Janet L. Miller, Deputy Counsel (Bar No. 011963)
Nicole D. Klobas, Deputy Counsel (Bar No. 021350)
Arizona Department of Water Resources
Legal Division
3550 N. Central Ave.
Phoenix, AZ 85012
Telephone: (602) 771-8472
Fax: (602) 771-8686
jlmiller@azwater.gov
ndklobas@azwater.gov

IN THE SUPERIOR COURT OF THE STATE OF ARIZONA

IN AND FOR MARICOPA COUNTY

IN RE THE GENERAL ADJUDICATION OF ALL RIGHTS TO USE WATER IN THE GILA RIVER SYSTEM AND SOURCE	W-1 (Salt), W-2 (Verde), W-3 (Upper Gila), and W-4 (San Pedro) (Consolidated) (Assigned to Hon. Mark H. Brain) **ARIZONA DEPARTMENT OF WATER RESOURCES' NOTICE OF FILING THIRD PROGRESS REPORT**

DESCRIPTIVE SUMMARY: The Arizona Department of Water Resources hereby files its third progress report concerning certain work undertaken in the Gila River adjudication for the San Pedro River watershed.

NUMBER OF PAGES: Three (+ 52-page attachment)

DATE OF FILING: April 4, 2016

Attached is the third progress report by the Arizona Department of Water Resources ("ADWR") filed since April 15, 2015 concerning implementation of a cone of a depression test in the San Pedro River watershed, as well as other work undertaken by ADWR in the Gila River and Little Colorado River adjudications. On April 15, 2015, ADWR filed in the Gila River adjudication a progress report concerning the development of a cone of depression test that would be applied to wells located outside of the subflow zone in the San Pedro River watershed[1] to determine whether the cones of depression would result in a 0.1 foot drawdown at the boundary of the subflow zone ("Initial Progress Report"). On January 28, 2016, ADWR filed another progress report concerning the continuing development of a cone of depression test as well as other adjudication-related activities in both the Gila and Little Colorado River adjudications ("Second Progress Report").

In the attachment hereto, ADWR presents its next progress report that describes certain methodologies that ADWR proposes to use for cone of depression testing in the San Pedro River watershed together with other work being undertaken by ADWR for the San Pedro River watershed ("Third Progress Report"). This report addresses the following: (1) the reliability and quality of data available for cone of depression testing, (2) the suitability of certain models for cone of depression testing, (3) the delineation of the subflow zone for mountain front streams, and (4) the development of abstracts of proposed water rights for *de minimis* uses.

Over the next several months, ADWR anticipates that further progress will be made on the work described in this report. ADWR intends to issue a report describing procedures that will be used for cone of depression testing by the end of this calendar year. ADWR's preliminary work on mountain front streams has been completed in large part, but ADWR's issuance of a report that delineates the subflow zone for mountain front streams will depend on when the Arizona Geological Survey will be able to conduct the necessary site investigations and mapping. ADWR will continue to take steps to develop a fully functional Geographic Information System that can be used to

[1] The delineation of the subflow zone for the San Pedro River watershed is before the Court for decision.

create abstracts of water rights for *de minimis* uses in the San Pedro River watershed, to the extent that it does not interfere with ADWR's other adjudication-related work.

DATED this 4th day of April, 2016.

ARIZONA DEPARTMENT OF WATER RESOURCES

Janet L. Miller, Deputy Counsel
Nicole D. Klobas, Deputy Counsel

ORIGINAL of the foregoing sent by first-class mail this 4th day of April, 2016, to:

Clerk of the Superior Court for Maricopa County
Attention: Water Case
601 W. Jackson Street
Phoenix, AZ 85003

COPIES of the foregoing sent by first-class mail on this 4th day of April, 2016, to:

Honorable Mark H. Brain
Maricopa County Superior Court
Central Court Building, Suite 12A
201 West Jefferson
Phoenix, AZ 85003-2205

Special Master Susan Ward Harris
Maricopa County Superior Court
Central Court Building, Suite 3A
Phoenix, AZ 85003-2205

COPIES of the foregoing notice sent by first-class mail this 4th day of April, 2016 to all parties on the court-approved mailing list for W-1, W-2, W-3, W-4 (consolidated).

ATTACHMENT

THIRD PROGRESS REPORT

This is the Third Progress Report filed by the Arizona Department of Water Resources ("ADWR" or "Department") since April 15, 2015 concerning certain work undertaken by the ADWR in the Gila River and Little Colorado River adjudications. This report addresses the following: (1) the reliability and quality of data available for cone of depression testing, (2) the suitability of certain models for cone of depression testing, (3) the delineation of the subflow zone for mountain front streams, and (4) the development of abstracts of proposed water rights for *de minimis* uses.

I. DATA AVAILABLE FOR CONE OF DEPRESSION TESTS

By order dated September 15, 2005 (filed October 4 2005), Judge Ballinger, then presiding over the Gila River adjudication, directed ADWR to "utilize a *reasonably reliable* steady state model for use in evaluating the effect of cones of depression." 2005 Order at 42, ¶ 7 (emphasis added). The reliability and types of data required for steady state cone of depression testing are addressed below.

A. Reliability of Data

In response to ADWR's Initial Progress Report, ADWR received numerous comments from the parties regarding the reliability of the data to be used in cone of depression testing. The discussion below provides additional information regarding the types of data and the methodology for using that data in the cone of depression testing.

The issue of data quality and reliability was addressed at length by Judge Ballinger in his 2005 Order regarding cone of depression testing. Judge Ballinger acknowledged that there are inherent limitations in the data necessary for steady state cone of depression testing, but that ADWR must employ reasonable and focused processes to ensure that highly reliable data is obtained and utilized. The Court stated:

> In evaluating the Department's proposed cone of depression test, the Court must keep in mind both that absolute accurate quantification is not possible, and a hodgepodge system of uncertain reliability is not acceptable. Even though some requisite data for accurate cone of depression measurements 'will often be either unknown or poorly known,' ADWR is charged with adopting a test that is 'realistically adaptable to the field' and measurement standards that are 'the least expensive and delay-causing' efficient methods that provide 'a high degree of reliability.' In judging whether the Department has satisfied these directions, the Court accepts that '[c]onducting cone of depression tests requires numerous assumptions and considerable judgment and, in many cases, the test results will only provide a rough approximation of actual field conditions.'

2005 Order at 28-29 (citing ADWR 2002 subflow report).

The Court further directed ADWR to implement a "focused and reasonable mechanism for obtaining highly reliable data" to satisfy the requirements of *Gila IV*.[1] The Court stated:

> The Special Master's recommendation with respect to cone of depression measurements addresses the objector's concerns by making clear that ADWR's proposed methods will satisfy the requirements of *Gila IV* and the 'highly probable' clear and convincing evidentiary standard only if the Department implements a focused and reasonable mechanism for obtaining highly reliable data which are used in setting model parameters.

2005 Order at 30.

Thus, the Court acknowledged that absolute or perfect data is not a realistic expectation for cone of depression testing, but that a focused and reasonable mechanism for obtaining highly reliable data must be used. The Court directed ADWR to utilize efficient methods that are the least expensive and delay-causing while providing a high degree of reliability.

Data required for steady state cone of depression testing include: 1) steady-state pumping rates; 2) well locations; and 3) aquifer parameters. ADWR has developed what

[1] *In re the General Adjudication of all Rights to Use Water in the Gila River System and Source*, 198 Ariz. 330, 9 P.3d 1069 (2000).

it believes is a focused and reasonable mechanism for obtaining highly reliable data for each of these general data categories. The process for each data category is summarized below.

B. Steady-State Pumping Rate

ADWR received comments from the parties regarding how ADWR proposed to determine the pumping rate to be assigned to each well for purposes of cone of depression testing. In order to conduct cone of depression testing, a steady-state pumping rate must be determined for each well based on a continuous "24/7" rate.[2] ADWR will not use reported or claimed pumping rates, such as 35 gpm for an exempt well, as these typically reflect a maximum pumping rate for a specified amount of time but generally not on a continuous basis.

ADWR's process for determining the steady-state pumping rate of each well will involve two steps. First, ADWR will determine the total annual volume (in acre-feet) of water pumped to supply one or more uses for each well in the San Pedro River watershed, including wells reported in the Final San Pedro River Watershed Hydrographic Survey Report ("San Pedro HSR"). Also included will be new or replacement wells, as described in ADWR's records, that have been installed since the publication of the San Pedro HSR that provide water to uses described within the HSR. New and replacement wells will be added to the maps contained in Volume 9 of the San Pedro HSR and will be analyzed using the cone of depression test.

Second, ADWR will convert the total annual volume of water pumped by each well into a steady-state flow rate in gallons per minute (gpm) using the following formula:

Pumping Rate (gpm) = Total Annual Volume (acre-feet) x 325,851 gallons/365 days/1,440 minutes.

[2] "24/7" refers to a well that is pumping 24 hours a day, 7 days a week.

The total annual volume necessary for this equation will be determined as described below.

C. Total Annual Volume of Water

ADWR intends to base its methodology for determining the total annual volume of water for each well on quantification procedures approved by Judge Goodfarb, who presided over the Gila River adjudication in 1991 when the San Pedro HSR was issued. Judge Goodfarb specified the types of water uses and quantities to be reported in HSRs, and approved ADWR's procedures for quantifying those water uses. (San Pedro HSR, Vol. 1, App. C at C-1 to C-3). The primary water uses that can be supplied by water pumped from a well are: irrigation, domestic, industrial, mining, municipal, and stockwatering.

1. <u>Irrigation Uses</u>

ADWR quantified irrigation uses in the San Pedro HSR based on the following court-approved procedures:

- The quantities of use specified by existing court decrees;
- The estimated maximum observed use during the last five-year period of ADWR's investigation; and
- A regional use application of uniform water duties within regional farming conditions derived from average cropping patterns and efficiencies.

(*Id*. at C-1.) In response to comments to the Preliminary San Pedro HSR, ADWR added the following quantification procedure that went beyond the court order:

- The Maximum Potential quantity based on the highest water using crop (generally alfalfa) that could be grown.

A detailed description of the irrigation quantification procedures is presented in Appendix C of Volume 1 of the San Pedro HSR at pages C-4 through C-79.

For cone of depression testing, ADWR plans to utilize the estimated maximum observed use during the last five-year period of ADWR's HSR investigation as the total annual volume for an irrigation use. ADWR believes that the estimated maximum observed use is the most reasonable quantification of actual use.

2. Domestic Uses

For the San Pedro HSR, ADWR found that the majority of domestic uses in the San Pedro River Watershed were supplied by groundwater and have irrigation of less than two acres. ADWR was not required to determine quantities of use for these domestic uses. Rather, ADWR reported quantities of use for irrigation of greater than one-tenth of an acre associated with domestic uses supplied by surface water. This irrigation is reported in the San Pedro HSR as "other irrigation" and only applies to irrigation by surface water (*Id*. at C-88). Therefore, it is not applicable to the determination of total annual volume of use from wells.

Although the San Pedro HSR did not include a quantification of domestic uses supplied by water withdrawn from a well, Judge Goodfarb did describe a methodology that could be used if domestic uses were reported in an HSR (*Id*. at C-1). By decision dated March 17, 1989 ("1989 Decision"), referenced in Appendix C to the San Pedro HSR, Judge Goodfarb indicated that ADWR could use a maximum of 10 acre-feet for each domestic use based on an area of ownership or lease of up to 2 acres, including gardens, lawns, and pastures. Under this methodology, the 10 acre-feet quantity would be reduced in proportion to the size of the irrigated parcel so that a single acre would have a reported 5 acre-foot water duty. This decision further stated that reductions in quantity could be based on area reductions down to one-tenth of an acre. (1989 Decision at 7-8).

ADWR plans to utilize the quantification procedures for domestic water uses specified in Judge Goodfarb's 1989 Decision. For domestic uses supplied by water pumped from a well, ADWR will use 10 acre-feet as the total annual volume of water on an irrigated parcel of land up to 2 acres and reduce the total quantity in proportion to the size of the irrigated parcel, except for domestic *de minimis* water use discussed below.

By order dated September 27, 2002 in the *In Re Sands Group of Cases* ("2002 Order"), Judge Ballinger adopted the definition of domestic *de minimis* water use set forth by Special Master Thorson in a Memorandum Decision dated November 14, 1994 ("1994 *De Minimis* Decision"). (2002 Order, ¶ 1 at 5.) Special Master Thorson defined domestic *de minimis* uses as individual domestic uses for a single family household from a well that serves household purposes and outdoor activities on adjacent land not exceeding 0.2 acres. Special Master Thorson further determined that the most reasonable estimate of these individual self-supplied domestic uses is 1.0 acre-feet per year, based on a typical household of three persons and irrigation and watering of pets and animals on an adjoining 0.2 acres of land. (1994 *De Minimis* Decision, Finding of Fact No. 52 at 26). For cone of depression purposes, ADWR plans to adopt Special Master Thorson's *de minimis* water use definition and utilize 1 acre-foot (equivalent to a steady-state pumping rate of 0.62 gpm) as the total annual volume for domestic *de minimis* uses.

3. <u>Industrial, Mining, and Municipal</u>

ADWR prepared a separate report for each of the industrial, mining, and municipal uses included in the San Pedro HSR. The general procedures for quantifying water use for each of these use categories are described below.

For the San Pedro HSR, ADWR conducted on-site inspections and interviews to gather information on the operation and characteristics of industrial, mining and municipal water uses, and where possible, historical water usage was obtained. ADWR also obtained water usage data from the Arizona Corporation Commission, although this data was primarily limited to private water companies within the municipal use category. ADWR prepared major user reports describing the operation, water use characteristics, and past water use activity for each industrial, mining, or municipal use. (San Pedro HSR , Vol. 1, Appendix C at C-87). The amount reported was generally the highest water usage during ADWR's five-year investigation period, unless other factors, such as current or projected economic conditions, which may have affected water use were encountered (*Id*.). For cone of depression testing purposes, ADWR plans to utilize the highest reported annual water use for each industrial, mining, or municipal use reported in the San Pedro HSR as the total annual volume. The total annual volume will be distributed evenly between all of the active wells to calculate the steady-state pumping rate for each well.

4. Stockwatering from Wells

Pumping from wells to fill impoundments and drinkers was not reported in the San Pedro HSR; therefore, there is no currently available quantity data to include in cone of depression testing related to stockwatering from wells. (*Id*. at C-84). Given the absence of data, and the difficulty in quantifying the numbers and types of animals being watered, ADWR proposes that stockwatering from wells be assigned a pumping rate of 0.62 gpm, equivalent to an annual use of one acre-foot.

5. Multiple Wells and Water Uses

In the event that one well supplies water to multiple uses, or multiple wells supply water to one or more uses, ADWR proposes to assign a total annual volume to each well based on the following:

1. *When one well supplies water to multiple uses*, the total annual volume will equal the sum of all quantified uses.

2. *When multiple wells supply water to one use*, the total annual volume of water use will be divided equally and assigned to each well.

3. *When multiple wells supply water to multiple uses,* the total annual volume of water uses will be pro-rated equally to each well.

4. *When well water is shared among multiple watershed file reports (this scenario is generally associated with irrigation uses),* ADWR will conduct a case-by-case determination of the total annual volume of water use assigned to each well.

D. Well Location

In its Initial Progress Report, ADWR identified certain deficiencies in well location information in its databases, which in many cases is based on the centroid of a 10-acre subsection. Several parties submitted comments stating that precise or more accurate well location data is required for cone of depression testing.

ADWR agrees that cone of depression testing requires a sufficiently reliable location in order to identify those wells located outside of the subflow zone whose cone of depression would result in a 0.1 foot drawdown at the boundary of the subflow zone based on steady-state modelling. The locations of wells within 10-acre subsections (the ¼, ¼, ¼ of a section described by a cadastral location) through which the subflow zone boundary passes must be accurately known to determine on which side of the boundary they are located. For many wells located outside of the subflow zone boundary, an initial calculation of the cone of depression drawdown at the subflow zone boundary will be either significantly greater or significantly less than the 0.1 foot standard, and therefore a location described within 10-acres will be sufficient. For wells where the calculated cone of depression drawdown approaches 0.1 feet, accurate locations within the 10-acre subsection will need to be determined.

ADWR will determine the accuracy required for an individual well's location using an iterative process. If changing the distance used to calculate the cone of depression drawdown by +/- 330 feet[3] (one-half the length of the side of a square 10-acre subsection) changes whether the well passes or fails the cone of depression test, then ADWR will conduct additional investigations, including the possibility of a site visit with a GPS device, to accurately map the well location.

[3] The locations of many wells within the HSR are described based on information provided by the well owner and though most often described to the nearest ¼, ¼, ¼ of a section (10 acres), they may only be described to the nearest section (640 acres), ¼ section (160 acres), or ¼, ¼ section (40 acres). For these wells, instead of +/- 330 feet to determine whether additional investigations are necessary, ADWR will use one-half the length of the side of a 640-acre, 160-acre or 40-acre square subsection as appropriate.

ADWR proposes to use the following steps to ensure that sufficiently reliable well locations are determined for use in cone of depression testing:

1) Import well locations mapped in Volume 9 of the San Pedro HSR into ADWR's Geographic Information System (ArcGIS) environment. These wells were initially mapped using aerial photographs with field verification. Their locations are sufficiently accurate for cone of depression testing and for determining on which side of the subflow zone such wells are located.

2) Import other well locations referenced in the San Pedro HSR to the center of the subsection described by their cadastral location within ADWR's ArcGIS environment. The locations of wells in subsections through which the sub-flow zone passes will be tabulated for further investigations to determine on which side of the boundary they are located.

3) Review ADWR records to identify new or replacement wells installed since the publication of the San Pedro HSR that serve water uses included in the San Pedro HSR. Map these wells as described in Step 2.

4) For any domestic uses that ADWR determines to be *de minimis* as defined in the 1994 *De Minimis* Decision, ADWR will calculate the distance from the subflow zone, using available aquifer parameter data, where the withdrawal of 1 acre-foot per year (0.62 gpm steady-state) will cause a drawdown of 0.1 feet at the subflow zone. This information will be used to draw a line parallel to and outside of the subflow zone. The locations of wells in subsections through which the *de minimis* delineation line passes will be tabulated for further investigations to determine on which side of the boundary such wells are located. *De minimis* domestic wells outside the *de minimis* delineation line would not be included in cone of depression testing.

5) Conduct preliminary cone of depression testing and identify wells with cones of depression that approach 0.1 feet at the subflow boundary. Repeat the testing for these wells by changing the distance to the subflow boundary used in the calculation

by +/- 330 feet, or other appropriate distance (as described above). If such changes impact whether or not the well passes the cone of depression test, then tabulate such wells for further investigations.

6) Conduct additional investigations to determine sufficiently accurate well locations for those wells identified as needing additional investigations in steps 2, 4, and 5. Such investigations may include site visits with GPS devices.

7) Finalize cone of depression testing using the final well locations determined in step 6.

ADWR believes the procedures described above will ensure that well locations are sufficiently accurate to meet the requirements for cone of depression testing.

E. Aquifer Parameters

As noted in the Initial Progress Report, the modeling of the steady-state drawdown caused by a well's pumping requires, among other data, information concerning aquifer boundary conditions and transmissivity. Table 1 in the Initial Progress Report provided a list of reports containing aquifer parameters and summarized that information. Comments to the Initial Progress Report included suggestions for additional reports to be included in Table 1. These reports have been added and are being reviewed to compile additional aquifer parameters for the San Pedro River watershed.

