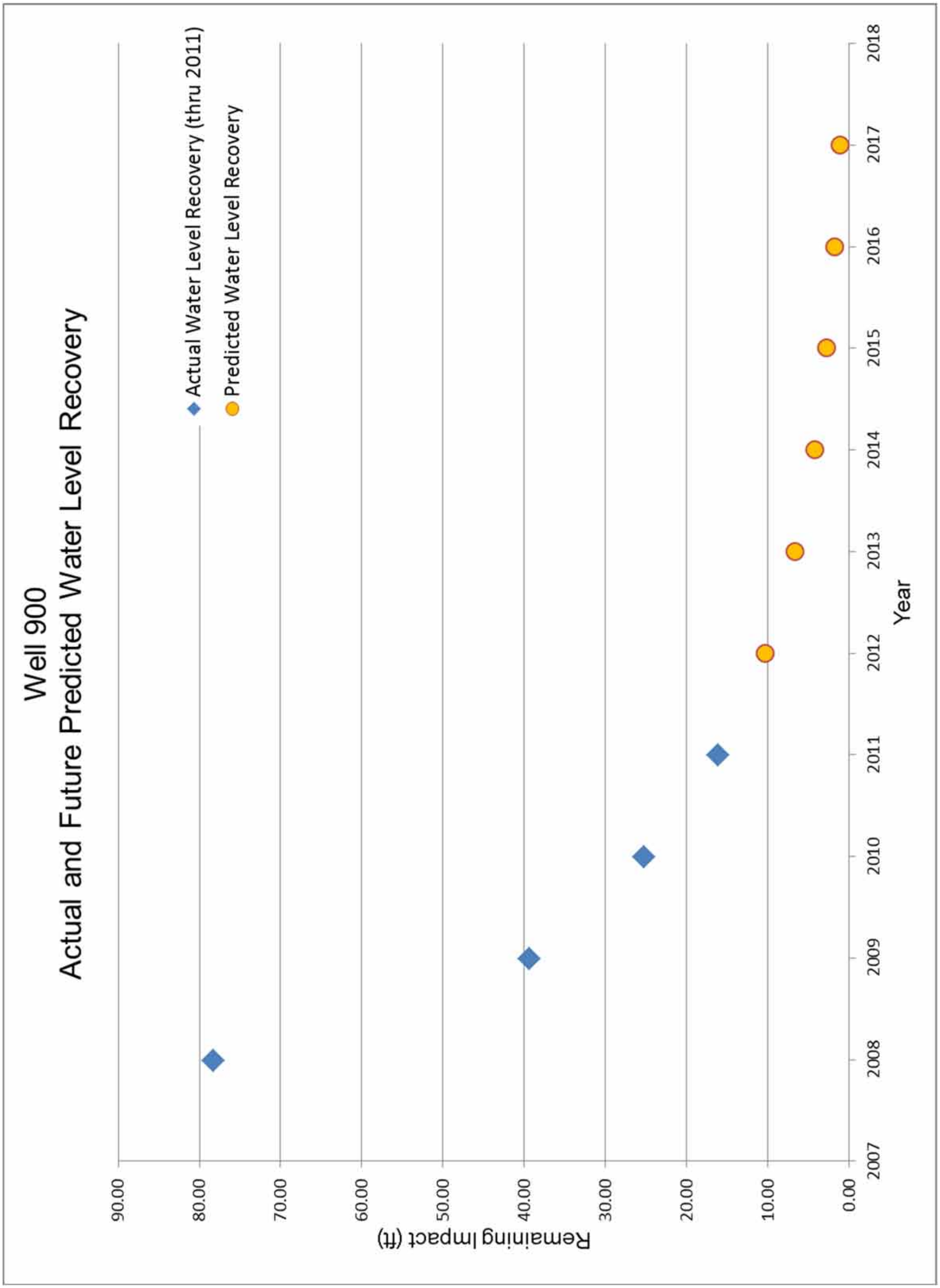


Figure 180. Groundwater recovery prediction for Well 900 using the difference between modeled and actual data.

The analysis or model developed for use with the groundwater in the vicinity of Well 900 has many of the same advantages of other models discussed in this document thus far. For example, it uses existing and available information and it attempts to model the system in a deterministic fashion. Moreover the model is fairly simplistic, easily understood and easily updated. Validation was good to actual measurements during the pre-impact timeframe and the post-impact results are reasonable.

Limitations must also be mentioned. Some of these are similar to others such as sampling error or model resolution (one year as opposed to daily). Additionally the temporal span of the data set is limited allowing only 1 degree of freedom for the recession equation. The nature of this data set will bias the results toward recession and small response to recharge and also creates constraints for validity (such as head in Well 900 below 2245 feet or Well 950 above 2560 feet). This well was more difficult to quantify with respect to precipitation and therefore was linked indirectly through another groundwater site, Well 950. This Well 950 has become a proxy for up-gradient groundwater but there is no direct proof of tie between the two sites (such as tracer tests or chemical sampling).

Flows leaving the system are lumped by proxy into a dependent variable (Average Annual Head in Well 900). There are no direct measurements for this term as an independent variable. Additionally while this variable may be fairly stable with surface water sites, it can fluctuate with down-gradient groundwater discharges. Other potential sources for recharge and discharge may exist which are not included in this model. The effects of other sources may have first or second order effects on the system and could change the overall response. Still, even with these limitations the advantages are strong and the model provides reasonable and predictable results. Annual evaluation will determine whether this continues to be the case.

Summary Table for Recovery Analyses

AHW

Canyon	Site	Maximum Impact	Current Impact	Predicted Time to Recovery	Comments
Devil's	Well 900	260 ft	9 ft	2016	Steady Recovery
Badger	Well 951.1	50 ft	41	2026 to 2060	Recovery may increase after 951.2 recovery
	Well 951.2	85 ft	17	2018	Steady Recovery
Sycamore	Well 952	100 ft	18 ft	2020	Steady Recovery
	Well 903				

AHE

Canyon	Site	Maximum Impact	Current Impact (beginning 2012)	Predicted Time to Recovery	Comments
Borea	Well 907	12 ft	none		Recovered
	Well 908	45 ft	none		Recovered
	Spring 45	12 gpm	none		Recovered
	Stream 154	18 gpm	none		Recovered
Little Sand	Well 954.1	60 ft	15-20 ft	2014	Recovery dependent on lower
	Well 954.2	195 ft	17 ft	2014	Steady Recovery
	Well 909	10 ft	none		Recovered
	Spring 44	2 gpm	none		Recovered
	Stream 509	30 gpm	none		Recovered
	Stream 155	27 gpm	none		Recovered
Sand Canyon	Well 956.1	80 ft	20 ft	2018	Steady Recovery
	Well 956.2	125 ft	25 ft	2018	Steady Recovery
	Spring 48	4 gpm	2.5 gpm		Flows currently 50% of predicted
	Stream 636	3 gpm	Slight		Appears to be recovered or close
	Spring 53	2.5 gpm	0.5 gpm		Flows currently 40% of predicted
	Spring 54	3 gpm	None		Appears to be recovered
	Stream117	40 gpm	None		Appears to be recovered

Tectonics

The San Andreas fault (SAF) is the significant tectonic feature in California, running roughly from the northwest part of the state to the southeast through the Salton Trough and terminating in the Gulf of California. This is a right-lateral strike-slip feature which creates a motion whereby the land on one side of the fault travels in a horizontal plane to the right relative to the land on the other side of the fault. Beginning from an area roughly southwest of Bakersfield (the southern end of the Carrizo Plains) and running to the Salton Sea, the SAF shifts bearing from about 40 degrees west of north to about 70 degrees west of north. The resulting directional change creates regional compressive forces which are relieved through local compressional and extensional features in the form of normal and reverse faults along the larger SAF. Near Cajon Pass and moving southeast away from the Mojave Desert, the SAF bifurcates to become the San Jacinto fault running to the south and continues on easterly as the SAF toward the Salton Sea. At the point of bifurcation, the stress and movement is transferred between the two systems and potential movement along the SAF is thought to diminish rapidly from slip rates of 28 mm/yr at Cajon Pass to 13mm/yr at Badger Canyon to about 2 mm/yr by the time it slides past City Creek (Willis, Weldon II, & Bryant, 2008). Locally sections of the SAF, known as the San Bernardino North section and San Bernardino South section, run along the base of the San Bernardino Mountains and parallel the project area. The Arrowhead Tunnels portion of the Inland Feeder Project begins and ends on what was called the North Branch of the San Andreas fault (currently known as the Mill Creek Fault, (McGill, Owen, Weldon, & Kendrick, 2011)). This right-lateral strike-slip fault splays off of and slightly to the north of the SAF near Devil's Canyon and the western-most tunnel portal.

