APPLICATION OF THE NORTHERN ARIZONA GROUNDWATER FLOW MODEL (NARGFM) TO THE UPPER VERDE RIVER - POTENTIAL FUTURE DECLINES DUE TO ADDITIONAL GROUNDWATER EXTRACTION*

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ABSTRACT

The work discussed in this paper was carried out to study (A) the accuracy and predictive capability of the U.S. Geological Survey (USGS) Northern Arizona Regional Groundwater-Flow model (NARGFM) within the Big Chino, Little Chino, and Verde sub-basins; (B) illustrate historical change in base flow at the USGS Paulden and Clarkdale streamgages; and (C) perform forward-looking simulations for the period 2005-2110 that evaluate potential effects on base flow in the upper Verde River resulting from (1) unchanged water demand from 2005 through 2110, (2) continuing drought, (3) increased water demand, (4) extraction of 12,000 acre-feet per year (ac-ft/yr) of groundwater from the central part of Big Chino Valley beginning in 2020, and (5) the cumulative effect of cases (1) through (4).

This report builds on earlier work by the USGS in cooperation with the Verde River Basin Partnership (VRBP) and the Town of Clarkdale that applied the NARGFM in a series of simulations to gain a greater understanding of the past and potential future human impacts on the Middle Verde River's streamflow.

Testing of NARGFM showed that excellent agreement was found between historically observed and simulated groundwater elevations within the area of concern. In addition, simulated trends in both groundwater elevation and discharge to the Verde River are accurate to within industry-standard ranges.

New simulations using NARGFM show that the cumulative effect of continuing drought, increased water demand, and extraction of 12,000 ac-ft/yr of groundwater from the Big Chino Valley indicates a loss of base flow to the Verde River at the Paulden streamgage of 12.8 cfs between 2005 and 2110. Inasmuch as the base flow at the Paulden streamgage in 2005 was ~19 cfs, this would leave only 6.2 cfs in the river at the streamgage by 2110.

Regional planning of water use within Yavapai County is needed now. Senators John McCain and Jeff Flake recently sent a letter to County officials urging them "to develop

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a long-term water management strategy that protects the Verde River". In a similar vein, this paper independently uses the NARGFM in a forward-looking manner to explore the potential effects of continued and increased groundwater extraction on base flow to the Upper Verde River and nearby water wells. The results demonstrate that significant decreases are expected and that regional planning is needed to address the future water supply for Yavapai County.

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INTRODUCTION

In 2011, the U.S. Geological Survey (USGS) released a report entitled “Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona” (Pool et. al. 2011[2]). The purpose of this model is to help assess the adequacy of the Northern Arizona regional groundwater supply and the potential effects of increased groundwater use on water levels, stream flow, and riparian vegetation. The authors state that the model is intended to be used by resource managers to examine the hydrologic consequences of various groundwater development and climate change scenarios.

Recently, the model was used, as planned, to estimate how human stresses on the hydrologic system would affect streamflow in the Upper and Middle Verde River by 2110 (Garner, et. al. 2013[3]). The NARGFM was also used in support of a successful application to the Arizona Department of Water Resources (ADWR) for a Modification of Designation of Adequate Water Supply for future development of groundwater resources within and adjacent to the City of Flagstaff (AMEC, City of Flagstaff – Water Resources Sustainability Study Coconino County, Arizona July 12, 2012). The author also understands that NARGFM is currently being used independently by the Cities of Cottonwood and Clarkdale for water resource planning purposes.

This paper extends the work of Garner et. al. to specifically address potential changes of base flow in the Upper Verde River caused by the proposed groundwater extraction in the Big Chino sub-basin by several municipalities. The anticipated effect of this pumping on groundwater levels in nearby wells is also evaluated.

The numerical model (hereafter referred to as NARGFM) has been run to verify the results discussed in the above reports, to add the additional pumping, and to prepare independent graphics to clarify the discussion with respect to the Big and Little Chino sub-basins. Comparison with the Arizona Department of Water Resources Prescott Active Management Area (PrAMA) model is also included (http://www.azwater.gov/AzDWR/Hydrology/Modeling/Prescott_Home.htm).

[2] D.R. Pool, Kyle W. Blasch, James B. Callegary, Stanley A. Leake, and Leslie F. Graser (2011). Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona. USGS “Scientific Investigations Report 2010-5180.

[3] Garner, Bradley D., D.R. Pool, Fred D. Tillman, and Brandon T. Forbes (2013). Human Effects on the Hydrologic System of the Verde Valley, Central Arizona, 1910–2005 and 2005–2110, Using a Regional Groundwater Flow Model. USGS Scientific Investigations Report 2013–5029.

BACKGROUND

The NARGFM report clearly describes its genesis and purpose (throughout this document, text in italics is quoted from the two USGS reports[2,3]).

> *In 1999, the Arizona Department of Water Resources (ADWR) started the Rural Watershed Initiative (RWI), a program that addresses water-supply issues in increasingly populated rural areas, with an emphasis on regional watershed studies. The program encourages the development of partnerships between local stakeholders and resource agencies, such as the U.S. Geological Survey (USGS), to develop information needed to support resource planning and management decisions. The Arizona Water Science Center (AZWSC) of the USGS, in cooperation with ADWR, has completed three initial RWI studies focusing on the hydrogeologic framework and conceptual understanding of groundwater resources in northern and central Arizona. The three completed RWI studies[4] include the Coconino Plateau, the upper and middle Verde River watersheds, and the Mogollon Highlands. These three study areas have had, or likely will have rapid population growth and increased use of groundwater supplies. A numerical groundwater-flow model of the region that includes the area of the RWI studies was deemed necessary so that future investigators can assess the effect of anticipated increased use of groundwater. Hydrologic information and understanding gained during initial RWI studies was used to develop the groundwater flow model*

Geology of the Study Area

In a traditional model paper, this section would contain a review of all previous work in the study area and the applicability of the results to development of the numerical model. Since this has already been done by the USGS and described in detail in the Blasch et. al., 2006[4] and the NARGFM[2] reports, it will not be repeated here. However, it is important for the reader to understand that the observed geologic structures in the Big Chino, Little Chino and Verde Valley sub-basins, hereafter known as the Area of Concern (AOC), are represented in the model. Figure 1 shows the model area and the specific area of concern (AOC) for this paper.

Knowledge of the hydrologic properties of the geological units that constitute the regional and localized aquifers within the watersheds is essential for establishing a conceptual and numerical framework for the movement of water through the

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[4] Blasch, K.W., J.P. Hoffman, L.F. Graser, J.R. Bryson, and A.L. Flint, 2006. Hydrogeology of the Upper and Middle Verde River Watersheds, Central Arizona: USGS Scientific Investigations Report 2005–5198.
Bills, D.J., M.E. Flynn, and S.A. Monrow, 2007. Hydrogeology of the Coconino Plateau and adjacent areas, Coconino and Yavapai Counties, Arizona: USGS. Scientific Investigations Report 2005-5222.
Parker, J.T.C., W.C. Steinkampf, and M.E. Flynn, 2005. Hydrogeology of the Mogollon Highlands, central Arizona: USGS Scientific Investigations Report 2004-5294.

subsurface. Accurate estimates of aquifer properties, such as transmissivity, porosity, and specific capacity, are necessary for simulating groundwater flow through aquifers. Formation lithology and degree of fracturing largely determine the magnitude and direction of these properties. These properties had been determined from numerous laboratory studies of rock samples collected during the drilling of wells and from surface outcrops. Aquifer tests have been conducted within the Big and Little Chino watersheds to support groundwater investigations. During aquifer tests, a well is pumped for several hours to days while yield (volume per time) and change in water level (drawdown) in the pumped well and adjacent monitoring wells are recorded. The combined measurements of pumping and drawdown can be used to calculate aquifer properties. Thus, the AOC aquifers have been studied intensely by the USGS, Arizona Department of Water Resources (ADWR), U.S. Bureau of Reclamation (BOR), plus private consultants. Although additional data are always helpful, we know more about these aquifers than most others for which the USGS has developed similar regional-scale models.

THE NARGFM MODEL

Applying the geologic structures discussed above, the USGS constructed a numerical model to simulate the observed groundwater flow systems. The model is conceptualized on a three-dimensional finite-difference grid and uses the thoroughly tested, widely used and publicly available model code MODFLOW-2005. Previous models applied to the area used earlier versions of this same code known as MODFLOW-1996 and MODFLOW-2000. The hydrologic framework was established by the assignment of hydrologic features, including streams, springs and the lateral and vertical extents of aquifers. Then numerous data sets were assembled including aquifer hydraulic conductivity, porosity, specific yield, location of extraction wells, and their historical pumping rates (see ADWR Prescott AMA report, on-line data base from ADWR and appendices 1 and 2 of the NARGFM report). Additionally, monitor well data were assembled to enable the model-simulated groundwater elevations to be compared with the observed elevations.

An important objective for the NARGFM study was to estimate rates and distributions of recharge to the aquifers in the study area. *The primary methods that were used to estimate natural recharge included the Basin Characterization Model (BCM) developed by Flint and Flint (2008) and isotopic analyses developed by Blasch and Bryson (2007).* Special attention was applied to constraining the estimated recharge for the Big Chino, Little Chino, and Verde Valley sub-basins[5].

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[5] Flint, L.E., and Flint, A.L., 2008, Regional analysis of ground water recharge, *in* Stonestrom, D.A., Constantz, J., Ferré, T.P.A., and Leake, S.A., eds., Groundwater recharge in the arid and semiarid

Incidental recharge from agricultural irrigation was estimated for agricultural areas in the Big Chino, Little Chino, and Verde Valley sub-basins on the basis of estimated irrigation requirements and sources of irrigation water, that is, surface or groundwater supplies. Estimates for the Little Chino sub-basin were made for both surface water and groundwater irrigation on the basis of Prescott AMA groundwater-flow model.

Evapotranspiration of groundwater is through phreatophytes and subirrigated agriculture where depths to water are very shallow near stream channels. The only known area of subirrigated crops that may access shallow groundwater supplies is in the Williamson Valley and Big Chino Valley areas[6]. The large depths to groundwater in the study area limit the accessibility of groundwater by phreatophytes to narrow areas near perennial streams and springs. Rare areas of subirrigated agriculture that can access groundwater can be locally substantial in areas of groundwater discharge, but were considered of minor importance to the model on a regional scale. The results discussed in this paper do not involve the use of any new hydrologic data sets and rely strictly on the data sets assembled by the USGS. These data sets are available publicly and were obtained for use in this study from the USGS Tucson office web site[7]. The pumping and monitor-well data were "spot-checked" by comparison with the ADWR on-line databases. To enhance the model calibration evaluation, post 2005 groundwater elevation and river flow data were downloaded from the ADWR and appended to the USGS data sets.

