A DISCUSSION PAPER ON THE ACCURACY AND APPLICABILITY OF THE NORTHERN ARIZONA GROUNDWATER FLOW MODEL – WITH SPECIFIC REFERENCE TO THE PAULDEN, CHINO VALLEY, PRESCOTT AND PRESCOTT VALLEY AREAS.

By Dr. Peter Kroopnick, RG[1]

Abstract

The work discussed in this paper was carried out to explore the accuracy and predictive capability, within the Big Chino sub-basin and Prescott Active Management Area, of the U.S. Geological Survey (USGS) Northern Arizona Regional Groundwater Flow Model (NARGFM). I imported the model and the data upon which it is based into a graphical interface known as Groundwater Vistas. Results from running the model using the data supplied by the USGS confirm that the results presented in the USGS report are accurate.

The NARGFM model simulates groundwater level changes in response to human stresses (pumping) and environmental influences (recharge, outflow and evapotranspiration) using a 10-year average value for these parameters. Within the Area Of Concern (AOC), groundwater elevations range from 4,250 to 5,300 feet above mean sea level (amsl). Excellent agreement was found for the differences between observed and simulated elevations within the AOC, with the mean for most individual wells differing by less than 20 feet (Figure 7). Simulated trends in both groundwater elevation and discharge to the Verde River are also accurate to within industry standard ranges. Further comparison between the NARGFM model and a recent update to the Prescott AMA Model (Figure 10) also shows excellent agreement. These results indicate that the NARGFM model is an excellent tool for examining long-term changes in groundwater levels and related stream flow in the Paulden, Chino Valley, Prescott and Prescott Valley areas.

INTRODUCTION

This paper reviews the assumptions and the results from the U.S. Geological Survey's recent report entitled "Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona" (Scientific Investigations Report 2010-5180). The emphasis of the review is on the Big Chino, Little Chino and Upper Agua Fria sub-basins. The actual numerical model

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(hereafter referred to as NARGFM) has been run to verify the results discussed in the above report, and to prepare independent graphics to clarify the discussion. Comparison with the Arizona Department of Water Resources Prescott Active Management Area (Pr-AMA) models is also included.

BACKGROUND

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

> *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 include the Coconino Plateau (Bills and others, 2007), the upper and middle Verde River watersheds (Blasch and others, 2006), and the Mogollon Highlands (Parker and others, 2005). 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.*
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> *The Northern Arizona Regional Groundwater-Flow Model (NARGFM, was developed to help assess the adequacy of the [Northern Arizona] regional groundwater supply and potential for the effects of increased groundwater use on water levels, stream flow, and riparian vegetation. Hydrologic information and understanding gained during initial RWI studies was used to develop the groundwater flow model. The model* is *[intended] to be used by resource managers to examine the hydrologic consequences of various groundwater development and climate change scenarios.*

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[2] D.R. Pool, Kyle W. Blasch, James B. Callegary, Stanley A. Leake, and Lesie F. Graser (2011). USGS "Scientific Investigations Report 2010-5180.

Description of Physiography and 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[3] and NARGFM report, 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 Upper Agua Fria 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 subsurface. Accurate estimates of aquifer properties, such as transmissivity, porosity, and specific capacity, are necessary for simulating ground-water flow through aquifers. Formation lithology and degree of fracturing largely determine the magnitude and direction of these properties. These properties have 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 (Wirt et. al. 2005, Blasch, et. al. 2006, Arizona Department of Water Resources (ADWR), U.S. Bureau of Reclamation (BOR), plus private consultants), and while additional data is always helpful, we know more about these aquifers than most others for which the USGS has developed regional models.