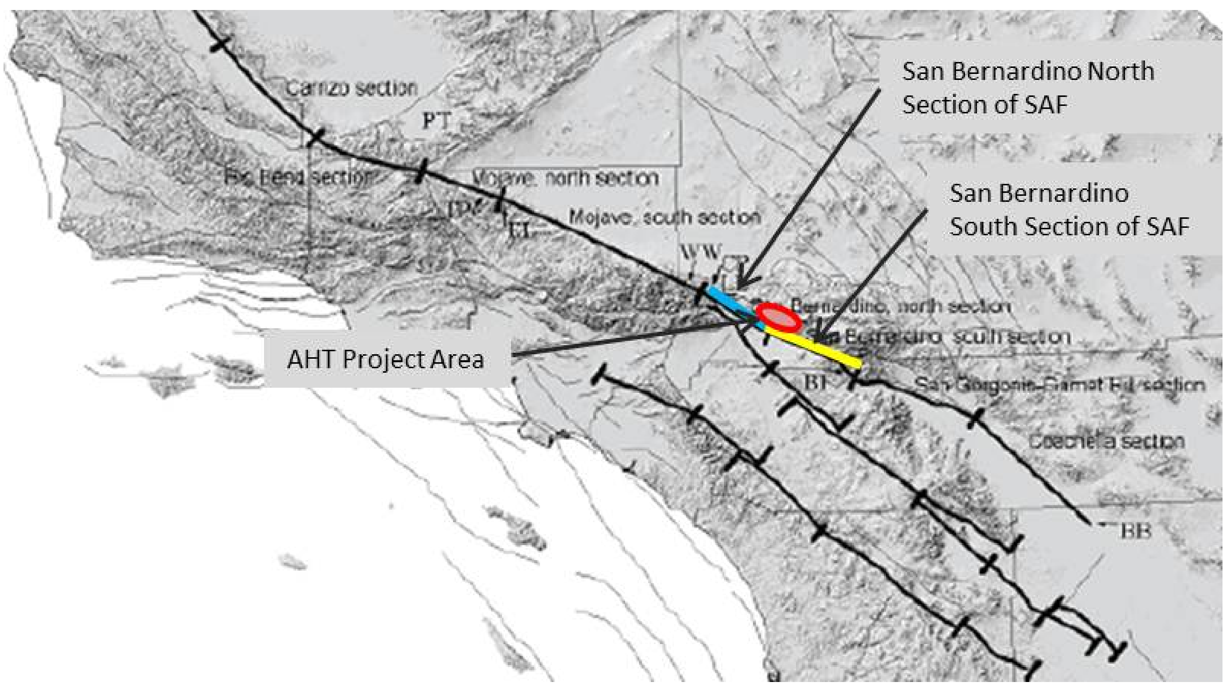


Figure 181. Depiction of major SoCal faults including segments of the San Andreas fault (upper and right-most heavy Lines); base map (Willis, Weldon II, & Bryant, 2008) with project area and related SAF segments added.

The linear feature (lineament) related to the SAF along the base of the San Bernardino Mountains and the project area is easy to see. This is the prominent fault in the area and irregularities in the basement rock from one side of the fault to the other propagate upward through the overlying alluvium as distinct irregularities. Additionally faults can provide a barrier to the movement of groundwater and water ponded up on one side of the fault provides surface expression available to vegetation. The result is very linear vegetation growth along the fault which can be seen in aerial photos. Trenching is used by seismologists to determine the relative movement of sediment along the fault along with rate of spread and potentially time between seismic events. Recent work by McGill and others over the course of the last decade has led to downgrading the potential seismic activity along this segment of the SAF. It should be noted that these return intervals and spread rates are averaged over long time periods (on the order of tens of thousands of years) and do not speak specifically to smaller or larger events within the temporal frame.

Another strong lineament within the project area is the North Branch SAF which roughly parallels the project alignment and the SAF from the western-most portal in Devil's Canyon to the eastern-most portal at the mouth of City Creek Canyon. Additionally notable and maybe not as visible from aerial photos are the Arrowhead Springs fault which runs along the base of the Arrowhead West project area and then crosses behind the Arrowhead East project area in Waterman Canyon. Within the Arrowhead East portion of the project, the 'N' fault runs roughly through the project area intersecting the alignment west of upper Sand Canyon. Furthermore the San Manual fault originates at the San Manual Indian Reservation and crosses the tunnel alignment near the east portal at the mouth to City Creek Canyon.

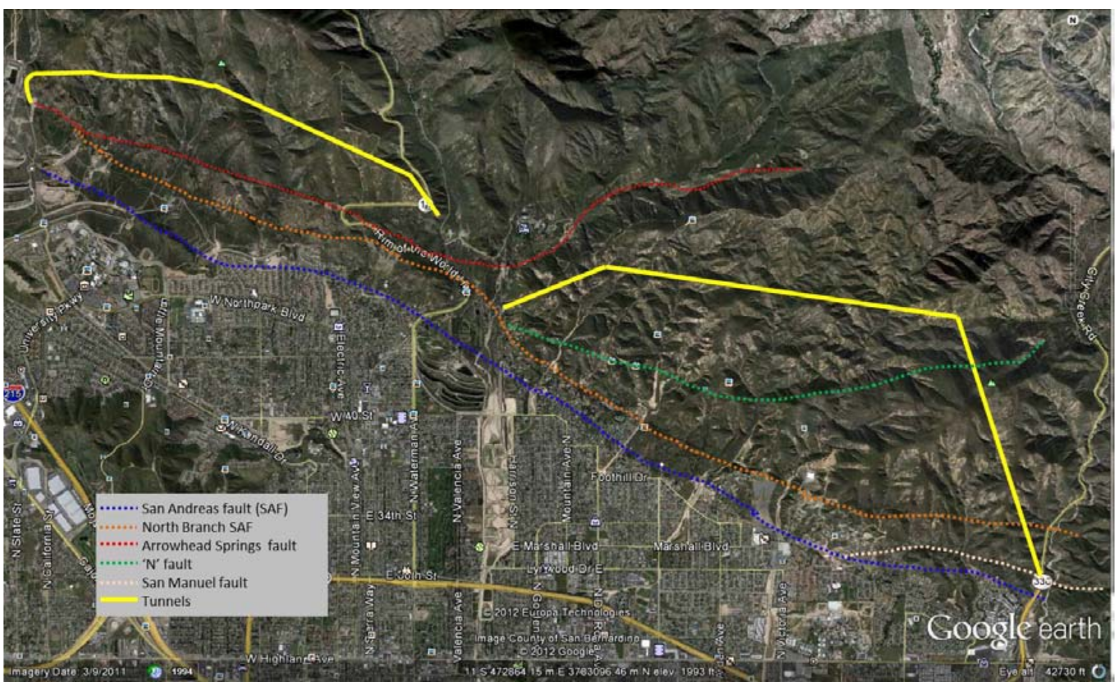


Figure 182. Satellite photo (Google Maps) of project area with tunnel alignment and major faults superimposed.

Seismic Risk

Based on a report generated and distributed by MWD (Metropolitian Water District, 2011), the Arrowhead Tunnels were originally designed to withstand a magnitude 7.5 earthquake on the SAF, San Bernardino South segment. Anticipated displacement was 10 to 13 feet. The recurrence interval is 200 years with 20% probability of occurrence in the next 30 years. Based on new work, this segment has been downgraded to an anticipated magnitude 7.25 with 5 to 8 feet of displacement. Subsidiary faults (North Branch SAF, Arrowhead Springs fault, etc.) are projected to have considerably less displacement (up to 2 feet). Based on a report compiled by the USGS for The Shakeout Scenario (Effects of a potential Magnitude 7.8 along the San Andreas fault in southern California), the potential displacements along this section of the SAF are far greater (Ponti & Treiman, 2008). For instance displacements at fault crossings near the Devil's Canyon Portal are cited to be in the neighborhood of 14 feet, while near the Waterman Canyon side of tunnel it is closer to 16 feet. Displacements then decrease to less than 2 meters near San Manual Indian Reservation, but increase to over 20 feet near the eastern-most portal near City Creek Canyon.

While no parts of the tunnel or its portals intersect the known lineation of the SAF, it does intersect some of the subsidiary faults. As a precaution against rupture, the inner steel liner within the tunnel was constructed with a 7/8-inch thick wall in the areas where it was known to cross a potentially active fault (as opposed to 1/2-inches in other areas).

Based on what is known about the area seismology and tunnel construction, the potential for rupture through shearing of the tunnel lining is probably very low. Although the risk of movement along any of the known faults large enough to cause rupture is assumed to be low, there is uncertainty inherent in seismic predictions. Part of this uncertainty comes from the statistical approach to assessing and predicting slip rates and return intervals and part of it is the result of deficiencies in prevailing knowledge, including the understanding and distribution of faults and their behaviors. For example, the 1994 Northridge earthquake was the result of a previously undetected blind thrust fault very close to but not part of the SAF. The SAF did not produce the movement in this event. In 1992 the Landers earthquake, a right-lateral strike-slip event, produced an average 10 to 13 feet of horizontal offset (20 feet maximum) and involved 5 different faults (some previously undetected) over a distance of 53 miles (Southern California Earthquake Data Center, SCEDC, 2007).

The ramifications of a breach in the tunnel lining pose almost no direct risk to surface resources, infrastructure or human life as the tunnel is generally well below ground level. Any resource risk is associated with groundwater flowing into the tunnel from the surrounding rock mass in the vicinity of the rupture and thereby causing some depletion to the aquifer. The amount of risk to groundwater dependent resources (includes groundwater aquifer and associated surface water expressions and their ecosystems) varies according to several factors, namely location of rupture, severity of rupture, duration of inflow, and connectivity of the aquifer to the surface water resources. A rupture very close to the west portal of the Arrowhead East tunnel would likely produce no impact to groundwater resources as the tunnel is located above the piezometric surface. However a rupture fairly close to the eastern portal of the Arrowhead West tunnel will have immediate consequences to local aquifers. Indeed, the piezometric surface in the vicinity of Well 903 began to decline significantly when the tunnel boring machine was within 2500 ft. This was probably due to a combination of connectivity through faulting and inter-bedding of potentially more permeable material such as marble. A depletion of the aquifer in this area is not necessarily directly linked to an effect of surface water resources on Forest Service land (however there may be undefined risks to sites outside the Forest Service boundary).

