HYDROSPHERE
Resource Consultants

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To: Craig Roepke, NM Interstate Stream Commission

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Subject: Findings from the Mangas Trench and Gila Groundwater Basin Hydrologic Review

Executive Summary

This letter report presents the findings of Hydrosphere's review of available hydrologic data relating to the Mangas Trench formation in the Gila and Mimbres Basins, including the *Supplement on Water Use and Wellfield Service – Town of Silver City Water Plan* by Balleau Groundwater, Inc. We performed independent analyses to estimate individual components of the water budget and have identified potential uncertainties that may exist.

Additionally, we utilized the existing MODFLOW model of Grant County to evaluate impacts on nearby water rights and surface water flows in the that might be or have been affected by pumping in the Mangas Trench near Silver City.

We provide cost estimates related to suggested alternatives for meeting the increasing water demands in the Silver City and surrounding Grant County areas.

1.0 Introduction

This letter report presents the findings of our review of the available hydrologic data relating to the Mangas Trench formation in the Gila and Mimbres Basins, including the *Supplement on Water Use and Wellfield Service Town of Silver City Water Plan* by Balleau Groundwater, Inc. (2006), also referred to as the "Balleau report" throughout this memo. In addition to the Balleau report, we have reviewed numerous technical reports related to the Gila and Mimbres Basins, as well as undertaking our own independent analyses.

Based on our efforts, we have the following findings and opinions:

- The Balleau report employs an enhanced version of the New Mexico Office of the State Engineer (NMOSE) Mangas Trench Groundwater Model (or "Model") to develop projections of Silver City's wellfield service life over a 40-year planning period. The addition of the Multi-Node Well (MNW) package is valid and beneficial for addressing the water supply issues being considered by their study (i.e., Silver City wellfield productivity in the future).

- The Model is based on previously-estimated volumetric water budgets, observed groundwater levels, well logs from across the area, Mangas Springs discharge, Gila River baseflow gains, and measured and estimated hydraulic conductivitues and transmissivities.

- Estimates of groundwater underflow to the Gila and Mimbres Basins computed by the Model and presented in the Balleau report are consistent with available water table contour maps and aquifer parameter values.

- Modeled groundwater discharges to the Gila River from the Mangas Trench formation are consistent with observed baseflow gains from the river gage data. However, the assumption that half of this water is sourced in the Model area is a potential uncertainty that could lead to a change in the overall water budget. Considering a reasonable range of contribution of observed baseflow gains coming from the Model area east of the river suggests that the current estimated discharge to the Gila River of 4,860 AFY could change on the order of +/- 2,000 AFY.

- Recharge to the Gila and Mimbres Basins is reasonable, based on available precipitation data and a relative comparison using developed groundwater flownets. We also performed independent estimates of recharge based on precipitation data and a chloride mass balance, as well as using the Maxey-Eakin approach.

- We utilized the Grant County transient MODFLOW model to evaluate effects of pumping select wellfields on the Gila River, Mangas Springs, and water levels in nearby domestic wells. Modeling results indicate that the full impacts of Silver City wellfield pumping would not be felt for decades.

1.1 Basis for Opinions

Our opinions are based upon the review of numerous documents and sources of information, including those listed below. Data and information contained in these documents were utilized to support our hydrologic analysis of the Gila and Mimbres Basins and Silver City water resources. If additional data and/or information becomes available that contradicts the findings of these studies, we reserve the right to modify our opinions.

1. Balleau Groundwater, Inc., February 2006. *Supplement on Water Use and Wellfield Service -- Town of Silver City Water Plan DRAFT*, Prepared for: Town of Silver City.

2. Avon, L. and T.J. Durbin, 1994. *Evaluation of the Maxey-Eakin method for estimating recharge to ground-water basins of Nevada*, Water Resources Bulletin 30 (1): p. 99-111.

3. Baldys, Stanley, III, Lisa K. Ham, and Kenneth D. Fossum, 1995. *Summary Statistics and Trend Analysis of Water-Quality Data at Sites in the Gila River Basin, New Mexico and Arizona*, U.S. Geological Survey Water-Resources Investigations Report 95-4083, 86 p.

4. Daniel B. Stephens and Associates, Inc. (DBS&A) and Hydrosphere Resource Consultants (HRC), December 2003. *Socorro-Sierra Regional Water Plan, Volume 1.*

5. Daniel B. Stephens and Associates, Inc. (DBS&A), May 2005. *Southwest New Mexico Regional Water Plan Volume 1.*

6. Geohydrology Associates, 1981. *Water-Resources for East-Central Grant County, New Mexico.*

7. Hanson, R.T., J.S. McLean, and R.S. Miller, 1994. *Hydrogeologic Framework and Preliminary Simulation of Ground-Water Flow in the Mimbres Basin, Southwestern New Mexico*, U.S. Geological Survey: Water Resources Investigations Report 94-4011, 118 p.

8. Hawley, J.W., B.J. Hibbs, J.F. Kennedy, B.J. Creel, M.D. Remmenga, M. Johnson, M.M. Lee, and P. Dinterman (WRRI), March 2000. *Trans-International Boundary Aquifers in Southwest New Mexico*. Prepared by New Mexico Water Resources Research Institute.

9. Johnson, M.S., 2000. *Hydrologic Evaluation of Application GSF-1745 into GSF-1014 for Permit to Change Location of Well and Place or Purpose of Use in the Gila-San Francisco Underground Water Basin, Grant County, New Mexico*, NM Office of the State Engineer, Technical Division Hydrology Report 00-3.

10. Johnson, M.S., L.M. Logan, and D.H. Rappuhn, March 2002. *Analysis of Effects of Ground-Water Development to Meet Projected Demands in Regional Planning District 4, Southwest New Mexico*, NM Office of the State Engineer, Hydrology Report 02-04.

11. Koopman, F.C., F.D. Trauger, and J.A. Basler, 1969. *Water Resources Appraisal of the Silver City Area New Mexico*, NM State Engineer, Technical Report 36.

12. Maxey, G.B. and T.E. Eakin, 1949, *Ground Water in White River Valley, White Pine, Nye, and Lincoln Counties, Nevada,* Nevada State Engineer, Water Resources Bulletin No. 6, 23 p.

13. National Atmospheric Deposition Program (NADP) National Trends Network, 2007, Chloride concentration in precipitation for Site NM01 (southwestern NM), Accessed June 12, 2007, http://nadp.sws.uiuc.edu.

14. Trauger, F.D., 1972, *Water Resources and General Geology of Grant County, New Mexico*, NM State Bureau of Mines and Mineral Resources Hydrologic Report 2.

15. U.S. Geological Survey website, Accessed March 6, 2007, www.usgs.gov.

16. Watson, P., P. Sinclair, and R. Waggoner, 1976, *Quantitative Evaluation of a Method for Estimating Recharge to the Desert Basins of Nevada*, Journal of Hydrology 30: p. 335-357.

17. Wilson, B.C., 2001, *Projected Water Demands in Grant, Hidalgo, and Luna Counties, New Mexico, 2000 to 2040*, New Mexico Office of the State Engineer.

2.0 Review of Balleau Report

The Balleau report includes a detailed account of historical water use in the Silver City area, as well as a 40-year projection for the town's wellfield service life. Using population growth trends for the town of Silver City and surrounding areas, Balleau determines the length of time for which the presently-configured water supply system can meet projected demands. Balleau also revised the current Model with a well hydraulics component in order to account for the declining yield associated with wells as future pumping lowers water levels to near the lowest allowed for operation. The Balleau report also analyzes sustainable yield for the wellfields to develop a future water schedule intended to account for the rising demand.

2.1 Review of Historical Literature

The Balleau report provides a general review of previous work regarding wellfield service life in the Silver City area, which includes the following:

- Koopman and others (1969) evaluated wellfield service life for Silver City and surrounding areas in Grant County in terms of how long it would take wells to reach half of their initial water column. Their study considered declining well yields and potential for development of additional wells. They identified alternatives to extend wellfield service life, such as extending wellfields and limiting production.

- Trauger and others (1980[1]) revised earlier estimates of wellfield service life based on wellfield production and additional observations. Using a general computer model, they concluded that wellfield service life could be extended by development of new wells and wellfields.

- The Mangas Trench Groundwater Model of Silver City and surrounding areas was developed in MODFLOW by the NMOSE (Johnson, 2000; 2002) and includes hydrogeologic details of the Gila Group aquifer in the Gila and Mimbres Basins. Johnson and others (2002) used the Model to assess existing groundwater supplies and evaluate the effects of continued wellfield pumping to meet future demands by the towns of Silver City, Bayard, and Central. Remaining well water columns are reported for planning purposes, but specific wellfiels service life is not addressed.