THE NARGFM MODEL

Based upon the geologic structure 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 publically 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. In preparation for running the model, the structural framework was established by the assignment of boundaries, including streams, springs and the lateral and vertical extents of aquifers. Then numerous data

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[3] Blasch et. al., 2006. Hydrogeology of the Upper and Middle Verde River Watersheds, Central Arizona, USGS Scientific Investigations Report 2005–5198.

sets were assembled including aquifer hydraulic conductivity, porosity, specific yield, location of extraction wells, and their historical pumping rates (see ADWR Prescott AMA reports, on-line data base from ADWR, and appendices 1 and 2 of the NARGFM report). Additionally, monitor well data was assembled to enable the model-simulated groundwater elevation levels to be compared with those observed.

An important objective for 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[4].

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[5]*. 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 data sets and rely strictly on the data sets assembled by the USGS. These data sets are available publicly and were obtained from the USGS Tucson office web site[6]. The pumping and monitor well data were spot-checked by comparison with the ADWR on-line data bases.

Spatial and Temporal Aspects

The NARGFM model simulates groundwater conditions from 1910 through 2005 over a 92,664 square-mile area. The simulation period was divided into nine multi-year

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[4] 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 southwestern United States: U.S. Geologi-cal Survey Professional Paper 1703, p. 29–59. Blasch, K.W., and Bryson, J.R., 2007, Distinguishing sources of ground water recharge by using δ_2H and δ_{18}O: Ground Water, v. 45, no. 3, p. 294–308.

[5] *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).*

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

periods of generally 10 years each since 1938. The final period encompasses 2000 to 2005. No seasonal or annual variations were simulated. In contrast, the ADWR Prescott AMA (Pr-AMA) 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.

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 Pr-AMA model has 48 rows, 44 columns and two layers. The Pr-AMA 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 text 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 Pr-AMA model represent only the top two layers of the NARGFM. Previous groundwater models, including the Pr-AMA 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 Pr-AMA 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 (e.g. areas where the rock material has been eroded away). Figures 3, 4 and 5 show the Area of Concern (AOC). The light blue boundary in Figure 3 defines the horizontal extent of the Big and Little Chino sub-basins on Layer 1. Layer 2 (Figure 4) is slightly larger in extent, while layer 3 (Figure 5) underlies the entire extent of these sub-basins. 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 Used For This Paper

The numerical simulations discussed in this paper were performed using the NARGFM model data sets and files downloaded from the USGS. 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 version 5.47 (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. 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.

SIMULATION RESULTS

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 8,433 measurements from 94 wells, in the entire model area, were included in the data sets supplied. For the AOC plus the Verde River Basin, 3,777 observations were included.

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 are 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 following letters 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 all of the 94 monitor wells included in the NARGFM model. 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 5,500 and 6,500 feet there are 583 outlier results with residual (observed – calculated) water level values of >300 feet. Close inspection indicates that most of these values are from wells located in the Little Colorado River Plateau basin. The outliers are from multiple wells that at some times respond appropriately but at other times display large errors. 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 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)[7]. An NRMSD of less than 5% is considered an excellent result. Values between 5 and 10% are generally considered acceptable.

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

The NARGFM results (excluding the outliers) have an NRMSD of 2% (average residual of 45 feet) indicating an excellent calibration has been achieved (Figure 6).

For only the AOC (Figure 7)[8], there are 34 well locations and the NRMSD is 5% or an average residual of 20 feet. The general agreement between observed and simulated groundwater elevation within the AOC (Figure 7) indicates that the model is satisfactorily calibrated for this area as well as for the entire region.

The time-dependency of the simulated and observed groundwater levels for the AOC is shown in Figures 8 and 9. It is not possible to display all 34 wells in this manner. The 10 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.

In general, Figure 8 shows that most of the simulated groundwater elevations track the observed elevations over the wide range of approximately 1,000 feet and across three sub-basins.

Examining Figure 8 in detail indicates that the highest groundwater elevation is seen for well Y-6 on the Yavapai-Prescott Indian Reservation. The simulated and observed values are identical, but the data collection record is short and displays only a small variation.