Spatial and Temporal Aspects

The NARGFM model simulates groundwater conditions from 1910 through 2005 over a 92,664 square-mile area. The original simulation period was divided into nine multi-year periods of generally 10 years each since 1938. The 10th and final period encompasses 2000 to 2005. No seasonal or annual variations were simulated. In comparison, the PrAMA model covered 485 square miles and used two stress periods per water-year including a 210-day irrigation season from April through October and a 155-day, non-irrigation, stress period from November through March. It would have been a Herculean task for the USGS to assemble sufficient pumping data to simulate bi-annual pumping over the much larger NARGFM region. In addition, such data does not exist for much of the region and the ~10-year averaging process used in the NARGFM averages out most of the shorter term changes anyway.

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southwestern United States: USGS Professional Paper 1703, p. 29–59. Blasch, K.W., and Bryson, J.R., 2007, Distinguishing sources of ground water recharge by using $\delta^{2}H$ and $\delta^{18}O$: Ground Water, v. 45, no. 3, p. 294–308.

[6] Yavapai County surveyed 1,325 acres of subirrigated crops in these areas consisting entirely of pasture grasses (John Munderloh, Yavapai Water Coordinator, written communication to USGS, 2004).

[7] http://pubs.usgs.gov/sir/2010/5180/NARGFM_Model_Data_Sets.zip

The NARGFM model grid consists of 600 rows, 400 columns, and three layers. The grid cell size is 0.62 by 0.62 miles (1km by 1km) encompassing Northern Arizona from New Mexico to Nevada. By contrast, the ADWR PrAMA model has 48 rows, 44 columns and two layers. The PrAMA grid-cell size is 0.5 by 0.5 miles. The NARGFM model is thus not quite as fine as the ADWR model, but the difference is minor and does not produce significant differences. The NARGFM model grid was rotated 60 degrees clockwise to match the primary geologic structural trends that also are believed to strongly influence anisotropy of groundwater flow. Figures included in this paper will display the model area with either no rotation or a 30 degree rotation (all model calculations were performed using the USGS 60 degree rotation). Showing the full 60 degree rotation is confusing and figures produced by the model software would be difficult to read.

The geologic features incorporated into the model layers are shown in Figure 2. The layers for the PrAMA model represent only the top two layers of the NARGFM. Previous groundwater models, including the PrAMA model, analyzed groundwater basins or sub-basins defined by administrative needs instead of hydrological flow boundaries. Because groundwater flow is continuous through aquifers that cross boundaries of the groundwater basins, and because groundwater withdrawals in one basin can potentially capture groundwater flow from adjacent basins, only a regional model can simulate the effect of changes in any basin or sub-basin on another. The NARGFM model was developed to better represent regional groundwater movements. Simulation on a regional basis does not diminish the ability to simulate groundwater flow in individual basins or sub-basins (e.g. the PrAMA where the grid sizes are similar). Accurate simulation of groundwater flow in any sub-area of the regional model depends on the quality of data used to define the local hydrogeologic system and stresses on that system.

Three layers were used to represent the primary aquifers in the NARGFM model (Figure 2). It was necessary to simplify the observed geology in order to incorporate it into the model. It should be pointed out that those areas of differing aquifer properties were incorporated within each layer to represent as accurately as possible the aquifer conditions. From the NARGFM report:

> *Layer 3 is the lowest of the layers, extends across the entire model domain, and represents the Redwall-Muav aquifer and crystalline rocks that are exposed at the land surface in the southern and eastern parts of the model domain where the Redwall-Muav aquifer is absent. Layer 2 extends only partially over the model domain and represents the Supai Formation on the Colorado Plateau, sand and gravel in the Verde and Big Chino Valleys, and the lower volcanic unit in the Little Chino Valley and Upper Agua Fria sub-basin. Layer 1 is the uppermost and least extensive model layer and represents the Coconino aquifer*

> *on the Colorado Plateau, the thick silt and clay and adjacent interbedded alluvial deposits in the Big Chino Valley, the fine-grained part of the Verde Formation in the Verde Valley, and the upper alluvial layer in the Little Chino Valley and Upper Agua Fria sub-basin.*

A consequence of the mapping of aquifer properties onto the 3 layer grid is that several sub-basins are bounded by regions of no-flow—areas in which rocks of very low transmissivity (generally granitic or other crystalline rocks of Precambrian age) form the uppermost model layer. Figures 3, 4 and 5 show the Area of Concern (AOC), with the sub-basin outlines in dark blue. The light blue area in Figure 3 defines the areas inactive in the model within the Big and Little Chino sub-basins on Layer 1. The active area (white) in Layer 2 (Figure 4) is slightly larger in extent, while layer 3 (Figure 5), which underlies the entire extent of these sub-basins, is active throughout. Groundwater in the shallower layers, such as the Big Chino sub-basin, flow vertically into layers 2 and then 3 before flowing horizontally between the sub-basins.

Model Runs Assessing Accuracy and Predictive Capability

Two stages of model runs were performed in the preparation of this report. The first stage to be discussed used the model data sets as presented in the 2011 USGS NARGFM report. The objective of this stage of the study was to be able to provide independent review of the NARGFM's accuracy and applicability.

The numerical simulations discussed for this stage were performed using the NARGFM model data sets and files downloaded from the USGS web site on May 10, 2011. The data files were imported into a graphical model pre-processor permitting visualization of all the input parameters and simulation results. The pre-processor used is a commercially available computer program called Groundwater Vistas versions 5.47 and 5.51 (Environmental Simulations, Inc.). The data sets were imported into Microsoft Excel and examined for completeness. Particular attention was paid to the Well and Observation data sets. All data sets were found to be as represented in the model report. In some cases, the observation data were updated from the original model end period of 2005 and extended to 2013 by downloading the newer information from the ADWR on-line well data base. Observed groundwater elevation data from several additional wells in the AOC were also added to achieve greater areal coverage. Simulations were performed on an Intel based laptop personal computer and generally took about 12 minutes each. Within the model, all dimensions are specified in units of meters and days. For comparison with other data sets, most of the figures presented here are shown in units of feet and years.

Creation of Forward-looking Model Runs

The second stage of the modeling followed the design of the Garner 2013 study. The Garner study had two objectives: (A) to estimate how human stresses on the hydrologic system in and around the Verde Valley changed streamflow in the Verde River from 1910 through 2005; and (B) to examine future changes using three hypothetical human-stress conditions for 2005 to 2110. These changes are mostly due to groundwater withdrawals from and incidental and artificial recharge into the various aquifers included in the NARGFM model. To isolate the human-caused changes, several of the natural changes that might occur in the future were removed from the forward-looking model runs (similar to the procedure of Gardner et. al.). These changes include natural recharge and evapotranspiration which were then held constant at the long-term average value. The Garner study did not incorporate projected natural recharge changes derived from global-climate model forecasts. It also did not include consumptive use of surface water for irrigation, despite being a human stress, because there has been insufficient hydrologic investigation of this process.

Prior to examining Forward-Looking results, a “natural-conditions” run was executed in which all human stresses over time were excluded in order to assess the relative changes attributable solely to human stresses.

Numerous complex scenarios that consider variable future human stresses can be conceived and tested. Such scenarios, however, require considerable and wide-ranging data, such as population and per-capita water-use projections, and currently are not practical to be developed for either of the groundwater basins in the AOC.

Instead, three hypothetical scenarios, in which human stresses were changed at varying rates, were developed for the 2005–2110 time-period. The purpose of these hypothetical future scenarios was not to predict any specific reality, but to demonstrate and quantify the relative response of the hydrologic system to varying human stresses.

The three Garner[3] scenarios were developed as follows:

1. Unchanged human stresses, 2005–2110. The distribution and amount of human stresses that existed in 2005 are continued unchanged at those same rates and locations into the future.

2. Increased human stresses, 2005–2110. This model run begins with human stresses as they existed in 2005, maintains these human-stress levels until 2010, increases them by 3 percent of the 2005 value, uncompounded, for each of the next five decades (for a total of up to 15 percent increase over 2005 levels by the year 2060), and then holds them unchanged at the increased level for the following 50 years.

3. Decreased human stresses, 2005–2110. This model run is the inverse of the increased-human-stresses model run. It begins with human stresses as they existed in 2005, maintains these levels until 2010, decreases them by a total of

15 percent over the subsequent 50 years, and then holds them unchanged at the decreased level for the following 50 years.

Human stresses were changed or maintained in these ways across the entire model domain, not just within the Verde Valley.

The numerical simulations, performed in stage two of this study and discussed next, implemented the first two of the above Garner scenarios by modifying the previous NARGFM data sets. First, the model time period was extended to 2110. To accomplish this, simulation period 10 was extended from 2005 to 2020. An additional simulation period 11 was then added to cover the time period 2020 to 2110. A separate period starting in 2020 was necessary to allow a new Big Chino pumping center, as described below, to start at this time. Recharge and evapotranspiration rates for simulation periods 10 and 11 were set to those used in the NARGFM simulation period 2.

The 3% increase and constant rate pumping data sets were supplied by Don Pool (personal communication, April 25, 2013). To test the relationship between pumping at the Big Chino Water Ranch and the long term effect on the Verde River, an additional scenario was created in which five hypothetical wells were added to the model with a combined extraction rate of 12,000 ac-ft/yr.

The selection of 12,000 ac-ft/yr requires explanation. Although the Big Chino Valley is likely to experience significant additional groundwater withdrawals because of subdivision growth, the more immediate and specific stress is the withdrawal and exportation of groundwater to the PrAMA. The City of Prescott has plans to import at least 8,000 ac-ft/yr with planned capacity and rights to just under 12,000 ac-ft/yr. The Town of Chino Valley has rights to just fewer than 4,000 ac-ft/yr with no specific plan in place. Considering the above, 12,000 ac-ft/yr was selected as a reasonable stress level to demonstrate the effect of the exportation of groundwater from the Big Chino Valley.

SIMULATION RESULTS 1938 to 2005 – STAGE 1

Analysis of NARGFM Accuracy and Predictive Capability

The accuracy of the groundwater elevations simulated by the USGS was assessed by comparison with observed data collected from monitoring wells. The USGS selected monitor well data from publically available sources such as the ADWR data base based on the availability of 10 or more water level measurements during multiple decades and were presented in Appendix 2 of the report. The NARGFM report states that "*much of the earliest water-level data is concentrated in the Little Chino sub-basin because the earliest groundwater development was in that area*". A total of 3,778 measurements from 94 wells, covering in the entire model area, were included in the data sets supplied.