- Wilson (2001) estimated future demand for Silver City based on population projections.

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[1] This reference is listed in the Balleau report (p.5) as Trauger and others, 1980; however, the only reference cited in the references section (p.30) is Trauger, 1972.

2.2 Interpretation of Data

The major objectives of the Balleau analysis and report included: (1) compilation of current water use, (2) projection of future water use, and (3) usage of the Model to evaluate Silver City's wellfield service life.

The projected water demand for Silver City was developed based on previous studies and projections (Geohydrology Associates, 1981; DBS&A, 2005) and evaluation of additional water tap trends which reflect the water service area. Although the population growth rate decreased slightly from 2000 to 2004, the number of new water taps serviced by Silver City increased. Balleau analyzed growth rate trends ranging from a low of 1.2% per year to a high of 2.9% per year, and assumed a per capita water use of 155 gallons per day. Based on these rates, Silver City exceeds its permitted water right in 16 to 38 years. These demand projections can be scaled downward with reasonable and attainable reductions in the per capita use rate.

The Model was utilized to evaluate the long-term yield of the wellfields. In general, no changes were made to the Model setup, aquifer properties, or the overall water budget resulting from Model calibration. Balleau used the Model to analyze alternative well sites for Silver City which could potentially meet the unmet demands for water, as well as examining the potential option of importing surface water to the Silver City water system to meet this demand. Details regarding upgrades and changes are discussed in Section .

2.3 Use and Upgrade of the NMOSE Model

The NMOSE previously developed a calibrated groundwater flow model of the Mangas Trench formation using MODFLOW. No modifications were made to the structure (e.g., boundary conditions, recharge regime, aquifer extent and properties) of the Model. Balleau used the Model to examine a number of scenarios for meeting the projected demand for water use in the Silver City area.

The Balleau report upgraded the Model with the drawdown-limited, MNW package for MODFLOW. The MNW package allows users to simulate wells that are production-limited based on the lowest practical pumping level in specific wells, and accounts for individual well efficiency with a constant that relates head loss to the pumping rate. In other words, the MNW package accounts for decreasing yield of specific wells as they approach maximum allowed drawdown levels for pumping. *Based on our previous experience with MODFLOW and with the MNW package in particular, it is our opinion that the upgrade to use of the MNW package made in the Balleau report is valid and beneficial for addressing the water supply issues being considered by their study.*

Information on domestic well pumping from the NMOSE Water Administration Technical Engineering Resource System (WATERS) database was compiled and added to the Model to account for regional domestic well water use.

Alternative well sites were considered at three locations: a new Gila Basin well (Continental Well), a replacement for the Anderson well, and a replacement for the Gabby Hayes well.

Results indicate that the Continental well exhibits on the order of 100 feet of drawdown and the most interference with other Silver City wells; the other two sites produce on the order of 50 feet of drawdown.

Balleau used the Model to simulate the scenario of using imported surface water to meet future water demands. For this case, they assumed that half of the maximum projected increase in water demand (or 1.45%) could be supplied by a new water source and piped to the town. Results indicate that under these conditions, the wellfield as currently configured is capable of supplying the other half of this projected growth over the next 40 years.

Sensitivity to pumping water-level reserve was also examined. Results indicate that the water-level pumping reserve would have to be lowered by approximately an additional 50 feet to provide an additional 1,000 AFY of sustainable yield with the expected growth of 2.9% in water demand.

The long-term wellfield yield is evaluated coniditions of: (1) wells as presently configured and (2) wells deepened by 300 feet. If the wells are deepened, the long-term sustainable yield is increased substantially.

3.0 Detailed Technical Critique and Independent Analyses

In this section, we provide a detailed summary of our review, analyses, and findings related to a review of groundwater resources and water budgets for the Gila and Mimbres Basins. This critique is focused on the technical aspects of estimating sustainable groundwater development for the Silver City area, and modeled baseflows to the Gila River discharging from the Mangas Trench formation.

3.1 Hydraulic Basin Analysis

In this case, "hydraulic analysis" refers to approaches of estimating groundwater flow through a basin using observed water levels and measured or inferred hydrologic properties of the aquifer. This should be considered a first-order type of analysis for developing estimates for comparing to quantifications developed by previous researchers, including Balleau. One can undertake a limited hydrologic basin analysis by reviewing water level maps for the basin (e.g., Johnson, 2000, Figure 7; Koopman et al., 1969, Plate 1). Such maps can be used along with other information such as aquifer thickness, hydraulic conductivity, and/or transmissivity, as input into the groundwater flow equation to calculate expected groundwater discharge.

For our analysis, we used values from different sources to evaluate the potential range of reasonable underflow values (see Table 1). Our results were in the same range of estimates presented in Balleau (2006) and Johnson (2000).

- The calibrated-Model underflow to the Mimbres Basin was 9,770 AFY (Johnson, 2000); we calculated values in the range of 8,200 to 11,200 AFY, which is equivalent to a difference of -16 to +15%.

- The calibrated-Model rate for the remainder of outflows to the Gila River and Mangas Springs was 6,100 AFY (Johnson, 2000); we calculated values in the range of 5,400 to 6,000 AFY, which is equivalent to a difference of -11 to -2%.

Table 1. Data and source of information used in hydraulic basin analysis calculations.

Data Type	*Sources*
Water table contour map	Johnson, 2000 Koopman et al., 1969
Transmissivity	Koopman et al., 1969 Johnson, 2002
Hydraulic conductivity	Hanson et al., 1994
Aquifer thickness	Johnson, 2002

3.2 Water Budget Uncertainty Analysis

The Balleau report cites the Model as simulating 15,900 AFY flowing through the Gila Group (Mangas Trench) aquifer under steady-state (or pre-development) conditions. Of this, approximately 9,800 AFY discharges as underflow to the Mimbres Basin, and the remaining 6,100 AFY flows into the Gila Basin (1,300 AFY to Mangas Spring, and 4,800 AFY to the Gila River). These estimates are consistent with Table 6 in Johnson (2002). In this section, we discuss uncertainties that may exist in individual components, and how this may affect the overall water budget.

The water budget discussion in Johnson (2002) offers the following information regarding initial estimates of inflow and outflow components:

- The average baseflow contribution from groundwater to Mangas Springs is based on streamflow measurements recorded at a gage ¼-mile below the spring.

- Groundwater discharge to the Gila River is based on gains to the Gila River between Cliff and Redrock gages as estimated by Trauger (1972), and assuming that roughly half of this originates from the Model area.

- Recharge in the Gila Basin was based on the assumption that under steady-state conditions, discharge must be balanced by recharge. Water level contours of Trauger (1972) indicate groundwater recharge occurs in the Big Burro Mountains and possibly other areas along the Continental Divide in the Gila Basin.

- Underflow to the Mimbres Basin is based on groundwater discharge from the San Vicente Arroyo sub-basin, as estimated by Trauger (1972).

- Recharge in the Mimbres Basin was based on estimates of recharge contributing to groundwater flow in the Mimbres Basin (WRRI, 2000). Water level contours of Trauger (1972) indicate groundwater recharge occurs in the Pinos Altos Range and possibly other areas along the Continental Divide in the Mimbres Basin. Initial distribution of this recharge was based on Hanson et al. (1994).

3.2.1 Outflows

Outflows from the Gila Basin inlcude discharge at Mangas Springs and groundwater discharge to the Gila River. Outflow from the Mimbres Basin is to the San Vicente Arroyo.

Mangas Springs discharge (Gila Basin)

We were unable to locate any flow data for Mangas Springs or Mangas Creek on the USGS website or elsewhere online. Therefore, we assumed that the reported value of 1.8 cfs or 1,300 AFY (Johnson, 2002; Trauger, 1972) is accurate and based on a reasonable length of historical flow data. *A regular measurement program should be instituted to verify this assumption.*

Underflow to Gila River (Gila Basin)

Johnson (2000, reference to Trauger, 1972) reported total groundwater discharge to the Gila River between the USGS Cliff and Redrock gages to be 19 cfs or 13,800 AFY. Additionally, he assumed that at most half of this discharge originates in the Model drainage area to the east, or 6,900 AFY. The modeled rate based on calibration was 4,860 AFY.