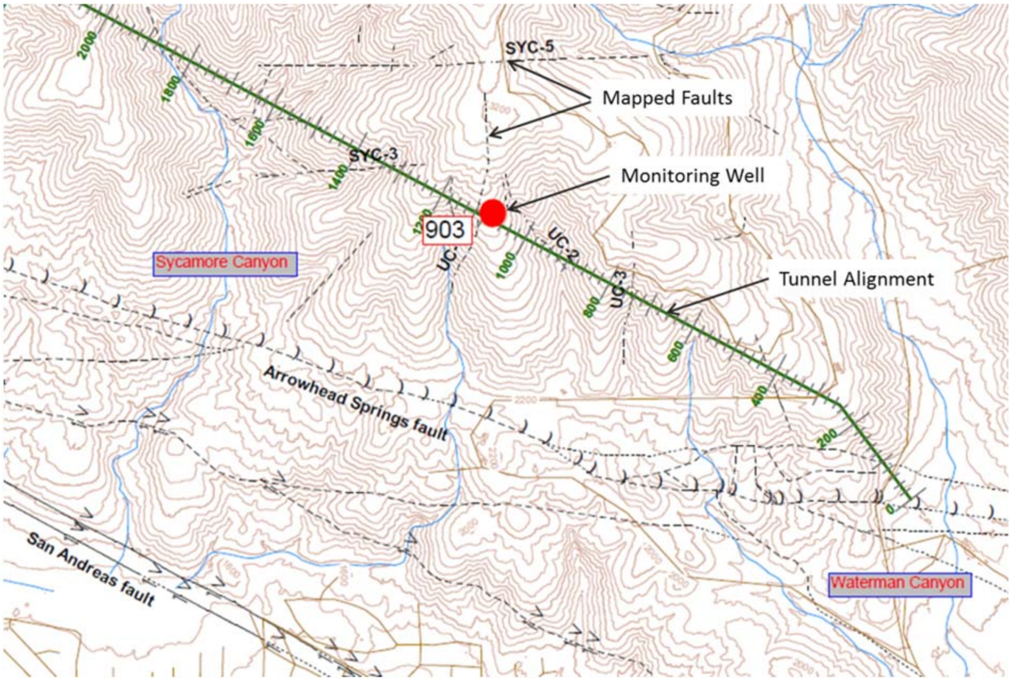


Figure 183. Topographic map showing the position of Well 903 relative to the tunnel alignment and local faults.

A rupture in the area of the Borea Canyon fault is potentially damaging to both the aquifer and to the associated springs and biology in Borea Canyon.

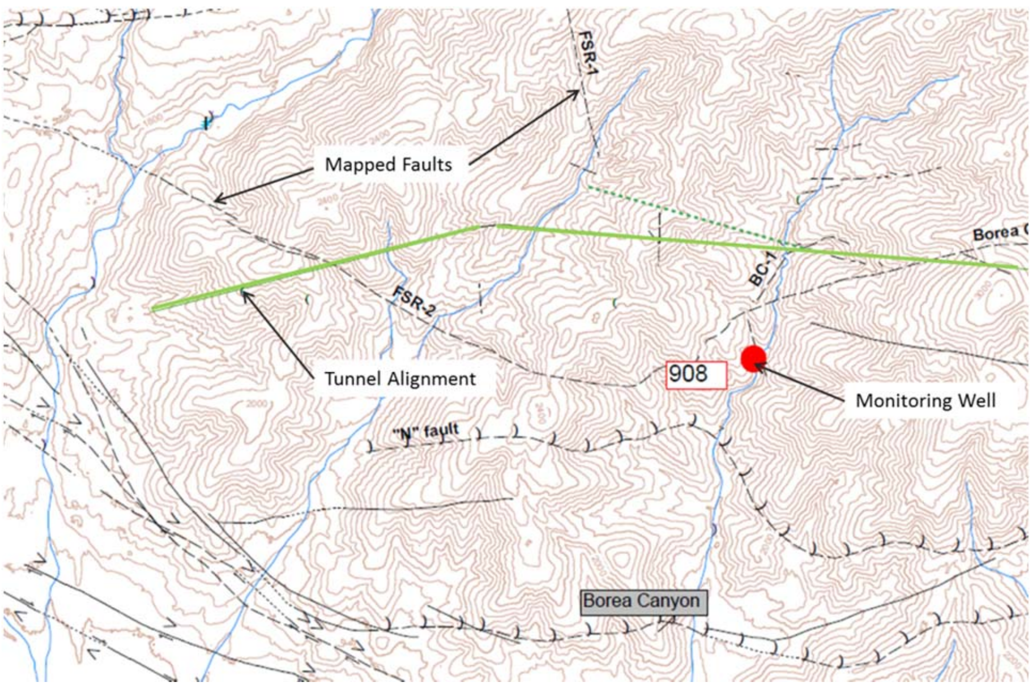


Figure 184. Topographic map showing the position of Well 908 relative to the tunnel alignment and local faults.

Seismic Event Response Plan

Although the risk of tunnel rupture is considered low, the potential damage to Forest Service resources can be significant; therefore the Forest Service and MWD have worked collaboratively on a Seismic Event Response Plan (SERP). This plan has been developed to assist managers and technical specialists associated with both agencies (MWD and FS) in event of such an occurrence. The plan outlines the steps to be taken in the event of an earthquake of Magnitude 5.5 or greater along the proximal portion of the SAF or in case of ground rupture on any other fault which crosses the tunnel alignment. The plan is meant to be general enough to allow key personnel flexibility in the evaluation and decision making process yet specific enough to allow use of available tools.

The key component of this plan is a network of monitoring wells which have been in operation before and during the construction of the Arrowhead Tunnels. These wells have been retained for monitoring based on certain characteristics and monitoring will continue until 2022 (10 yrs) or until transducer failure, whichever comes first. Upon completion of monitoring some of these sites will have over 25 years of total consistent data which should help with aquifer characterization. The objective of the monitoring wells is to provide a network of groundwater data that has a long baseline period, is reliable and hopefully fairly predictable under natural conditions. Moreover the majority of the sites have some type of analysis which predicts pressure changes based on variables with quantifiable and obtainable data. In addition most of these wells have demonstrated effects related to dewatering as a result of construction. This information may also prove valuable in the future when attempting to separate anomalous behavior from natural behavior.

Section 4 – Well Decommissioning discusses the procedure for securing these wells once the monitoring period is complete. It is anticipated that in the event there is a need to track groundwater pressure changes in an area, the wells can be re-activated and monitoring can continue. Of course there are many things which can affect the infrastructure or the data which could render the well(s) ineffective. Some of these issues are discussed in *Section 3 – Well Monitoring*.

Section 3. Well Monitoring

Scope and Purpose

Groundwater monitoring has been an integral part of this project from the early days of data acquisition and preliminary design beginning in the late 1980's and early 1990's. Of the fifty-nine geotechnical boreholes that were drilled on this project to characterize ground conditions for mining and tunnel construction, thirty-three we converted for use as groundwater monitoring sites. Twenty-five have been used in conjunction with Forest Service resource monitoring. Although groundwater monitoring was not the primary consideration for the site location in most instances, the data provided has proved invaluable to the Forest Service and to MWD during the life of the project. Retrofitting many of these wells, by MWD, with multi-level (nested) transducers allowed monitoring of aquifers at different levels enabling technical specialists to determine characteristics such as groundwater flow directions and storage changes with depth. In some cases the multi-completion piezometers provided information necessary to detect groundwater barriers which appeared to shield surface resources from groundwater effects in lower aquifers.

With the construction portion of the project completed the status of these wells becomes a question. Some of the wells have out lived their useful life and either they provide information that is no longer necessary for FS resource monitoring or the instrumentation no longer functions and cannot be replaced. In areas where recovery has occurred and resource monitoring is not anticipated to be beneficial in the foreseeable future full decommissioning of the infrastructure is anticipated. In some cases the equipment (most notably the vibrating wire transducers which are grouted in place) has failed beyond repair. These latter wells will also be decommissioned such that they will permanently be removed from service. Methods for decommissioning are described in Section 4.

Some of the monitoring wells however still provide valuable information to the FS and its technical staff. Of the thirty-three wells tracked by the FS over the life of this project eleven will continue to be monitored by the FS. Two additional wells, installed between 2001 and 2004, lie proximal to the east and to the northeast boundaries between the San Manuel Tribe and Forest Service lands. Monitoring will be discontinued in these two wells (Wells 957 and 959) after the 2012 monitoring season, but they will be decommissioned such that monitoring could continue in the future if needed.

Wells reserved for retention by the FS generally fall into two categories; those monitored for the primary purpose of ecological recovery and those monitored as part of the SERP. Of the eleven wells selected for additional monitoring, two of these wells (Well 950 on AHW and Well 958 on AHE) are primarily control wells. These two exhibit no effects from mining, but have been and are being used in conjunction with recovery monitoring at other sites.