Comments to the Initial Progress Report also included a suggestion for prioritizing methods of estimating transmissivity as follows, with the most reliable listed first: 1) long-term aquifer tests; 2) short-term aquifer tests; 3) specific capacity tests; and 4) the ADWR driller's log program, which estimates transmissivity from lithology logs. ADWR plans to utilize this priority list.

II. CONTINUED ANALYSIS OF MODELS SUITABLE FOR CONE OF DEPRESSION TESTS

A. Thiem Equation

In the Initial Progress Report, ADWR indicated that it would be evaluating the use of the Thiem equation, numeric models and analytic models for cone of depression testing. Based on the difficulties inherent in using the Thiem equation, as acknowledged by ADWR in the Initial Progress Report, and comments received from the parties, ADWR will not be conducting further analysis of the Thiem equation.

B. MODFLOW

In its discussion of the Upper San Pedro (USP) groundwater model in the Initial Progress Report, ADWR made the statement that "the assumption that a true 'steady-state' existed for pre-development conditions is in question." A comment was received requesting further discussion of this issue.

The statement in the Initial Progress Report was based on the following statements in the USGS Upper San Pedro groundwater model report. According to the USGS (2007, p. 31):

> Initial conditions for simulating transient ground-water flow approximate steady-state conditions, which were defined by a period of negligible changes in inflow, outflow, or storage. Hydrologic records indicate that the ground-water system in the Upper San Pedro Basin has undergone storage change in response to several types of changes in recharge or discharge since about 1900. *Observed variations in baseflow at the Charleston and Palominas streamflow-gaging stations during the period of record indicate that the ground-water system has changed (Pool and Coes, 1999) and that true steady-state conditions have not existed.* A period of minimal change must, therefore, be chosen as the initial conditions to calibrate the steady-state aquifer hydraulic properties and flow terms and to simulate the transient variations in the ground-water system. Ideally, initial conditions also would represent a period before the system changed significantly. The temporal and spatial distribution of hydrologic data, however, prevented definition of the pre-ground-water withdrawal period and required approximation of steady-state conditions by using later data….

(Emphasis added.) The USGS (2007, p. 45) further stated:

> *No true steady-state initial conditions exist according to available records* that indicate that the ground-water flow system has changed in response to changes in discharge through well withdrawals and evapotranspiration rates and changes in stream-channel morphology, including channel incision and widening of the floodplain.

(Emphasis added.)

Although the USGS states that a "true" steady-state did not exist in the Upper San Pedro watershed (circa 1900), the steady-state conditions and parameters adopted by the USGS may be sufficient for the purpose of cone of depression testing. To examine this question more fully, the relative impact of different inputs and parameters on steady-state model results could be further evaluated by conducting sensitivity analyses on relevant model inputs, such as: distributed recharge, head-dependent boundary conditions, streamflow routing and riparian evapo-transpiration parameters. Additional analysis and discussion of the USGS Upper San Pedro model is provided in Appendix 1.

The USGS Upper San Pedro model (a numeric model) has a grid cell size of 250 meters by 250 meters (820 feet by 820 feet). It should be possible to refine this model grid to almost any grid cell size and configuration required for cone of depression testing using the USGS MODFLOW USG (unstructured grid) package USGS (2013), which is described as follows on the USGS website (http://water.usgs.gov/ogw/mfusg/):

> **MODFLOW-USG** (for **U**n**S**tructured **G**rid) was developed to support a wide variety of structured and unstructured grid types, including nested grids and grids based on prismatic triangles, rectangles, hexagons, and other cell shapes. Flexibility in grid design can be used to focus resolution along rivers and around wells, for example, or to subdiscretize individual layers to better represent hydrostratigraphic units.
>
> MODFLOW-USG is based on an underlying control volume finite difference (CVFD) formulation in which a cell can be connected to an arbitrary number

of adjacent cells. To improve accuracy of the CVFD formulation for irregular grid-cell geometries or nested grids, a generalized Ghost Node Correction (GNC) Package was developed, which uses interpolated heads in the flow calculation between adjacent connected cells.

Although the USG package potentially provides a means of refining the USGS Upper San Pedro model grid in the vicinity of individual wells and in the area of the San Pedro River and the subflow zone, the USG package has not been tested on the model, so the impact of grid modification on results would have to be evaluated. In some cases, the steady-state cone of depression drawdown could be clearly determined to be greater than or less than 0.1 foot at the subflow zone boundary, regardless of whether the model grid configuration exactly coincides with that boundary. In other cases, it is possible that the modeled cone of depression would be essentially linear in the vicinity of the subflow zone boundary, so that it would be possible to reasonably interpolate the drawdown from the cone of depression at the subflow zone boundary. Due to the potential time requirements involved in grid modification and testing, any initial use of the USGS Upper San Pedro model for cone of depression testing would have to be done with the current model grid structure.

Additionally, the calculation of steady-state drawdown for any model cell in the USGS Upper San Pedro model requires a difference calculation between the "true" model-simulated steady state head without pumping and the model simulated head with pumping. For the analysis in Appendix 1, the drawdown calculations and data processing have been handled as external "post-processing" activities; however this labor intensive approach may be inefficient and impractical for "production" cone of depression testing. Potential methods of automated the processing of model results will likely be necessary for future work.

C. WinFlow©

WinFlow© is a computer groundwater flow model tool that simulates two-dimensional flow for steady-state and transient conditions. WinFlow© is available in the commercial software package AquiferWin32© (ESI, 2011). The steady-state module in Winflow© uses the "analytical element method" (AEM) developed by Strack (1988). The AEM produces composite analytical solutions across a user-defined modeling domain by superimposing the cumulative effects of multiple "analytical elements" and boundary conditions defined by the user. Analytical elements represent hydrological features such as pumping wells, gaining or losing river reaches, and areas of recharge. The model calculates results using a grid, the size of which can be set by the user. Results at locations between grid points are calculated through interpolation.

As discussed in the Initial Progress Report, the steady-state calculations within Winflow© rely on a mathematical point, the "reference head," where the head[4] is fixed. If drawdown is calculated, drawdown at the reference head will always be zero. If head changes are calculated, the head at the reference head will remain constant. WinFlow's requirement of assigning a single reference head to steady-state groundwater simulations is problematic for situations where multiple boundary conditions exist and no single reference head may adequately represent the true complexity of the steady-state groundwater flow field and associated boundary conditions. The examples that follow were designed to reduce, at least to a certain extent, the inherent uncertainty created by this limitation.

Figure 1 shows the steady-state drawdown calculated at a 200 gpm pumping well located 15,580 feet west of the western subflow zone boundary and 18,040 feet east of the mountain front, labeled in the figure as a "No Flow Boundary." The example provided is analogous to the USGS Upper San Pedro (USP) numeric model example discussed in Appendix 1. The hydraulic conductivity (K) used is the weighted average (9.4 ft/day) of the Ks of layers 2, 3, and 4 from the USP model at Row 226 and Column 198, the location of the hypothetical pumping well. The aquifer thickness is 1300 feet, the total thickness of layers 2, 3, and 4 at the pumping well location in the USP model. Layer 5 was not included in the Winflow© analysis because it represents a confined system.

[4] Head is a combined measure of the elevation and water pressure at a point in an aquifer.

In Figure 1, there is a single pumping well and the reference head (set at 4,250 feet and shown as a green arrow) is located 10 miles north of the point labeled "A" on the No Flow Boundary. (Note that the well is located along the X-axis and the "No Flow Boundary" is the Y-axis.) In this example, the 0.10 foot drawdown contour approaches the reference head (remember drawdown at the reference head will always be zero) and drawdown at the subflow zone boundary is 0.72 feet. Note that in Figures 1-5, the drawdown contour interval is one foot, and the initial contour is 0.10 feet.

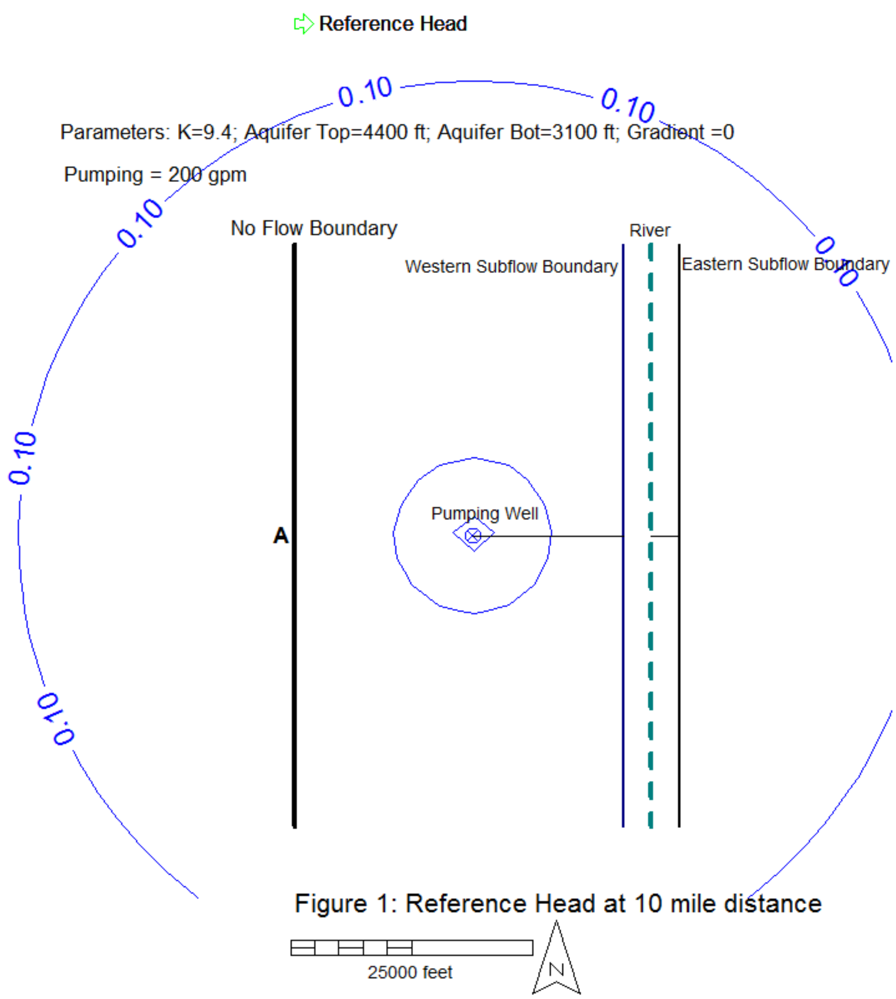


Figure 1: Reference Head at 10 mile distance

In Figure 2, the reference head has been moved to 20 miles north of Point A and all other conditions remain the same. Now the 0.10 foot drawdown contour is nearly completely off the figure and drawdown at the subflow zone boundary is 1.09 feet. These examples show that the placement of the reference head dominates the drawdown calculations when there is no recharge present in the model.

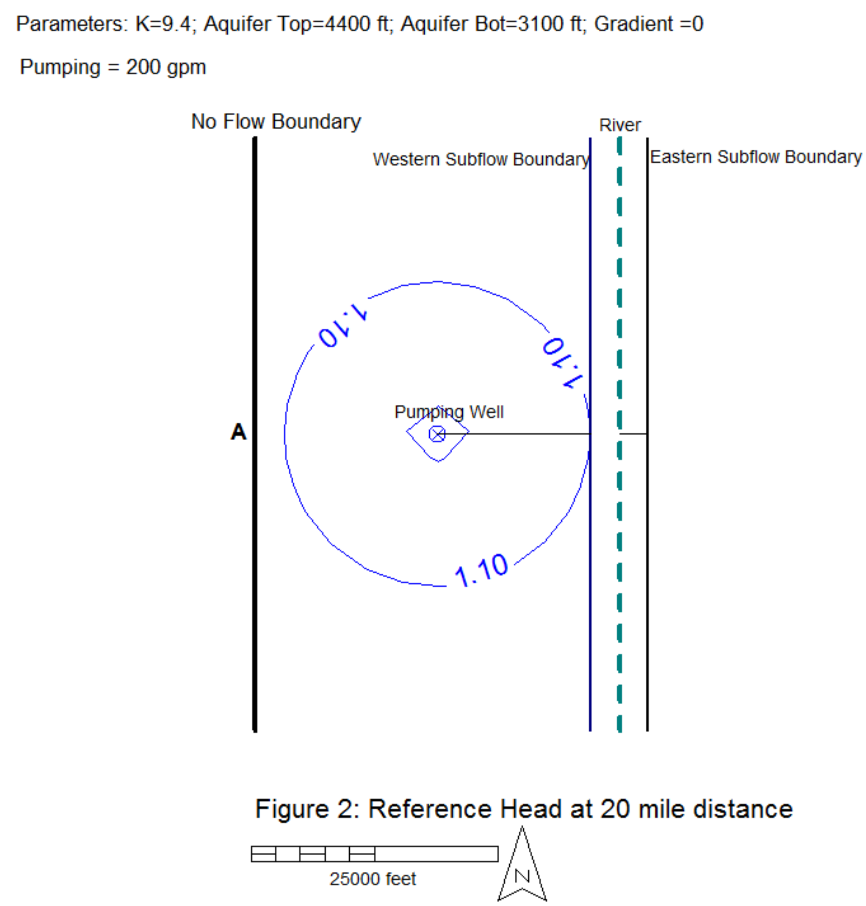


Figure 2: Reference Head at 20 mile distance

In Figure 3, a recharge well, labeled "Positive Image Well" has been added to the model. This well supplies water to the model at the same rate (200 gpm) as the pumping well removes water. It is located the same distance east of the line labeled "River" as the pumping well is located west of the River. The Positive Image Well emulates the presence of a river, a source of recharge, at the point equidistant between the Pumping Well and Positive Image Well. In this example, the reference head has been located on the Y-axis (labeled No Flow Boundary) at a point above Point A that is 10 times the distance from the

No Flow Boundary to the western subflow zone boundary. This distance was selected to move the reference head, (which is necessary for the calculations in the model) far enough away from the area of interest to reduce its impact on the calculations. The calculated drawdowns at the western subflow boundary resulting from pumping rates of 200, 100, 35, and 20 gpm using this scenario are presented in Table 1 below.

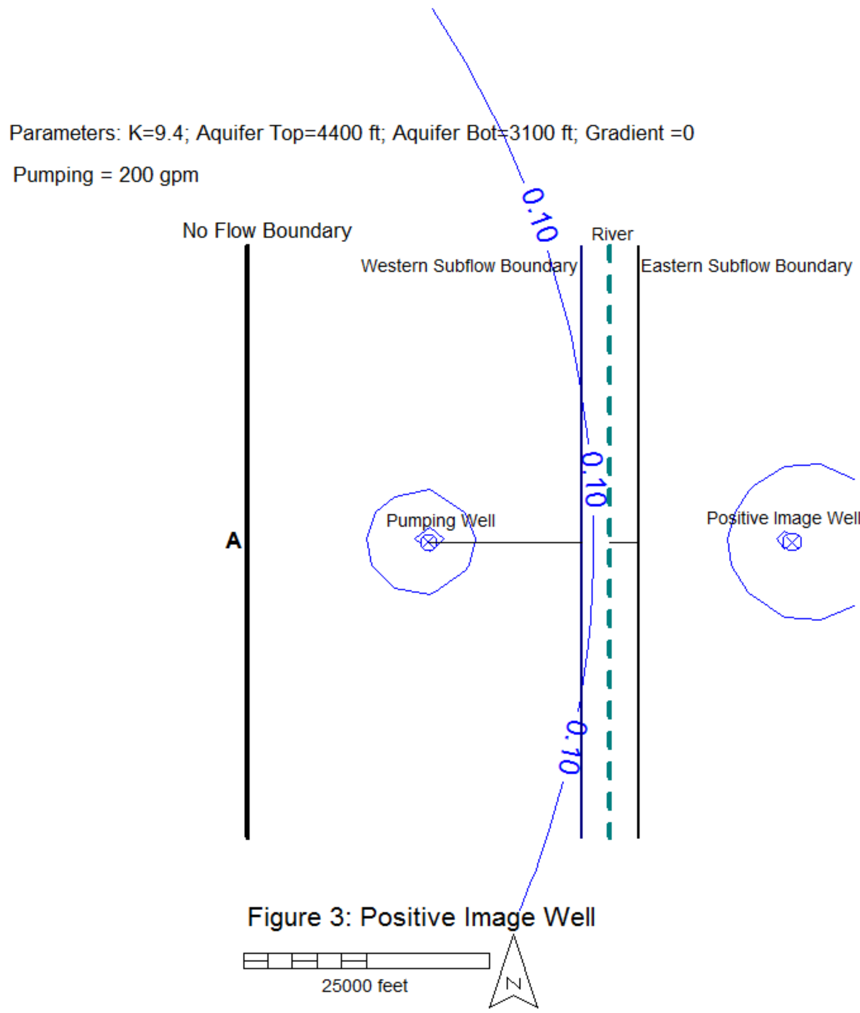


Figure 3: Positive Image Well

In Figure 4, pumping from two additional image wells, one pumping and one recharge, located west of the No Flow Boundary line has been added to the model. Analogous to how a positive image well emulates a river, these image wells emulate the impact of a no flow boundary. They are placed west of the No Flow Boundary line the same distance as the wells they are mirroring are located east of the no flow boundary. All other aspects of the model are the same as in Figure 3.

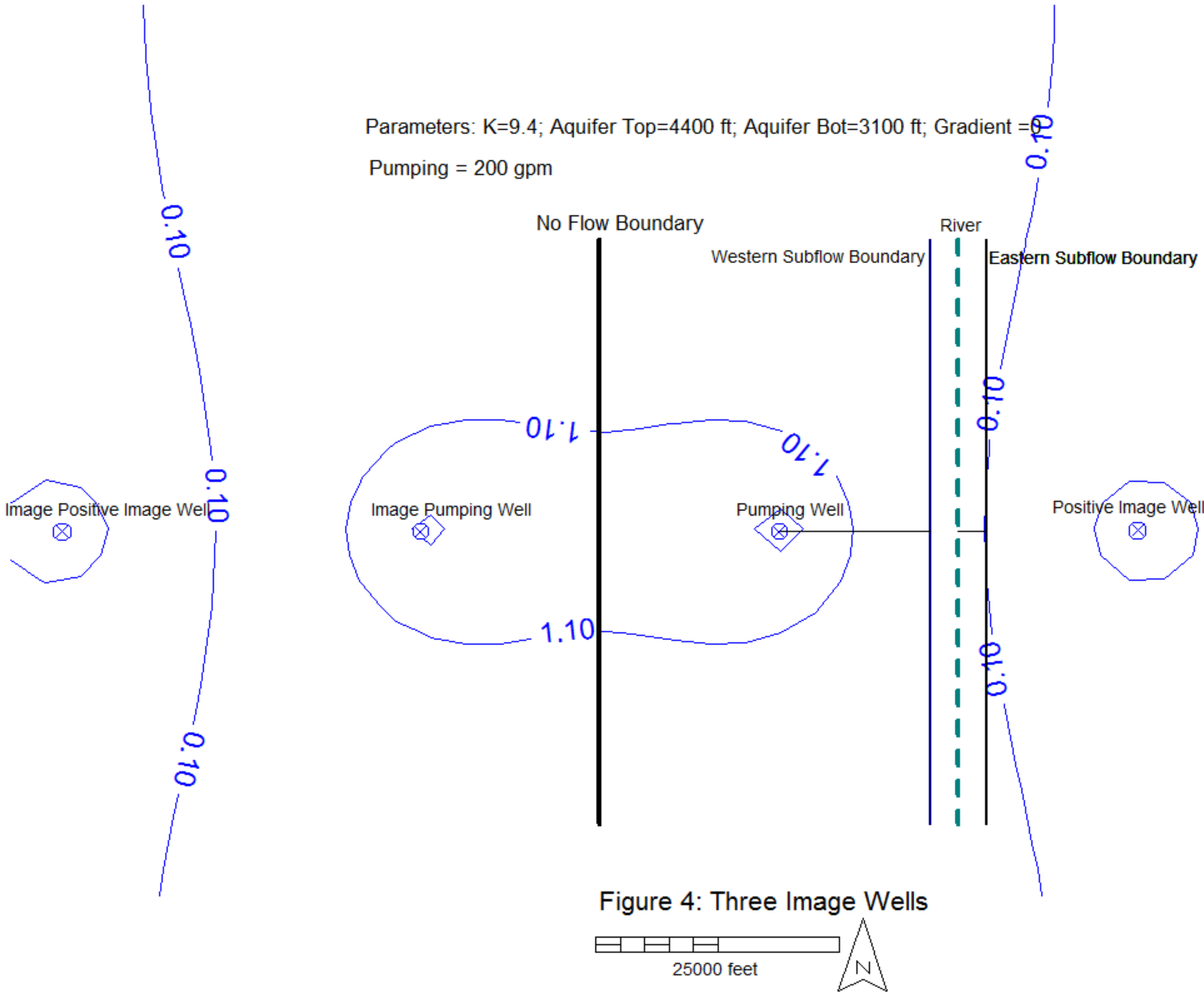


Figure 4: Three Image Wells

Figure 5 displays an unorthodox approach regarding placement of the reference head. In this example, the reference head was placed at the edge of the eastern subflow zone boundary opposite the pumping well, and recharge was removed from the model. Conceptually, the presence of recharge within the subflow zone is implied by restricting the extent of the cone of depression to the edge of the subflow zone. As noted, this example is unorthodox and would require extensive analysis before additional consideration.