We undertook an independent analysis of USGS gage data between Cliff and Redrock. There was overlapping data at the two gages for the years 1942-1951 (available online). In order to verify that this data range was representative of the long-term gain, we compared the 1942-1951 streamflow at Redrock to the entire record of data available for that gage, or 1942-Mar.2007.[2] This analysis indicated that the average streamflow for 1942-1951 (135 cfs) was lower than the long-term average for all data available for the Redrock gage (242 cfs). This implies using the 1942-1951 time period was drier than an "average" year; using data from this time period may result in under-estimating underflow to the Gila River[3].

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[2] There is no streamflow data for Oct. 1955 to Oct. 1962.

[3] This possibility is diminished somewhat by the fact that the period of missing data (1955-1962) did include some fairly dry years.

According to our analysis of the 1942-1951 USGS gage data. the average gain between these gages was 14.4 cfs or 10,459 AFY. If we assume that of this flow, 1,300 AFY was from Mangas Springs via Mangas Creek; therefore, the total groundwater baseflow contribution to the Gila River averages 12.6 cfs or 9,159 AFY. Using the assumption that half of this originates in the Model drainage area to the east. our estimate is 4,579 AFY, which is within 10% of that modeled by Johnson (2002).

While it is not unreasonable to assume that 50% of the Gila River's baseflow gain originates from the Mangas Trench aquifer to the east. we believe that it is possible that slightly more or slightly less than half may originate within the Model area to the east based on precipitation maps of New Mexico. To illustrate the potential range of uncertainty due to the assumption of how to apportion Gila River baseflow gains. We used a range of 30 to 70% contribution from the Model area. Over this range, *our estimates of underflow to the Gila River from the Mangas Trench aquifer to the east range from 2,748 to 6,411 AFY. a significant difference from that modeled in Johnson (2002) and cited in Balleau (2006).* Table 2 presents a summary and comparison of values.

Table 2. Summary of uncertainty analysis associated with the underflow component to the Gila River.

	Johnson, 2002 (AFY)	HRC estimated (AFY)	Difference (AFY)	% Difference
Modeled GW underflow to Gila River from Model area (50%)	4,860	4,579	-281	-6%
Assuming 30% from Model area	na	2,748	-2,112	-77%
Assuming 70% from Model area	na	6,411	+1,551	+24%

Evaporative Losses (Gila Basin)

Losses due to evapotranspiration (ET) are estimated to be a minor part of the water budget and are not included in the Model. They are significant only in areas where the water table is close to the ground surface. such as near the Gila River and at Mangas Springs where they are estimated to be on the order of 1.2 cfs or 869 AFY (Johnson. 2002; reference to Trauger, 1972). When compared to the total volume of water flowing through the system. ET represents less than a 5 % potential source of error if not included in the Model. This quantity is not specifically included in the Model (Johnson, 2000, Table 6), we assume that the recharge rates are "net recharge rates" that account for additional losses due to ET; otherwise, the steady-state water budget would not balance.

Underflow to Mimbres Basin

Johnson (2002) estimated 10,000 AFY of underflow to the Mimbres Basin, and Model calibration yielded an estimate of 9,770 AFY. Other sources have estimated 8,400 AFY[4] (Hanson et al., 1994). *This difference is relatively small (no more than 1,370 AFY), and represents a potential difference of up to 15% in this component of the water budget.*

3.2.2 Inflows

Recharge to the Gila Basin consists of primarily mountain-front recharge. For the Mimbres Basin, the initial recharge distribution from mountain-front recharge and bedrock aquifer recharge was based on Hanson et al. (1994). No additional or independent estimates of recharge were attempted by Johnson (2000).

In the discussions below in this section, we also present our independent estimates of recharge based on (1) a chloride mass balance approach for the Mimbres Basin and (2) the Maxey-Eakin approach (Maxey and Eakin, 1949), which assumes a direct relationship exists between precipitation and recharge (see Table 1). DBS&A and HRC (2003) estimated recharge in the Socorro-Sierra area in New Mexico based on the Maxey-Eakin approach. They checked the accuracy of this method by comparing Maxey-Eakin recharge estimates to field measurements from the closed Alamosa Creek Basin (which is located just northeast of the northern Mimbres Basin), and determined that the Maxey-Eakin approach under-estimated recharge by roughly half of the observed basin drainage. They also cite other references (Watson et al., 1976; Avon and Durbin, 1976) which have independently evaluated the Maxey-Eakin approach.

Table 3. Maxey-Eakin recharge percentages (reproduced from DBS&A and HRC, 2003).

Precipitation (in/yr)	*Percentage of Precipitation that becomes Recharge*
0-8	0%
9-12	3%
12-15	7%
15-20	15%
>20	25%

Mountain-front recharge (Gila Basin): Big Burro Mountains, Silver City Range

The amount of recharge was estimated by others to be no more then 8,200 AFY (Trauger, 1972; Hanson et al., 1994); the amount in the calibrated Model was 5,580 AFY. Water level contours indicate groundwater recharge occurs in the Big Burro Mountains and possibly other areas along the Continental Divide. Because the amount of recharge was based on balancing the steady-state discharge from the Gila Basin, potential sources of uncertainty in this estimate are the same as discussed above regarding outflows for the Gila Basin.

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[4] According to WRRI (2000, p.39), this value reported by Hanson (1994)was subsequently revised to a value presumably closer to 10,000 AFY.

Based on a precipitation map of the Model area (see Figure 1) in conjunction with observed groundwater level maps (Johnson, 2000; Koopman et al., 1969), it seems reasonable to assume that relatively more precipitation recharges the groundwater in the Mimbres Basin than recharges the Gila Basin.

We performed a groundwater flownet analysis using water level contour maps from Johnson (2000) and Koopman et al. (1969). This confirmed that the relative amount of recharge to the Mimbres Basin is probably greater than that to the Gila Basin. Specifically, the highest precipitation tends to occur in the Pinos Altos and Silver City Ranges. Groundwater level maps indicate that recharge from this precipitation flows southward toward Silver City and to the east side of the Continental Divide (along the north Model boundary; see Figure 2). Another relatively significant source of precipitation occurs in the Big Burro Mountains, which likely flows generally northeast and through both the Gila and Mimbres Basins.

Independent Maxey-Eakin Estimate (Gila Basin)

Using a method based on Maxey-Eakin, we estimated recharge in the Gila Basin; the results are presented in Table 4. Details are as follows:

- *Option A*: Based on the NM precipitation map (Figure 1), the minimum precipitation which occurs within the Gila Basin and within the Model area was estimated to be 15 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 11,713 AFY.

- *Option B*: Based on the NM precipitation map, the maximum precipitation which occurs was estimated to be 19 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 31,792 AFY.

- *Option C*: Based on the NM precipitation map and a weighted average, the precipitation which occurs was estimated to be 16.2 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 27,107 AFY.

- *Option D*: Based on the Mimbres weather station which has precipitation data from 1971-1974, the average precipitation is 13.5 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 10,542 AFY.

- *Option E*: Using the most reliable precipitation data (option C), we adjusted the percentage suggested by Maxey-Eakin until we arrived at a value of recharge similar to that modeled by Balleau (2006). The resulting percentage was 4.5%, as compared to the 15% suggested by the Maxey-Eakin method.

We thus see that independent estimates of recharge to the Mangas Trench aquifer in the Gila River Basin range up to over three times higher than that suggested and modeled by the NMOSE and Balleau.

Table 4. Independent estimates of recharge for the Gila Basin by Hydrosphere, based on Maxey-Eakin.

	Source/ Precip. Data	*Precip. (in/yr)*	*% of precip. that becomes recharge*[5]	*Recharge (in/yr)*	*Recharge (AFY)*[6]
A	NM precip map, minimum	15	7%	0.09	11,713
B	NM precip map, maximum	19	15%	0.24	31,792
C	NM precip map, weighted avg	16.2	15%	0.20	27,107
D	Mimbres weather station	13.5	7%	0.08	10,542
E	Match Balleau's estimate of 8,200 AFY	16.2	4.5%	0.06	8,132

Mountain-front and bedrock aquifer recharge (Mimbres Basin): Big Burro Mountains, Pinos Altos Range, Silver City Range

The amount of recharge was previously estimated to be 10,000 AFY based on WRRI (2000) and balancing the steady-state discharge; the modeled amount was 10,340 AFY based on calibration. Water level contours indicate groundwater recharge occurs in the Pinos Altos Range and possibly other areas along the Continental Divide.

Independent Maxey-Eakin Estimate (Mimbres Basin)

Using a method based on Maxey-Eakin, we estimated recharge in the Mimbres Basin; the results are presented in Table 5. Details are as follows:

- *Option A*: Based on the NM precipitation map (Figure 1), the minimum precipitation which occurs within the Mimbres Basin and within the Model area was estimated to be <7 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 0 AFY.