Well (B-14-02)14BAD is located just south of Willow Lake (Figure 5). The observed levels are consistently higher probably because recharge, from the lake to the aquifer, is not included in the model. Neither Granite Creek nor Watson and Willow Lakes are included in the model.

Well (B-15-02)17ABA is located west of the Town of Chino Valley (Figure 5) and shows good agreement for early times 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 west 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 more pronounced decrease with time. This well is directly west and upgradient of the beginning of the Verde River which will be discussed at the end of this section. Well (B-16-02)28BDD (Figure 4) in the Little Chino Sub-basin (red line and open squares) matches the observed decreasing trend and values during the 1945 to 1960 time frame and again at later time between 1980 and 2005. A slight over-

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[8] The screened interval of three of the wells spans two layers hence the total of 37 wells given previously.

calculation of about 10 feet is seen between 1960 and 1980. A total decrease of 64 feet is seen in the simulated result.

Wells with groundwater elevations between 4,250 and 4,800 feet amsl are shown on an expanded scale in Figure 9. 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-16-02)28BDD (discussed with respect to Figure 8) has been replaced with well (B-16-01)14CCC in Figure 9 and located in Figure 5. This latter well is located east of Granite Creek 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 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.

Finally a well from the Upper Agua Fria sub-basin (B-14-01)15ABA located in Prescott Valley (Figure 5) is shown in Figure 8 (but not Figure 9). This is an indicator well co-located with a water supply well. There are also several other water supply wells in the vicinity. For this case, the observed values show a significant decline between 1970 and present. The simulated values also decline, but not as rapidly as the observations. This reason for this lack of response is not known, but may be due to excessive drawdown in the pumping well during rapid cycling of the pump versus the long pumping periods employed in the model. Nevertheless, the data agree favorably between 1970 and 1995 and follow a decreasing trend.

For this review I did not model the simulated flux to the Del Rio Springs or the Verde River, both of which were discussed in the USGS report. In the case of Del Rio Springs (reproduced in Figure 10A), excellent agreement was found for the later times of 1995 to present. The simulated flow in the 1940s seems excessive, but no data exist between 1945 and 1990. Del Rio Springs will be discussed more in the next section of this paper.

For the Verde River near Paulden (Figure 11A), no data are available before 1960. After 1960, the simulated results represent excellent agreement considering the 10-year averaging process. Flow in the Verde River is discussed in more detail in the next section of this paper.

THE Pr-AMA Model AND FLOW AT DEL RIO SPRINGS AND THE VERDE RIVER

In 1995 ADWR developed the first Pr-AMA Groundwater Flow Model encompassing the Little Chino and Upper Agua Fria sub-basins (Corkhill and Mason, 1995). This was a 2-layer model which consisted of a heterogeneous upper alluvial unit (UAU), and a less transmissive lower volcanic unit (LVU). The first model update (Nelson, 2002) added a confined LVU aquifer zone in the northern UAF sub-basin and modified natural recharge to include episodic recharge along Lynx Creek and the Agua Fria River. In 2006 the model was further updated to include additional hydrogeologic data from exploratory test wells, and was extended to include portions of Williamson Valley and Mint Wash (Timmons and Springer, 2006). A provisional 2011 update is now available, in which non-linear regression was used to calibrate horizontal and vertical hydraulic conductivity, long-term steady state recharge, and steady underflow from the Little Chino and Upper Agua Fria sub-basins (Nelson, 2011)[9].

This latest calibration is purported to improve the accuracy of the model but the results are only available for a few wells. Nelson shows results for several wells along Granite Creek but none of them were depicted in the USGS report. Examination of the USGS simulation for well (B-16-01)20CBC shows that the observed groundwater elevation averages approximately 171 feet higher than the simulated, while the revised ADWR simulated results now agree almost exactly with those observed. This difference is not unexpected, since the NARGFM model does not include Granite Creek as an active stream. It is recommended that the new ADWR calibrated parameters for this area should be incorporated into the NARGFM model in the next revision.