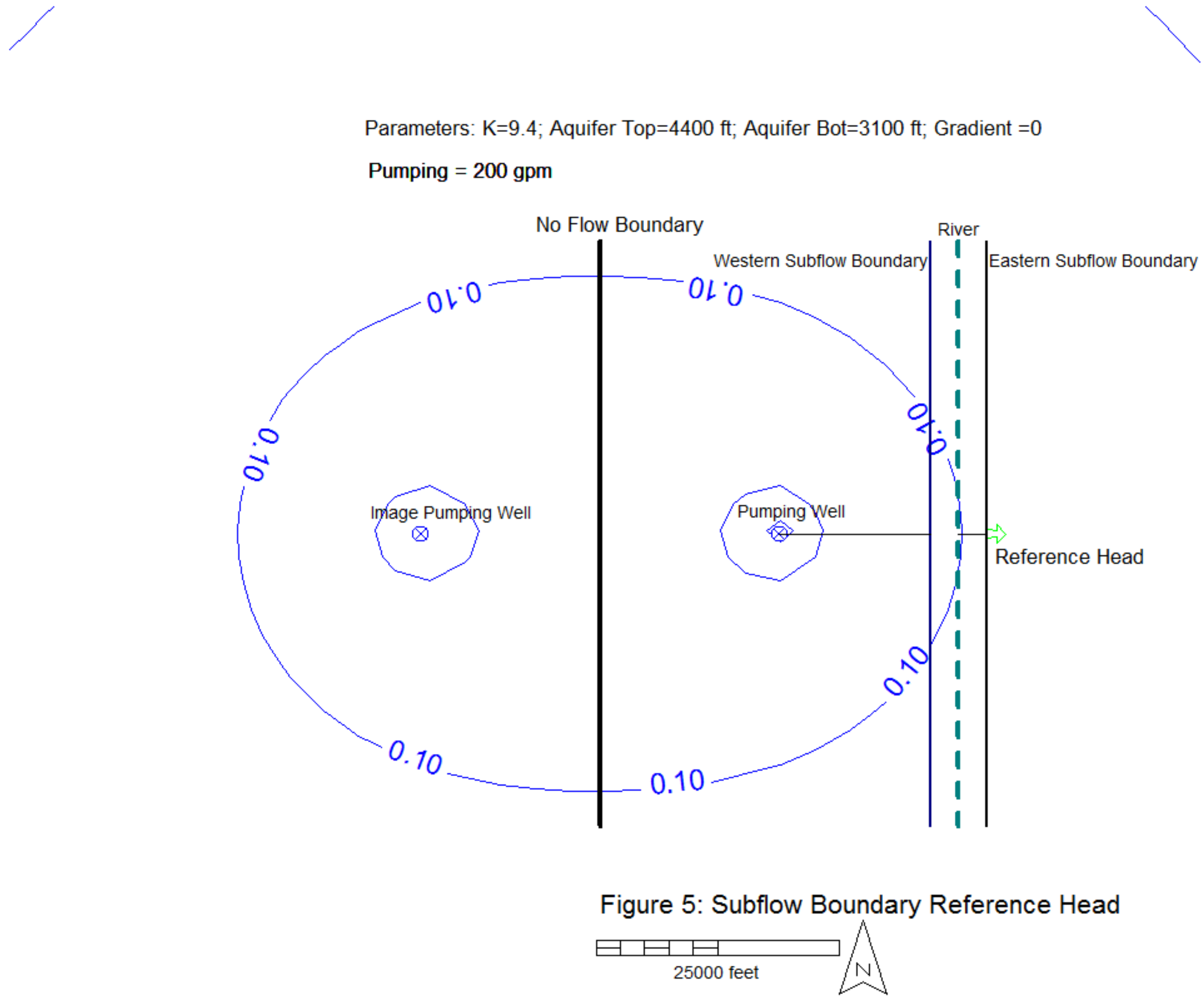


Figure 5: Subflow Boundary Reference Head

In Figure 6, recharge is provided to the model through the use of a constant head line sink analytical element, rather than through the use of recharge wells. The reference head is at the same location as used in Figures 3 and 4, but a gradient of 0.0025, similar to pre-development conditions in the USP model, has been added to the model. Drawdowns must now be calculated by running the model without pumping, and then with pumping and determining the difference in head between the two runs.

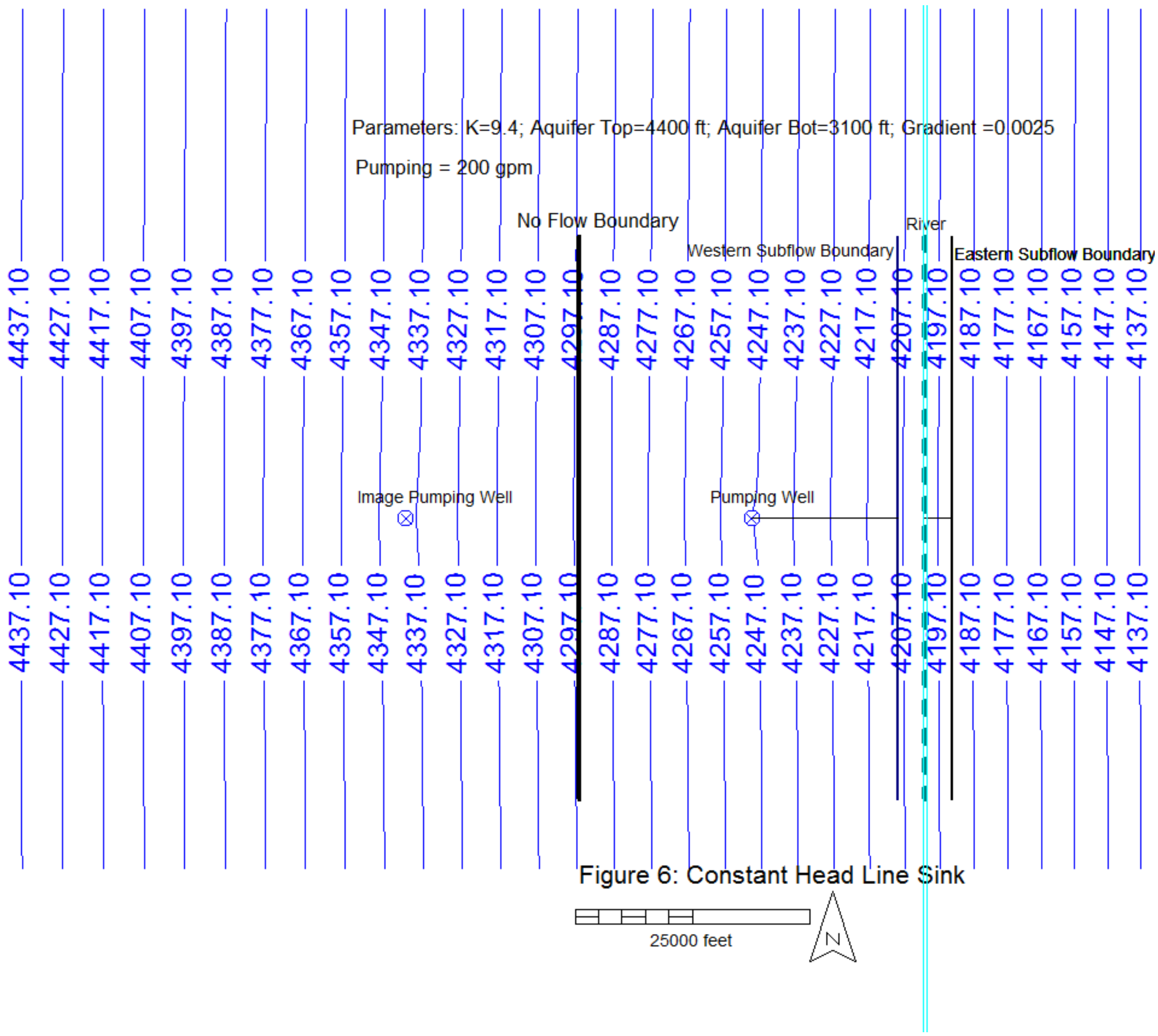


Figure 6: Constant Head Line Sink

Table 1 was prepared to compare the calculated drawdowns at the western subflow boundary for various pumping rates using the Winflow© examples depicted in Figures 3, 4, 5 and 6 with the drawdowns calculated using the USP model as discussed in Appendix 1. The drawdowns presented for the USP model are the average drawdowns for Layers 2, 3, and 4 at each pumping rate without the addition of surface runoff. Because wells do not pump in a steady-state, and the impacts of other wells, recharge, and discharge cannot be isolated from the impact of the subject well, it is not possible to conduct field measurements to determine which of the results displayed in Table 1 is most accurate. The results must be considered in light of the reasonableness of the assumptions and data used in the calculations.

Table 1 – Comparison of Calculated Drawdowns at the Western Subflow Boundary

Pumping Rate (GPM)	USP Model	Figure 3: One Image Well	Figure 4: Three Image Wells	Figure 5: Reference Head	Figure 6: Line Sink
	Drawdown (ft)				
200	0.37	0.17	0.47	0.24	0.18
100	0.19	0.09	0.23	0.12	0.09
35	0.07	0.03	0.08	0.04	0.03
20	0.03	0.02	0.05	0.02	0.01

Although not all groundwater modeling methods and software that were presented in the responses ADWR received to its Initial Progress Report have been discussed in this Third Progress Report, ADWR will continue to review those comments and recommendations for potential application to cone of depression testing. ADWR intends to propose a cone of depression test prior to the end of this year that most reasonably calculates drawdown at the subflow zone boundary and meets the other requirements of the Court.

III. DELINEATION OF SUBFLOW ZONE FOR MOUNTAIN FRONT STREAMS

By Minute Entry Order filed October 12, 2012 (“2012 Order”), ADWR was required to identify and delineate subflow zones associated with “mountain front” streams throughout the San Pedro River watershed (2012 Order at 23). By order filed July 6, 1994 (“1994 Subflow Order”), Judge Goodfarb defined mountain front streams as “stream segments in transition from bedrock canyons to alluvial basins… Many streams make a transition from bedrock canyon streams, with narrow younger alluvium bounded by hard rock, to alluvial valley streams with younger alluvium bounded by tributary aquifers.” (1994 Subflow Order at 31). The Court defined bedrock canyon streams as “streams [that] are perennial or intermittent streams located in canyons bounded by consolidated tributary aquifers or impermeable bedrock." (1994 Subflow Order at 30)

The Court also adopted the following stream type definitions:

> "*Perennial streams* discharge water continuously through the year. Their source of supply is normally comprised of both direct runoff from precipitation events or snow melt, and baseflow derived from the discharge of groundwater into the stream."
>
> "*Intermittent streams* discharge water for long periods of time, but seasonally. For example, an intermittent stream may flow all winter, every winter, but never flow continuously during the summer. During seasons when base flow is maintained, groundwater is contributing to the stream. During seasons of discontinuous streamflow, natural and cultural losses may be greater than the contribution from groundwater, resulting in a losing stream or, the amount of groundwater discharge itself may have decreased due to natural or cultural uses."
>
> "*Ephemeral streams* discharge water only in response to precipitation events or snowmelt, and do not have a baseflow component at any time of the year; they flow out sporadically. The groundwater system and surface water system do not establish a hydraulic connection in these systems."

(1994 Subflow Order at 23, emphasis added). The 1994 Subflow Order was affirmed "in all respects" by the Arizona Supreme Court in *Gila IV*. (Gila IV, 198 Ariz. At 344, 9 P. 3d at 1083, ¶ 48.)

In the 1994 Subflow Order, Judge Goodfarb held that the subflow zone must be adjacent to and beneath a perennial or intermittent stream; but not an ephemeral stream, unless there is a saturated zone connected to similar zones beneath upper and lower stream segments (ephemeral stream exception). (1994 Subflow Order at 35). By order filed October 4, 2005 (dated September 15, 2005) ("2005 Subflow Order"), Judge Ballinger held that these stream conditions must be determined at "predevelopment" times. (2005 Subflow Order at 18-24).

ADWR performed the following steps in its preliminary analysis of potential subflow zones associated with mountain front streams in the San Pedro River watershed: 1) identified and mapped mountain front boundaries in the watershed; 2) identified and mapped perennial or intermittent streams based on existing data sources; 3) combined the information in steps 1 and 2 to identify and map where perennial and intermittent streams cross the contact between bedrock and alluvial materials; and 4) used imagery to assess the channel geometry of the stream at the contact between bedrock and alluvial materials, *i.e.* the mountain front boundary, and evaluate whether floodplain Holocene alluvium might potentially be present in sufficient width and thickness to create a subflow zone. ADWR used these steps to create a Project Geodatabase, as described further below.

ADWR utilized the Arizona Geological Survey (AZGS) 2002 published state geologic map of Arizona (available as a GIS cover) as the basis for creating ADWR's statewide bedrock/hardrock shapefile found in ADWR's ArcGIS library. The AZGS map, differentiates bedrock/hardrock units from basin fill sedimentary units and provides a method for defining the mountain front boundaries specific to a watershed. This existing GIS cover was used in this analysis.

ADWR reviewed the sources of data and information that were used in the 2009 Subflow report to establish predevelopment streamflow conditions. Several of these sources are only applicable to the San Pedro River and the other major streams in the watershed and did not provide information applicable to the mountain front regions of the watershed. ADWR identified five sources of other information, already converted to GIS (shapefile) formats, which showed mapped locations of perennial and intermittent[5] streams in mountain front regions of the San Pedro River watershed. These five data sources are listed below:

[5] The sources reviewed defined "intermittent" slightly differently than the 1994 Subflow Order. Nonetheless, ADWR used the mapped intermittent streams from these additional sources.

- U.S. Geological Survey (USGS), 2016. *USGS Surface-Water Data for the Nation, National Water Information System (NWIS) data for Arizona: Web Interface* at http://waterdata.usgs.gov/nwis/sw (accessed January 2016);
- Brown, D.E., Carmony, N.B., and Turner, R.M., 1981. *Drainage Map of Arizona Showing Perennial Streams and Some Important Wetlands*. 1 sheet (1:1,000,000);
- Arizona Game and Fish Department, 1997 & 1993, Statewide riparian inventory and mapping project: GIS cover;
- Sonoran Desert Conservation Plan, 2000. *GIS Coverages of Perennial Streams, Intermittent Streams, and Areas of Shallow Groundwater*. Pima Association of Governments; and
- ADWR, 2016, Registry of surface water rights; ADWR Engineering & Permits Division.

Based on ADWR's review of the sources listed above, a total of 82 perennial and intermittent streams (reaches or segments) were identified and imported into the Project Geodatabase. The 82 classified streams were attributed in a table with respect to their location in the watershed, stream or canyon system name, flow direction, stream type, classification source or sources (if more than one), overall length, and apparent floodplain width at the mountain front boundary, if the stream crossed the boundary.

The majority (48 of 82) of perennial and intermittent classified streams were found to be located in the higher mountain elevations of the watershed in hardrock/bedrock mapped regions. ADWR considered these streams to be bedrock canyon streams and they were not subject to further analysis.

Of the remaining 34 streams, 22 were intermittent and seven were perennial streams that crossed the mountain front boundary. Five more streams had mapped perennial reaches that approached the mountain front boundary but did not cross it. These streams were retained for additional analysis because of the possibility that the reaches below the mapped perennial reach might potentially be intermittent at the mountain front boundary.

ADWR then assessed the 34 intermittent and perennial streams that cross (or potentially cross) the mountain front boundary using remote sensing techniques to evaluate whether floodplain Holocene alluvium might potentially be present in sufficient width to establish a subflow zone along the stream. Factors evaluated included floodplain geometry and riparian vegetation.

The following aerial photo data was downloaded into the Project Geodatabase and analyzed:

- Historical Aerial Imagery, 1935, 1:24,000, Soil Conservation Service (ADWR internal source);
- Digital Orthophoto Quarter Quads (DOQQs), 1992, 1996, 1:24,000, U. S. Geological Survey (ADWR internal source);
- Topographic Maps, 1950s-1980s, 1:24,000 and 1:250:000, U.S. Geological Survey, ESRI Map Service http://goto.arcgisonline.com/maps/USA_Topo_Maps; and
- Modern Aerial Imagery, 2010 to 2015, 1-m resolution, ESRI World Imagery Map Service http://goto.arcgisonline.com/maps/World_Imagery .

ADWR's assessment focused on the location where the stream crossed the contact between the bedrock/hardrock and the alluvium, specifically measuring the streambed or active floodplain width at that point and evaluating whether recent alluvial deposits were potentially present outside the current channel. Topographic maps were also used for the channel width determinations in areas where other imagery was insufficient or vegetation canopy made stream measurements difficult. Recent modern aerial imagery was found to be of excellent resolution. Using these imagery sources allowed ADWR to measure channel or active floodplain widths and to compare one stream reach with another.

Based on its aerial photo assessment of the 34 mountain front stream candidates, ADWR plans to contract with the AZGS to perform an initial site reconnaissance of 12 mountain front streams that show visible evidence of alluvial deposition. These are described in Table 2 below. The purpose of the site reconnaissance will be to determine which of the 12 streams, if any, would require additional detailed mapping to identify the extent of the floodplain Holocene alluvium and potential subflow zone.