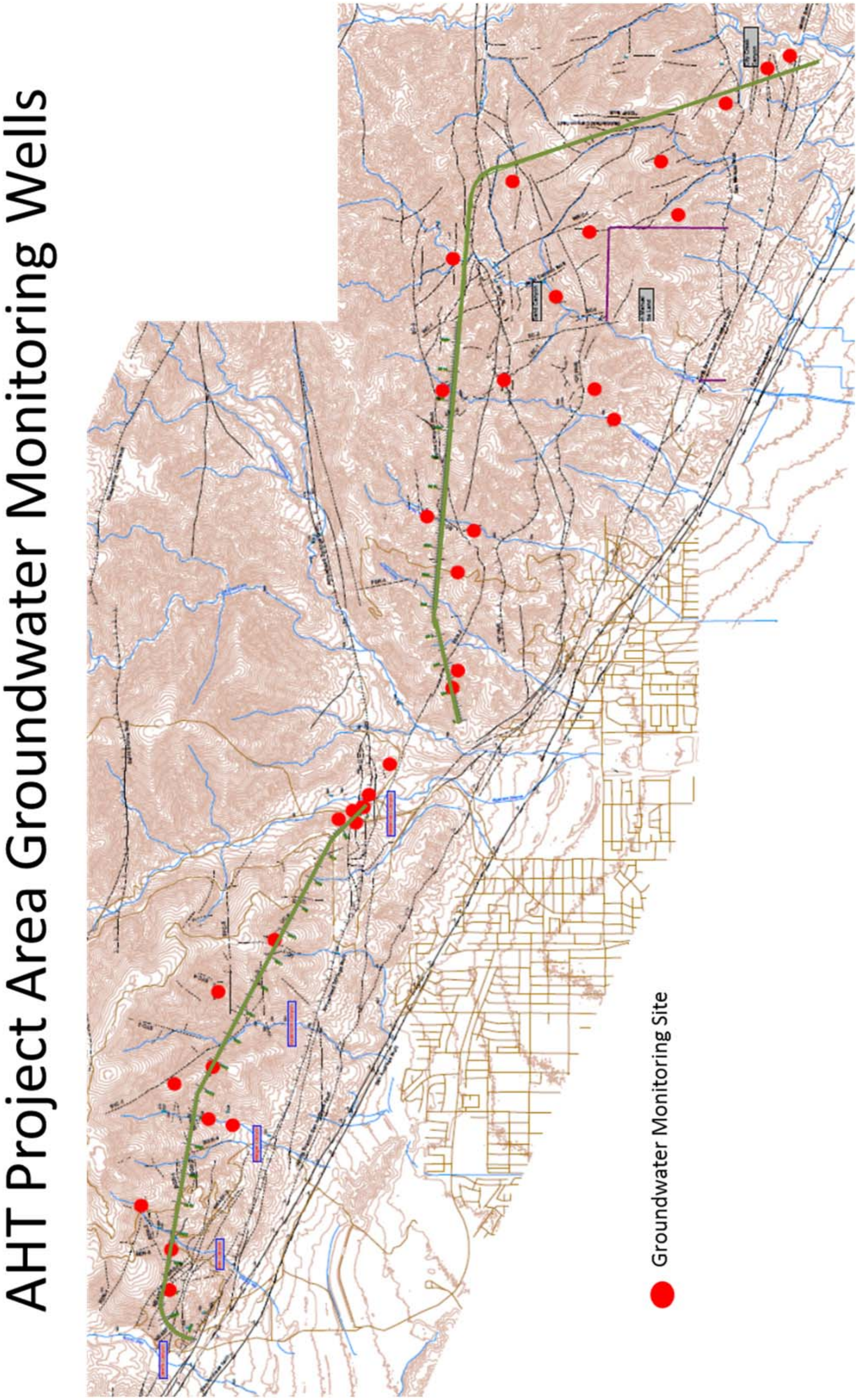


Figure 185. Topographic map showing all Arrowhead Tunnels Project groundwater monitoring wells relative to faults, hydrologic features and roads.

Seismic Event Response Plan (SERP) Monitoring

Most of the wells which will be monitored beyond 2012 are classified as SERP wells. Although many of these wells have not yet reached ecological recovery, their primary purpose after this year is implementation of the SERP should the need arise. On the Arrowhead Tunnels project the use of baseline monitoring information has proven to be an effective way to understand changes associated with groundwater systems. History has shown that a minimum of 10 years of data is generally necessary to characterize these systems. It is often difficult to understand cause and effect relationships associated with changes in state as most variables are at best inferred. In sites lacking sufficient data any aquifer characterization, variable supposition or correlative relationship is extremely marginal. If any of these wells are to be useful in the future, baseline information is of paramount importance. It is recommended that 10 years of consistent monitoring take place on all wells (through 2022). For a small number of wells this baseline information will initiate after ecological recovery has occurred. For most baseline data acquisition will occur as recovery continues to progress and some years beyond ecological recovery. For some wells such as Well 911 and the upper completion of Well 912 ecological recovery will most likely not occur within the foreseeable future and this next decade will allow understanding and characterization of the aquifer based on its current state.

The following description lists the SERP Wells and their rational for selection;

Arrowhead West SERP Wells

Well 900

This well is located along the North Branch of the San Andreas fault (AKA Mill Creek fault) just south and east of its splay from the San Andreas fault. It is proximal to the tunnel alignment near the west bend and not far from the portal. It has a good predictive model using Well 950 as a control. This site still exhibits impact from mining with predicted ecological recovery by about 2016.

Well 950

This well is located in the upper reaches of Ben canyon and is easily accessible from Cloudland Truck Trail. It appears to have experienced no mining related groundwater impacts and is used as a correlative variable in the Well 900 prediction model. It is a control well.

Well 951

Located on the northeast ridge above Badger Canyon, this site is well connected with the groundwater in the area and displayed initial effects while the TBM was half a mile to the east mining through the Sycamore-1 fault. Additionally there have been a number of micro-seismic events recorded since 1940 (Southern California Earthquake Center, 2011). A good fitting predictive model has been developed for this site; both upper and lower aquifer completions. Based on this analyses it is predicted ecological recovery will occur in the lower aquifer by 2018. The range for the upper aquifer is 2026 to 2060 but may be very dependent on recovery of the lower one.

Well 903

This is the eastern most well along the west tunnel alignment on FS land and is located on the UC-1 fault. This well appears to be hydrologically connected to aquifers in the vicinity of the Arrowhead Springs fault which crosses the alignment near the Strawberry portal. Micro-seismology is particularly high in this area (Bearmar, 2012). Further analysis still needs to be completed in order to determine ecological recovery in this well although rebound appears to be steady and predictable.

Arrowhead East SERP Wells

Well 908

Located in the bottom of Borea Canyon it is one of the western most wells proximal to the eastern tunnel alignment. This area is a convergence of several mapped faults including the Borea Canyon fault and the FSR-2 fault, which may be a splay off of the Arrowhead Springs fault. It is also located just north of the N fault. There is no micro-seismology recorded in Borea Canyon, however some has occurred in Harris Canyon to the west. Additionally the predictive model is associated with this site, although it will require a few summertime flow readings to be measured at Site 45. This site appears to have reached ecological recovery.

Well 911

Located mid-way between the tunnel alignment and the San Manuel Indian Reservation, the aquifer in this area experienced significant drawdown (approximately 250 feet) during the initial mining in City Creek and appears to have a high degree of connectivity to the rock surrounding the tunnel. Shortly after intersecting the San Manuel fault Well 911 and the upper piezometer in Well 912 experienced a rapid decline in pressure. The San Manuel fault is a reverse fault brought on by compressive forces along the east-west bend in the San Andreas and this fault offsets lithologically and chronologically different bedrock units. Well 911 has no recovery model as pre-impact baseline data was insufficient, however it is not anticipated that this well would reach ecological recovery in the foreseeable future. The baseline data will be used to characterize the aquifer in its current post-impact state.

Well 912

The upper and lower completions in this well appear to penetrate the San Manuel fault based on borehole lithology (Metropolitian Water District of Southern California, 2001). The upper unit contains quartz monzonite similar to rock located north of the fault while the lower unit lies within cataclastic quartz diorite material typical to the south. Both wells were impacted within the first six months of tunnel construction in 1998 and recovery has been slow. These wells also suffer from a lack of pre-impact baseline data and it is anticipated that current efforts will help to characterize current aquifer conditions.

Limitations

There are many variables which are currently difficult to quantify when projecting the usefulness of these SERP monitoring wells into the future. The first and most obvious is equipment serviceability. While data recorders and other surface equipment can be replaced, failure of the vibrating wire transducer signals the end of monitoring. This equipment will be permanently grouted into the borehole (as discussed in the next section on Decommissioning) with no chance of retrieval or replacement.

A changing climate could potentially induce substantial changes to the aquifer structure through significant recession brought on by diminished rainfall. Additionally, because storage parameters and surface connectivity can vary with head in the upper aquifers (those defined by the “water table”) large amounts of recharge in excess of what has been experienced over the extent of the baseline period can produce an uncharacteristic hydrograph.

In the past, earthquakes of substantial magnitude have caused pressure changes to groundwater in the project area. The Hector Mine Earthquake, mentioned in the mining history section, caused pressure drops in some wells and increases to others. Still some wells remained unaffected or manifested only the minutest perturbations. It is not known how groundwater would respond to an earthquake which would be sufficient to cause a rupture of the tunnel lining or if wells in the vicinity would still be serviceable. Still the use of several wells, including distal control wells which also show earthquake effects, may provide valuable information to project managers and technical specialists when evaluating next steps.