ADWR also showed new results for the discharge at Del Rio Springs, reproduced here in Figure 10B along with the NARGFM results (Figure 10A). The long term trend in graphs A and B 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. The ADWR results show more variation with time because the model uses two pumping cycles per year while the USGS model uses a 10-year pumping cycle (5 years between 2000 and 2005). Comparison of these two graphs shows clearly that the long term trends can be studied using the NARGFM model.

The flow in the Verde River near Paulden as simulated by the NARGFM is shown in Figure 11A. The Pr-AMA model does not include the Verde River so no comparison

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[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 is equivalent to 1.38 cubic feet per second.

between models can be made. It was discussed above, that the overall trend at the Paulden Gauge compares well with the simulated flow of approximately 17,500 acre-feet/year or about 24 cfs (Figure 11A). It is widely believed 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. While the 10-year averaging process for the NARGFM precludes simulation of the short term observed variations, Figure 11B 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 Gauge (USGS 09503700, location shown in Figure 5). The base flow tracks the change in groundwater 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 flow lag the pressure changes by between 1 and 3 years.

Sensitivity

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 Figure 6 (NRMSD of 2%) indicates an excellent calibration was obtained. It is possible that this result is not unique and that is some other combination of parameters could produce the same result. This would be highly unlikely given the wide range of observations (3,000 to 6,500 feet of groundwater elevation) and the many basins included. A separate sensitivity analysis could be performed for the AOC by either using a nested model or through the use of other modeling tools such as the USGS UCODE program or PEST as was used by the ADWR. Such an analysis is beyond the scope of this review.

Another source of potential error could arise due to numerical deficiencies in the mathematical technique used by the model to solve the various equations. There are many methods for solving the simultaneous equations resulting from the finite-difference method. The USGS results were obtained using the well known PCG2 solver (Hill, 1990). Solver sensitivity was tested by using the GMG solver (Wilson and Naff, 2004), and by changing the convergence criteria when using the PCG2 solver. No appreciable changes in the model results were obtained during these model runs, indicating that the model is mathematically stable.

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[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 are likely related to changes in climate and (or) ground-water withdrawal".*

CONCLUSIONS

The work discussed in this paper was carried out to explore the accuracy and predictive capability of the U.S. Geological Survey model “Regional Groundwater-Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona” (Scientific Investigations Report 2010-5180). I imported the model and the data upon which it is based into a graphical interface known as Groundwater Vistas. 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.