Table 2 – Selected Mountain Front Streams

Stream/Canyon Name	**Reach/Segment Location (TRS)**	**Reach/Segment Description**
Turkey Creek	T21S R18E S34	North through Canelo Hills to Babocomari River
Lyle Canyon	T21S R18E S35	North through Canelo Hills to Babocomari River
Redfield Canyon	T11S R19E S34	West from Galiuro Mountains to San Pedro River
Hot Springs Canyon	T13S R20E S6	West from Galiuro Mountains to San Pedro River
Kielberg Canyon	T10S R19E S16	West from Galiuro Mountains to San Pedro River
Turkey Creek	T7S R19E S21	North from Galiuro Mountains to Aravaipa Creek
Ramsey Canyon	T23S R20E S10	Northeast from Huachuca Mountains toward San Pedro River
Miller Canyon	T23S R20E S24	Northeast from Huachuca Mountains toward San Pedro River
Garden Canyon	T22S R20E S32	Northeast from Huachuca Mountains toward San Pedro River
Paige Creek	T14S R19E S10	Northeast from Rincon Mountains to San Pedro River
Espiritu Canyon	T13S R18E S11	North then Northeast from Rincon Mountains to San Pedro River
Buehman Canyon	T12S R18E S4	East then Northeast from Santa Catalinas to San Pedro River

IV. ABSTRACTS OF PROPOSED WATER RIGHTS FOR *DE MINIMIS* USES

ADWR reviewed the orders entered by Judge Ballinger and Special Master Thorson[6] concerning *de minimis* uses in the San Pedro River watershed. The purpose of the review was to assess whether GIS tools and techniques could be used to readily create abstracts of proposed water rights for *de minimis* uses without impairing ADWR's progress on other adjudication-related tasks.

Special Master Thorson's 1994 *De Minimis* Decision, as adopted by Judge Ballinger in 2002, concluded that certain stockwatering, stockpond and domestic beneficial uses were *de minimis* uses for which water rights abstracts should be created using information from the San Pedro HSR. These *de minimis* uses were described as follows:

- All <u>stockwatering</u> [SW] uses, meaning the instream watering of stock at unimproved or improved locations on a stream, creek, spring, or similar source.

- All <u>stockponds</u> [SP], meaning those ponds or other artificial facilities, used solely for the watering of stock or wildlife, that individually have a capacity of no more than (<u><</u>) 15 ac-ft. As the following discussion indicates, the method of quantifying stockponds with individual capacities no more than (<u><</u>) 4 (*i.e.*, assigning a uniform volume) differs from the method of quantifying larger stockponds.

- All <u>domestic</u> uses [DM], as that term is defined in Conclusion of Law No. 6,[7] so long as they are supplied by the landowner or occupant from a well or surface water source ("self-supplied") and provide water for a single family household and associated outdoor activities on adjoining land not exceeding <u>(<) 0.2 acres. Remaining domestic uses will be adjudicated during the normal course of the adjudication.</u>

---

[6] Special Master Schade considered information related to certain *de minimis* that were defined as non-domestic uses, but deferred any further work on those uses by report dated February 16, 2006.

[7] Conclusion of Law No. 6 defines "domestic use" as the use of privately supplied water by persons in a permanent dwelling, the watering of pets and farmyard animals, and the irrigation of lawns, gardens, and orchards on land adjoining the dwelling. 1994 *De Minimis* Decision at 38, n. 14.

(1994 De Minimis Decision at 38-39).

The 1994 *De Minimis* Decision also recognized that wildlife is a beneficial use and that, "[a]n appropriation of water may be made for the joint watering of stock and wildlife (WL) at the same pond or instream location. Two beneficial uses, SW or SP and WL, will be assigned for these joint uses." *Id.*, Conclusion of Law No. 5 at 13. Also see *Id*. At 44.

The 1994 *De Minimis* Decision identified water right characteristics or attributes required to be used to create a water right abstract for each of the *de minimis* uses defined in the decision, absent unusual circumstances. These water right attributes and determinations are described below (1994 *De Minimis* Decision at 40-43):

1. Proposed Water Right Number (PpWR No.): The HSR Watershed File Report (WFR) number (*e.g.* 111-18-10) to which is appended the abbreviation for the beneficial use and a unique serial number (which may be the same as the potential water right (PWR) number reported in the watershed file report) (*e.g.* SP001) to create a PpWR No. (*e.g*. 111-18-10-SP001).

2. Requirement of a Statement of Claimant: The number of a statement of claimant (SOC) filed in the adjudication for a particular *de minimis* use must be matched to a proposed water right number. If an SOC is not matched to a PpWR No., the *de minimis* use will be listed in the "no water right awarded" section of the catalog of proposed water rights.

3. Basis of Water Right: A preadjudication filing or other legal basis. A potential water right for a particular *de minimis* use must be matched with a "preadjudication filing or other legal basis" in order for a water right abstract to be created, or the use will be listed in the "no water right awarded" section of the catalog of proposed water rights.

4. Ownership: The name of the landowner listed in the WFR.[8]

5. Beneficial (Type of) Use: The information contained in the WFRs and the definitions of stockwatering, stockponds, wildlife, and domestic.

6. Priority Date: The apparent date of first use listed in the potential water right section of the WFR. If the WFR is incomplete or ambiguous, this sequence should be used: 1) "the earliest date set forth in a judicial decree or Water Rights Registration Act filing; or 2) the earliest date set forth in any other preadjudication filing, adjudication filing, or other admissible credible evidence." Assign the priority date based on the day, month and year, if available. If the day is not available, then assign the priority date using the last day of the month and year. If neither the day nor month is available, then assign the priority date as the last day of the year.

7. Source of Water: Only if the WFR indicates that surface water is being used, will the abstract describe the source of water as "surface water". If the WFR indicates that underground water is being used, or the source is uncertain, the source of water will be described as "not yet determined."

8. Place of Use: Describe depending on the type of use. For *stockwatering* use the information in the "use" section of the WFR; for *stockponds* use the information in the "reservoir" section of the WFR; and for *domestic* use the information in the "use location" section of WFR. For each of these uses, describe the place of use to the nearest ¼, ¼ section, or the ¼, ¼, ¼ section if there are two or more uses in the same ¼ ¼ section.

9. Quantity: Use Conclusions of Law (COL) Nos. 10, 14, 16, 17, 19, 20 and 25. The adjudicated quantity for *stockwatering* will state "reasonable use." COL No. 10 at 31.The adjudicated quantity for *stockponds* will be determined as follows: (a) "not to exceed (≤) 4 ac-ft with continuous fill" for all stockponds having a capacity of 4 acre feet or less (COL 14 at 32);(b) for State Land Department stockponds having a capacity greater

[8] Note that Judge Ballinger's 2002 Order states that it, "does not address the legal ownership of water rights on state and federal lands, an issue outside of the scope of the Special Master's *De Minimis* Report." (2002 Order at 5).

than 4 acre feet, the amount claimed on the statement of claimant with continuous fill (COL 16, 20 at 32-33); (c) ADWR may use previously compiled field surveys or regression analysis as a basis for determining the volume of those stockponds having a capacity not exceeding 4 acre-feet (COL 17 at 32);and (d) ADWR may use previously compiled field surveys or regression analysis as a basis for determining the volume of those stockponds having a capacity greater than 4 acre-feet, but no greater than 15 acre-feet, which "will be adjudicated as the quantity of each of these rights" with continuous fill (COL 19 at 32). The adjudicated quantity for *domestic* will be "not to exceed one acre-foot per year" "for domestic rights supplied by the landowner or occupant from a well or surface water source providing water for a single family household and associated outdoor activities on adjoining land not exceeding ($\leq$) 0.2 surface acres ('self-supplied residential domestic right')." (COL 25 at 33).

One of ADWR's challenges in creating water right abstracts for *de minimis* uses is the current digital state of the San Pedro HSR. ADWR's electronic records currently do not contain the digital information used to produce the maps found in Volume 9 of the HSR. ADWR has been able to take the original (hard copy) printed maps, digitally scan them, and then import them into its GIS environment.

The original HSR investigation findings, published as WFRs in Volumes 2-6 of the 1991 San Pedro HSR, are contained in a legacy system at ADWR and can be retrieved, provided ADWR can map to the system and return consistent and accurate results when querying. ADWR is currently testing the queries and, at this time, sees no reason that the complete retrieval and use of the digital HSR data would not be possible. The WFR boundaries, stockponds, stockwatering, and wildlife use locations have been successfully entered into the ADWR's GIS for the Sierra Vista sub-watershed of the San Pedro River watershed as a test case.[9] ADWR plans to marry the tabular (non-spatial) San Pedro HSR data with the geographical (spatial) boundaries and water use locations to create a fully-

[9] *De minimis* domestic uses are significantly more challenging because they must be separated from non-*de minimis* domestic uses, something not anticipated when the San Pedro HSR was prepared. ADWR is currently evaluating how best to accomplish this task.

functional GIS geodatabase that can be used to assist in the continuing adjudication processes in the San Pedro River watershed.

ADWR anticipates that it will be able to produce draft *de minimis* proposed water right abstracts, linked to locations in a functional GIS, for stockwatering, stockpond, and wildlife uses in the Sierra Vista sub-watershed in the near future. These abstracts will list both the original land owner and the new landowner, based on recently acquired assessor's information, where appropriate. The processes developed for the Sierra Vista sub-watershed could then be applied to the remainder of the San Pedro River watershed.

V. NEXT STEPS

Over the next several months, ADWR anticipates that further progress will be made on the work described in this report. ADWR intends to issue a report describing procedures that will be used for cone of depression testing by the end of this calendar year. ADWR's preliminary work on mountain front streams has been completed in large part, but ADWR's issuance of a report that delineates the subflow zone for mountain front streams will depend on when the AZGS will be able to conduct the necessary site investigations and mapping. ADWR will continue to take steps to develop a fully functional GIS geodatabase that can be used to create abstracts of water rights for *de minimis* uses in the San Pedro River watershed, to the extent that it does not interfere with ADWR's other adjudication-related work.

References

USGS, 2007. Ground-Water Flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, United States, and Northern Sonora, Mexico. USGS Scientific Investigations Report 2006-5228.

USGS, 2013. MODFLOW-USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and tightly Coupled Processes Using a Control Volume Finite-Difference Formulation. USGS - Chapter 45 of Section A, Groundwater Book 6, Modeling Techniques.

APPENDIX

Appendix:
Additional ADWR Analysis of the USGS Upper San Pedro Groundwater Flow Model

In its review of the potential applicability of various modeling methods to conduct cone of depression testing, ADWR utilized the USGS Upper San Pedro (USP) Groundwater Flow Model (USGS, 2007) to evaluate the theoretical impacts of hypothetical well pumping under steady-state conditions (Figure 1).

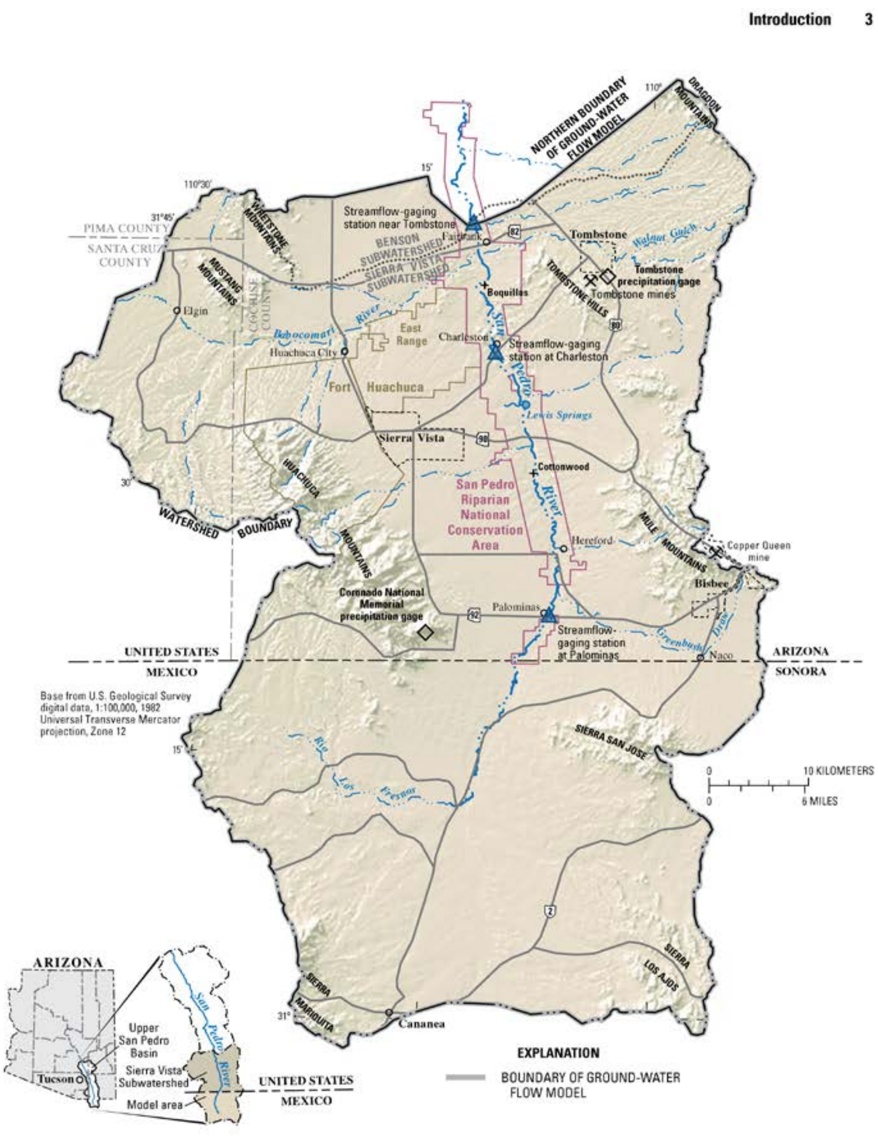


Figure 1. Model area within the Upper San Pedro Basin, Arizona, United States and Sonora, Mexico.

Figure 1 USGS Upper San Pedro Groundwater Flow Model Area (USGS, 2007)

The USGS Upper San Pedro groundwater flow model is a finite-difference numerical groundwater flow model developed using the USGS MODFLOW code. The USP model has a finite-difference gird composed of 440 rows, 320 columns and 5 layers. All model cells are 250 x 250 meters or (820 x 820 feet) in horizontal dimension and of variable thickness ranging from 0 to +1,500 meters (Figure 2).

Conceptual Model of the Ground-Water Flow System 7

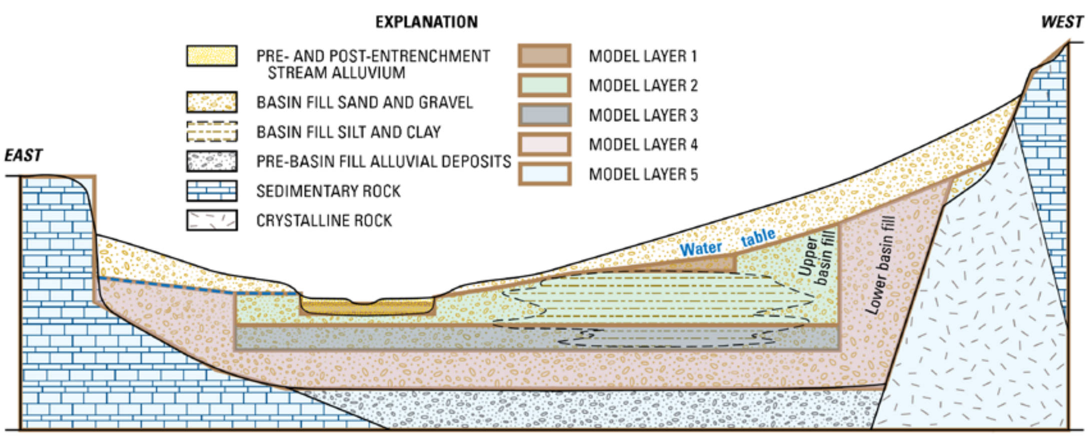


Figure 3. Generalized hydrogeologic section and extent of numerical model layers, Upper San Pedro Basin, United States and Mexico.

Figure 2 Conceptual Model of the USP Groundwater Flow System (Original Fig.3 USGS, 2007)

ADWR's evaluation of the USGS Upper San Pedro groundwater flow model was conducted by placing a hypothetical pumping well in model cell Row=226, Col=198, Layer=4, which is in the vicinity of the Palominas gage. The hypothetical well location, D(23-21) 25CDD, was not selected to represent any existing well (Figure 3). However, the hypothetical well was located sufficiently close to the western boundary of the San Pedro River Floodplain Holocene Alluvium (FHA) so that simulated pumping by a well (over a typical range of pumping rates) would cause a range of steady-state drawdown at the FHA boundary that would include 0.1 foot. The distance from the well to the western boundary of the FHA is about 15,580 feet (Figure 3). ADWR's analysis revealed that the usefulness of the USGS Upper San Pedro model for cone of depression testing has certain limitations.

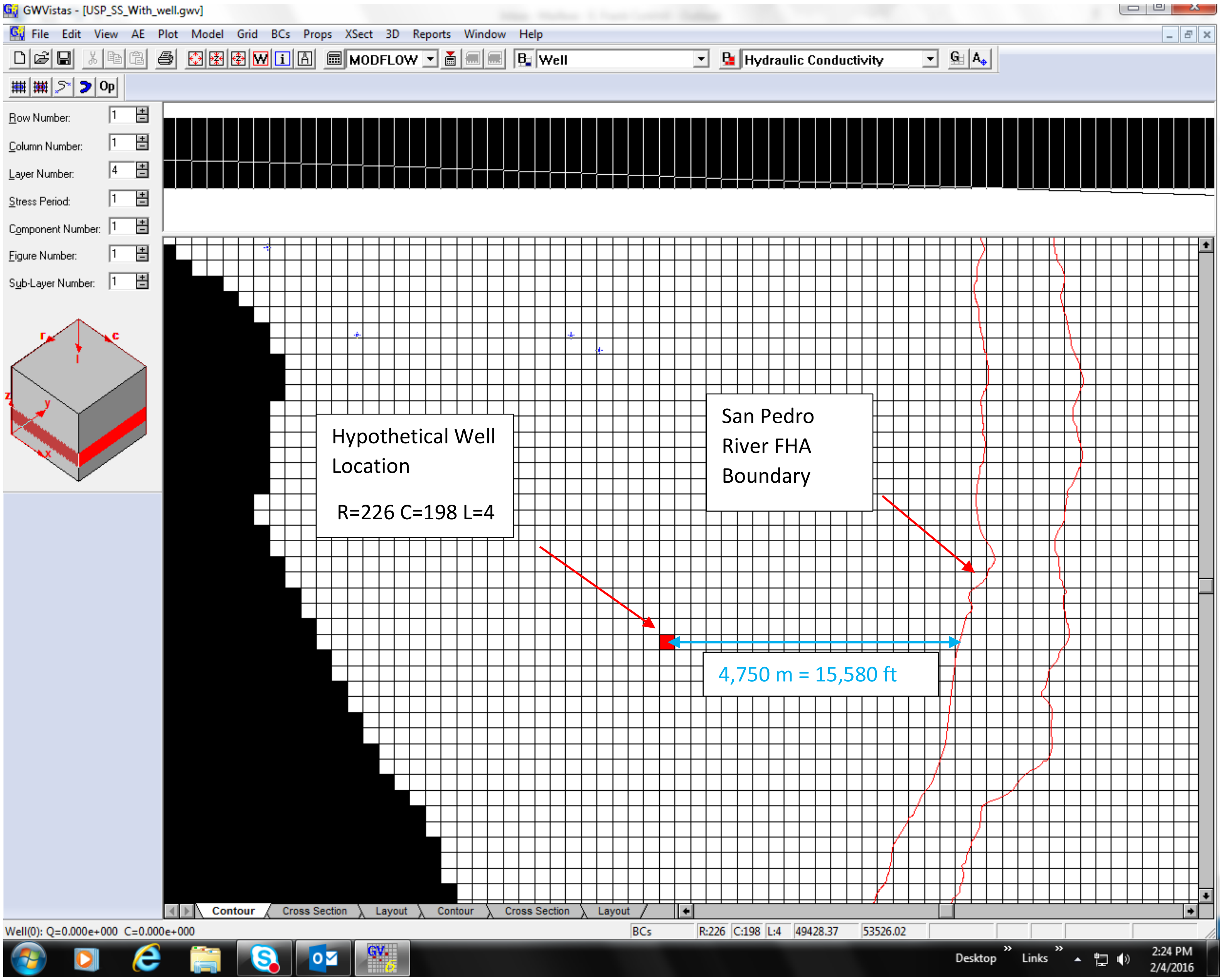


Figure 3 Location of hypothetical pumping well and FHA boundary

Evaluation of Steady-State Pumping Impacts (Methodology)

The evaluation of hypothetical, steady-state well pumping impacts was conducted as follows:

1. A steady-state, no-pumping simulation was run to provide baseline heads (simulated water levels).
2. Multiple steady-state model runs were then made to simulate typical well pumping rates for the area, from 200 gallons per minute (gpm) to less than 1 gpm.
3. Steady-state drawdown was calculated on a cell-by-cell basis for each pumping simulation by subtracting simulated pumping heads from the baseline non-pumping, steady-state heads.
4. Simulated cumulative water budgets were reviewed for each model run (Table 1).
5. West-to-east vertical profiles of steady-state drawdowns along model Row 226 were constructed for pumping simulations ranging from 200 gpm to 0.31 gpm (Figures 4 – 10) to determine and illustrate the steady-state drawdown at the shortest distance from the hypothetical pumping well to the San Pedro River FHA boundary (which, for the purposes of this analysis, was also assumed to be the smallest drawdown along any portion of the FHA boundary).
6. A series of 35 gpm steady-state pumping simulations was also run that included variable amounts of runoff in the streamflow routing package at the approximate location of the USGS Palominas streamgage 9470500. These runs were conducted to evaluate potential impacts of including stream runoff in the USGS USP model (which the current version of the USGS model does not include) on the cone of depression results. These results are discussed in the following section.
7. A 5-well, steady-state drawdown analysis was run to evaluate potential impacts of pumping from multiple wells on the cone of depression results. These results are also discussed in the following section.