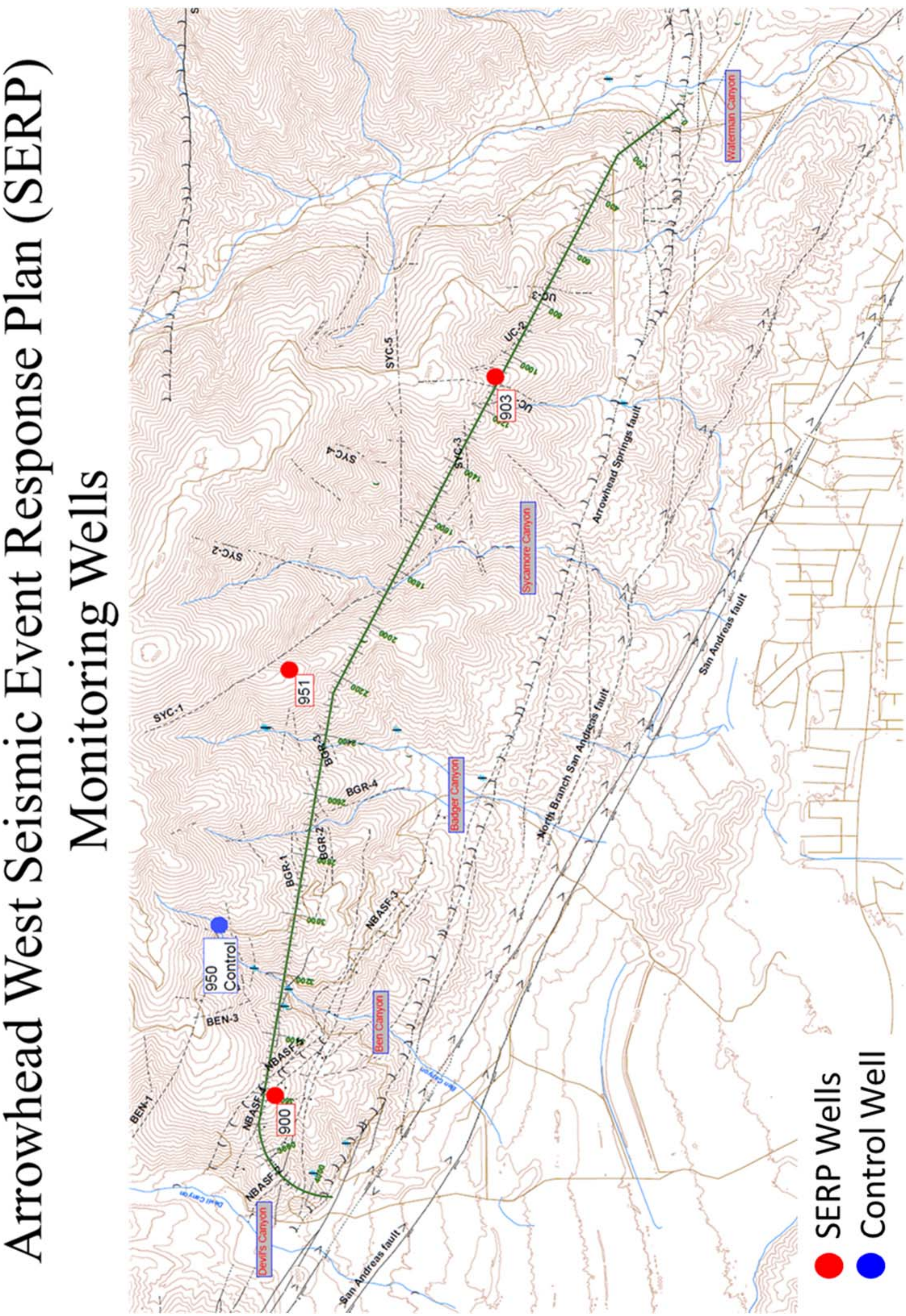


Figure 186. Topographic map showing the locations of wells used in SERP on Arrowhead West.

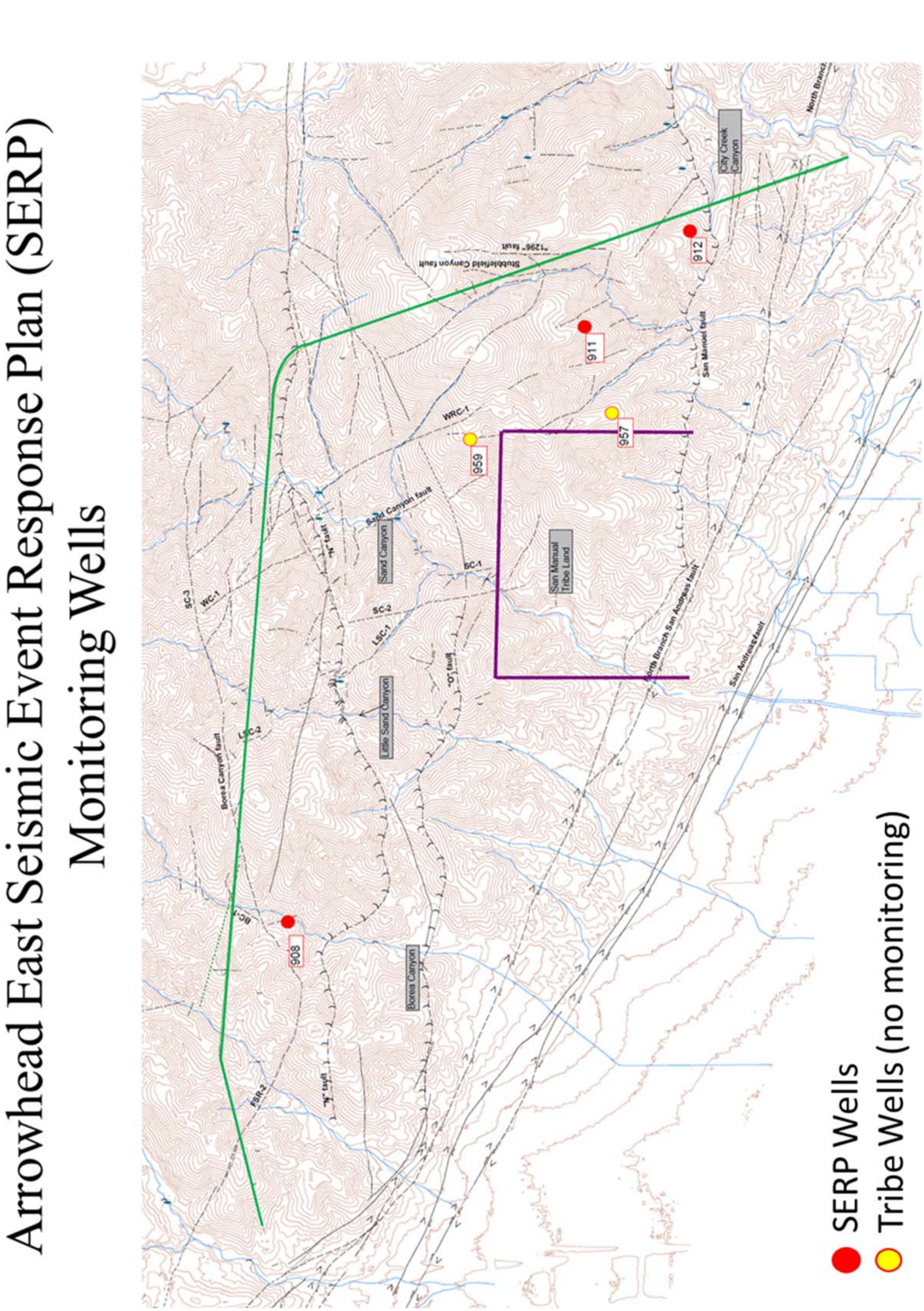


Figure 187. Topographic map showing the locations of wells used in SERP on Arrowhead East.

Recovery Monitoring

The Forest Service is a multiple use resource management agency. One of the resources the FS is responsible for managing is water, including groundwater. Part of this management process is the characterization of aquifers which may potentially be adversely affected through activities on or around FS lands. Monitoring an affected aquifer to recovery or near recovery allows land managers to make informed decisions about proposed future activities in an area, especially when considering cumulative effects. Many groundwater sites have been proposed for continued monitoring as part of the SERP. Monitoring of most of these sites will continue through and past recovery. There are a few sites which still have impacts to groundwater in areas of importance yet for various reasons are not important to the SERP. These sites were proposed and accepted as groundwater recovery monitoring sites. The monitoring time for these sites varies and hopefully they will be monitored to ecological recovery; which may not coincide with the decadal monitoring associated with the SERP wells. In most cases this monitoring is anticipated to be approximately 6 years or less. The attached map shows the recovery monitoring wells and their anticipated time to ecological recovery.

The following description lists the Recovery Monitoring Wells and their rational for selection:

Arrowhead West Recovery Monitoring Wells

<u>Well 952</u>

Only the lower completion will be monitored as there was no manifestation of construction related impacts in the upper portion of this monitoring well. This will be the only Recovery Monitoring Well on Arrowhead West. This site is located on the northeast hill slope above Sycamore Canyon. There appears to be good connectivity to Well 903, ½-mile to the southeast, as it responded to tunneling within weeks of Well 903 potentially through the marble layers. Micro-seismicity is high, but there are already two wells, one to the east and one to the west, that are monitoring groundwater in this area, therefore it would be redundant as a SERP Well. Groundwater impacts to this area were significant (greater than 100 feet initially) and ecological recovery has not yet taken place, but is expected to be within a few feet by 2020.