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[5] Based on Maxey and Eakin (1949).

[6] Calculated based on an area of 209 mi^2, or 133,861 acres, for the Gila Basin model area.

- *Option B*: Based on the NM precipitation map, the maximum precipitation which occurs was estimated to be 17 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 37,050 AFY.

- *Option C*: Based on the NM precipitation map and a weighted average, the precipitation which occurs was estimated to be 13 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 13,222 AFY.[7]

- *Option D*: Based on the Mimbres weather station which has precipitation data from 1971-1974, the average precipitation is 13.5 in/yr. Using this value and Maxey-Eakin, recharge in the basin was estimated to be 13,730 AFY.

- *Option E*: Using the most reliable precipitation data (option D), we adjusted the percentage suggested by Maxey-Eakin until we arrived at a value of recharge similar to that modeled by Balleau (2006). The resulting percentage was 5.5%, as compared to the 7% suggested by the Maxey-Eakin method.

Our most reliable, independent estimates of recharge for the Mimbres Basin are within the same order of magnitude as that suggested and modeled by Balleau. Additionally, it seems realistic to use a value of 5.5% to represent the amount of precipitation that becomes recharge.

Table 5. Independent estimates of recharge for the Mimbres Basin by Hydrosphere, based on Maxey-Eakin.

	Source/ Precip. Data	***Precip. (in/yr)***	***% of precip. that becomes recharge***[8]	***Recharge (in/yr)***	***Recharge (AFY)***[9]
A	NM precip map, minimum	7	0%	0	0
B	NM precip map, maximum	17	15%	0.21	37,050
C	NM precip map, weighted avg	13	7%	0.08	13,222
D	Mimbres weather station	13.5	7%	0.08	13,730
E	Match Balleau's estimate of 10,000 AFY	13.5	5.5%	0.06	10,788

Chloride Mass Balance (Mimbres Basin)

Using chloride concentration in groundwater data provided in Hanson et al. (1994, Table 8), we can use a chloride mass balance (CMB) approach to estimate the amount of recharge in the Mimbres Basin based on observed groundwater chloride concentrations for the basin discharge

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[7] For comparison: the weighted average for the Mimbres Basin is 12.6 in/yr (calculated from average annual precipitation map provided in Hanson et al., 1994, Figure 2).

[8] Based on Maxey and Eakin (1949).

[9] Calculated based on an area of 272 mi^2, or 174,352 acres, for the Mimbres Basin model area.

area. Using a chloride concentration of 0.1 mg/L in precipitation (NADP, 2007), our estimates ranged from 2,177 to 7,402 AFY to the Mimbres Basin, which is lower than that estimated and modeled by Balleau by 30 to 80% (see Table 6). There was not sufficient data available to perform a similar chloride mass balance recharge analysis for the Mangas Trench aquifer in the Gila Basin.

The CMB method to recharge estimation assumes that all chloride in the system originated as atmospheric fallout. If there are other sources of chloride to the system (e.g., subsurface geologic formations, water recycling as irrigation return flows), then the CMB recharge estimate will be biased to a lower value.

Table 6. Independent estimates of recharge for the Mimbres Basin by Hydrosphere, based on a chloride mass balance approach.

Chloride Concentration in Groundwater (mg/L)	*Recharge Rate (in/yr)*	*Recharge (AFY)*[10]
50	0.027	7,402
90	0.027	4,112
150	0.027	2,467
170	0.027	2,177

3.3 MODFLOW Modeling

We obtained the groundwater model files from Balleau Groundwater for the Grant County, NM model (pers. comm., David Romero, *Balleau Groundwater*, May 2007). Using this model, we developed river response curves to estimate impacts of pumping and also evaluated drawdown which is likely to occur at nearby domestic wells. To evaluate the long-term response of groundwater levels and baseflow discharge to Mangas Spring and the Gila River, models were run for 200 years using MODFLOW-96. Pumping was specified in the model for 100 years, then was turned off and recovery of the groundwater system was simulated for 100 years. Individual model runs included pumping at only one location in any single run. In addition to the currently existing Silver City wellfields (Franks in the Gila Basin and Woodward near the Mimbres/Gila Basin divide) and proposed replacement well (Continental), we performed two model runs in which we placed a pumping well adjacent to the Gila River at distances of 2,640 and 7,920 feet from the river (Gila River 1 and Gila River 2, respectively). A summary of model runs are listed in Table 7.

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[10] Calculated based on an area of 5,140 mi^2 for the Mimbres Basin area (Hanson et al., 1994, p.2).

Table 7. Details of MODFLOW model runs used in analysis.

Model Run	*Pumping Loc'n (no. of wells in model)*	*Total Pumping, cfd/AFY*	*Comments*
mangas12	No pumping	0 / 0	
mangas13	Franks Wellfield (6)	133,589 / 1,120	Existing Silver City wellfield
mangas14	Continental Well (1)	119,261 / 1,000	Proposed well location
mangas15	Woodward Well (6)	187,573 / 1,573	Existing Silver City wellfield
mangas16	Gila River 1 Well at 2,640 ft from Gila River	119,261 / 1,000	Hypothetical well
mangas17	Gila River 2 Well at 7,920 ft from Gila River	119,261 / 1,000	Hypothetical well

3.3.1 Impact of Pumping on Gila River and Mangas Springs

To evaluate impacts of Silver City municipal pumping on the Gila River, we looked at the difference in the constant head rate of the model cells that represent the Gila River. These results indicate that effects from pumping current or currently proposed rates for Silver City wells (Franks, Woodward, and Continental) (Table 7), which are near the Gila/Mimbres Basin boundary, have a relatively insignificant impact, or on the order of less than 0.1 cfs (70 AFY); pumping wells nearer to the Gila River (Gila River 1 and Gila River 2) have a more significant impact on the order of 1.3 cfs (950 AFY) (Figure 3). Lagged depletions to the Gila River from Franks wellfield are the most significant of the Silver City wellfields; these impacts reach a maximum difference 190 years after the start of pumping, or 90 years after pumping has stopped. In other words, *there is a significant lagged response time at the river to pumping at the City's wells located roughly15 miles away.*

To evaluate impacts of individual pumping on Mangas Springs, we looked at the difference in the drain rate of the model cell representative of Mangas Springs. These results indicate that effects from pumping are on the order of 0.05 to 0.13 cfs (35 to 95 AFY) for all models run (Figure 4). Impacts from pumping a well near the Gila River have a faster response time; however, the gratest impacts occur due to pumping at Franks wellfield. Keeping in mind that the estimated flow rate of Mangas Springs is on the order of 1.8 cfs or 1,300 AFY, the magnitude of this impact is relatively significant (2.7 to 7.3% of measured spring flow when considering effects of individual pumping scenarios, or up to 25% when considering the combined or cumulative impact). *This impact of Silver City wells combined with exempt domestic wells in the vicinity constitutes a threat to dry up the springs.*

From the difference in surface water rate (including river and drain flow) due to pumping, we calculated the volumetric river response, or the percentage of pumping that is being derived from depletion of surface water (Figure 5). This graph indicates that the Silver City wellfields located near the Gila/Mimbres divide have minimal long-term impacts on the Gila River, but lagged depletions associated with this pumping will stretch out for centuries into the future. *Wells located closer to the river causes maore immediate impacts on baseflows, which offers important considerations related to a sustainable conjunctive use plan to develop water resources in the basin.*

3.3.2 Impact of Pumping on Nearby Domestic Wells

To evaluate the impacts of Silver City pumping on nearby water rights and/or domestic wells, we evaluated drawdown after 40 and after 100 years of pumping using the MODFLOW model discussed above. We performed a search of the NM SEO WATERS database for wells within approximately two miles of Frank's, Continental, and Woodward wells; WellID, total well depth, initial depth to water, initial water column, and corresponding model cell information for these wells are presented in Table 8. A separate model run was performed to evaluate the impacts of each of the three Silver City wellfields; results are presented in separate sub-sections below.

Rules for Gila/Mimbres Basins define "critical" as exceeding a drawdown rate of 2.5 ft/yr or depletion of 75% of the initial water column.

Frank's Wellfield

Frank's wellfield is pumped in the mangas13 model run. The maximum observed drawdown at any nearby domestic well after 40 and 100 years is 67 and 94.1 feet, respectively (Table 9). The maximum drawdown rate after 40 and 100 years is 1.7 and 0.9 ft/yr. The water column is significantly depleted at a number of the nearby wells.