Results of Well Pumping Analyses

Individual Wells

Cone of depression tests were conducted for several steady-state model runs with a hypothetical well located in model cell Row=226, Col=198, Layer=4. Hypothetical pumping rates ranging from 200 gpm to 0.31 gpm were simulated (Table 1). The difference (drawdown) between simulated steady-state water levels from a non-pumping "baseline" model run and pumping model runs (200 gpm to 0.31 gpm) are shown along model row 226 (Figures 4 – 10). The results show that model simulated drawdowns exceeded 0.1 foot for at least one model layer[1] at the western boundary of the FHA for pumping rates that were greater than or equal to 20 gpm (Figures 4 – 7). The results showed that model simulated drawdown was less than 0.1 foot for all model layers at the western boundary of the FHA for pumping rates that were less than or equal to 10 gpm (Figures 8 – 10).

[1] Note that model layer 5 is confined in this analysis. Drawdowns in Layer 5 are declines in head rather than declines in the water table measured at the subflow zone boundary.

SS Pumping Rate (gpm) ->	0	0.31	0.5	1	5	10	20	35	100	200
Acre-Feet/Year	0	0.5	0.8	1.6	8	16.1	32.2	56.35	161	322
INFLOW		Steady-State Water Budget For 1 Day (Units = Meters^3)								
Storage	0	0	0	0	0	0	0	0	0	0
Con. Head	0	0	0	0	0	0	0	0	0	0
Drains	0	0	0	0	0	0	0	0	0	0
ET	0	0	0	0	0	0	0	0	0	0
Recharge	58102	58102	58102	58102	58102	58102	58102	58102	58102	58102
Stream Leakage	26749	26749	26749	26751	26753	26756	26764	26776	26826	26893
Total Inflow	84851	84851	84851	84852	84854	84857	84866	84877	84928	84995
OUTFLOW		Steady-State Water Budget For 1 Day (Units = Meters^3)								
Storage	0	0	0	0	0	0	0	0	0	0
Constant Head	2675	2675	2675	2675	2675	2675	2675	2675	2674	2674
Wells	0	2	3	5	27	54	109	191	544	1089
Drains	1501	1501	1501	1501	1501	1501	1501	1501	1500	1500
ET	22340	22340	22340	22340	22338	22336	22331	22324	22293	22244
Recharge	0	0	0	0	0	0	0	0	0	0
Stream Leakage	58331	58328	58327	58324	58310	58291	58246	58185	57908	57484
Total Outflow	84847	84846	84846	84845	84851	84857	84862	84875	84921	84991
IN - OUT	4	5	5	7	4	0	4	2	7	4
% Discrepancy	0.00	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00

Table 1 Simulated Steady-State Water Budgets

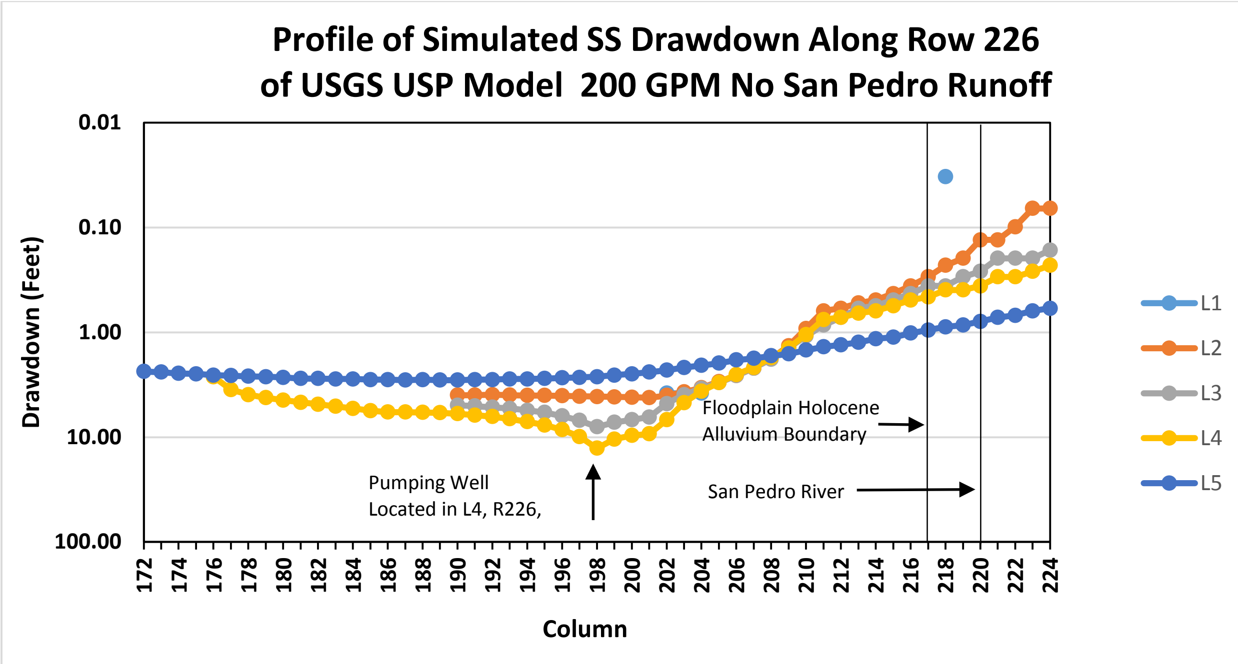


Figure 4 Profile of SS drawdown caused by a well pumping 200 GPM (No Stream Runoff Simulated)

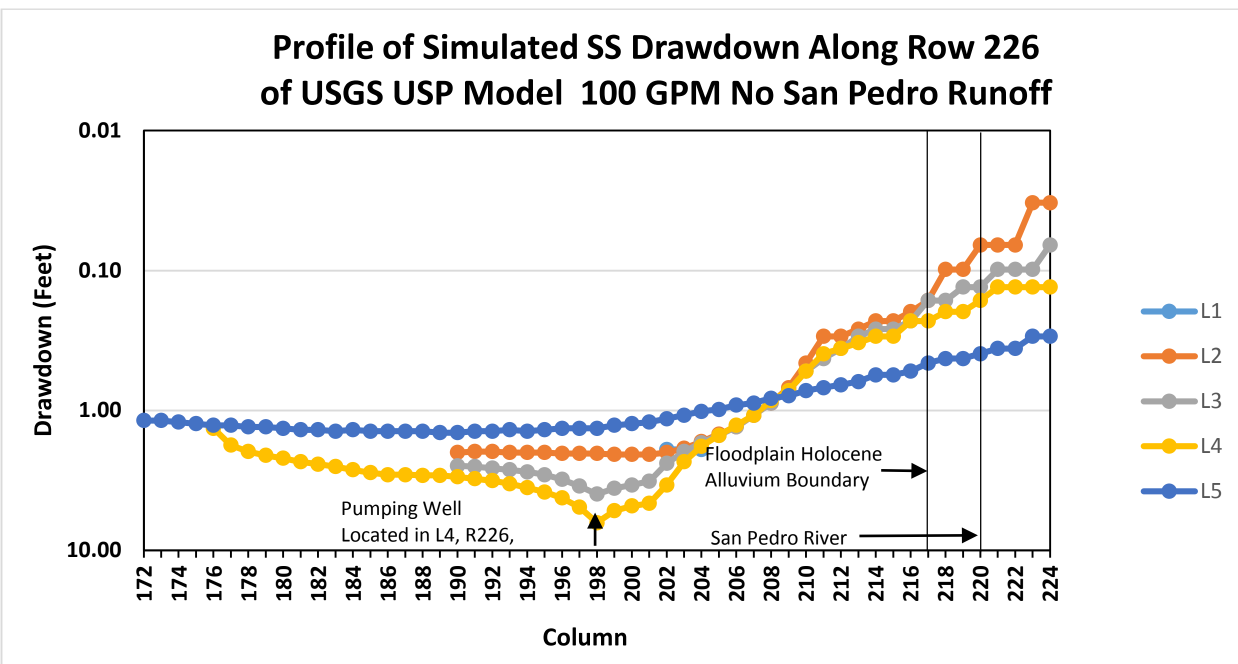


Figure 5 Profile of SS drawdown caused by a well pumping 100 GPM (No Stream Runoff Simulated)

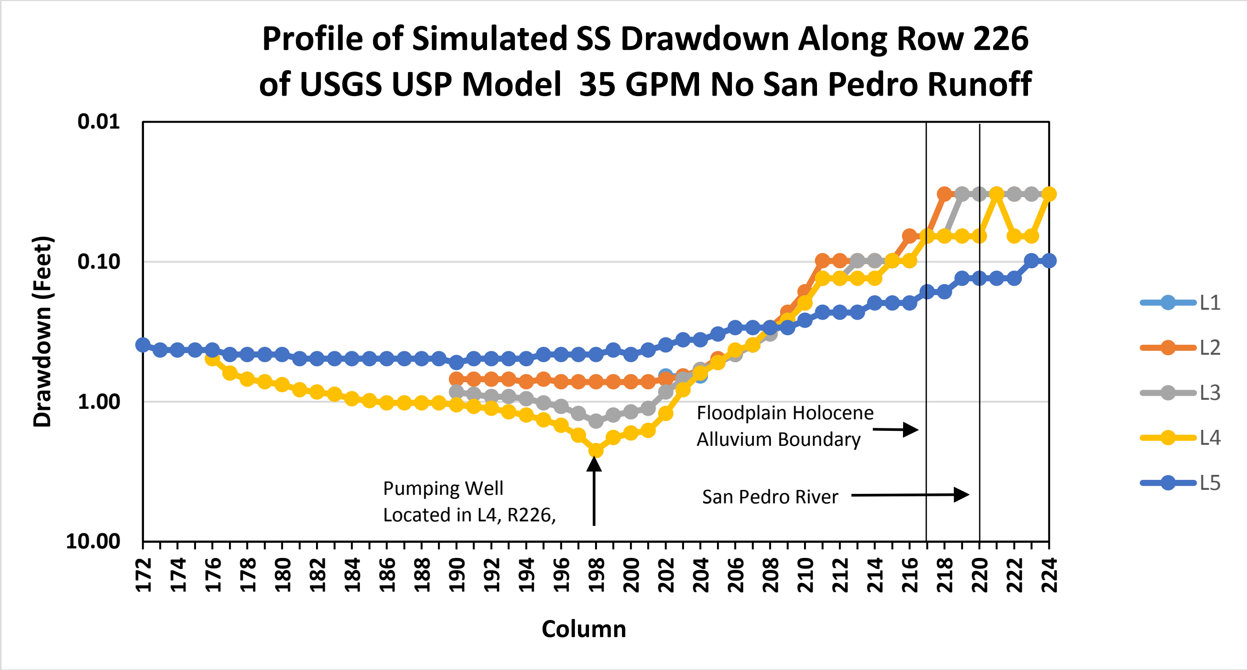


Figure 6 Profile of SS drawdown caused by a well pumping 35 GPM (No Stream Runoff Simulated)

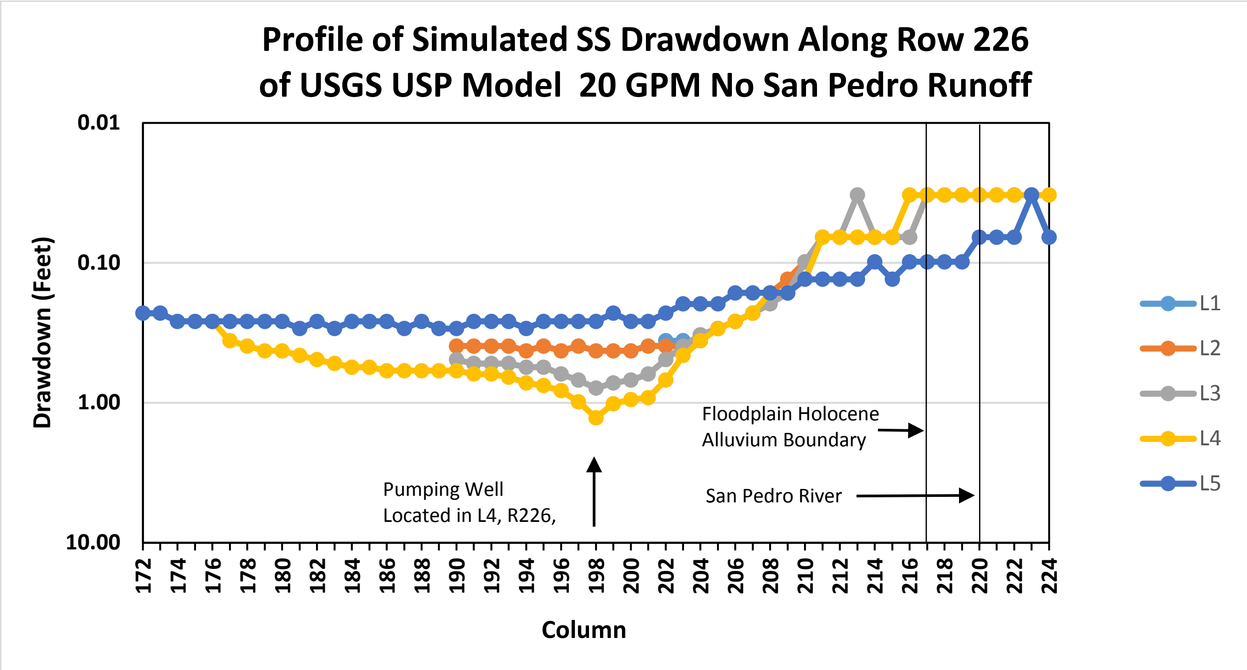


Figure 7 Profile of SS drawdown caused by a well pumping 20 GPM (No Stream Runoff Simulated)

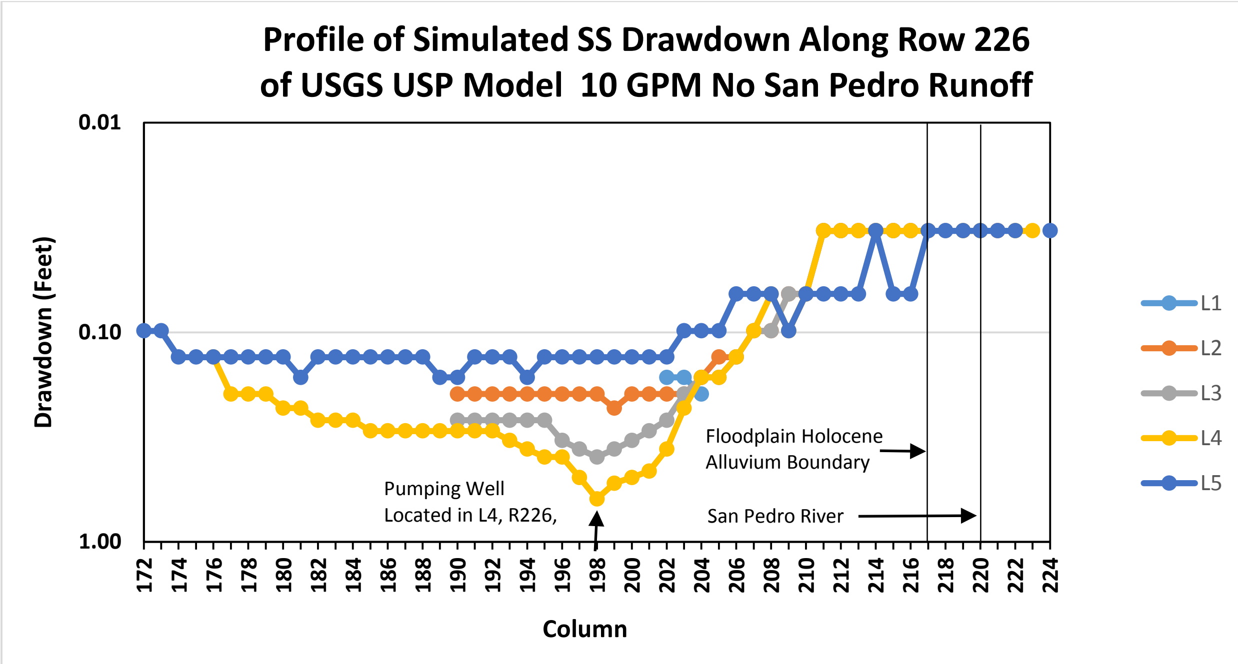


Figure 8 Profile of SS drawdown caused by a well pumping 10 GPM (No Stream Runoff Simulated)