Arrowhead East Recovery Monitoring Wells

<u>Well 954</u>

Located in the upper reaches of Little Sand Canyon, both upper and lower completions were significantly impacted with the lower one displaying an initial drop of almost 200 feet. Early rebound corrected the deficit within the first year, but impacts to groundwater remain in both regions of the aquifer. This is a biologically significant canyon with listed species and their habitat identified in the lower reaches. As such this canyon was under intense observation by the FS. It appears that down canyon effects to both ground and surface water are no longer evident and only the upper canyon still manifests effects of tunnel construction. These effects are quickly diminishing and full ecological recovery is expected to take place within 5 years or less. A recovery model of this site has been constructed using the lower completion in un-impacted Well 958 at the lower end of the canyon.

Well 956

Sand Canyon has been intensely scrutinized by MWD, the FS and San Manuel tribe over the course of the project, especially from 2006 on. The canyon is generally divided into an upper, mid and lower canyon with the lower canyon on the San Manuel Tribe lands. Well 956 has long been recognized as representative of the upper canyon groundwater resources. During the late summer, surface flow between the upper and mid canyons is often disconnected, but groundwater generally provides an infusion which maintains small pools for aquatic species and wildlife in side canyons even when the main channel is dry. It is therefore a valuable resource for the upper canyon groundwater dependent ecosystem. The upper and lower portions of the aquifer are strongly connected with groundwater generally moving downward through the system. Rebound has been steady and is still taking place with the gap between construction related effects to the groundwater and ecological recovery quickly diminishing. As with Well 954 in Little Sand Canyon, a recovery model has been constructed using Well 958. Full ecological recovery is predicted to be complete by 2018.

Well 958

Located in the lower portion of Little Sand Canyon and south of the O fault, this remains one of the few wells that did not manifest tunneling impacts. This well also borders San Manuel Reservation to the west and is a control site. The lower completion is used in the recovery analyses for Wells 954 and 956 and it is anticipated that monitoring will continue in this well through the completion of recovery in the other two groundwater sites.

Limitations

As with the SERP wells there are factors which may reduce the utility of these wells in performance of their objective. Equipment failure is of primary concern, but rapid and significant changes to the monitored aquifer would potentially render the associated recovery analyses invalid.

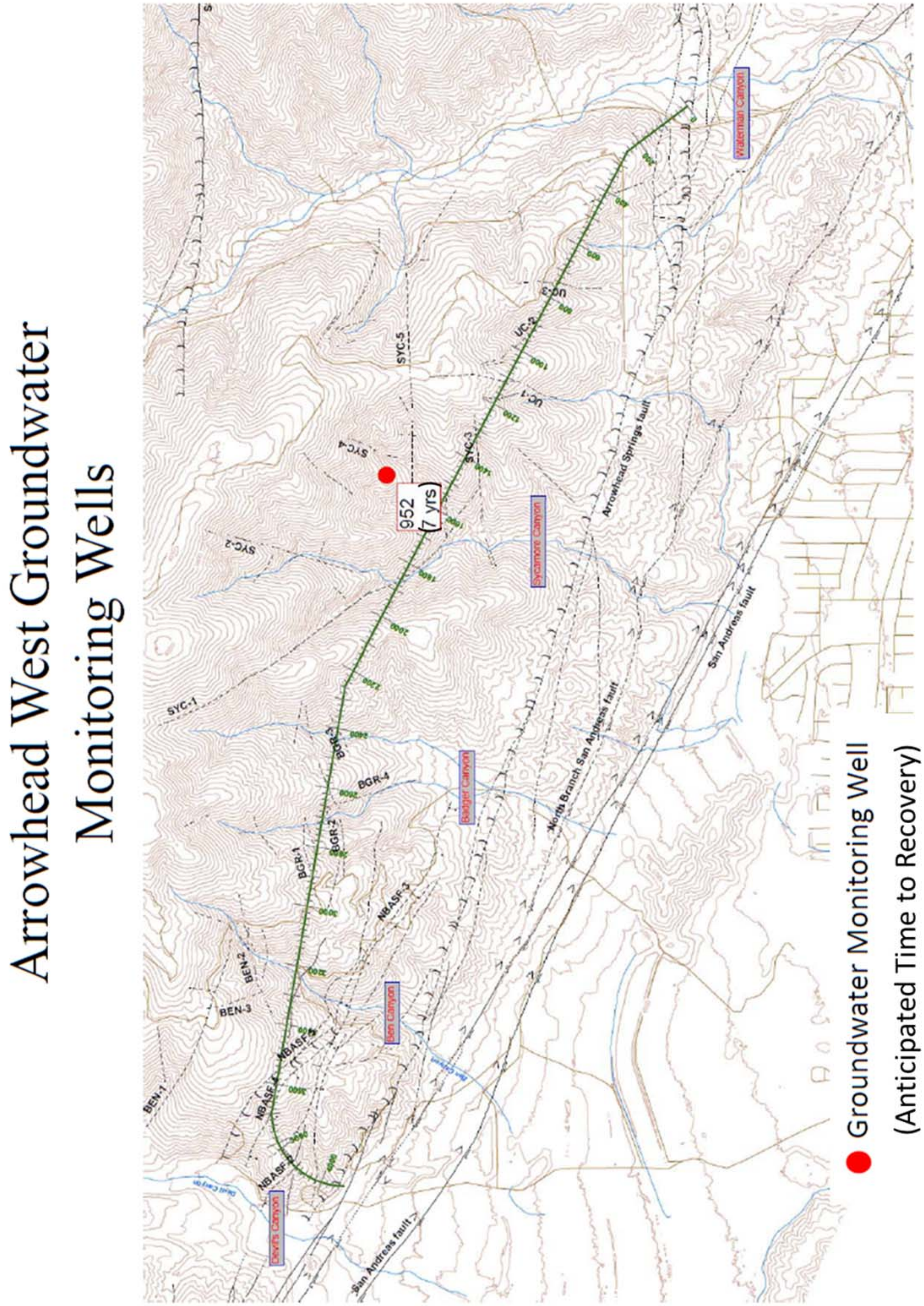


Figure 188. Topographic map showing the locations of remaining non-SERP monitoring wells and anticipated length of monitoring on Arrowhead West

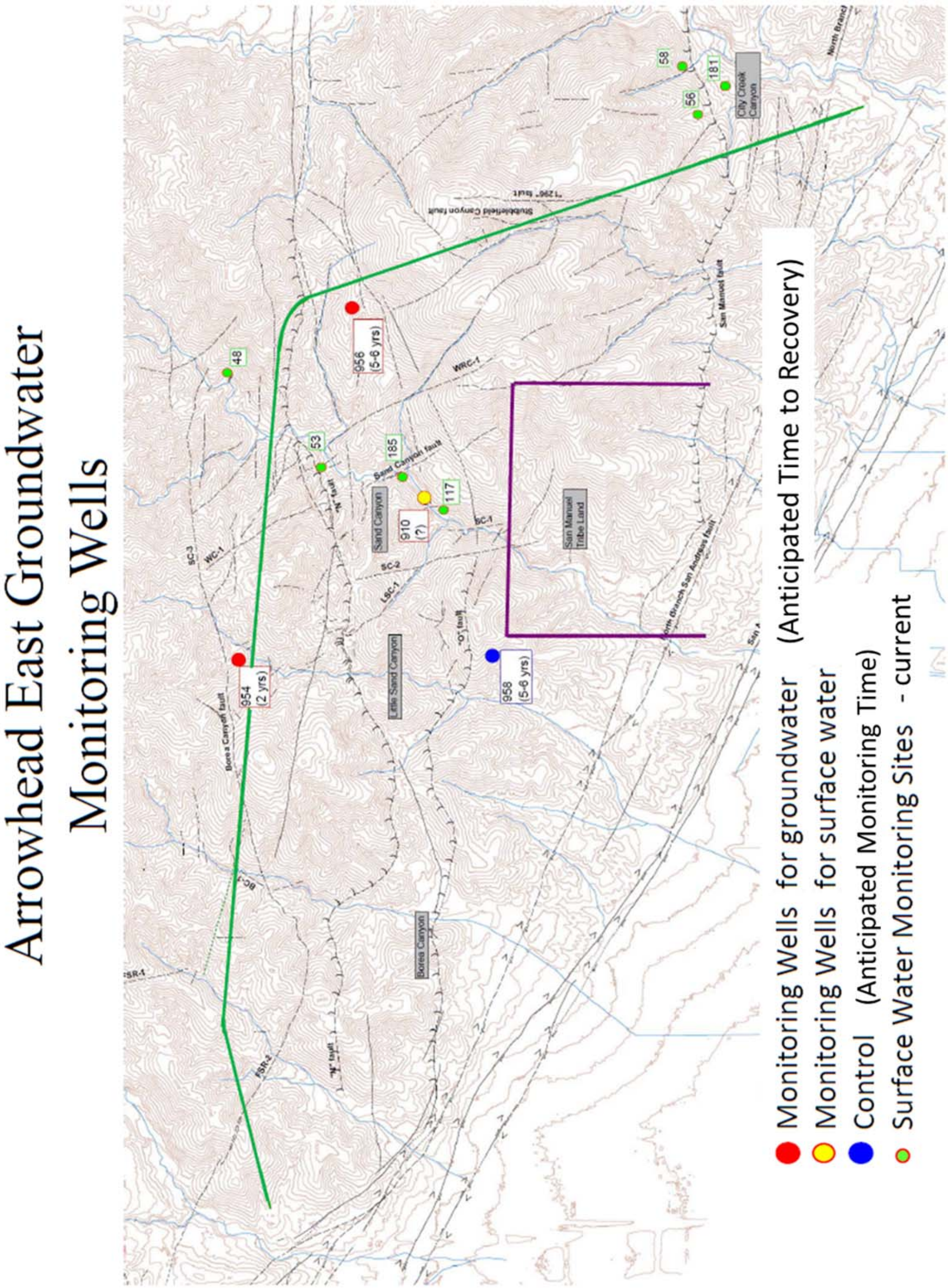


Figure 189. Topographic map showing the locations of remaining non-SERP monitoring wells and anticipated length of monitoring on Arrowhead East