The well identification codes used in this paper (such as (B-14-02)14BAD) are based on the Bureau of Land Management's system of land subdivision. The land survey in Arizona is based on the Gila and Salt River meridian and base line, which divide the State into four quadrants designated by capital letters A, B, C and D in a counterclockwise direction beginning in the northeast quarter. The first digit of a well ID indicates the township, the second the range, and the third the section in which the well is situated. The letters that follow the digits indicate the well location within the section following a counterclockwise direction beginning in the northeast quarter. Most of the wells in the AOC are in the B quadrant and townships 14 through 19. Details on these wells can be found on the ADWR Wells-55 data base.

Figure 6 shows a plot of observed vs. calculated groundwater elevations for the 94 wells and 3,778 observations included in the NARGFM model. The Multiple observations arise because water levels in a well have been measured over time, generally between 1940 and 2013. Wells plotting on the diagonal line have the observed and calculated values equal to each other. Most well water levels plot very close to this line, indicating a highly accurate simulation spanning a range of elevations from 3,000 to 6,500 feet above mean sea level (amsl). Between 5,300 and 6,500 feet there are 561 outlier results (15%) with residual (observed – calculated) water level values of >300 feet. Close inspection indicates that 74% of these values are from wells located in the Little Colorado River Plateau basin, 20% from the Verde Valley and 6% from the Coconino Plateau regions. The outliers are from multiple wells that at some times respond appropriately but at other times display large errors. None of these large differences are from the Big Chino, Little Chino or Aqua Fria basins. The USGS attributes these errors to a large anisotropy and locally steep vertical hydraulic gradient in the Coconino aquifer that could not be simulated accurately without using a finer grid resolution. The statistics shown at the bottom of Figure 6 exclude these outliers. None of the outliers were located in the AOC and only one well had all of its data excluded.

It is accepted practice in the modeling community to judge a model's calibration accuracy based on the Root Mean Square (RMS) of the value of the residuals (also called the Deviations) divided by the total range of the observations (called the Normalized Root Mean Square of the Deviations - NRMSD)[8]. An NRMSD of less than 5% is considered an excellent result. Values between 5 and 10% are generally considered acceptable. The NARGFM results (excluding the outliers) have an NRMSD of 1.9% (average residual of 44.5 feet) indicating an excellent calibration has been achieved (Figure 6).

[8] Anderson, M.P.; Woessner, W.W. (1992). *Applied Groundwater Modeling: Simulation of Flow and Advective Transport* (2nd Edition ed.). Academic Press

For only the Big Chino sub-basin (Figure 7), there are 25 well locations and the NRMSD is 3% or an average residual of -1.8 feet. The general agreement between observed and simulated groundwater elevation within the Big Chino sub-basin (Figure 7) indicates that the model is also satisfactorily calibrated for this area. It should be noted that several data points with model calculated values between 4,400' and 4,500' and observed values of about 4,300' plot off the 1:1 line. These anomalous wells are near Walnut and Antelope Creeks and will be discussed in a later section of the paper.

The time-dependency as well as the range of the simulated and observed groundwater levels for the AOC is shown in Figure 8. It is not possible to display all 25 wells in this manner. The eight that are displayed were selected to represent each of the sub-basins and layers within the AOC. Several similar plots were also given in the NARGFM report and excellent agreement is shown between the simulations run as part of this review with those presented by the USGS. The locations and layers (indicative of the depth) for the selected wells are shown in Figures 3 through 5. Note that the range of groundwater elevation shown in Figure 8 is 500' and that over this range all the simulated and observed data are very similar.

Examining Figure 8 in detail indicates that the highest groundwater elevation is seen for well (B-15-02)17ABA located west of the Town of Chino Valley (Figure 5) and shows good agreement for early times (~1940) but only fair agreement in 2005 (residual of 40 feet) with the simulated results showing a slightly greater decline over time than is observed (blue line and square symbols). Well (B-17-02)06BBB (displayed at the bottom of Figure 8 and its location seen in Figure 3) is located northwest of the Town of Paulden. In this case the simulated result is also very close to the observed groundwater level but about 20 feet higher and shows a slightly more pronounced decrease with time. This well is west and upgradient of the beginning of the Verde River which will be discussed at the end of this section. Well (B-16-04)14BBB1 is located in Williamson Valley (Figure 4) on the west side of Mint Wash (light green line and triangles). The observed and simulated groundwater elevations track each other exactly, but show little variation between 1950 and 2005. Well (B-16-01)14CCC is located east of Granite Creek (Figure 5) and shows the simulated groundwater elevation is 24 feet low between 1940 to 1955, in excellent agreement between 1960 and 1982, but is low by about 10 feet between 1994 and 2002. The total simulated decrease of 64 feet compares well with the observed decrease of 78 feet. Well (B-16-02)14CDA (Figure 4) is located within the Little Chino Sub-basin (dark green line and circles) and shows excellent agreement throughout the data collection period of 1945 to 2005 with a decrease of 69 feet.

Wells (B-19-04)04BDB and (B-19-04)10ADA (pink and orange) are both in layer 1 (shallow) of the Big Chino sub-basin (Figure 3). Both are shown in order to obtain a continuous record of observations from 1955 to present. No trends are seen over this time period but the simulated and observed groundwater elevations are all within 10 feet of each other.

The model is also capable of simulating the flow of water passing a specified location. One such location for which observed data are available for comparison with simulated values is at the USGS streamflow gaging station 09503700 Verde River near Paulden located on the Verde River approximately 7 miles east of the Town of Paulden (Figure 9A). In discussing the flow of groundwater into a river, one must use the term 'base flow' to differentiate the groundwater contribution from surface flows after a rainfall or snowmelt event. Total river flow at a gaging station is measured and recorded and available from the USGS. No data are available before 1963 (the streamgage was installed in 1963). After 1963, the simulated results represent excellent agreement considering the 10-year averaging process used in NARGFM. Flow in the Verde River is discussed in more detail in the next section of this paper.

The flow to the Del Rio Springs was also simulated using NARGFM and the results can be compared to the observed flow and the simulations from the ADWR Prescott AMA groundwater model (Nelson, 2011)[9]. The long term trends for both NARGFM and the PrAMA models are very similar with the initial 1939 flow rates agreeing (6.5 cfs for the NARGFM and 5.5 cfs for the ADWR models)[10]. The 2005 flow rates are also the same at 1 cfs.

Simulated Historical Change in Upper Verde River Base Flow at the Paulden and Clarkdale Streamgages

The base flow in the Verde River near Paulden between 1938 and 2005, as simulated by the original NARGFM, is shown in Figure 9A. Also shown is the annual average base flow calculated from the observed flow at the Paulden streamgage. It was discussed above, that the overall trend at the Paulden streamgage compares well with the simulated base flow of approximately 17,500 acre-feet/year or about 24 cfs (Figure 9A). It has been shown previously that the base flow at the headwaters of the Verde River near Paulden is controlled by the groundwater elevation difference between the Big Chino aquifer and spring discharge in the Verde River[11]. While the 10-year averaging process for the NARGFM precludes simulation of the short term observed variations, Figure 9B compares the pressure head of Well (B-17-02)06BBB (height in feet of water above the 4,234 feet amsl elevation of Verde Springs) with the base flow (in units of cubic feet per second - cfs) at the Paulden streamgage (USGS 09503700, location shown in Figure 5 as Pldn-G). The base flow tracks the change in groundwater

[9] Nelson, Keith (2011). 2011 Provisional Update of the Prescott AMA Groundwater Flow Model. Arizona Department of Water Resources. Arizona Hydrological Society, 24th Annual Symposium, September 18-20, 2011.

[10] To aid in this discussion, note that 1,000 acre-feet/year (ac-ft/yr) is equivalent to 1.38 cubic feet per second (cfs).

head, indicating that any change in groundwater elevation within the Big Chino aquifer will be observed in the Verde River[11]. It should also be noted that the changes in base flow lag the pressure or water level changes by between 1 and 3 years.

Simulations of historical changes in base flow of the Upper Verde River due to human activities – 1910 to 2005 (after Garner et. al.).

Before discussing the forward looking simulations, it is instructive to determine the human impact to the river that has already occurred due to groundwater extraction for agricultural, livestock, and domestic use. The original NARGFM model was modified by removing all the groundwater extraction (and injection) and running for the period 1910 to 2005. Consequently, this run reflects the natural variation in groundwater elevations and stream flow due solely to climate. The difference between this simulation and that performed using the known extraction and injection rates reported for the same period reflects the change caused by human activities. The base flow at the Paulden and Clarkdale streamgages was estimated to have decreased by about 4,900 ac-ft/yr (7 cfs) between 1910 and 2005[12] due to human activity (Figure 10). The simulated results at the Paulden and Clarkdale streamgages are the same because there is very little human activity in this reach of the river. Figure 10 also shows that because of the considerable human activity in the Verde Valley, a significantly larger reduction (14 cfs) has occurred at the streamgage located southeast of Camp Verde (triangles).

The 2005 base flow at the Paulden streamgage was approximately 19 cfs, thus the estimated pre-development base flow would have been 26 cfs (19 plus 7). This is slightly lower than the original NARGFM simulation shown in Figure 9A of 30 cfs. It should be noted that measurement or calculation of base flow in the various studies used methods that differed from the VRBP study (for example hydrograph separation). Differing time ranges for averaging were used among the various studies as well. In any case, any apparent under or over-estimation of the absolute magnitude of base flow at a gage does not affect the ability of the models to evaluate the relative changes in base flow attributable to human activities.

Summary of Discussions Regarding the Accuracy of NARGFM

The USGS has not performed a formal sensitivity analysis of the NARGFM to quantify potential errors in the various parameter datasets. However, the very low error seen in the statistical results presented in Figures 6 and 7 (NRMSD of 2% and 3% respectively)

[11] The base flow used in this graph was determined by Doug McMillan by calculating the lowest average daily flow for each year. Blasch et. al. 2006 also noted that "*Patterns in base flow variations are similar to those in water levels in well (B-17-02)06bbb in Big Chino Valley, and stated that they are likely related to changes in climate and (or) ground-water withdrawal*".

[12] Garner and others 2013, pg 18. Graph prepared by P. Kroopnick from data in Appendix Table 1.2, pg. 35.

indicates an excellent calibration was obtained. It is possible that this result is not unique; thus some other combination of parameters could produce the same result. However, this would be highly unlikely given the agreement between observed and simulated water levels over a wide range of observations (3,000 to 6,500 feet of groundwater elevation) and the many basins included.