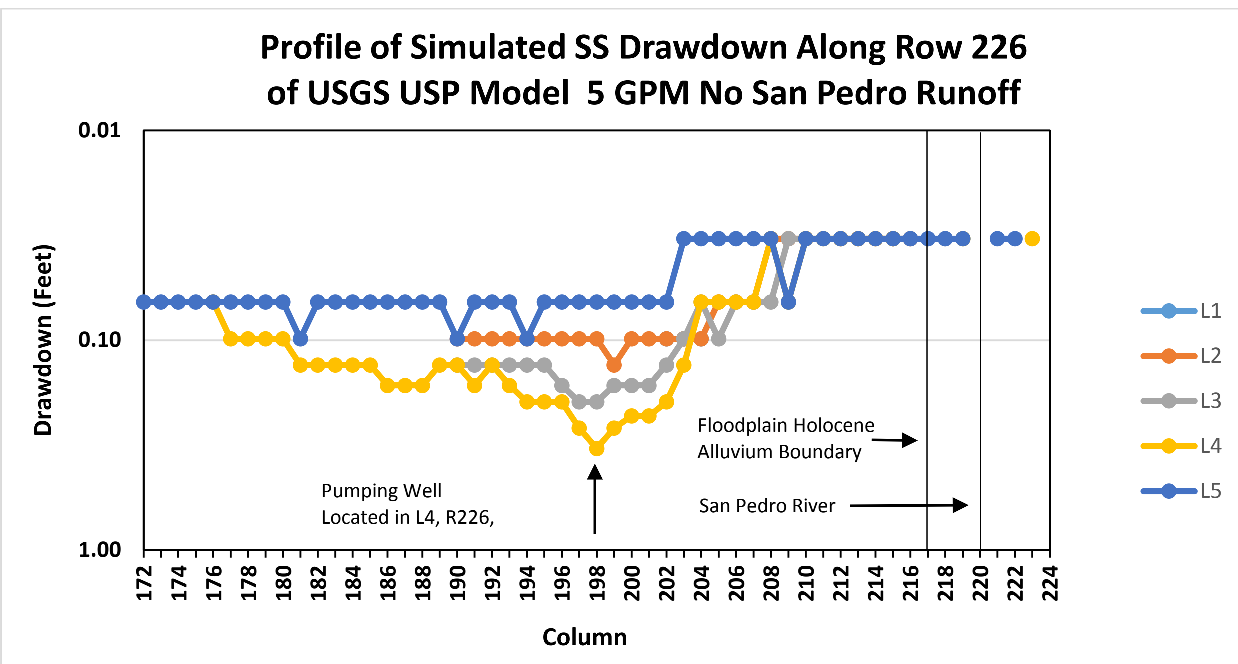


Figure 9 Profile of SS drawdown caused by a well pumping 5 GPM (No Stream Runoff Simulated)

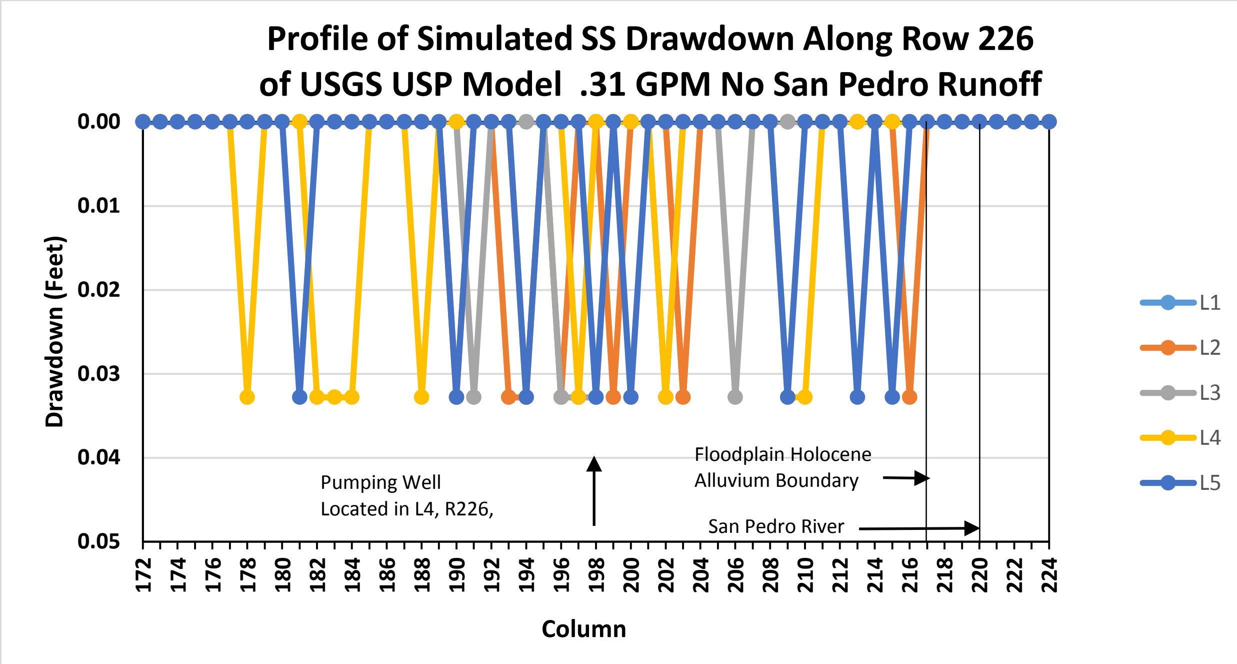


Figure 10 Profile of SS drawdown caused by a well pumping .31 GPM (No Stream Runoff Simulated)

Based on a review of Figures 7 and 8, it is apparent that for a well pumping at the described location and depth, the hypothetical steady-state drawdown at the FHA boundary becomes less than 0.1 foot below the pumping rate of 20 gpm. This result is instructive because it demonstrates the general range of pumping rates (for a given distance from the FHA boundary) that would not equal or exceed the 0.1 foot of drawdown limit. Drawdown calculations for pumping rates smaller than 5 gpm were also less than 0.1 foot. However, drawdown calculations for small pumping rates showed inconsistencies that may be related to numerical grid-size, solver convergence and numerical truncation issues. For example, the calculated drawdown for the 0.31 gpm steady-state pumping rate oscillated from 0.00 to about 0.033 feet between the hypothetical well location and the FHA boundary (Figure 10).

Because the numerical inconsistencies are associated with very small drawdowns, the inconsistencies may have little impact on cone of depression tests. However, numerical inconsistencies associated with small drawdowns may limit the use of the USGS model as tool for cone of depression testing.

Individual Wells Including Stream Runoff

The USGS Upper San Pedro model simulates groundwater discharge to the San Pedro and the Babocomari Rivers using the MODFLOW streamflow-routing package ("STR1 package"). The STR1 package, as implemented in the USGS Upper San Pedro model, does not simulate surface runoff from individual or seasonal runoff events; therefore, the model does not simulate inflow from upland channels (USGS, 2007, p. 30).

For many modeling studies, the exclusion of surface water runoff (flood flows) may have limited impact on model results; particularly in situations where water tables near streams may be shallow and predominantly gaining stream conditions may exist. In such situations, most surface water runoff may be rejected as recharge and simply flow from the area through the surface water system. In the USGS Upper San Pedro model, the only source of water that is available for potential recharge along "losing" stream reaches is groundwater that was discharged to the river channel in upstream "gaining" reaches (upstream baseflow). Thus the exclusion of surface water runoff from the USP model may impact model results.

The exclusion of surface runoff may be problematic for cone of depression testing, because the MODFLOW STR1 package limits leakage through the streambed to the aquifer in a stream reach if the calculated amount of leakage is greater than the amount of streamflow that enters the reach (USGS, 1989, p. 7). The sensitivity of USP model results to the inclusion of stream runoff was tested by placing a range of surface water runoff into the USP - STR1 Package near the U.S. / Mexico International border (Row = 252, Col=205, Layer=1, Segment = 56, Reach = 1). The estimated annual surface water runoff at this location was estimated from the USGS Palominas streamgage (09470500). The period of record for this gage covers the periods from 8/1950 to 9/1981 and 10/1995 to 9/2015. Over the period of record, mean monthly streamflow (discharge) at Palominas was about 28.7 CFS and median monthly streamflow (discharge) was 2.1 CFS (Figure 11). The median monthly streamflow of 2.1 CFS at this location was similar to steady-state baseflow of 1.3 CFS simulated by the USGS Upper San Pedro model at that location. Inspection of Figure 11 reveals the highly seasonal character of streamflow on the San Pedro River at that location, where about 76 percent of the annual flow during the period of record occurred during the 3-month summer monsoon season (July, August, September).

The highly seasonal nature of hydrologic processes in the San Pedro River watershed makes it difficult to define a true steady-state simulation. In order to deal with this situation, recent models developed for the area, including the USGS Upper San Pedro model, have adopted an "Oscillatory Steady-State" to provide initial conditions for transient modeling (USGS, 2007, p. 35). In the USP model, a 30-year oscillatory steady-state simulation was completed to simulate predevelopment seasonal evapotranspiration conditions (USGS, 2007, p. 35). Although the oscillatory steady-state is the preferred approach for developing initial conditions for transient modeling, it is unclear whether and how the "oscillatory steady-state" method could be adapted to meet "steady-state" cone of depression testing. It is also unclear what magnitude of annual surface runoff would be representative of typical or average conditions to use in a true steady-state simulation.

In spite of these complexities, ADWR estimated the average annual surface runoff for the San Pedro River at the International Border by subtracting the median monthly discharge at the Palominas gage from the mean monthly discharge (28.7 CFS – 2.1 CFS = 26.6 CFS). Since the methodology used only provided a rough estimate of annual surface water runoff (for the period of record), and the highly seasonal nature of the runoff made it difficult to quantify a representative annual volume of runoff for a true steady-state simulation, a sensitivity analysis was conducted to evaluate the range of impact on numerical model results.

The sensitivity of the steady-state model to inclusion of stream runoff is shown in Table 2 and Figures 12 – 19.

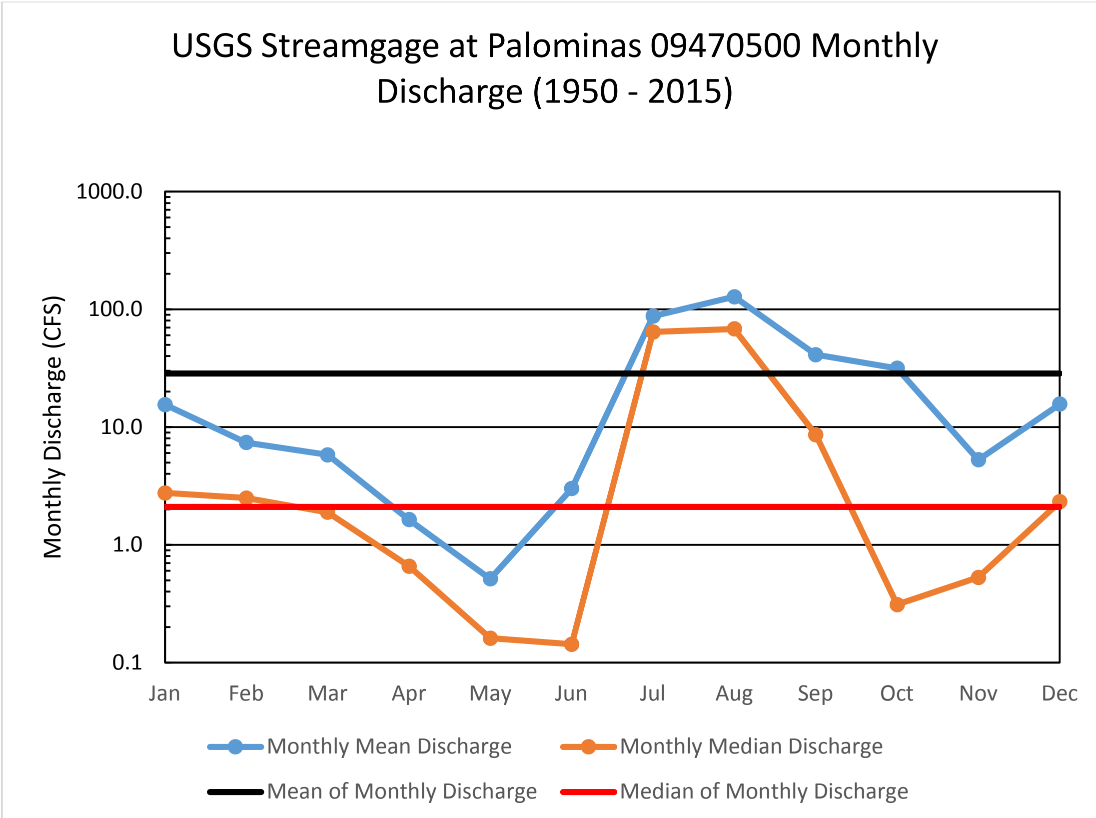


Figure 11. Monthly Discharge at USGS Streamgage at Palominas 095470500

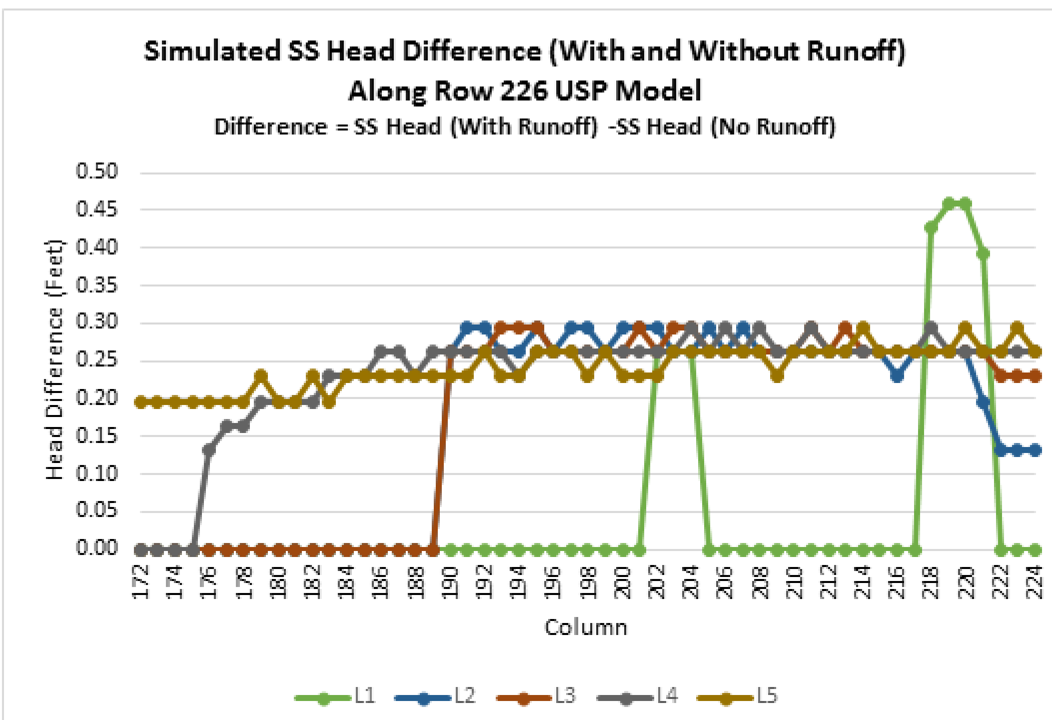
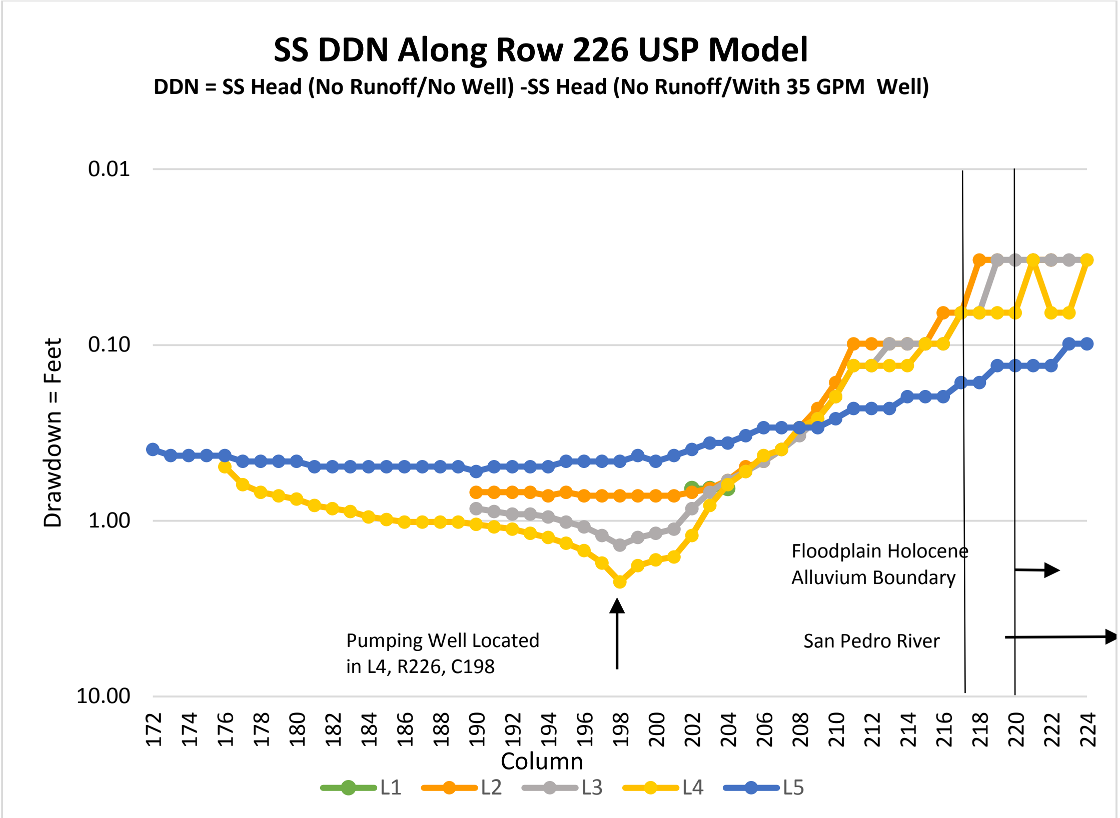


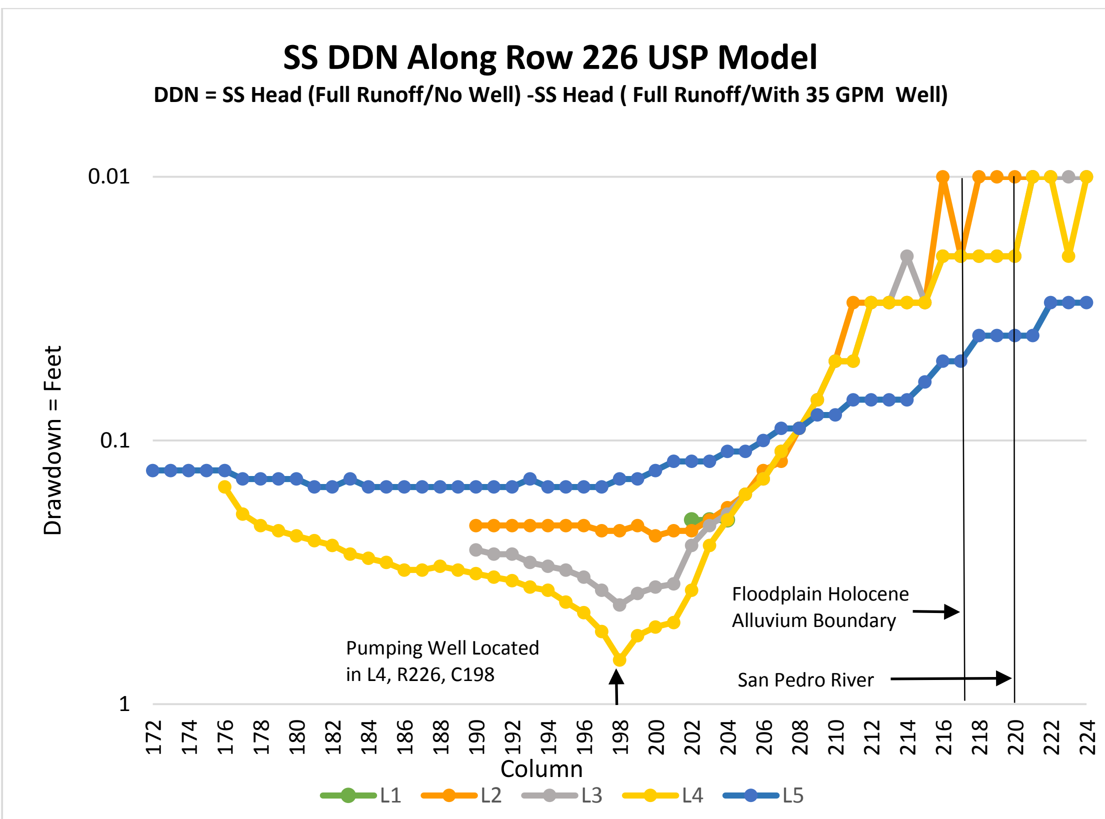
Figure 12 Difference between steady-state water levels for simulations (with and without runoff)