Groundwater Monitoring Process

In general, the actual monitoring of most of the groundwater sites will occur remotely. Boreholes will be outfitted with fresh instrumentation which allows the sites to be telemetered and the data downloaded remotely (the details of the well retrofits are covered in the next section on Decommissioning). Monthly remote downloading of the data will occur by the province geotechnical engineer or appointed responsible staff member. Updates to models will occur at minimum annually and a report shall be generated which can be forwarded to the San Bernardino National Forest Special Uses Permit Administrator and other members of the Forest staff as requested. Several sites will not be available for remote download due to their proximity to publically traveled roads (Wells 950 & 958). History has shown that sites which are visible and easily accessible become public nuisance sites with high occurrences of vandalism. These sites will therefore be downloaded manually at such an interval as to not exceed the maximum capacity of the data recorder.

At a frequency of at least once per year each site will be visited by the geotechnical engineer or one of her trained staff to inspect and/or maintain equipment and to maintain access. Most of these sites are remote and it is anticipated that only one to two sites can be accessed in a day’s time. Therefore a bi-monthly trip would allow several sites to be accessed while minimizing travel.

Once monitoring is complete at a particular site further decommissioning will be accomplished as described in Section 4.

Section 4. Well Decommissioning

All groundwater monitoring sites on FS lands will be decommissioned as part of the existing Special Uses Permit for Construction, Use and Maintenance of the Inland Feeder Project (Arrowhead Tunnels portion). For the purposes of this document, *decommissioning* refers to the process by which the monitoring wells are removed from service.

Within the context of this work there are several levels of decommissioning but upon conclusion of the current permit all wells will comply with the same basic premise; the potential for borehole related point source contamination of the aquifer will be removed.

Immediate Decommissioning - Destruction

Wells which have been excluded in the discussions above relating to SERP Monitoring Wells (including San Manuel Reservation boundary wells 957 & 959) or Recovery Monitoring Wells are scheduled for immediate decommissioning. Decommissioning will take place in the form of destruction and is permitted by the County of San Bernardino Department of Public Health, Environmental Health Services (DEHS). While DEHS is the enforcing agency governing destruction of monitoring wells in San Bernardino County, they refer to California Department of Water Resources (DWR) Monitoring Well Standards for destruction guidelines. For wells which have been constructed according to DWR standards for water wells or monitoring wells and are not located in areas of known or potential pollution or contamination, destruction generally involves the following (California Department of Water Resources - Southern District, 2002):

1. All wells will be verified free of obstructing material including pumps, monitoring equipment, and any debris that would block or inhibit sealing agents
2. Wells in unconsolidated alluvium, unconfined aquifer – upper 20 feet will be filled with suitable sealing material; remainder will be fill with suitable sealing material or suitable fill.
3. Wells penetrating several aquifers or formations – In all cases the upper 20 feet will be filled with suitable sealing material; "…*In areas where the interchange of water between aquifers will result in a significant deterioration of the quality of water in one or more aquifers, or will result in a loss of artesian pressure, the well shall be filled and sealed so as to prevent such interchange… To prevent the vertical movement of water from the producing formation, impervious material must be placed opposite confining formations above and below the producing formations for a distance of 10 feet or more.*" (California Department of Water Resources - Southern District, 2002).
4. Well penetrating fractured rock conditions just below surface – portions opposite this layer are to be filled with sand-cement grout, neat cement or concrete. If penetrating fractured rock conditions extend a considerable way, this sealing material can alternate with crushed rock.
5. Wells penetrating consolidated formations or non-fractured rock at and near surface – upper 20 feet will be filled with sealing material, the remainder with clay or suitable inorganic material.
6. Wells that have had permanent transducer installations and are currently sealed to the surface with cement or grout shall have all external equipment removed.

In all cases above grade infrastructure will be removed to a depth of at least 18 inches (DEHS requirements vary) and the area will be restored to its natural character including a grade which will not concentrate flow and create erosion issues.

Monitoring Wells Scheduled for Immediate Decommissioning:

<u>AHW</u>

- Well 901 – No construction effects
- Well 195 – Recovered
- Well 196 – Recovered
- Well 902 – Poor data quality; potentially failing transducer

<u>AHE</u>

- Well 907 - Recovered
- Well 953 – At or close to recovery; using Well 908
- Well 909 - Recovered
- Well 178 (Private land) - No construction effects
- Well 910 - No construction effects
- Well 955 (artesian) – Transducer failure
- Well 913 – Recovered
- Well 199 – Recovered

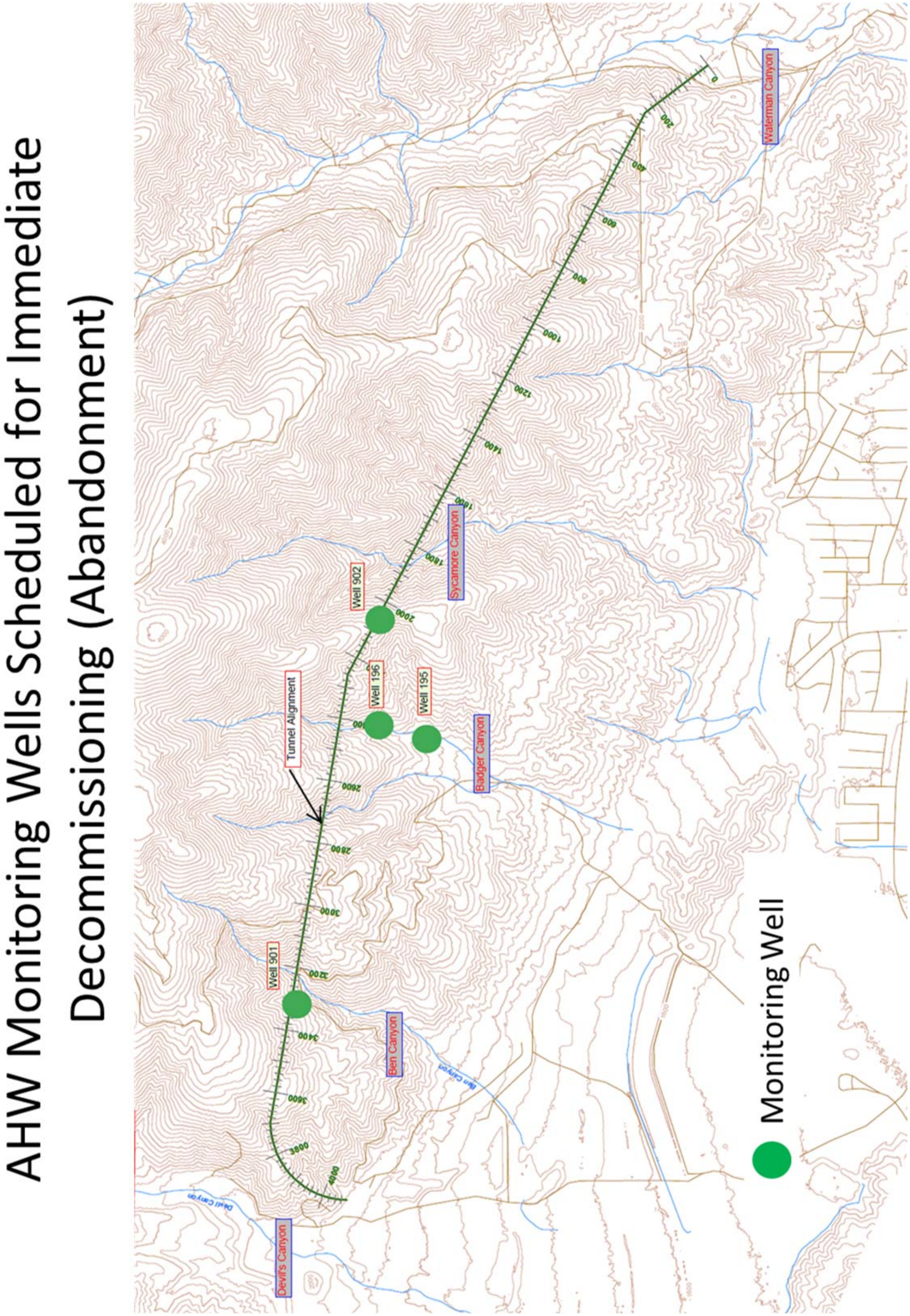


Figure 190. Topographic map showing the locations of monitoring wells which will be decommissioned in 2012 and 2013 on Arrowhead West.