Despite the excellent overall accuracy of the NARGFM simulations, several wells in the Big Chino sub-basin, near Walnut and Antelope Creeks, were not simulated as accurately as expected (offsets of up to 175'). Based on this, the Yavapai Water Advisory Committee (WAC), following recommendations from its Technical Advisory Committee (TAC), requested and funded supplemental studies by the USGS to address this difference as well as several other areas of concern identified by the City of Prescott and Towns of Prescott Valley and Chino Valley (Tri-Cities) regarding the accuracy of NARGFM. It is beyond the scope of this paper to discuss the specific objectives of these supplemental studies or the results. However, the USGS concluded at the end of the supplemental study, that inclusion of the four suggested changes in the conceptualization of the hydrogeology, resulted in only "slight" or "not large" changes in the simulated results[13]. Despite the conclusions of the supplemental studies, the objections of the Tri-cities have resulted in an indefinite delay in Yavapai County issuing approval for the USGS to run the model in a forward-looking manner to study future water use (scenarios) in the Big Chino and Little Chino sub-basins.

While, the USGS was conducting the supplemental study, the City of Prescott and the Town of Prescott Valley, entered into an agreement with the Salt River Project (SRP) to collect additional groundwater data and explore alternative conceptual models for the AOC. Under this agreement, SRP will also construct an independent model to study the effects of the future groundwater withdrawal from the Big Chino sub-basin and to develop a mitigation plan to reduce effects on the base flow to the Upper Verde River. The results from these studies will not available for eight to ten years.

In the absence of agreement among elected officials in Yavapai County to apply the NARGFM to the regional management of Verde River Basin water resources, the Verde River Basin Partnership (VRBP) and the Town of Clarkdale in cooperation with the USGS conducted and published the results of a series of simulations to explore the nature of human-caused stresses (groundwater pumping and artificial and incidental recharge) on the hydrologic system of the Verde River watershed (Garner and others, 2013). Currently, the Town of Clarkdale and City of Cottonwood are independently developing their own planning scenarios (based on the NARGFM). Recognizing that regional planning of water use within Yavapai County is needed now, Senators John

[13] Don Pool, USGS presentation to Yavapai County Water Advisory Committee, Investigated Questions about the NARGFM in the Big Chino Sub-basin, Preliminary Report, Unpublished, October 16, 2012.

McCain and Jeff Flake recently set a letter to County officials urging them "to develop a long-term water management strategy that protects the Verde River"[14]. With this in mind, I have independently used the NARGFM in forward-looking model runs, to study the potential effects of continued and increased groundwater extraction on base flow to the Upper Verde River and nearby water wells. This rest of this paper discusses the results of the study.

SIMULATION RESULTS, 2005 to 2110 – STAGE 2

Current Study - Forward-looking Simulations of Changes in Base Flow of the Upper Verde River – 2005 to 2110

Besides the above historical analysis of pre-development changes in base flow at the Paulden streamgage of the Upper Verde River, four additional cases will be examined here. They are summarized in Figure 13 which shows the decrease in cubic feet per second (cfs) for each case independent of the others. The last entry gives the cumulative potential decrease for cases 1 through 4.

Numerous complex scenarios that consider variable future human stresses can be conceived and tested. Such scenarios, however, require considerable and wide-ranging data, such as population and per-capita water-use projections, and currently are not practical to be developed for the groundwater basins considered here. Instead, the USGS-VRBP project developed three hypothetical scenarios for the 2005–2110 time period, wherein human stresses are changed at varying rates. The purpose of these hypothetical future scenarios was not to predict any specific reality, but to demonstrate and quantify the relative response of the hydrologic system to varying human stresses

For these forward-looking model runs, the NARGFM was modified as discussed previously by Garner and others (2013), for cases 1 and 3, or by Kroopnick (this paper), for cases 2 and 4, by increasing the length of simulation period 10 and adding an additional simulation period 11 to allow inclusion of years 2020 to 2110. Recharge was held constant for cases 1 and 3 at the average historical rate (equivalent to the USGS stress period 2). All changes were maintained for the entire model domain.

> ***Case 1 – Unchanged water demand***. This is designated as the base case. In this case, the model was run from 1910 through 2005 with the same values for pumping and artificial recharge that were used in the original NARGFM. For the period 2006 through 2110, pumping over the entire model domain was kept at the 2005 rate and natural recharge was held at the average value for the period 1910 through 2000. This forward-looking model run indicates that if no additional

[14] John McCain and Jeff Flake, published press release, June 28, 2013.

changes in withdrawals occur, the base flow will decrease by 4.1 cfs between 2006 and 2110. Figure 11 is a graphical representation of the decrease in flow at the Paulden, Clarkdale, and Camp Verde streamgages. The data shown in figure 11 are from Garner et. al. (2013), Appendix Table 1.4, pg. 39.

Case 2 – Continuing drought. The natural recharge used in the original NARGFM for the time period 2000 to 2005 was approximately 25% lower than the historical average based on the observed climatic conditions. To examine the potential effect of the current drought continuing unabated until 2110, the 2000-2005 recharge rate was applied for the entire period 2000 to 2110. This would result in a decrease in base flow of 1.4 cfs between 2005 and 2110 (Figure 13). The Kroopnick modified NARGFM was used for this simulation and the result subtracted from case 1 to isolate the effect of recharge from that of continued pumping.

Case 3 – Increased water demand. This case was developed by Garner et. al. (2013), to assess the effect of increased groundwater extraction throughout the entire model domain. The USGS prepared a data set which started with human stresses as they existed in 2005, maintained these human-stress levels until 2010, increased them by 3% of the 2005 value for each of the next five decades, and then held them unchanged at the increased level for the following 50 years. As seen in Figure 13, a model run using this data results in a forward looking estimate of a 2.9 cfs reduction in base flow at the Paulden streamgage.

Case 4 – Extraction of 12,000 ac-ft/yr of groundwater from Big Chino Valley. The Tri-Cities have long expressed the desire to import water from the Big Chino Valley to foster growth and achieve safe yield in the Prescott Active Management Area. Although the groundwater code generally prohibits the transportation of groundwater between basins, there are exceptions that allow for the importation of approximately 18,000 acre-feet per year from the Big Chino sub-basin to the Prescott Active Management Area. Prescott, with its partner Prescott Valley, has obtained rights to just under 12,000 acre-feet per year of this water. The two communities have plans to import at least 8,000 acre-feet per year with the possibility of importing the full amount. The withdrawal of water would be at the Big Chino Water Ranch, which was purchased for that purpose.

The Town of Chino Valley has obtained water rights, from retired Historically Irrigated Acreage, to approximately 4,000 acre-feet of water per year but has not defined a specific project location.

Although the amounts of water and withdrawal locations are not fully defined, the withdrawal of 12,000 acre feet per year at the Big Chino Water Ranch was selected to illustrate the time and effects of groundwater exportation on the Verde River. The year 2020 was selected as the starting date for this extraction and is considered the earliest likely date. Although the achievement of 100% of design capacity in the first year is not likely, it was selected for simplicity of analysis.

This case, therefore presents a forward-looking model run in which 12,000 ac-ft/yr (16.6 cfs) of groundwater is extracted from the central Big Chino sub-basin (the Big Chino Water Ranch) starting in 2020 and continuing to 2110 (Figure 12). The calculation indicates that a change in base flow of 4.5 cfs, due solely to this pumping, would occur at the Paulden and Clarkdale streamgages by 2110 compared to 2005.

Case 5 - Cumulative effect of continuing drought, increased water demand, and extraction of 12,000 ac-ft/yr of groundwater from Big Chino Valley.

The final entry in Figure 13 shows the cumulative effect (sum of cases 1 through 4) and indicates a loss of base flow to the Verde River at the Paulden streamgage of 12.8 cfs. Bearing in mind that in 2005 the baseflow was ~19 cfs, this would leave only 6.2 cfs in the river by 2110.

It has been noted (G. Beverly personal communication) that a further reduction in streamflow occurs between the Paulden streamgage and the Perkinsville Bridge streamgage of between 2 and 9 cfs for 2007 through 2010. Thus, it is likely that part of the Upper Verde River near and above Perkinsville would be dry by 2110 based on the cumulative effects discussed above.

Current Study - Forward-looking Simulations of Changes in Groundwater Elevations at Select Wells – 2005 to 2110

Current residents and water resource planners are also concerned with changes that are occurring in the groundwater elevations of the many stock, domestic and water supply wells in the region. The NARGFM can be used in a forward-looking manner to simulate the changes caused by the human impacts discussed in the previous section. For comparison, recent observed results are shown and all projections use the average historical natural recharge but include increased pumping.

To illustrate the impacts, several wells were selected for discussion here (Figure 14 shows the location of the wells). These wells were chosen as representative of the areas of concern and because they have sufficient historically observed groundwater elevations to allow comparison with simulated ones to demonstrate the accuracy of the simulations. The results are presented as hydrographs (figures 15-18) that show the groundwater elevation in feet above mean sea level (amsl) for a well plotted against time in years ranging from 1950 to 2110. The graphs also indicate the surface elevation at the wellhead and the elevation of the bottom of the screened interval for the well. The bottom elevation can be used to determine if a well will become dry during the simulation period. Wells are designated, in the following discussion, by their cadastral location (i.e., township, section and range. The quarter section designations of been omitted in Figure 14).

Well (B-17-02)06BBB – This well is located just north of the Town of Paulden and is currently owned by the Nine Cross Ranch (formerly Wineglass Ranch). Changes in water levels in this well were previously shown to correlate with the base flow in the Verde River as measured at the Paulden streamgage. Figure 15 shows the forward-looking model simulations to 2110 for cases 1 and 4 (continuation of 2005 pumping rate and the one time increase of 12,000 ac-ft/yr at the Water Ranch starting in 2020. Continued pumping at the 2005 rate would result in a reduction of the groundwater elevation between 2010 and 2110 of ~9 ft. As indicated in the hydrograph, the Water Ranch pumping would cause a further lowering of the groundwater by 15 ft. Adding the potential regional pumping increase of 3% per decade would reduce the level an additional 9.5 ft. to a final elevation of ~4221 ft. by 2110 (not shown on graph). This level is approximately 173 ft. above the bottom of the well which is at 4048 ft., so there is little chance this well will become dry over the studied time period.

Well (B-15-02)13CCB – This well is located approximately 0.5 mile NW of the City of Prescott Airport and is known as Deep Well Ranch #1. Between 1965 and 2010 a decrease of approximately 0.5 ft/yr is observed with the rate slowing between 1990 and 2010. This well is less than a mile from the City of Prescott waste water recharge basins. The calculated future decline rate is similar to the historical rate. No influence from the increased pumping at the Big Chino Water Ranch can be seen at this location. However, case 3 with an increase of 3% per decade over the entire model domain results in the well appearing to go dry by year 2082 as opposed to year 2111 as calculated for case 1 (Figure 16).