Units = Meters^3 / Day									
	No Well	No Well	Well 35gpm	Well 35gpm	Well 35gpm	Well 35gpm	Well 35gpm	Well 35gpm	Well 35gpm
	No Runoff	Full Runoff	Full Runoff	.75 Runoff	.50 Runoff	.25 Runoff	.10 Runoff	.05 Runoff	.00 Runoff
IN:									
STORAGE =	0	0	0	0	0	0	0	0	0
CONSTANT HEAD =	0	0	0	0	0	0	0	0	0
WELLS =	0	0	0	0	0	0	0	0	0
DRAINS =	0	0	0	0	0	0	0	0	0
ET =	0	0	0	0	0	0	0	0	0
RECHARGE =	58102	58102	58102	58102	58102	58102	58102	58102	58102
STREAM LEAKAGE =	26749	26854	26882	26850	26829	26804	26786	26777	26776
TOTAL IN =	84851	84956	84984	84951	84931	84906	84887	84878	84877
OUT:									

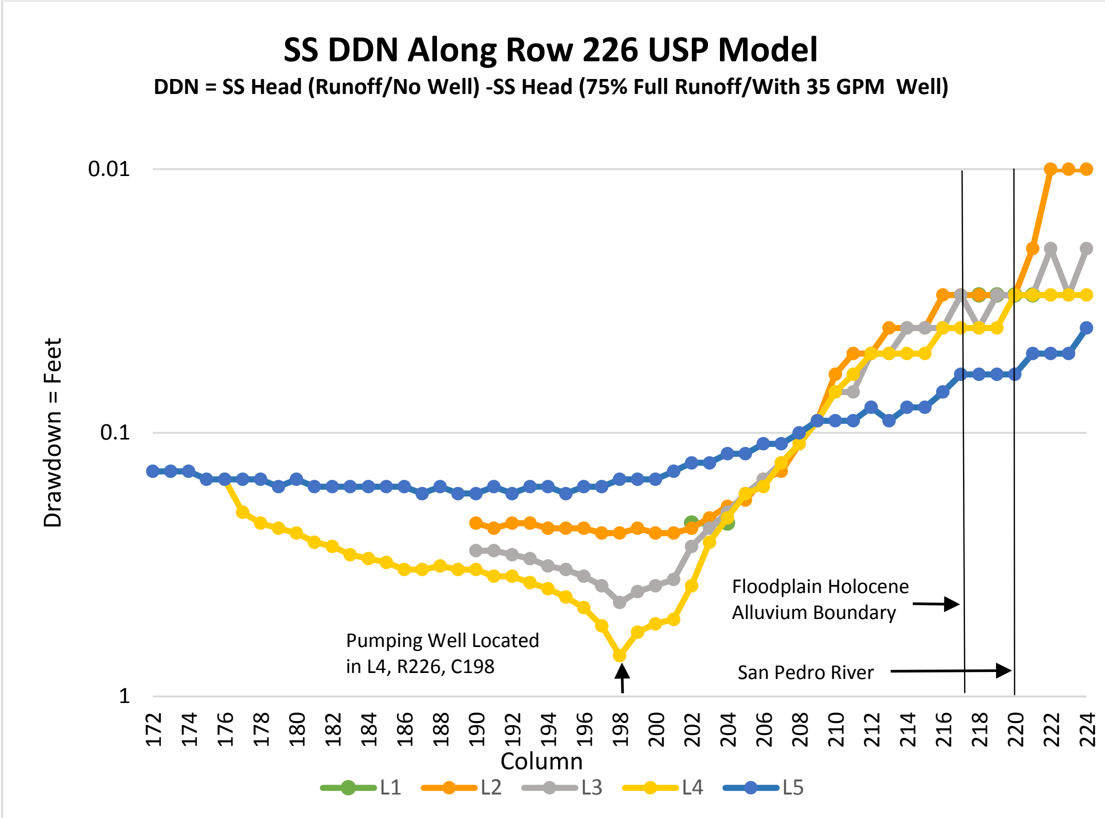
STORAGE =	0	0	0	0	0	0	0	0	0
CONSTANT HEAD =	2675	2676	2676	2676	2675	2675	2675	2675	2675
WELLS =	0	0	191	191	191	191	191	191	191
DRAINS =	1501	1501	1501	1501	1501	1501	1501	1501	1501
ET =	22340	22948	22933	22808	22667	22499	22375	22325	22324
RECHARGE =	0	0	0	0	0	0	0	0	0
STREAM LEAKAGE =	58331	57825	57677	57772	57896	58035	58146	58180	58185
TOTAL OUT =	84847	84950	84978	84947	84930	84900	84887	84871	84875
IN - OUT =	4	6	6	4	1	6	0	7	2
PERCENT DISCREPANCY =	0.00	0.01	0.01	0.00	0.00	0.01	0.00	0.01	0.00

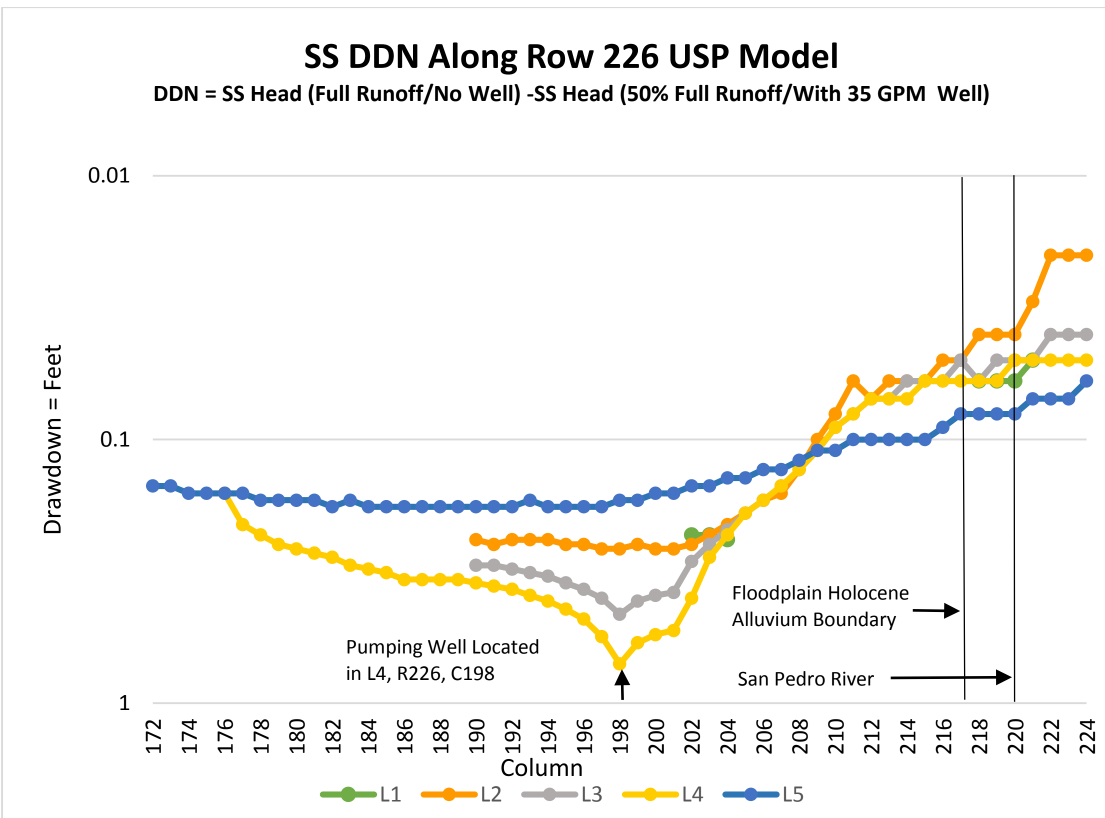
Table 2 Simulated Steady-State Water Budgets for Runoff Sensitivity Analysis



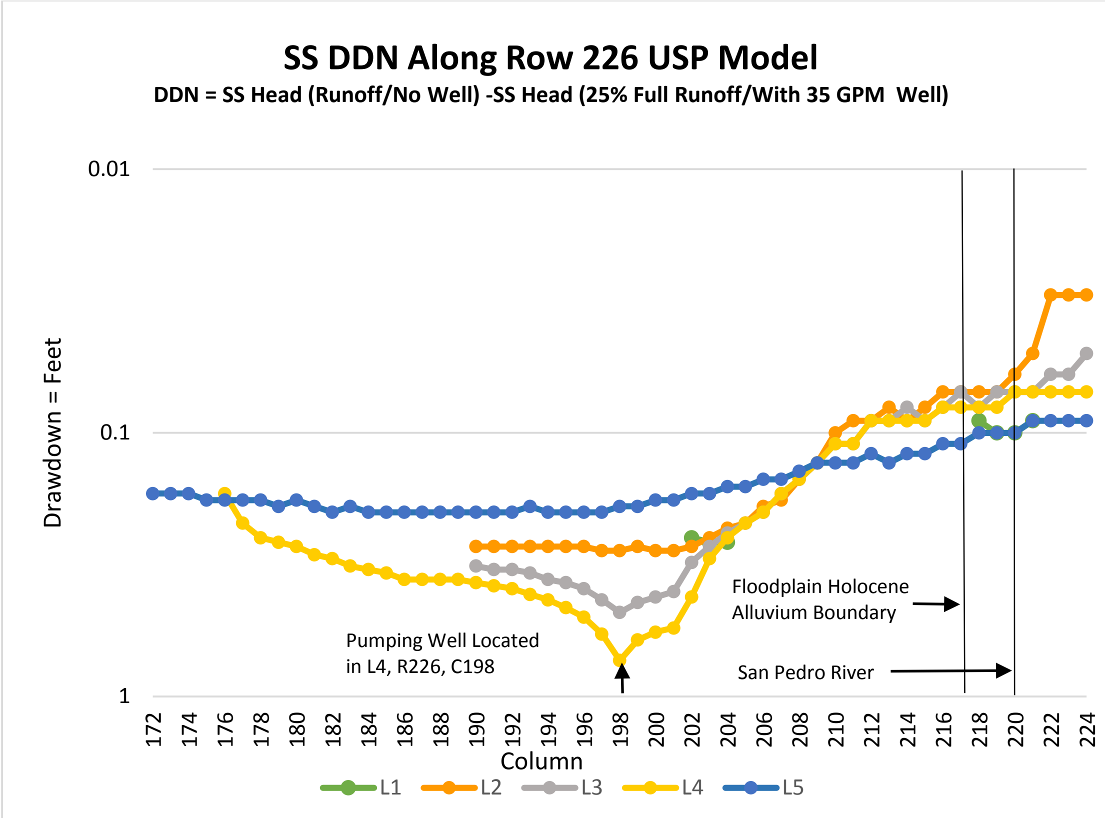


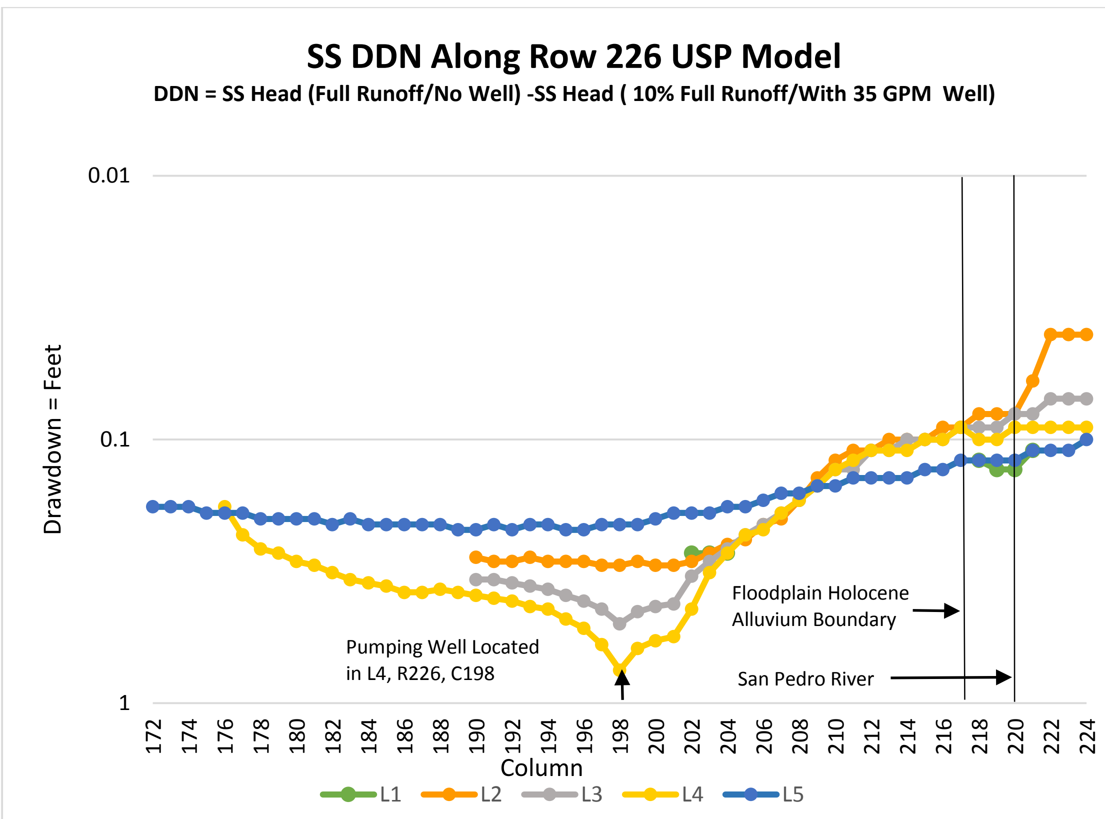
Figures 13 and 14 Steady-state drawdown with and without runoff





Figures 15 and 16 Steady-state drawdown with 75% and 50% runoff





Figures 17 and 18 Steady-state drawdown with 25% and 10% runoff

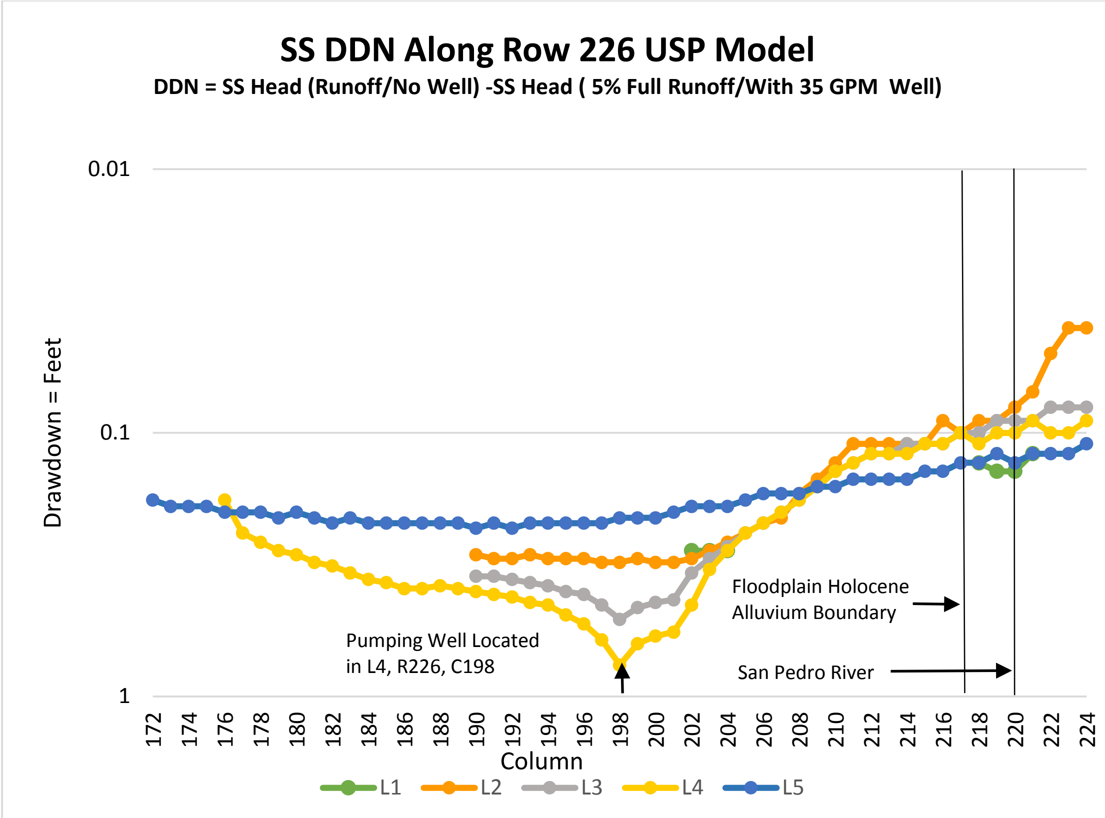


Figure 19 Steady-state drawdown with 5% runoff

The results of the runoff sensitivity analysis show that the steady-state model solution is impacted by the quantity of surface runoff included in model simulations. Review of Figure 12 shows that the inclusion of runoff in the STR1 package increases simulated heads in all model layers, with a maximum increase of about 0.45 feet in Layer 1 heads near the San Pedro River along row 226. The results show (Figure 13) that without surface runoff, simulated drawdown in Layer 5 is greater than 0.1 foot at the FHA boundary along row 226 with simulated well pumping of 35 gpm. The results also show that steady-state drawdowns for all model layers are less than 0.1 foot at the FHA boundary for simulations that include at least 50 percent of the full estimated annual runoff (Figures 14 -16).

Review of Tables 1 and 2 shows that simulated stream leakage (recharge) increases and groundwater discharge (baseflow) decreases in simulations that include increasing volumes of well pumping. The results also show that stream leakage increases and groundwater discharge decreases with increasing simulated runoff for constant rate well pumping simulations (Table 2). Based on these results, it is clear that the inclusion or exclusion of stream runoff, may be critical to the cone of depression evaluation of some wells.

Multiple Well Impacts

The impact of multiple wells pumping was tested for the 20 gpm simulation that did not include San Pedro River recharge. As discussed earlier, the 20 gpm pumping simulation (108.9 meters^3/day) did not cause a drawdown in any model layer that exceeded 0.1 foot at the San Pedro River FHA boundary. To test the impacts of multiple wells, 4 additional wells were added to the 20 gpm single-well simulation in model cells: (L=4, R=224, C=196), (L=4, R=224, C=200), (L=4, R=228, C=196), (L=4, R=228, C=200) (Figure 20). The distance from each outer well to the central well is about 2,300 feet.