Continental Well

The Continental well is pumped in the mangas14 model run. The maximum observed drawdown at any nearby domestic well after 40 and 100 years is 31.2 and 47.8 feet, respectively (Table 10). The maximum drawdown rate after 40 and 100 years is 0.8 and 0.5 ft/yr. The water column is significantly depleted at a number of the nearby wells.

Woodward Wellfield

The Woodward wellfield is pumped in the mangas15 model run. The maximum observed drawdown at any nearby domestic well after 40 and 100 years is 56.9 and 76.5 feet, respectively

(Table 11). The maximum drawdown rate after 40 and 100 years is 1.4 and 0.8 ft/yr. The water column is significantly depleted at a number of the nearby wells.

Table 8. Information for wells nearby Frank's, Continental, and Woodward wells.

Well ID	Total Depth (ft)	Init. Depth to Water (ft)	Init. Water Column (ft)	Model Cell
GSF-4178	450	320	130	(16,15)
GSF-2945	660	620	40	(17,22)
GSF-2969	505	465	40	(17,22)
GSF-3195	622	540	82	(17,22)
GSF-3397	695	600	95	(17,22)
GSF-2575	540	460	80	(17,26)
GSF-3926	777	680	97	(17,26)
GSF-4080	820	670	150	(17,26)
GSF-4122	860	648	212	(17,26)
GSF-3584	840	540	300	(17,27)
GSF-4127	940	720	220	(17,27)
GSF-2566	473	380	93	(18,22)
GSF-2570	465	375	90	(18,22)
GSF-2983	860	790	70	(18,22)
GSF-3074	500	430	70	(18,22)
GSF-2574	465	385	80	(18,23)
GSF-2990	630	555	75	(18,24)
GSF-2597	580	540	40	(18,25)
GSF-2614	560	465	95	(18,25)
GSF-4104	758	700	58	(18,25)
GSF-4109	655	600	55	(18,25)
GSF-4114	695	640	55	(18,25)
GSF-4175	760	600	160	(18,26)
GSF-3786	750	540	210	(18,27)
GSF-3976	800	755	45	(18,27)
GSF-4027	840	660	180	(18,27)
GSF-4082	800	620	180	(18,27)

Table 9. Summary of impacts on nearby domestic wells from pumping Frank's wellfield for 40 and 100 years.

Well ID	Init. Water Column (ft)	After 40 yrs pumping Modeled Drawdown (ft)	Drawdown Rate (ft/yr)	WC Depl (%)	After 100 yrs pumping Modeled Drawdown (ft)	Drawdown Rate (ft/yr)	WC Depl (%)
GSF-4178	130	40.6	1.02	31%	64.6	0.65	50%
GSF-2945	40	62.7	1.57	157%	89.7	0.90	224%
GSF-2969	40	62.7	1.57	157%	89.7	0.90	224%
GSF-3195	82	62.7	1.57	76%	89.7	0.90	109%
GSF-3397	95	62.7	1.57	66%	89.7	0.90	94%
GSF-2575	80	46.5	1.16	58%	70.4	0.70	88%
GSF-3926	97	46.5	1.16	48%	70.4	0.70	73%
GSF-4080	150	46.5	1.16	31%	70.4	0.70	47%
GSF-4122	212	46.5	1.16	22%	70.4	0.70	33%
GSF-3584	300	42.9	1.07	14%	66.1	0.66	22%
GSF-4127	220	42.9	1.07	19%	66.1	0.66	30%
GSF-2566	93	67.0	1.68	72%	94.1	0.94	101%
GSF-2570	90	67.0	1.68	74%	94.1	0.94	105%
GSF-2983	70	67.0	1.68	96%	94.1	0.94	134%
GSF-3074	70	67.0	1.68	96%	94.1	0.94	134%
GSF-2574	80	62.3	1.56	78%	88.7	0.89	111%
GSF-2990	75	57.3	1.43	76%	82.9	0.83	111%
GSF-2597	40	52.3	1.31	131%	77.1	0.77	193%
GSF-2614	95	52.3	1.31	55%	77.1	0.77	81%
GSF-4104	58	52.3	1.31	90%	77.1	0.77	133%
GSF-4109	55	52.3	1.31	95%	77.1	0.77	140%
GSF-4114	55	52.3	1.31	95%	77.1	0.77	140%
GSF-4175	160	47.7	1.19	30%	71.7	0.72	45%
GSF-3786	210	43.7	1.09	21%	66.8	0.67	32%
GSF-3976	45	43.7	1.09	97%	66.8	0.67	148%
GSF-4027	180	43.7	1.09	24%	66.8	0.67	37%
GSF-4082	180	43.7	1.09	24%	66.8	0.67	37%

Table 10. Summary of impacts on nearby domestic wells from pumping the Continental well for 40 and 100 years.

Well ID	After 40 yrs pumping				After 100 yrs pumping		
	Init. Water Column (ft)	Modeled Drawdown (ft)	Drawdown Rate (ft/yr)	WC Depl (%)	Modeled Drawdown (ft)	Drawdown Rate (ft/yr)	WC Depl (%)
GSF-4178	130	11.8	0.30	9%	25.7	0.26	20%
GSF-2945	40	25.7	0.64	64%	43.2	0.43	108%
GSF-2969	40	25.7	0.64	64%	43.2	0.43	108%
GSF-3195	82	25.7	0.64	31%	43.2	0.43	53%
GSF-3397	95	25.7	0.64	27%	43.2	0.43	45%
GSF-2575	80	28.8	0.72	36%	45.6	0.46	57%
GSF-3926	97	28.8	0.72	30%	45.6	0.46	47%
GSF-4080	150	28.8	0.72	19%	45.6	0.46	30%
GSF-4122	212	28.8	0.72	14%	45.6	0.46	22%
GSF-3584	300	29.1	0.73	10%	45.6	0.46	15%
GSF-4127	220	29.1	0.73	13%	45.6	0.46	21%
GSF-2566	93	27.4	0.69	29%	45.1	0.45	48%
GSF-2570	90	27.4	0.69	30%	45.1	0.45	50%
GSF-2983	70	27.4	0.69	39%	45.1	0.45	64%
GSF-3074	70	27.4	0.69	39%	45.1	0.45	64%
GSF-2574	80	28.5	0.71	36%	46.1	0.46	58%
GSF-2990	75	29.5	0.74	39%	46.9	0.47	63%
GSF-2597	40	30.3	0.76	76%	47.4	0.47	119%
GSF-2614	95	30.3	0.76	32%	47.4	0.47	50%
GSF-4104	58	30.3	0.76	52%	47.4	0.47	82%
GSF-4109	55	30.3	0.76	55%	47.4	0.47	86%
GSF-4114	55	30.3	0.76	55%	47.4	0.47	86%
GSF-4175	160	30.9	0.77	19%	47.8	0.48	30%
GSF-3786	210	31.2	0.78	15%	47.8	0.48	23%
GSF-3976	45	31.2	0.78	69%	47.8	0.48	106%
GSF-4027	180	31.2	0.78	17%	47.8	0.48	27%
GSF-4082	180	31.2	0.78	17%	47.8	0.48	27%
M-10369	56	19.4	0.49	35%	31.0	0.31	55%
M-5524	100	18.1	0.45	18%	29.6	0.30	30%
M-10568	391	18.1	0.45	5%	29.6	0.30	8%
M-7271	60	25.0	0.63	42%	38.0	0.38	63%
M-8305	83	25.0	0.63	30%	38.0	0.38	46%
M-9503	50	25.0	0.63	50%	38.0	0.38	76%
M-10428	221	25.0	0.63	11%	38.0	0.38	17%

Table 11. Summary of impacts on nearby domestic wells from pumping Woodward wellfield for 40 and 100 years.

		After 40 yrs pumping			After 100 yrs pumping		
Well ID	**Init. Water Column (ft)**	**Modeled Drawdown (ft)**	**Drawdown Rate (ft/yr)**	**WC Depl (%)**	**Modeled Drawdown (ft)**	**Drawdown Rate (ft/yr)**	**WC Depl (%)**
M-10369	56	34.3	0.86	61%	51.7	0.52	92%
M-5524	100	34.4	0.86	34%	51.7	0.52	52%
M-10568	391	34.4	0.86	9%	51.7	0.52	13%
M-7271	60	56.9	1.42	95%	76.5	0.77	128%
M-8305	83	56.9	1.42	69%	76.5	0.77	92%
M-9503	50	56.9	1.42	114%	76.5	0.77	153%
M-10428	221	56.9	1.42	26%	76.5	0.77	35%

3.4 Best Estimate of Sustainable Groundwater Development Rates for the Gila Basin and Silver City area

As noted in the Balleau report, the town of Silver City can divert a portion of the estimated 15,900 AFY of groundwater flow through the Gila Group aquifer in the Mangas Trench at the expense of reducing flow to Mangas Spring, the Gila River, and by beneficially salvaging evaporation losses from alluvial flats and playas in the Mimbres Basin (Balleau, 2006, reference to WRRI, 2000). However, potential uncertainties in the water budget such as discussed in Section could significantly change the amount of water that is available for diversion.