Well (B-16-02)22DBA – This well is located within the Town of Chino Valley and is also known as City of Prescott production well #2 (Figure 17). The observed data indicate a decrease in the water level of approximately 100 ft. between 1948 and 2013 (~1.5 ft./yr). The forward-looking model runs for case 1 shows the groundwater elevation decreasing by 75 ft between 2010 and 2110 (Figure 17). Under case 3 (3% per decade), the decrease would be an additional 58 ft. Thus the total decline under cases 1 and 3 would be 133 ft.

Well (B-15-02)30ADC – This well is located in the Granite Oaks Subdivision in Williamson Valley. The observed decrease of 97 ft. between 1999 and 2013 (~7 ft./yr) is typical for many wells in this area. The NARGFM model calculated results are approximately 150 ft. low for this well. However, the groundwater elevation is highly variable in this area, such that at a nearby well ((B-15-02)19DDC) that does not show any appreciably decline, the calculated water level in 2013 is the same as observed.

The calculated decline is half of the observed at approximately 3 ft./yr between 2000 and 2013.

The latest model developed for the PrAMA by ADWR gives a better fit between calculated and observed groundwater elevation in this area. For Granite Oaks their calculated result is approximately 40 ft. lower than observed and the decline is very similar to the observed[15]. The hydrogeology in the Williamson Valley area is characterized by a very steep hydraulic gradient with highly variable geologic conditions due to the presence of pockets of decomposed granite surrounded by clay and non-decomposed, non-fractured granite.

The forward-looking model runs for case 1 shows the groundwater elevation decreasing by ~83 ft. between 2013 and 2110 (Figure 18). Under case 3 (3% per decade) the decrease would be an additional 33 ft. For a total decline of 118 ft. or a rate of ~1.2 ft./yr.

Projected Regional Decrease in Groundwater Elevation between 2005 and 2110

The calculated decline in the regional water table, across the entire area of concern, is shown in Figure 19. Numerical calculations were performed using the Case 5 assumptions. The area shown is similar to that seen in Figure 14. The contours enclose an area in which the decline is indicated by either the number on the contour line or the color as coded in the caption. The area encompassing the Big Chino Water Ranch is seen to have declines of greater than 100 ft. between 2005 and 2110 (darkest green). Similarly, the area encompassing most of the Town of Chino Valley and Williamson Valley to the west is predicted to have over 100 ft. of decline. As expected, Granite Oaks well (B-15-02)30ADC (shown in Figure 18), indicates a decline of approximately 150 ft. over this same time period.

CONCLUSIONS

The work discussed in this paper was carried out to explore the accuracy and predictive capability of the U.S. Geological Survey model NARGFM "Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona" (Scientific Investigations Report 2010-5180). It also builds upon the forward-looking model runs carried out by Garner, et. al. (2013). Additional forward-looking model runs were performed by P. Kroopnick to examine the consequences of continued groundwater extraction within the Region and specifically, planned increases in groundwater extraction at the Big Chino Water Ranch by the City of Prescott and Town of Prescott Valley.

[15] Keith Nelson, ADWR. Personnel Communication, November, 2013.

Results from running the model using the data supplied by the USGS confirm that the model and data are complete, reproducible and consistent with the results published by the USGS and ADWR.

Additional graphics and statistical analyses have been prepared for this paper and are discussed herein with particular reference to the administrative Areas Of Concern (AOC) known as the Big Chino and Little Chino sub-basins Within the AOC, simulated groundwater elevations and those observed between 1939 and 2005 (Figs. 8 and 9) show excellent agreement. The agreement across such a wide area where groundwater elevation changes by over 1,000 feet indicates that the model is well calibrated.

Despite the excellent overall accuracy of the NARGFM simulations demonstrated in this paper, the City of Prescott and Towns of Prescott Valley and Chino Valley (Tri-Cities), have stated that the model is not sufficiently accurate and should not be used to explore the implications of future was use in the Big Chino and Little Chino sub-basins. These objections appear to have stalled the political decisions to move forward with application of the model to gain an understanding of the effects of future changes in water demand.

Meanwhile, the VRBP and Town of Clarkdale teamed with the USGS to conduct a series of simulations to gain a greater understanding of the past and potential future human impacts on the Verde River's streamflow. For these forward-looking model runs, the NARGFM was modified as discussed previously by Garner et. al. (2013) and by Kroopnick (this paper). Two of the forward-looking cases developed by Garner were repeated here and additional graphics were created to demonstrate the results for both the west and east sides of Mingus Mountain. Two additional cases were added to a) explore the affect of climate change (recharge/rainfall) and b) add the extraction of 12,000 ac-ft/yr of groundwater from the Big Chino Water Ranch starting in year 2020. This latter case is an approximation of possible plans of the City of Prescott and Town of Prescott Valley to build a pipeline and import water from the Big Chino sub-basin.

The cases discussed herein are summarized in Figure 13.

> Historical simulations of changes in base flow of the Upper Verde River – 1910 to 2005. This case represents the historical changes in base flow to the Upper Verde River caused by human activity between 1910 and 2005. A 6.7 cubic feet per second (cfs) reduction in flow has occurred at the Paulden streamgage.
>
> *Case 1* – Unchanged water demand. This is designated as the base case, since the model is run from 1910 to 2110 with no changes in pumping from those used in the original NARGFM. The pumping over the entire model domain was kept at the 2005 rate through 2110. This forward-looking model run estimates that if no

changes are made, the base flow at the Paulden streamgage will decrease by 4.1 cfs between 2005 and 2110.

Case 2 – Continuing drought. The natural recharge used in the original NARGFM for the time period 2000 to 2005 was approximately 25% lower than the historical average based on the observed climatic conditions. To examine the potential effect of the current drought continuing unabated until 2110, the 2000-2005 recharge rate was applied for the entire period 2000 to 2110. This would result in a decrease in base flow at the Paulden streamgage of 1.4 cfs between 2005 and 2110.

Case 3 – Increased water demand. This case was developed by Garner et. al. (2013) to assess the effect of increased groundwater extraction throughout the entire model domain. The pumping rates for all the existing wells within the model were increased by 3% of the 2005 value for each of the next five decades, and then held constant at the increased level for the following 50 years. This case results in a forward looking estimate of a 2.9% reduction in base flow at the Paulden streamgage.

Case 4 – Extraction of 12,000 ac-ft/yr of groundwater from Big Chino Valley. The Tri-Cities have long expressed the desire to import water from the Big Chino Valley to foster growth and achieve safe yield in the Prescott Active Management Area. Although the groundwater code generally prohibits the transportation of groundwater between basins, there are exceptions that allow for the importation of approximately 18,000 acre-feet per year from the Big Chino Valley to the Prescott Active Management Area. Prescott, with its partner Prescott Valley, has obtained rights to just under 12,000 acre-feet per year of this water. The two communities have plans to import at least 8,000 acre-feet per year with the possibility of importing the full amount. The withdrawal of water would be at the Big Chino Water Ranch, which was purchased for that purpose.

This case presents a forward-looking model run in which 12,000 ac-ft/yr (16.6 cfs) of groundwater is extracted from the central Big Chino sub-basin (the water ranch) starting in 2020 and continuing to 2110. The forward-looking model calculation indicates that a change in base flow of 4.5 cfs, due solely to this pumping, would occur at the Paulden and Clarkdale streamgages by 2110 compared to 2005.

Case 5 - Cumulative effect of continuing drought, increased water demand, and extraction of 12,000 ac-ft/yr of groundwater from Big Chino Valley. The final entry in Figure 13 shows the cumulative effect (sum of cases 2 through 4) and indicates a loss of base flow to the Verde River at the Paulden streamgage of 12.8 cfs. Bearing in mind that in 2005 the flow was ~19 cfs, this would leave only 6.2 cfs in the river by 2110.

It has also been noted that a reduction in flow occurs between the Paulden streamgage and the Perkinsville Bridge streamgage of between 2 and 9 cfs for 2007 through 2010 and again in 2013[16]. Thus it is likely that part of the Upper Verde River near and above Perkinsville would be dry by 2110 based on the cumulative effects discussed above.

Regional planning of water use within Yavapai County is needed now. Senators John McCain and Jeff Flake recently sent a letter to County officials urging them “to develop a long-term water management strategy that protects the Verde River”. Mindful of the senators’ comments, this paper independently used the NARGFM in a forward-looking model to explore the potential effects of continued and increased groundwater extraction on base flow to the Upper Verde River and nearby water wells. The results demonstrate that significant decreases are expected and that regional planning is needed to address the future water supply for Yavapai County.

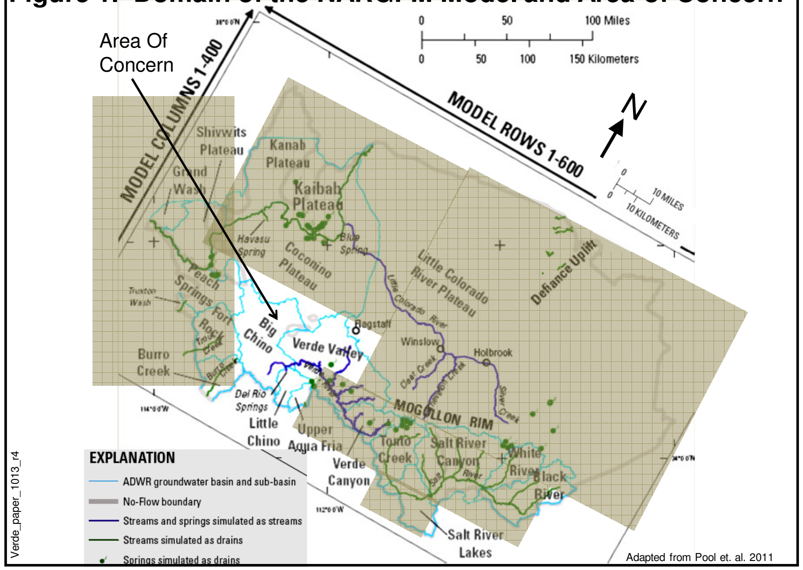
ACKNOWLEDGMENTS

I thank Ed Wolfe and John Zambrano who provided detailed comments which greatly improved this paper. Wayne Hood assisted with preparation of maps. The encouragement of the members of the Prescott Citizens Water Advocacy Group (CWAG) is also greatly appreciated. However, the commentary provided in this paper is the sole responsibility of the author.