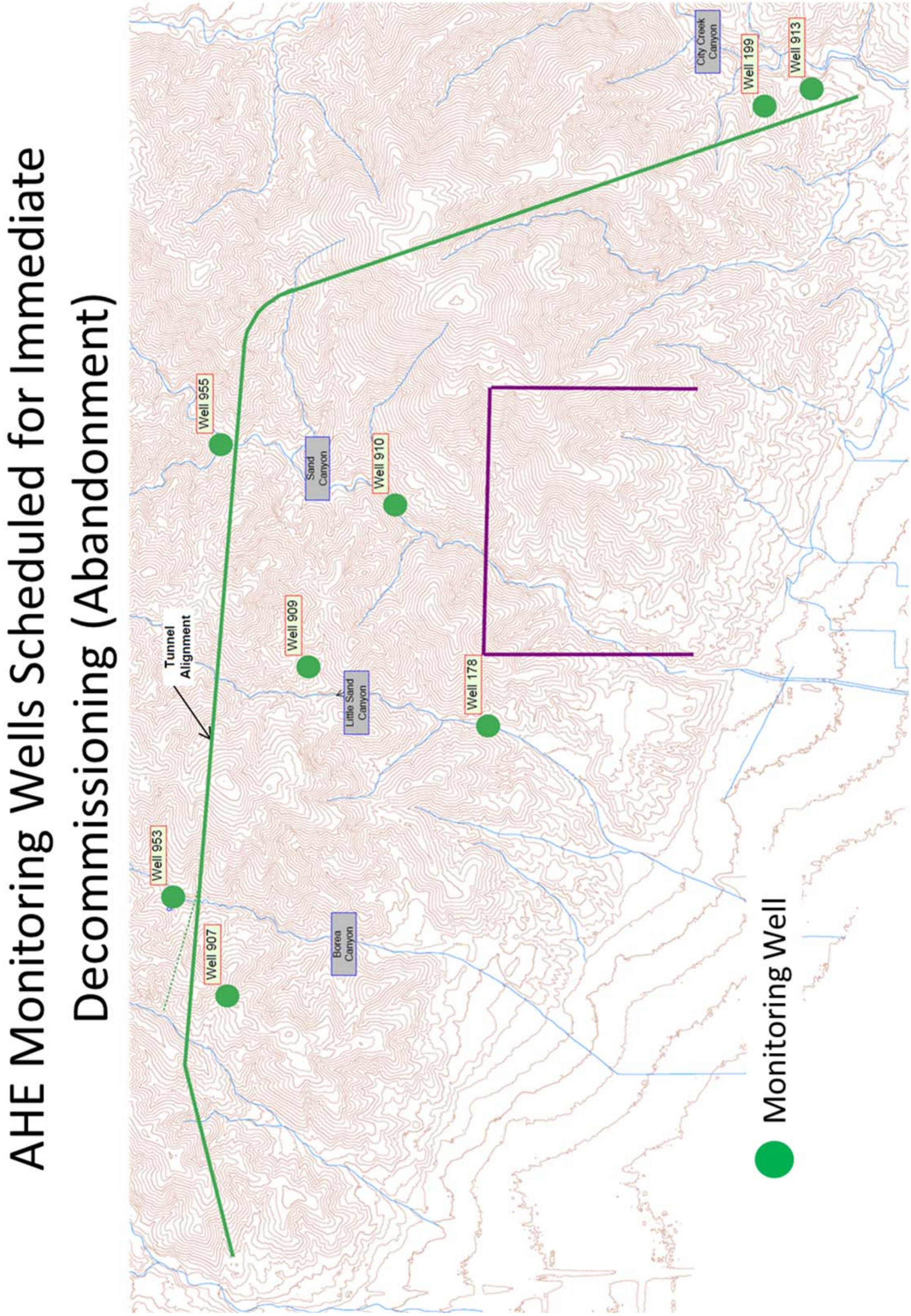


Figure 191. Topographic map showing the locations of monitoring wells which will be decommissioned in 2012 and 2013 on Arrowhead East.

Delayed Decommissioning

Wells reserved for current and future monitoring will be prepared for use by MWD under the current special uses permit for construction and maintenance of the Arrowhead Tunnels Project. Preparations vary by monitoring well but generally include:

1. Wells which currently have permanently installed transducer equipment and are sealed to the surface will be inspected to ensure above grade transducer wires are in good repair.
2. Wells constructed in accordance with DWR standards for water wells or monitoring wells and having open standpipes will be fitted with new transducer equipment and the borehole will be backfilled with clean sand or gravel to a point not less than 20 feet from the surface. From the surface to a point at least 20 feet below grade a suitable sealing material (per DWR standards) will be installed within the borehole.
3. Wells having multiple completions and a combination of a sealed transducer and an open borehole will be completed as in item 2 above.
4. All monitoring wells, with the exception of two, will be fitted with new data collection equipment. The exceptions are Wells 957 and 959.
5. A new telemetry network will be constructed for the purpose of remote data collection from all but four wells. The four exceptions are Wells 950, 958, 957 and 959.
6. Wells 957 and 959 will be decommissioned such that cables extending from the borehole will be secured with grease caps or other methods to prevent corrosion and stored inside the conductor casing. All surface equipment associated with the site (excluding borehole conductor casing and telemetry cables) will be removed and the area will be returned to its natural character. Above grade infrastructure such as the conductor casing will remain in place.
7. New accounts will be set up with the local mobile carrier for accessing digital modems. These accounts will be transferred to the Forest Service upon termination of the current Special Uses Permit.
8. MWD will ensure the workability of all equipment and systems prior to termination of the current Special Uses Permit.

Once the new Special Uses Permit for Operations and Maintenance of the Arrowhead Tunnels Project is in effect, the Forest Service geotechnical engineer will assume responsibility for well monitoring and equipment maintenance as outlined in Section 3. MWD has agreed to cover the cost of monitoring and maintenance through a cost recovery agreement with the Forest Service.

Once monitoring of a well is complete decommissioning can occur. All surface equipment associated with the site (excluding borehole conductor casing and telemetry cables) will be removed and stored for future use. All cables extending from the borehole will be secured with grease caps or other methods to prevent corrosion and stored inside the conductor casing. Most sites are remote and above grade conductor casing will not provide a hazard to humans or wildlife.

In the unlikely event that one or more of the SERP wells needs to be activated, the process will be reversed using available equipment. Initially data will need to be downloaded manually unless or until future project managers decide remote access to data is beneficial and desirable.

Schedule

Decommissioning and activities associated with delayed decommissioning are scheduled to begin after this current 2012 monitoring season, presumably in October. Plans are already underway and MWD is preparing to mobilize. A number of activities will require FS coordination and may have to occur within or outside certain windows. For instance, most sites will be accessed by helicopter. Coordination will need to occur with FS aviation to ensure there will be no conflict with other work or with fires. Some sites in canyon bottoms or near sensitive species habitat may need to have work postponed until a clearance is received from the FS biology staff. It is anticipated that all work will be complete and systems will be in place by the summer of 2013 or earlier.

Section 5. Effects

With the completion of the impervious steel liner in mid-2009 and subsequent connection to the pipelines at the portals, both sections of the Arrowhead Tunnels are effectively sealed. Water started flowing from Lake Silverwood to Diamond Valley Reservoir in mid-2010 and now flows at a rate of approximately 1000 cfs (Cynthisa, 2010). All four portals which connect pipeline to tunnel are off National Forest lands and there are no openings or other conduits within the tunnels themselves. They are essentially solid steel tubes from portal to portal. There should be no groundwater resource related effects to National Forest lands resulting from normal operations and maintenance of the Arrowhead Tunnels Project under the new Special Uses Permit. It is anticipated that tunnel inspections will occur periodically (approximately every 5 to 10 years) which will require shutdown of normal operations and drainage of the tunnels, but this activity will initiate off federal lands and should not affect forest activities or resources.

This said there are two operations which may have some effect on FS resources. The first is related to the current permit and lingering effects. Periodic inspections and maintenance of monitoring wells will in most cases require access of remote sites. It is anticipated that monitoring wells will generally be approached on foot by one to two individuals a couple of times a year. During the course of each visit a small p-line will be maintained using a Swedish brush axe in denser vegetation. It is hoped that maintenance of this kind will allow continued passage year after year. As the boreholes will be effectively sealed from the surface to a depth of at least 20 feet there should be no chance of groundwater contamination from the site. Some pruning of vegetation will occur around the borehole for convenience and vegetation blocking antennae or solar cells will have to be trimmed. Once monitoring has discontinued at a site, it will be decommissioned according to Section 4. All above grade equipment will be packed out and the site will be restored by the FS responsible staff. No other effects are anticipated as a result of the monitoring process.

A large magnitude earthquake with displacement along a fault intersecting a section of tunnel could potentially generate enough force to cause shearing or a breach in the steel liner. Based on current knowledge of local seismicity the possibility is considered very remote, but has been addressed in Section 2. Should such an event occur along the tunnel alignment in an area of high groundwater head, there is potential for inflow in the damaged area. The tunnel is designed to operate under open channel flow so total head in the tunnel is basically pressure head and in much of the alignment is lower than total head surrounding the tunnel. This situation could allow water from the surrounding aquifer to flow into the tunnel in the case of a lining breach. Should this happen, there is the potential for impact to groundwater resources. The amount of impact is variable and depends on overall head differential, the severity of the breach and the amount of elapsed time until inflows can be arrested. If water flowing into the tunnel is significant and in an area of connectivity to surface resources the potential for surface water impacts exists as well. The SERP has been created in response to this potential. Even though the potential is considered to be quite remote the risk to valuable forest resources could be high if leakage continues unimpeded and no monitoring of resources occurs.

Appendices

Appendix A. – Bibliography

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