Balleau (2006) discusses and evaluates the hydrological impacts associated with deepening current wells, three alternative well sites, and imported surface water to meet the demands associated with the high growth rate of Silver City. Estimated costs of these alternatives are presented in Table 12.

→ evaluation of estimates of wellfield production, pumping costs, well costs, distribution costs.

Table 12. Estimated costs of alternatives to meet increasing water demands for Silver City.

Alternative	(1) Current Wells, Deepened 300 feet	(2) Alternative Well Site: Continental Well	(3) Alternative Well Site: Anderson replacement	(4) Alternative Well Site: Gabby Hayes repl.	(5) Imported surface water: Gila Settlement	(6) Imported surface water: Tyrone Mine
Distance, Alternative to Existing Infrastructure	na	1.5 miles (to Franks)	1.5 miles (to Anderson)	1 mile (to Gabby Hayes)	no existing	3 miles (to Anderson)
Distance, Alternative to Silver City	na	2 miles	3 miles	2 miles	20 miles	7 miles
Pipeline Cost	$0	$	$	$	$	$
Depth	300 feet	900 feet[11]	900 feet[12]	680 feet[13]	na	na
Well Cost	$	$	$	$	$0	$0
Elevation Difference (surface)	na	+100 feet (5900 @ well; 6000 @ SS)	-60 feet (6060 @ well; 6000 @ SS)	+200 feet (5800 @ well; 6000 @ SS)	+1200 feet (4800 @ river; 6000 @ SS)	-400 feet (6400 @ mine; 6000 @ SS)
Pumping Station Cost	$	$	$0	$	$	$0
TOTAL COST	$	$	$	$	$	$

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[11] Based on average depth of current Frank's and Woodward wells.
[12] Based on depth of current Anderson well.
[13] Based on depth of current Gabby Hayes well.

4.0 Summary and Conclusions

This memo provides a summary of our detailed review and analysis of the water resources in the Mangas Trech aquifer in the Gila Basin. We utilized the Grant County transient MODFLOW model to evaluate effects of pumping select wellfields on the Gila River, Mangas Springs, and water levels in nearby domestic wells. Modeling results indicate that the full impacts of Silver City wellfield pumping from its current well fields would not be felt for decades.

Our opinions as they relate to our findings from the Mangas Trench and Gila Groundwater Basin hydrologic review are summarized at the beginning of this report in Section and are repeated here for completeness:

- The Balleau report employs an enhanced version of the New Mexico Office of the State Engineer (NMOSE) Mangas Trench Groundwater Model (or "Model") to develop projections of Silver City's wellfield service life over a 40-year planning period. The addition of the Multi-Node Well (MNW) package is valid and beneficial for addressing the water supply issues being considered by their study (i.e., Silver City wellfield productivity in the future).

- The Model is based on previously-estimated volumetric water budgets, observed groundwater levels, well logs from across the area, Mangas Springs discharge, Gila River baseflow gains, and measured and estimated hydraulic conductivitues and transmissivities.

- Estimates of groundwater underflow to the Gila and Mimbres Basins computed by the Model and presented in the Balleau report are consistent with available water table contour maps and aquifer parameter values.

- Modeled groundwater discharges to the Gila River from the Mangas Trench formation are consistent with observed baseflow gains from the river gage data. However, the assumption that half of this water is sourced in the Model area is a potential uncertainty that could lead to a change in the overall water budget. Considering a reasonable range of contribution of observed baseflow gains coming from the Model area east of the river suggests that the current estimated discharge to the Gila River of 4,860 AFY could change on the order of +/- 2,000 AFY.

- Recharge to the Gila and Mimbres Basins is reasonable, based on available precipitation data and a relative comparison using developed groundwater flownets. We also performed independent estimates of recharge based on precipitation data and a chloride mass balance, as well as using the Maxey-Eakin approach.

Based on our review, analyses, and findings, we offer the following recommendations for future characterization and analyses to reduce our current uncertainties related to water resource, and the potential for development of those resources, in the Mangas Trench aquifer in the Gila River Basin west of Silver City.

- The hydraulic basin analysis and chloride mass balance approach yield estimates of recharge to the basin in the same range, albeit with significant unquantified uncertainty. We recommend a detailed synoptic synoptic groundwater sampling for concentrations of environmental tracers (e.g., chloride, bromide, certain stable and radioactive isotopes) that may help reduce uncertainty in the recharge component of the basin water budget.

- We recommend the evelopment and implementation of a groundwater characterization and monitoring program to evaluate the vulnerability of flows at Mangas Springs to dry-up due to groundwater development.

- We recommend the development of a conjunctive groundwater – surface water management analysis tool to evaluate how development of water resources in the Managas Trench aquifer in the Gila Basin can proceed with minimal impact of surface water resources in the area.

These opinions are based on our detailed review of the Balleau report (2006) as well as available hydrologic data. If additional data and/or information becomes available which deviates significantly from previously reviewed data or my listed assumptions, we reserve the right to modify or expand upon our opinions.

5.0 Figures

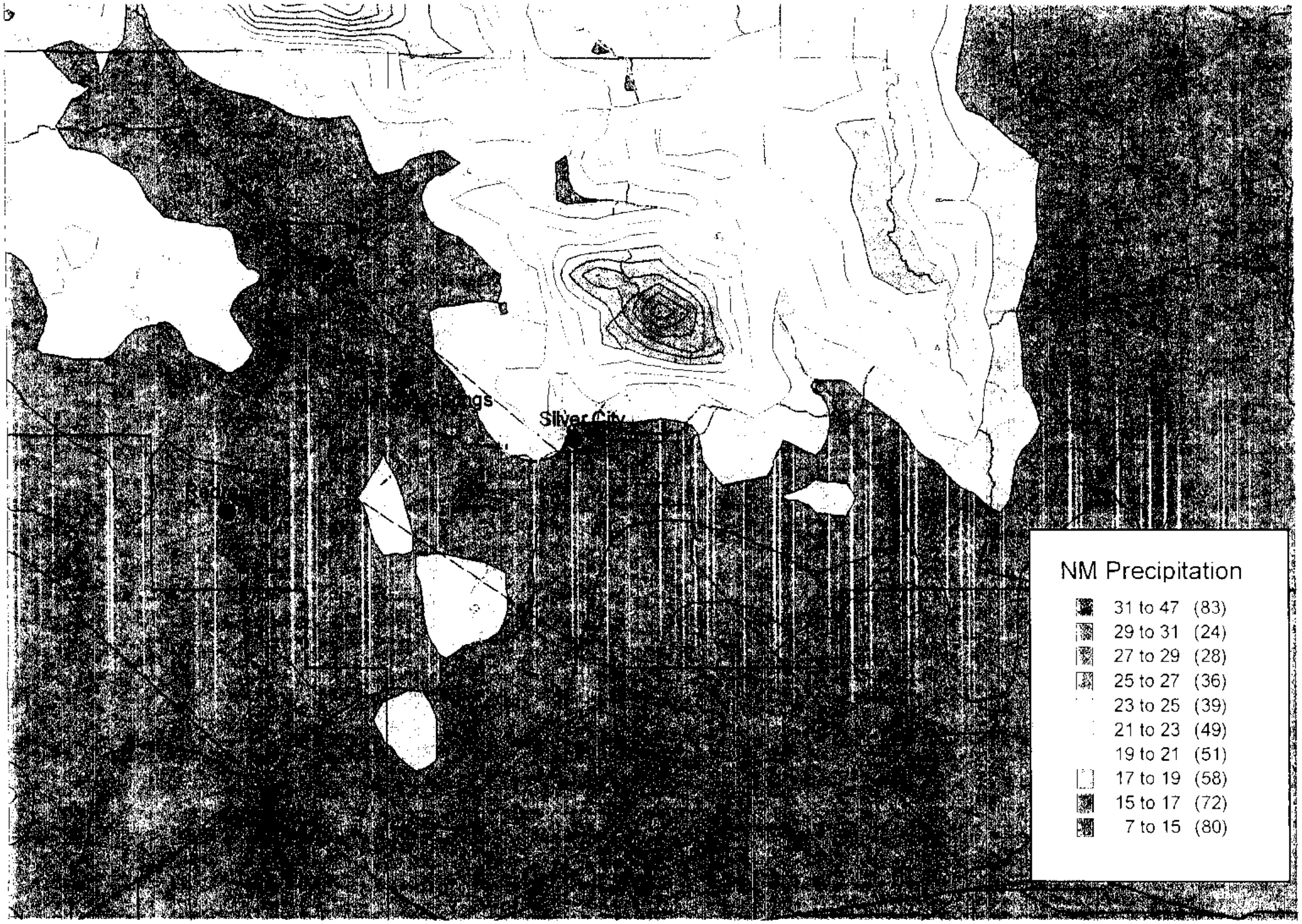

Figure 1. Map of the general study area in southwestern NM showing contours of precipitation. The approximate NMOSE Model boundary is marked in red; relevant towns are marked with red circles.