FIGURES

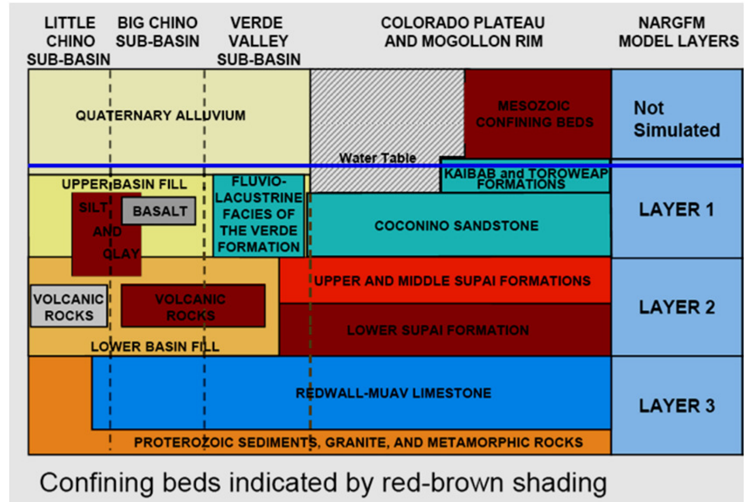
[16] Gary Beverly, Yavapai County Sierra Club, personnel communication, September, 2013

Figure 1. Domain of the NARGFM Model and Area of Concern



Adapted from Pool et. al. 2011

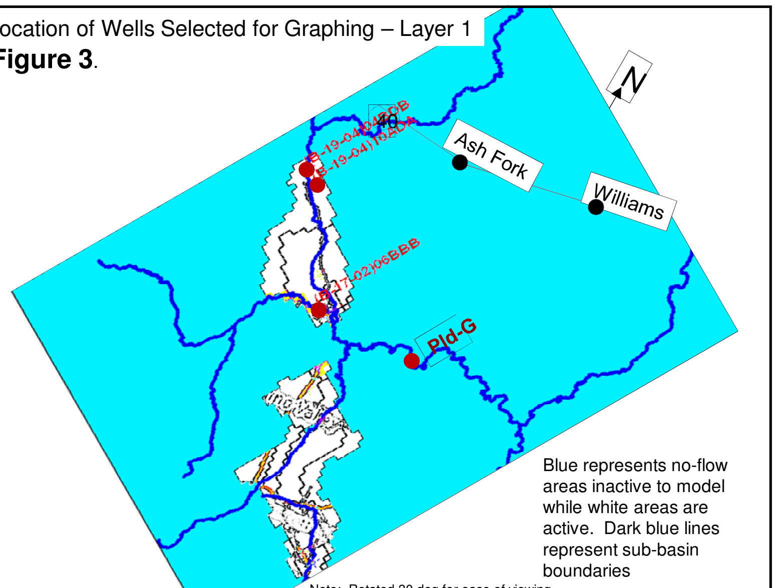
Figure 2. Conceptualized relations among the major hydrogeologic units and the NARGFM model layers



Pool et. al. 2011. Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems

Location of Wells Selected for Graphing – Layer 1

Figure 3.

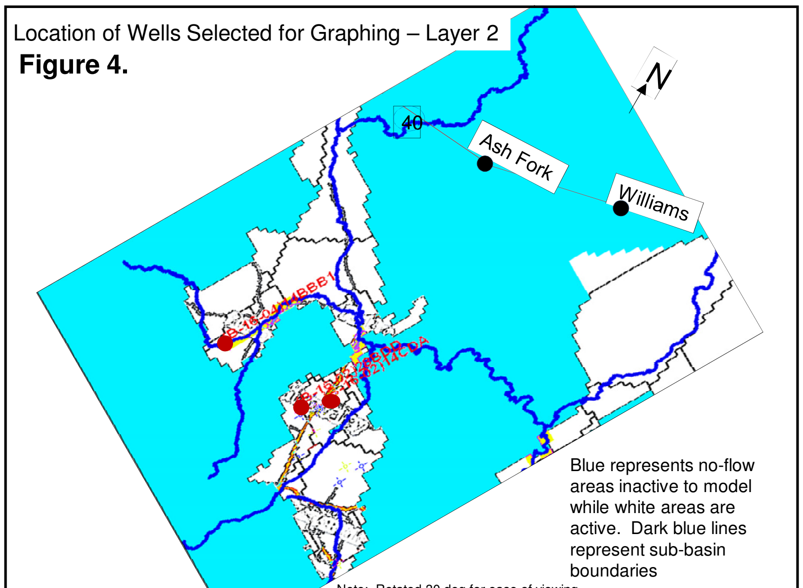


Blue represents no-flow areas inactive to model while white areas are active. Dark blue lines represent sub-basin boundaries

Note: Rotated 30 deg for ease of viewing.

Location of Wells Selected for Graphing – Layer 2

Figure 4.



Blue represents no-flow areas inactive to model while white areas are active. Dark blue lines represent sub-basin boundaries

Note: Rotated 30 deg for ease of viewing.

Location of Wells Selected for Graphing – Layer 3

Figure 5.

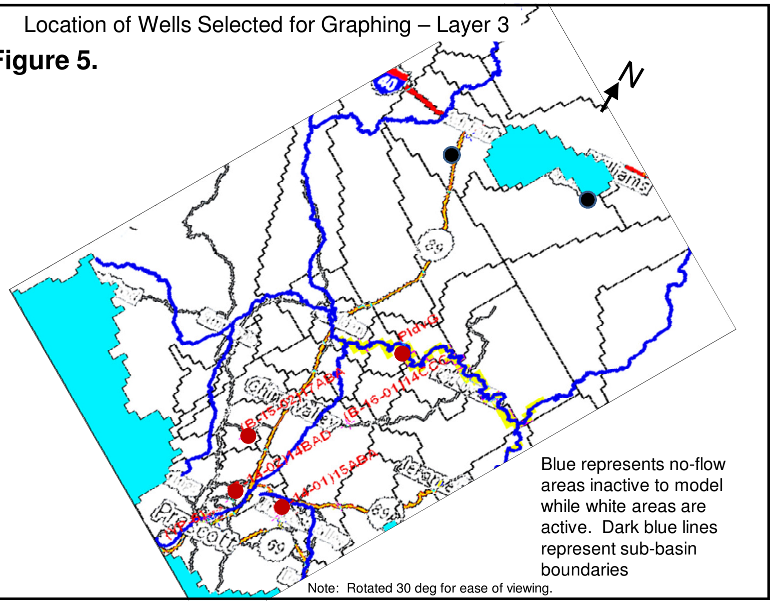
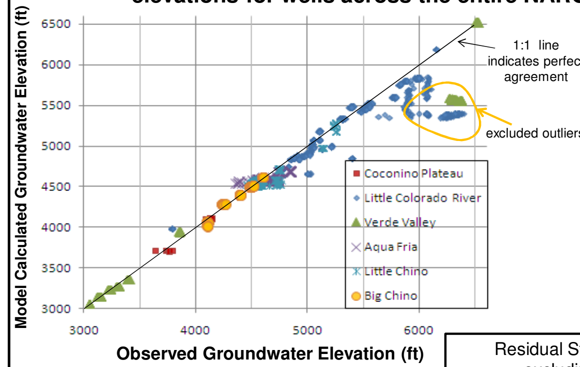


Figure 6. Comparison of observed vs calculated groundwater elevations for wells across the entire NARGFM area.



Summary of statistics For Residuals

(obs. – calc., feet amsl)

Note: Outliers (>300 ft residual) were removed (15%). None were in the area of interest.

Residual Statistics (feet), excluding outliers		
Average residual		44.5
Absolute average		57.0
Standard Deviation		66.7
Number of Obs.	93 wells	3,217
Root Mean Square Deviation		67.0
Range of Observations		3,500
Scaled average		1.3%
Scaled Abs. average		1.6%
Scaled Root Mean Square Deviation		1.9%

Figure 7. Observed vs. Computed groundwater levels for BC sub-basin

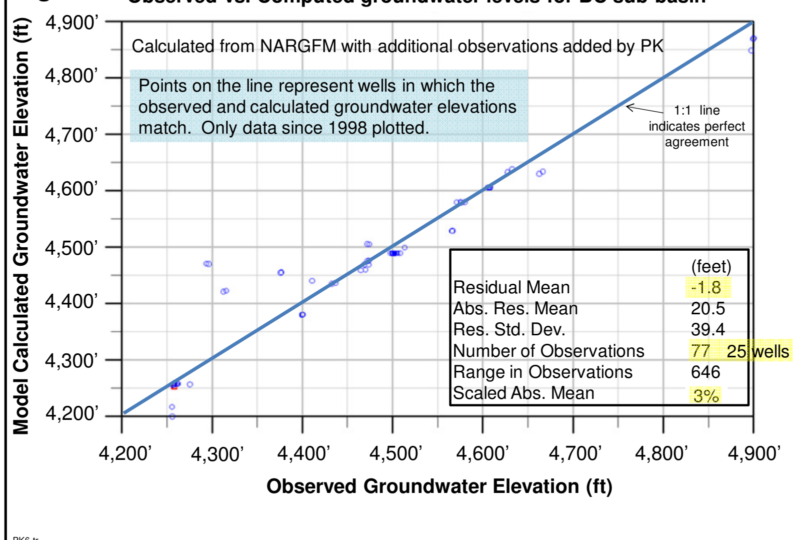
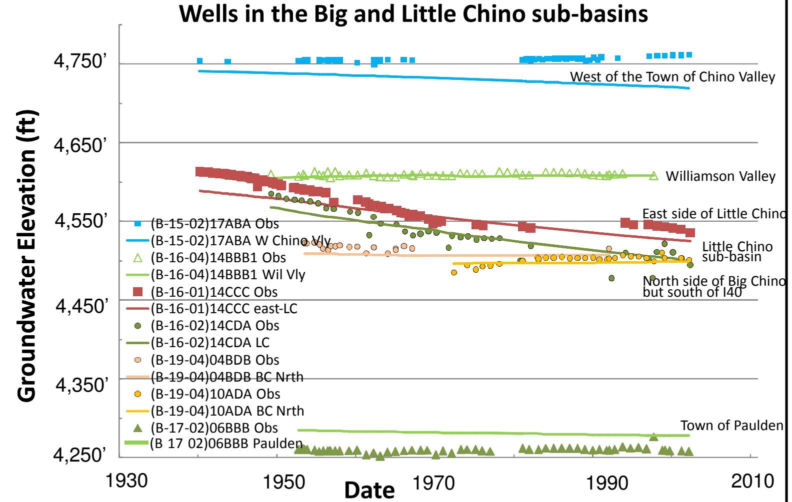


Figure 8. Hydrographs Showing Calibration for Several Wells in the Big and Little Chino sub-basins



Symbols represent observed groundwater levels. Lines represent levels calculated by model. Well locations shown in Figures 3, 4 and 5.