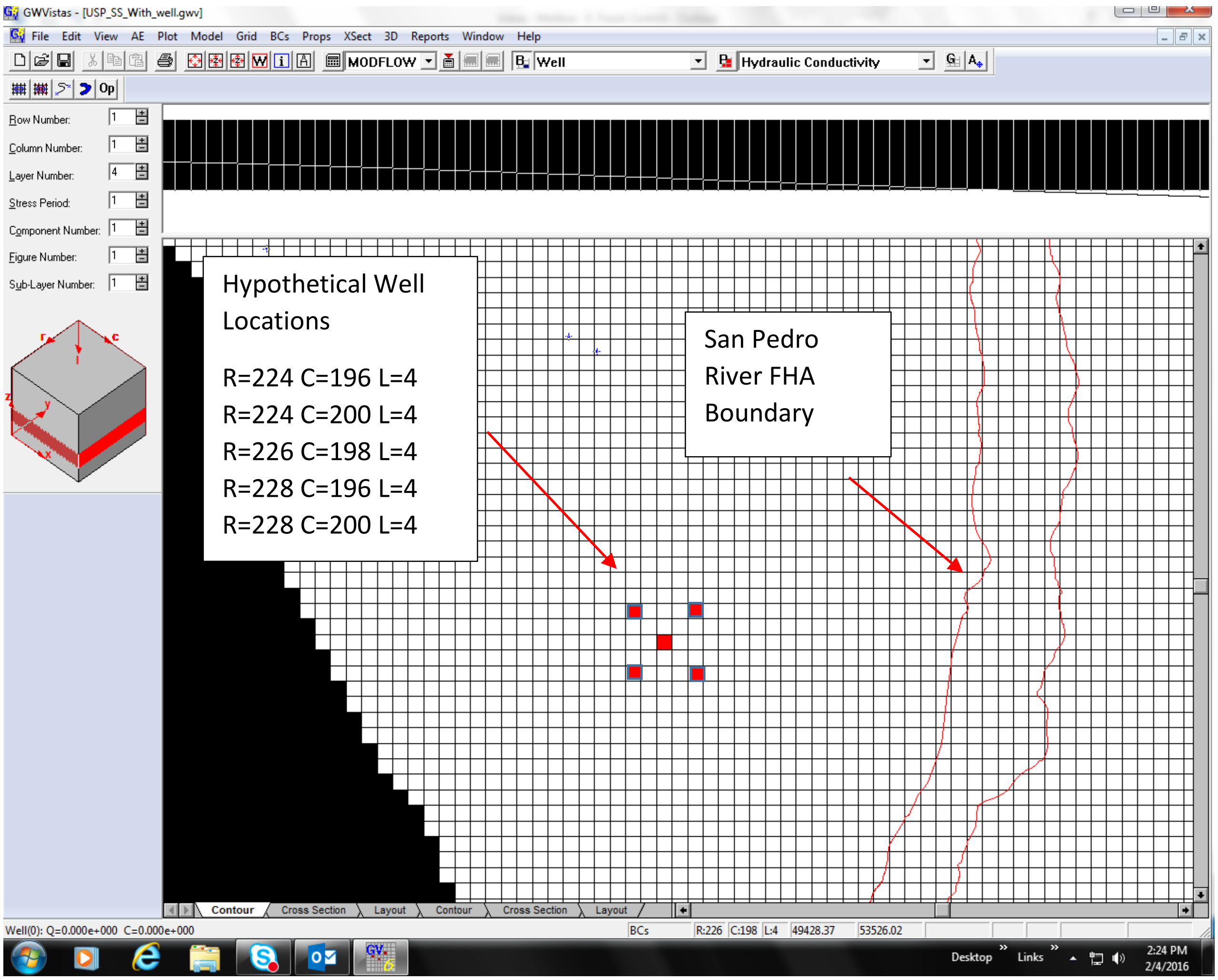
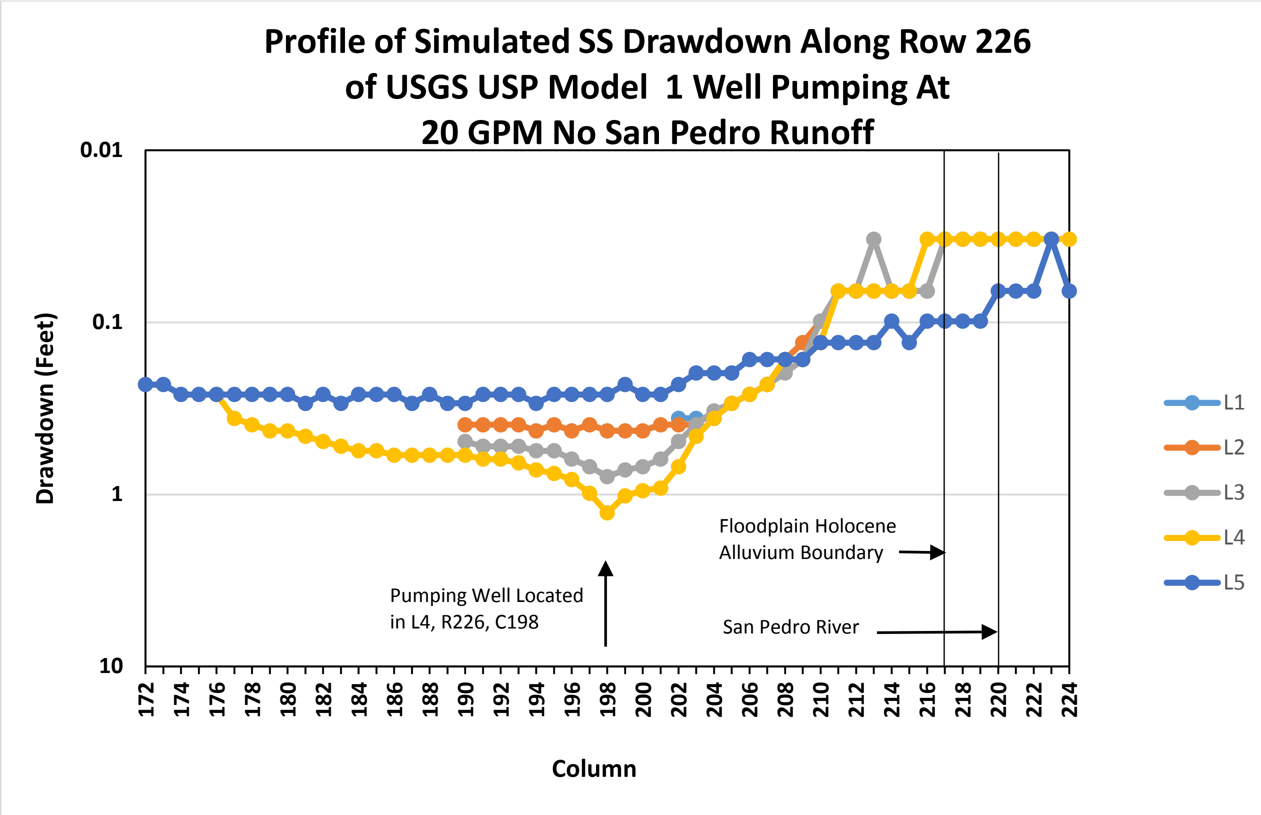


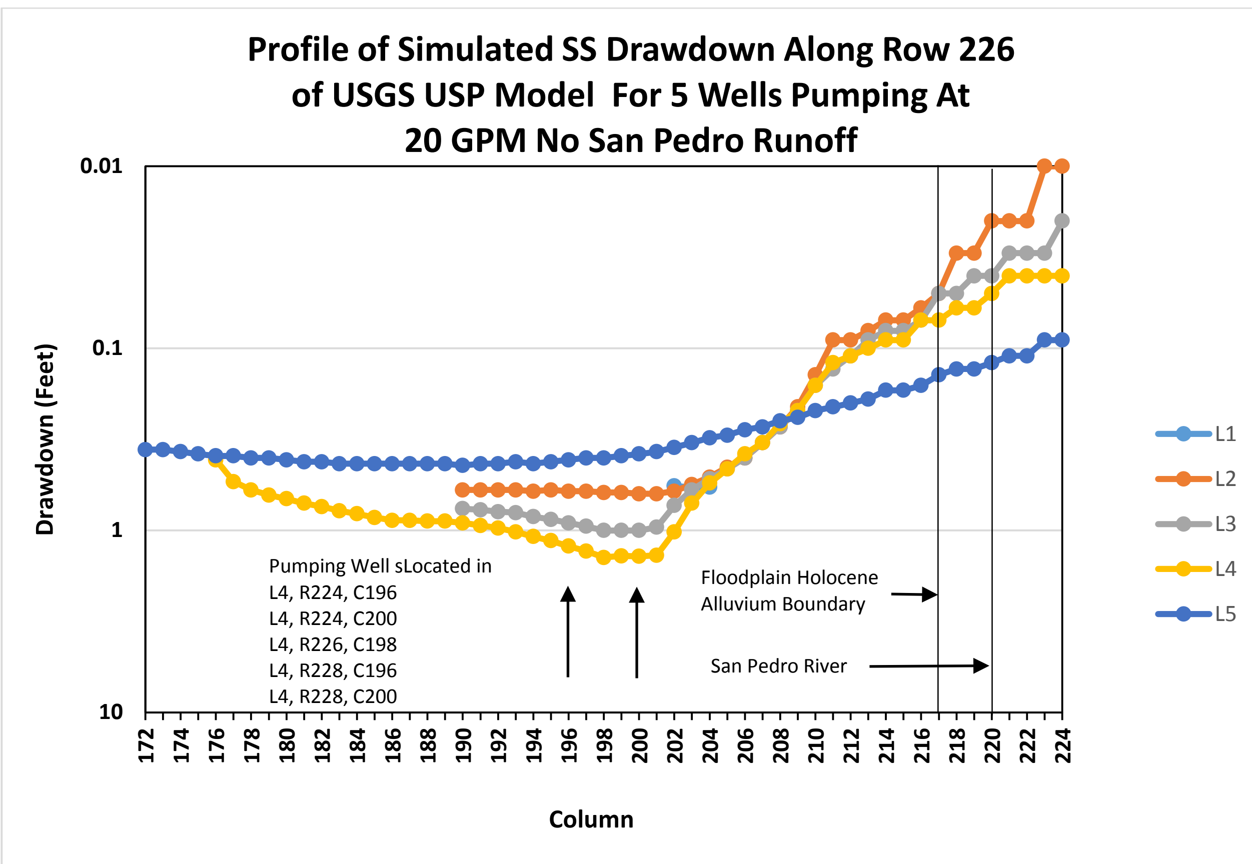
Figure 20 Locations of hypothetical wells for 20 gpm pumping simulation.

Table 3 Water budgets for 20 gpm single and multiple well simulations

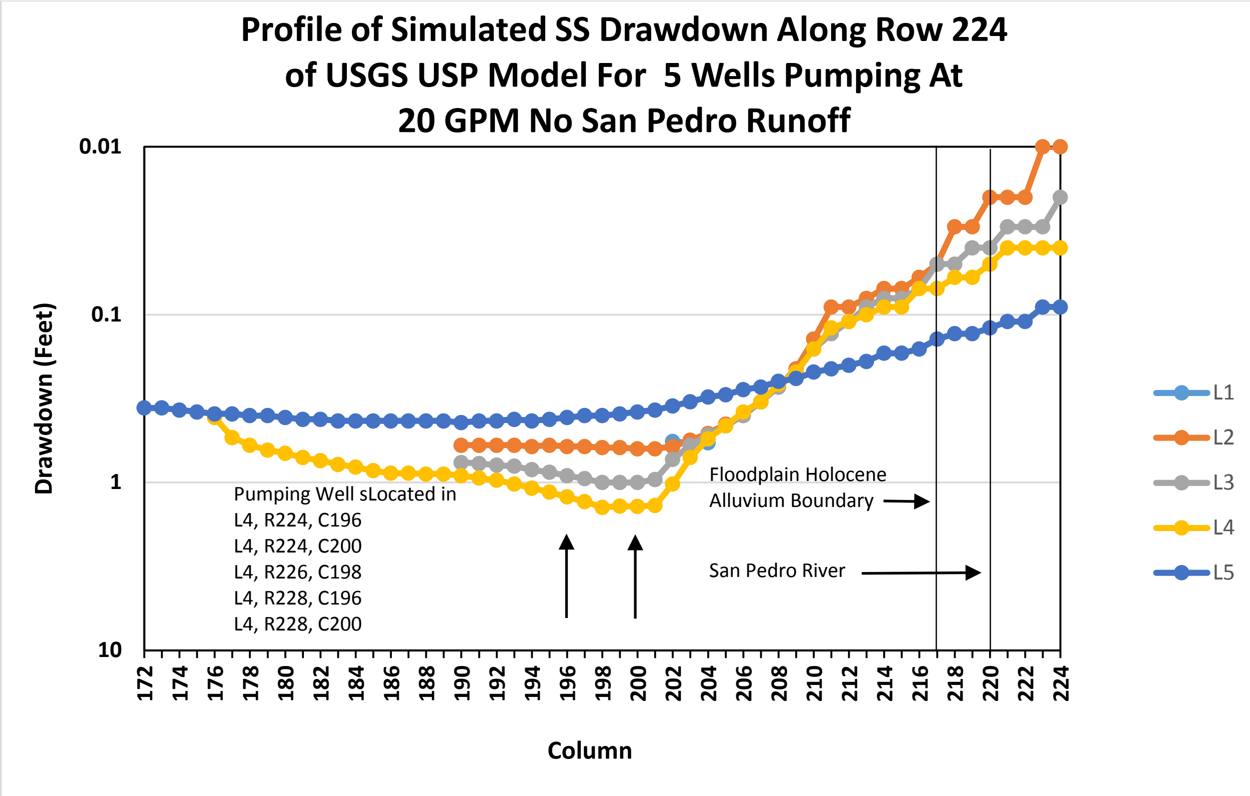
SS Pumping Rate (gpm) ->	20	100
Acre-Feet/Year	32.2	165
INFLOW	Steady-State Water Budget for One Day Meters ^3/ Day	
Storage	0	0
Con. Head	0	0
Drains	0	0
ET	0	0
Recharge	58102	58102
Stream Leakage	26764	26825
Total Inflow	84866	84927
OUTFLOW	Steady-State Water Budget for One Day Meters^3 /Day	
Storage	0	0
Constant Head	2675	2674
Wells	109	544
Drains	1501	1500
ET	22331	22293
Recharge	0	0
Stream Leakage	58246	57910
Total Outflow	84862	84922
IN - OUT	4	5
% Discrepancy	0.01	0.01

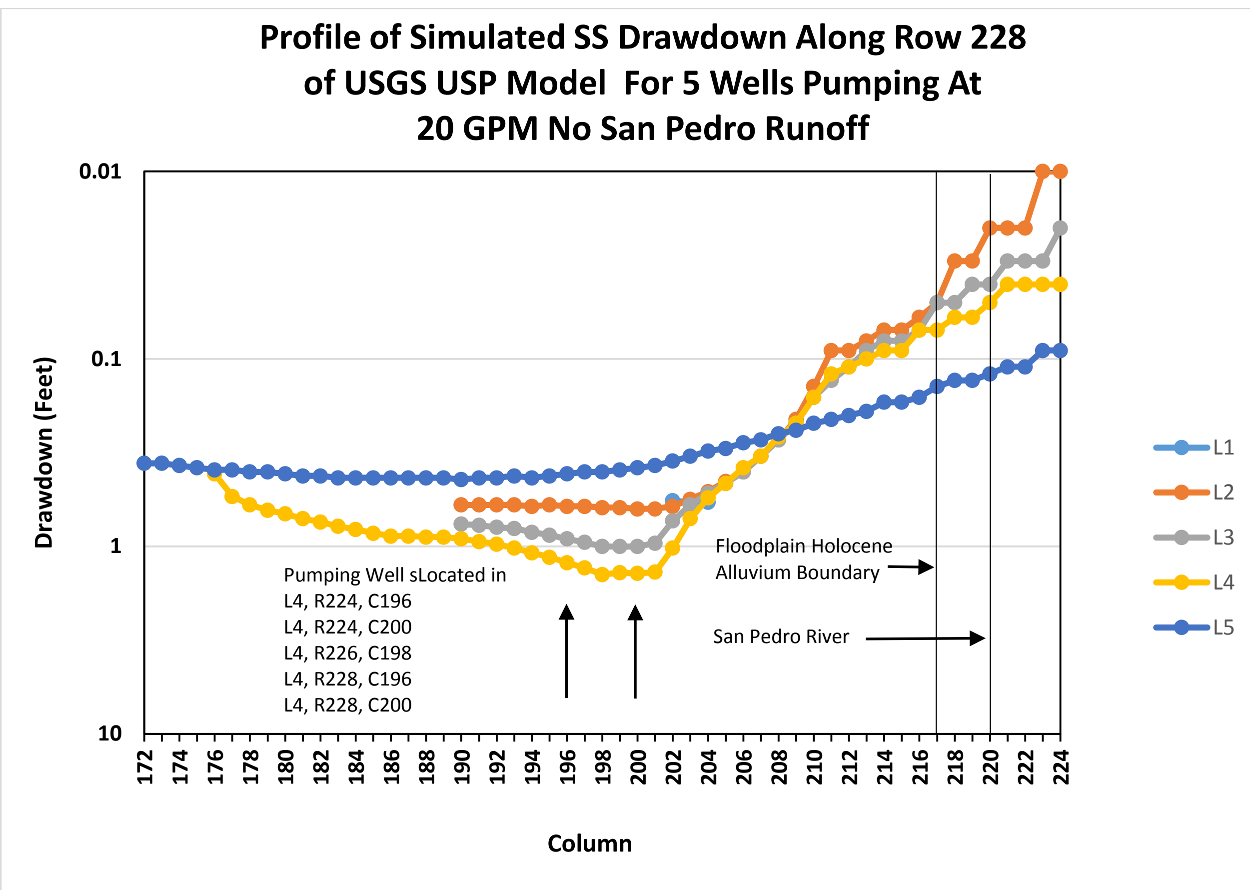
Results of the single and multiple well simulations are shown in Figures 21 – 24. The results show that the cumulative drawdown of the 5 hypothetical wells was in excess of 0.1 foot in Layer 5 at the FHA boundary. As expected, stream recharge increased, and groundwater discharge decreased with the additional simulated pumping (Table 3). Although the differences in simulated drawdowns are small in this example, the results are consistent with the concept that multiple wells pumping at individually allowable rates can have cumulative effects that exceed the 0.1 foot allowable drawdown standard.





Figures 21 and 22 Steady-state drawdown with single and multiple wells Row 224 and 226





Figures 23 and 24 Steady-state drawdown with multiple wells Rows 224 and 228

References

USGS, 2007. Ground-Water Flow Model of the Sierra Vista Subwatershed and Sonoran Portions of the Upper San Pedro Basin, Southeastern Arizona, United States, and Northern Sonora, Mexico. USGS Scientific Investigations Report 2006-5228.

USGS, 2013. MODFLOW-USG Version 1: An Unstructured Grid Version of MODFLOW for Simulating Groundwater Flow and tightly Coupled Processes Using a Control Volume Finite-Difference Formulation. USGS - Chapter 45 of Section A, Groundwater Book 6, Modeling Techniques.