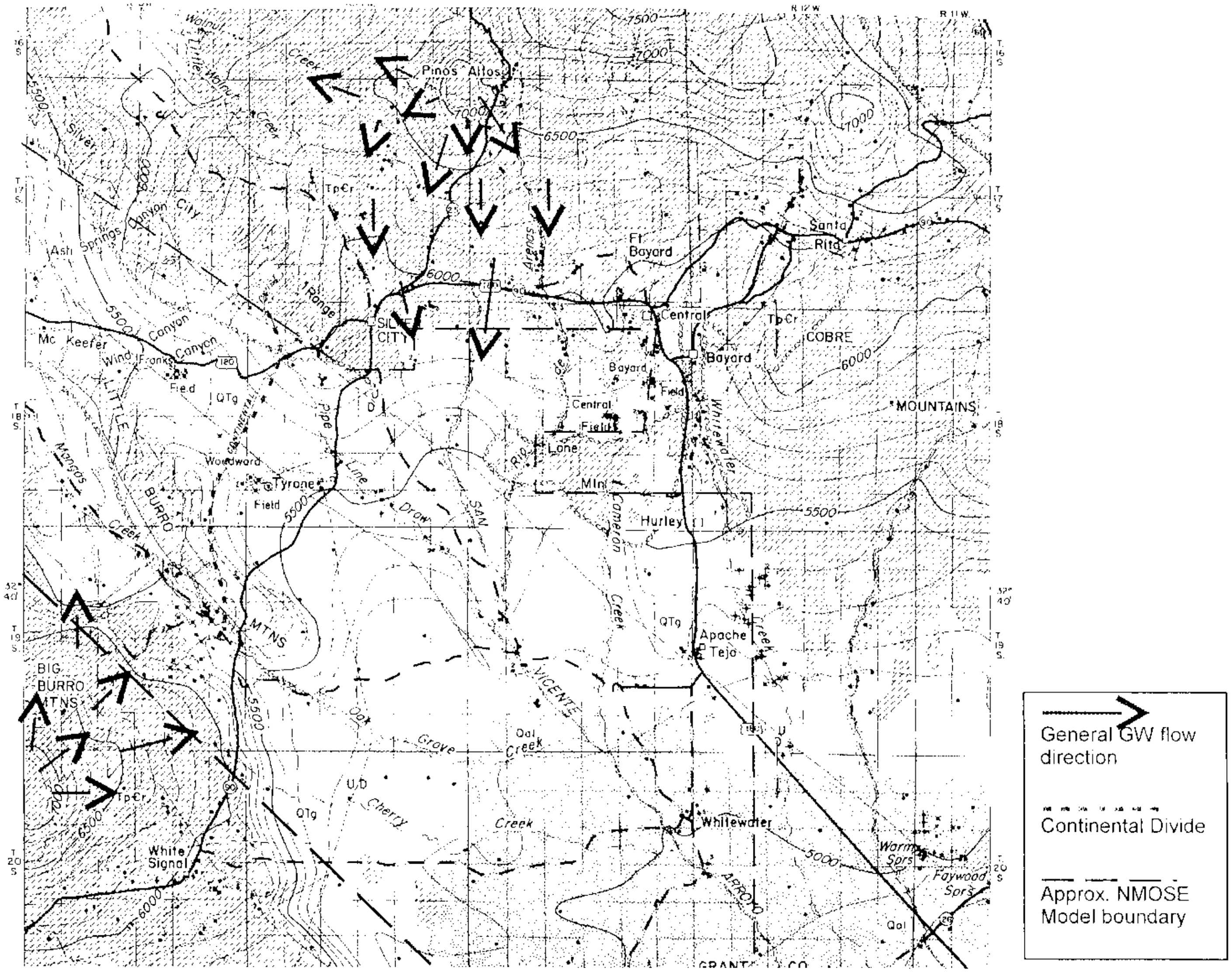

Figure 2. Map showing water table contours (from Koopman et al., 1969), modified with arrows to indicate the general direction of groundwater flow.

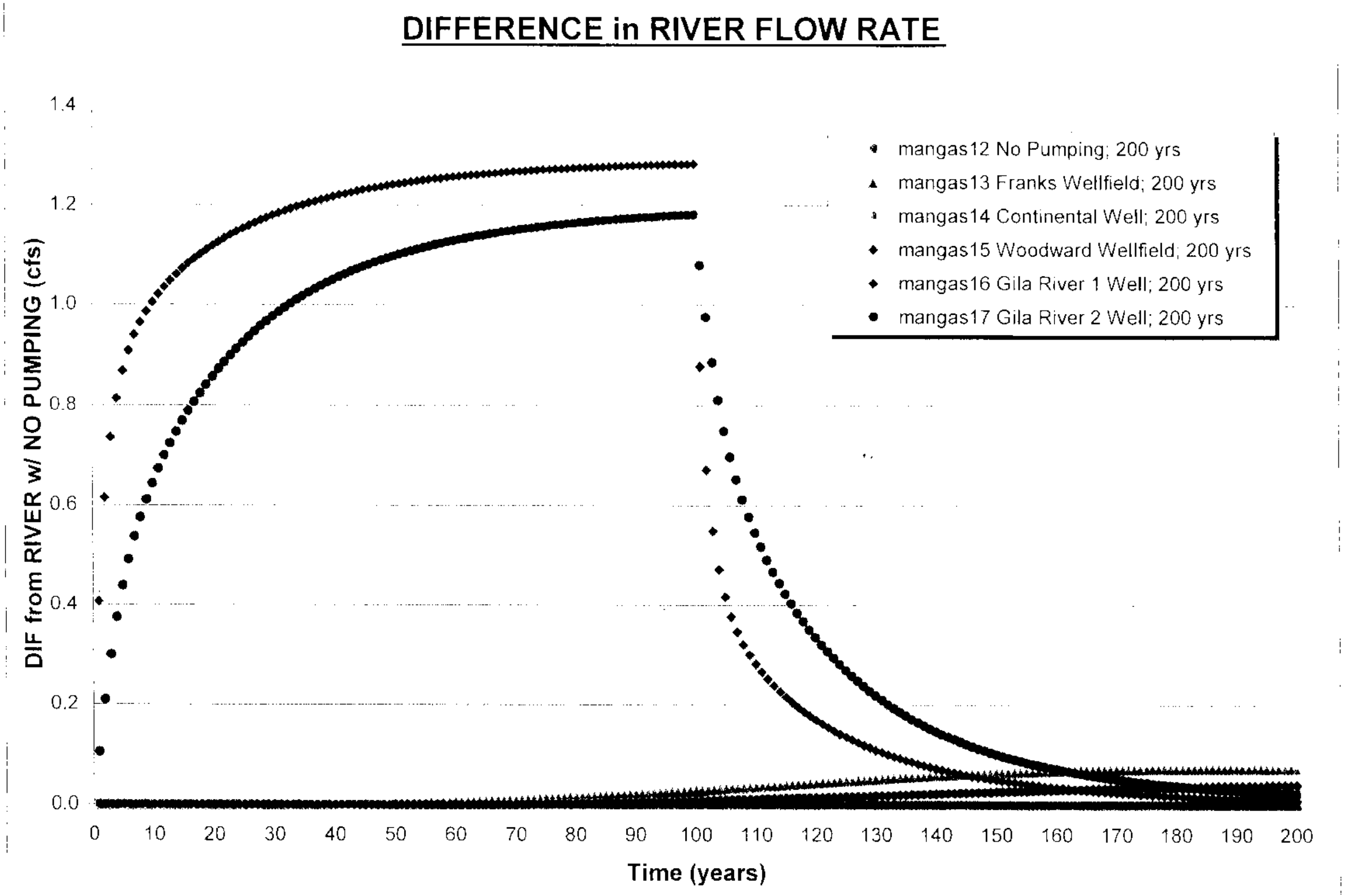

Figure 3. Graph of difference in Gila River flow rate (represented by constant head cells in the model) as a result of pumping various wells for 100 years.