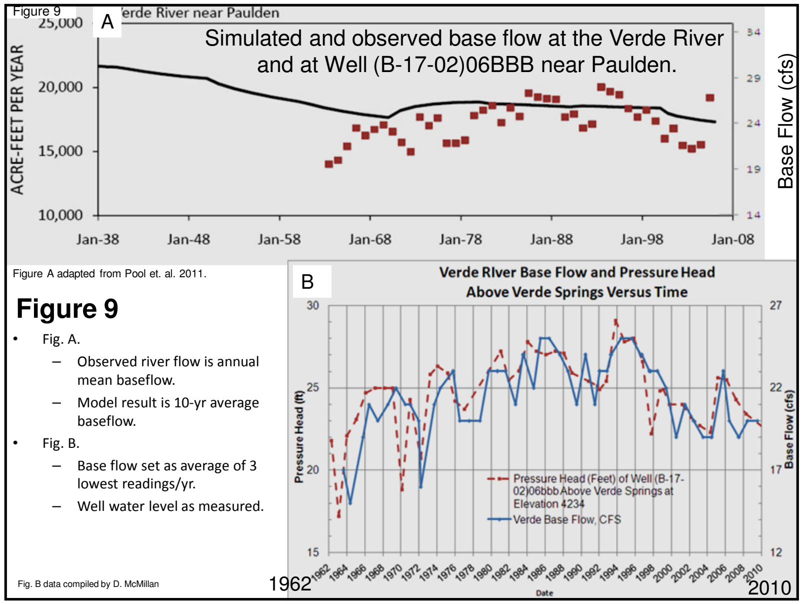


Figure 9
A
Verde River near Paulden
Simulated and observed base flow at the Verde River and at Well (B-17-02)06BBB near Paulden.
ACRE-FEET PER YEAR
25,000
20,000
15,000
10,000
Base Flow (cfs)
Jan-38
Jan-48
Jan-58
Jan-68
Jan-78
Jan-88
Jan-98
Jan-08
Figure A adapted from Pool et. al. 2011.
Figure 9
Fig. A.
Observed river flow is annual mean baseflow.
Model result is 10-yr average baseflow.
Fig. B.
Base flow set as average of 3 lowest readings/yr.
Well water level as measured.
Fig. B data compiled by D. McMillan
B
Verde RIver Base Flow and Pressure Head Above Verde Springs Versus Time
Pressure Head (ft)
Base Flow (cfs)
Pressure Head (Feet) of Well (B-17-02)06bbb Above Verde Springs at Elevation 4234
Verde Base Flow, CFS
1962
2010
Date

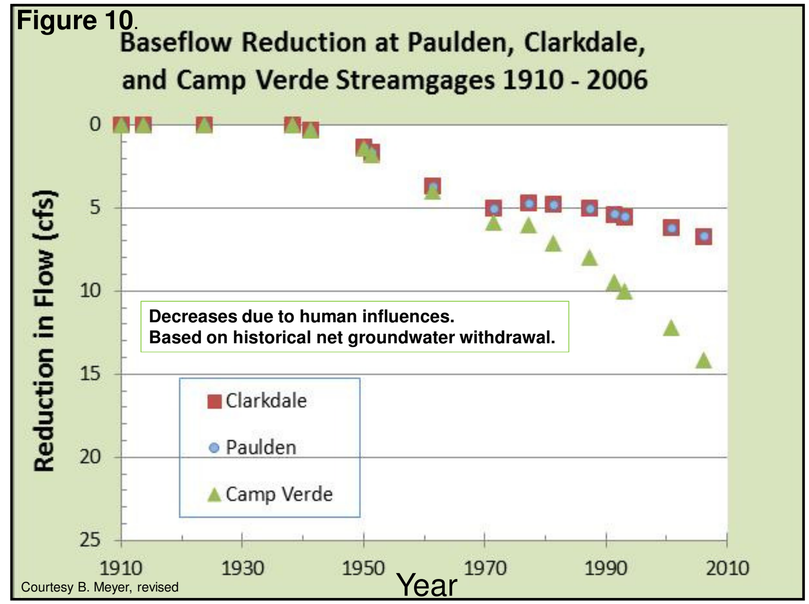


Figure 10.
Baseflow Reduction at Paulden, Clarkdale, and Camp Verde Streamgages 1910 - 2006
Reduction in Flow (cfs)
0
5
10
15
20
25
Decreases due to human influences.
Based on historical net groundwater withdrawal.
Clarkdale
Paulden
Camp Verde
1910
1930
1950
1970
1990
2010
Year
Courtesy B. Meyer, revised

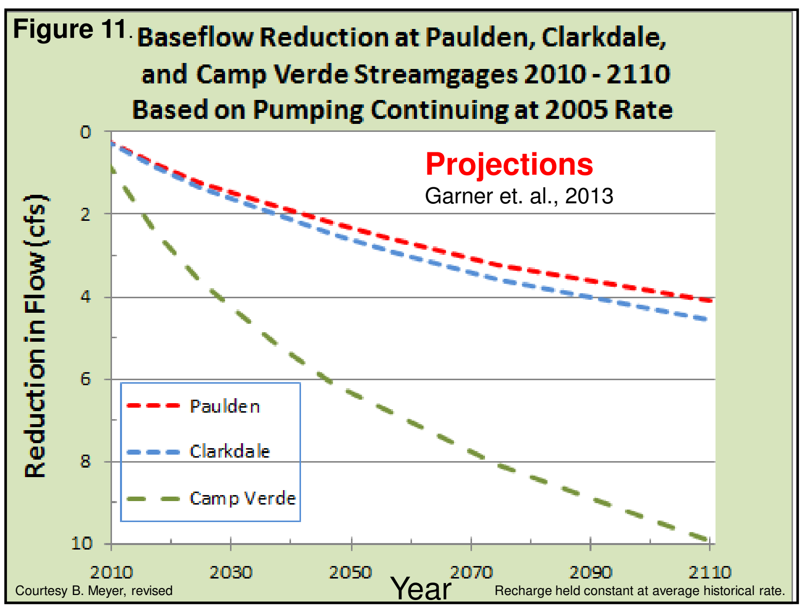


Figure 11.
Baseflow Reduction at Paulden, Clarkdale, and Camp Verde Streamgages 2010 - 2110
Based on Pumping Continuing at 2005 Rate
Projections
Garner et. al., 2013
Reduction in Flow (cfs)
0
2
4
6
8
10
Paulden
Clarkdale
Camp Verde
2010
2030
2050
2070
2090
2110
Year
Courtesy B. Meyer, revised
Recharge held constant at average historical rate.

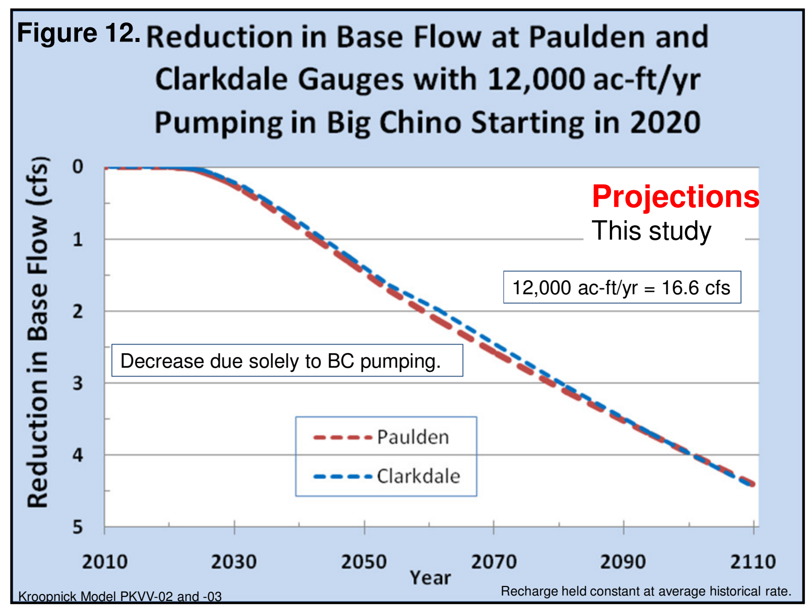


Figure 12.
Reduction in Base Flow at Paulden and Clarkdale Gauges with 12,000 ac-ft/yr Pumping in Big Chino Starting in 2020
Projections
This study
12,000 ac-ft/yr = 16.6 cfs
Decrease due solely to BC pumping.
Reduction in Base Flow (cfs)
0
1
2
3
4
5
Paulden
Clarkdale
2010
2030
2050
2070
2090
2110
Year
Kroopnick Model PKVV-02 and -03
Recharge held constant at average historical rate.

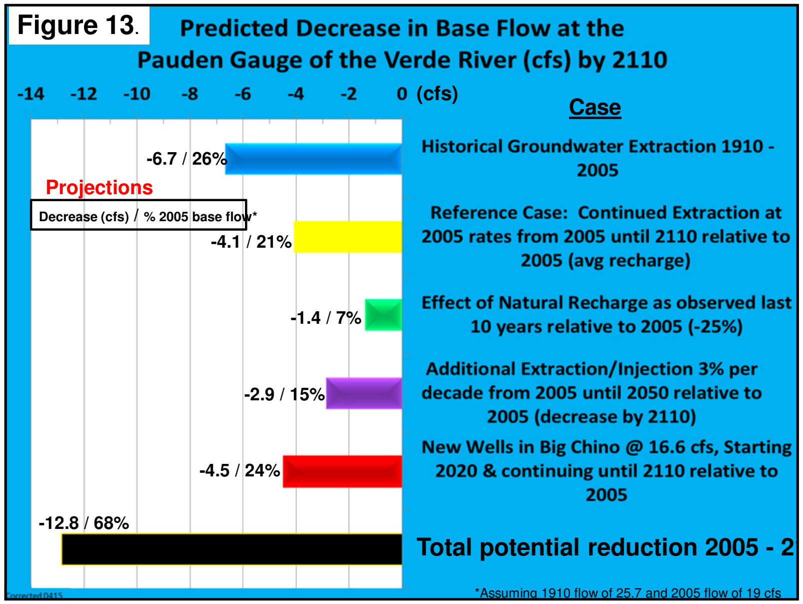


Figure 13.
Predicted Decrease in Base Flow at the Pauden Gauge of the Verde River (cfs) by 2110
-14 -12 -10 -8 -6 -4 -2 0 (cfs)
Case
-6.7 / 26%
Historical Groundwater Extraction 1910 - 2005
Projections
Decrease (cfs) / % 2005 base flow*
-4.1 / 21%
Reference Case: Continued Extraction at 2005 rates from 2005 until 2110 relative to 2005 (avg recharge)
-1.4 / 7%
Effect of Natural Recharge as observed last 10 years relative to 2005 (-25%)
-2.9 / 15%
Additional Extraction/Injection 3% per decade from 2005 until 2050 relative to 2005 (decrease by 2110)
-4.5 / 24%
New Wells in Big Chino @ 16.6 cfs, Starting 2020 & continuing until 2110 relative to 2005
-12.8 / 68%
Total potential reduction 2005 - 2
*Assuming 1910 flow of 25.7 and 2005 flow of 19 cfs

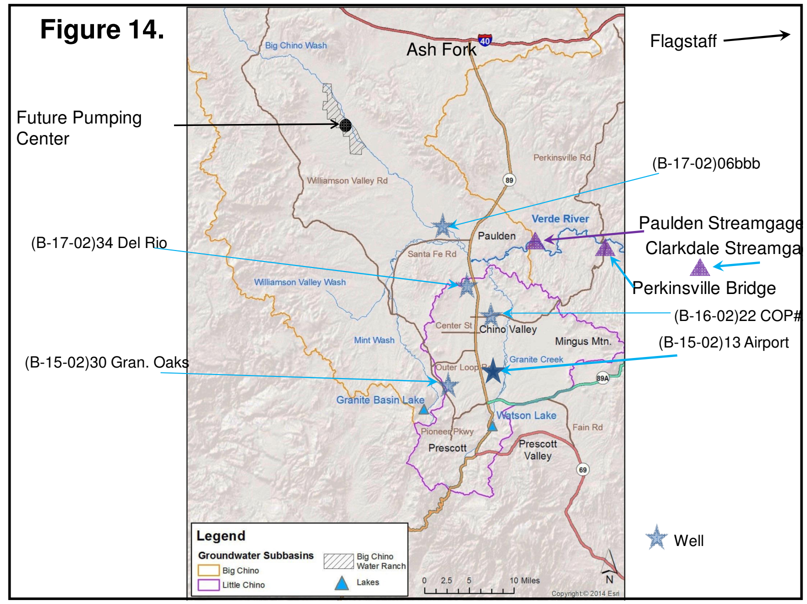


Figure 14.
Ash Fork
Flagstaff
Future Pumping Center
(B-17-02)06bbb
(B-17-02)34 Del Rio
Paulden Streamgage
Clarkdale Streamga
Perkinsville Bridge
(B-16-02)22 COP#
(B-15-02)13 Airport
(B-15-02)30 Gran. Oaks
Paulden
Verde River
Chino Valley
Mingus Mtn.
Granite Basin Lake
Watson Lake
Prescott
Prescott Valley
Legend
Groundwater Subbasins
Big Chino
Little Chino
Big Chino Water Ranch
Lakes
Well

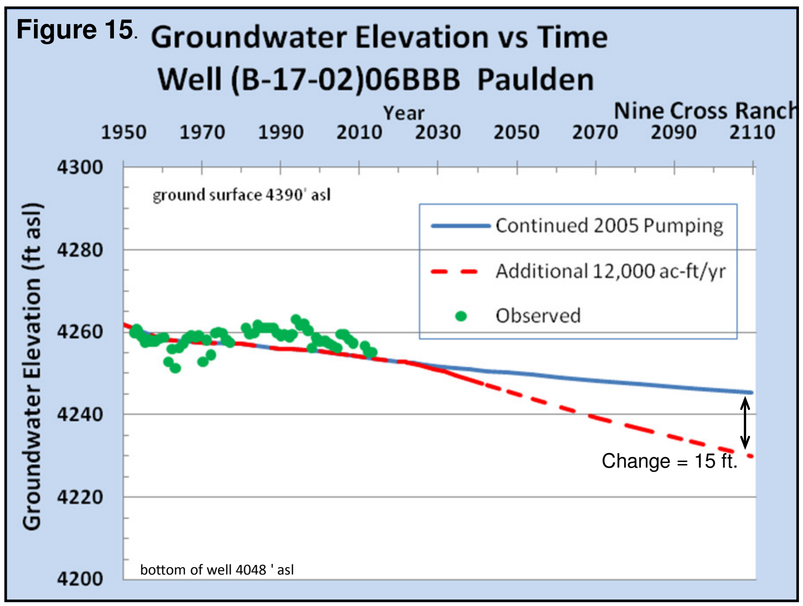


Figure 15.
Groundwater Elevation vs Time
Well (B-17-02)06BBB Paulden
Year
Nine Cross Ranch
1950 1970 1990 2010 2030 2050 2070 2090 2110
Groundwater Elevation (ft asl)
4300 4280 4260 4240 4220 4200
ground surface 4390' asl
Continued 2005 Pumping
Additional 12,000 ac-ft/yr
Observed
Change = 15 ft.
bottom of well 4048 ' asl

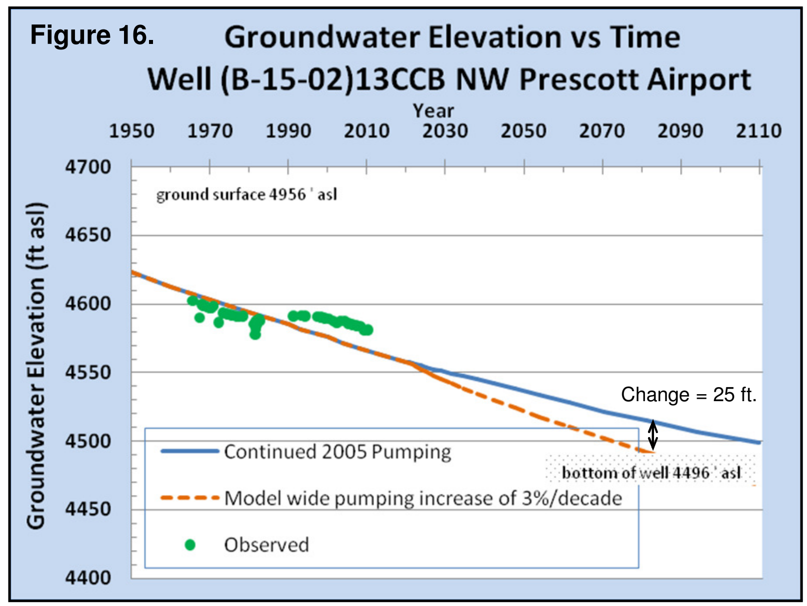


Figure 16.
Groundwater Elevation vs Time
Well (B-15-02)13CCB NW Prescott Airport
Year
1950 1970 1990 2010 2030 2050 2070 2090 2110
Groundwater Elevation (ft asl)
4700 4650 4600 4550 4500 4450 4400
ground surface 4956 ' asl
Change = 25 ft.
Continued 2005 Pumping
bottom of well 4496 ' asl
Model wide pumping increase of 3%/decade
Observed

Figure 17. **Groundwater Elevation vs Time**
Well (B-16-02)22DBA Chino Valley COP#2

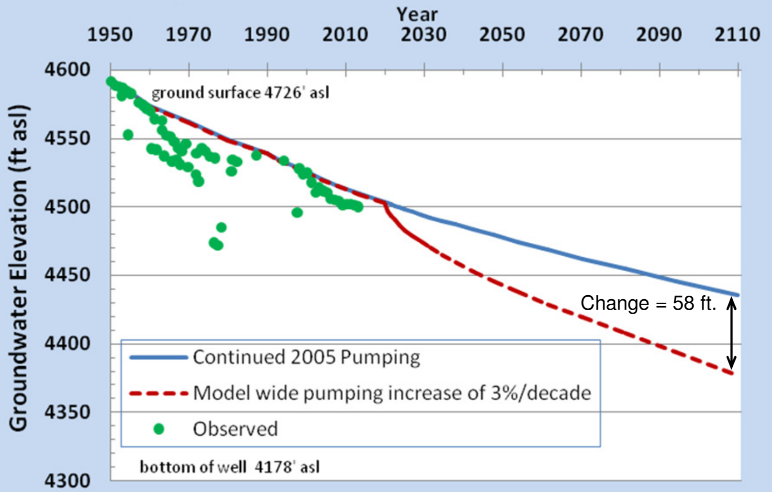
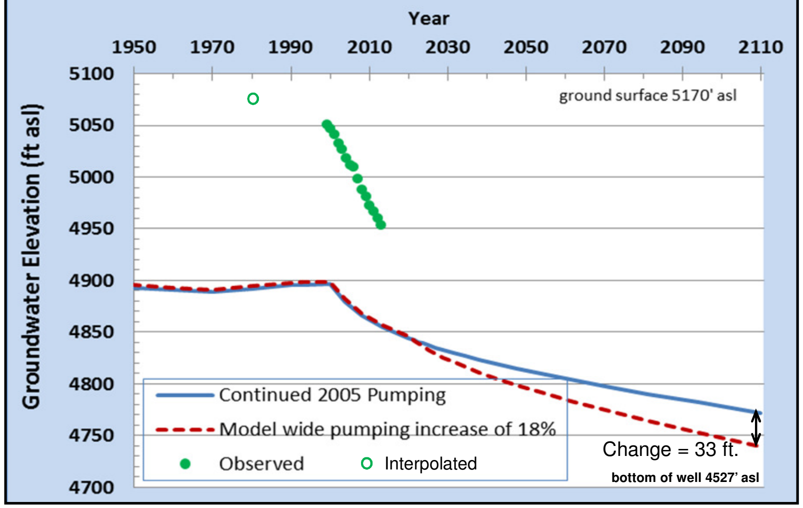


Figure 18. **Groundwater Elevation vs Time**
Well (B-15-02)30 ADC Granite Oaks



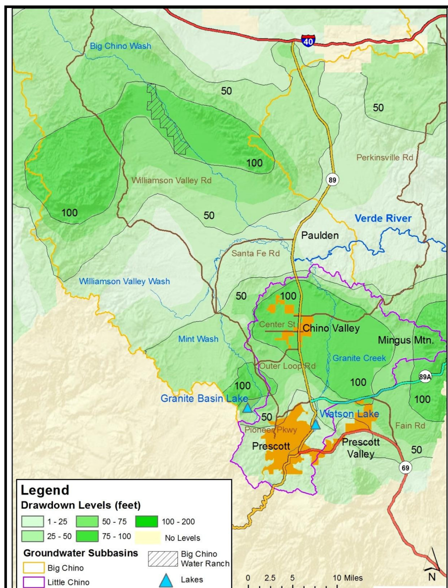


Figure 19.

Projected Cumulative Regional Decrease in Groundwater Elevation Between 2005 and 2110

Calculated combining all cases

Map prepared by W. Hood

Corrected 0415