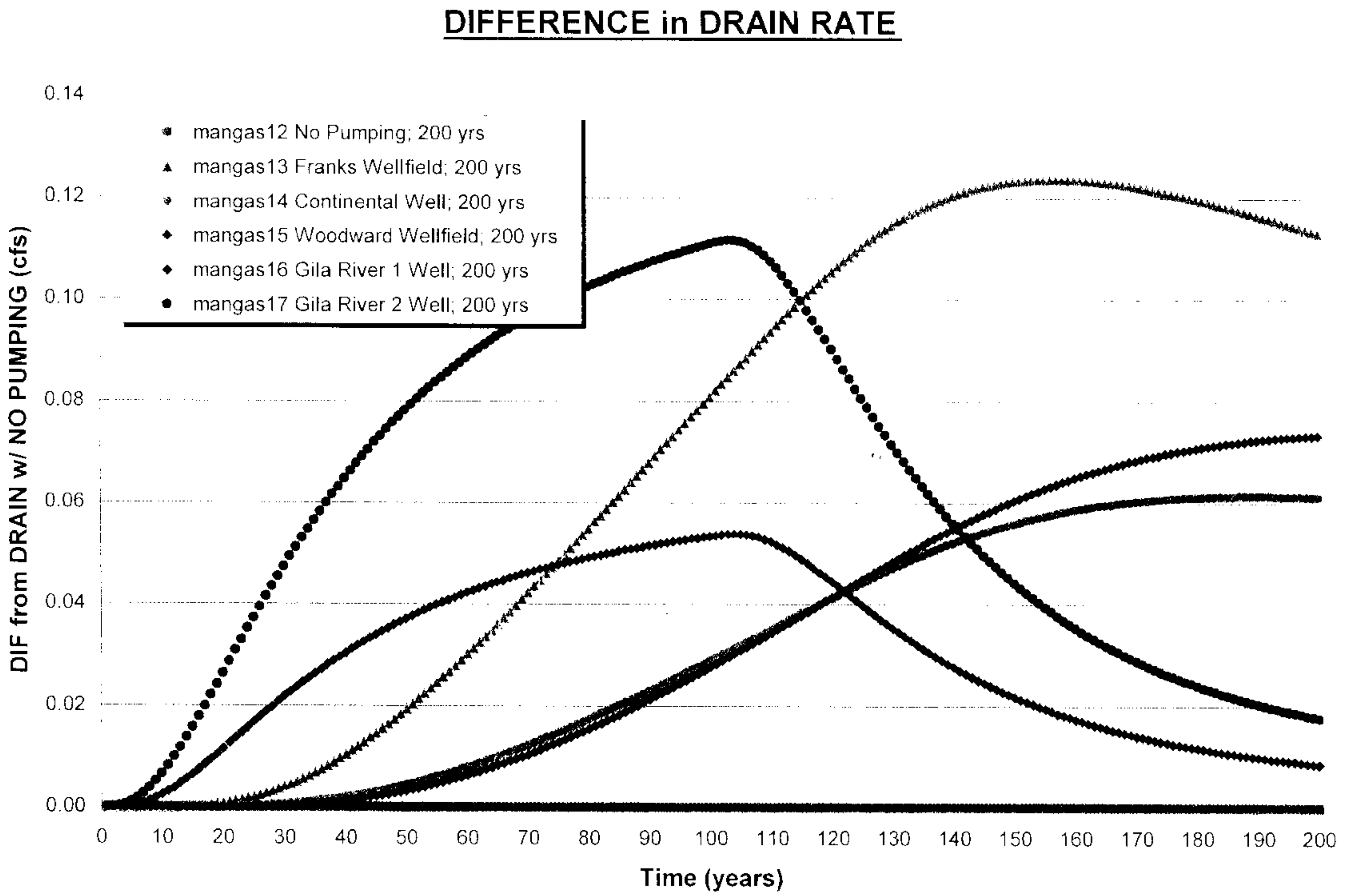

Figure 4. Graph of difference in Mangas Spring flow rate (represented by a drain cell in the model) as a result of pumping various wells for 100 years.

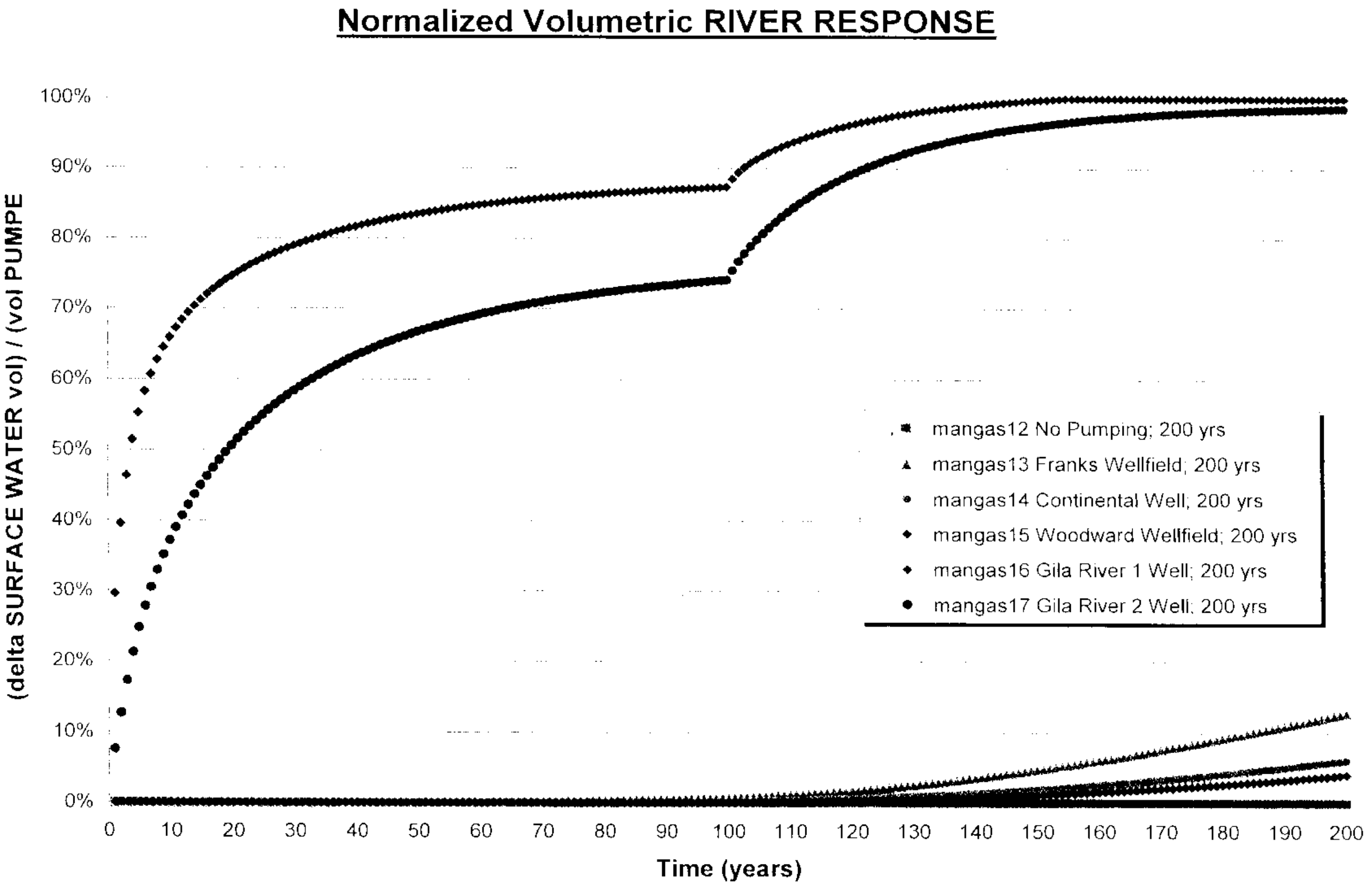

Figure 5. Graph of normalized volumetric river response as a result of pumping various wells for 100 years.