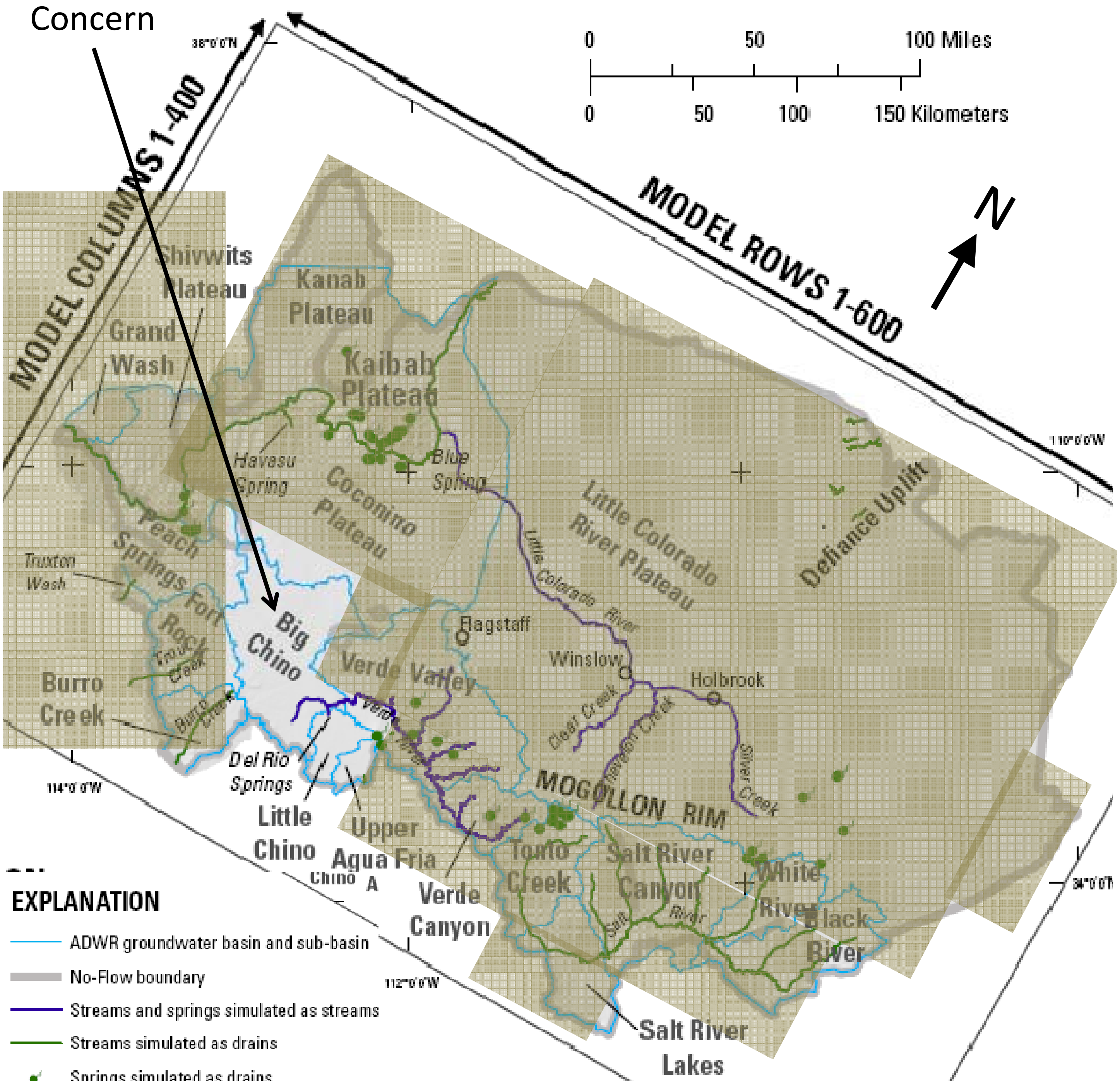
Additional graphics and statistical analyses have been prepared for this paper and are discussed herein with particular reference to the administrative Areas Of Concern (AOC) known as the Big Chino sub-basin, Paulden, Chino Valley, Prescott and Prescott Valley (see Figure 1 and Figure 7). Within the AOC, simulated groundwater elevations and those observed between 1939 and 2005 (Figs. 8 and 9) show excellent agreement. The wells shown in this paper were selected to represent each of the sub-basins over the time span of the model. The agreement across such a wide area where groundwater elevation changes by over 1,000 feet indicates that the model is well calibrated.

The sensitivity of the model to potential numerical errors in the solving of the mathematical equations was examined by running the model with different solution techniques, parameters and initial conditions. No appreciable changes in the model results were obtained during these model runs indicating that the model is mathematically stable.

The NARGFM model simulates groundwater level changes in response to human stresses (pumping) and environmental influences (recharge, outflow and evapotranspiration) using a 10-year average value for these parameters. Within this 10-year cycle, simulated trends in both groundwater elevation at the observation wells (Figures 8 and 9) and discharge to the Verde River (Figure 11) are accurate within industry standard ranges. Further comparison between the NARGFM model and a recent update to the Prescott AMA Model (Figure 10) also shows excellent agreement. These results indicate that the NARGFM model is an excellent tool for examining long-term changes in groundwater levels and related stream flow in the Paulden, Chino Valley, Prescott and Prescott Valley areas.

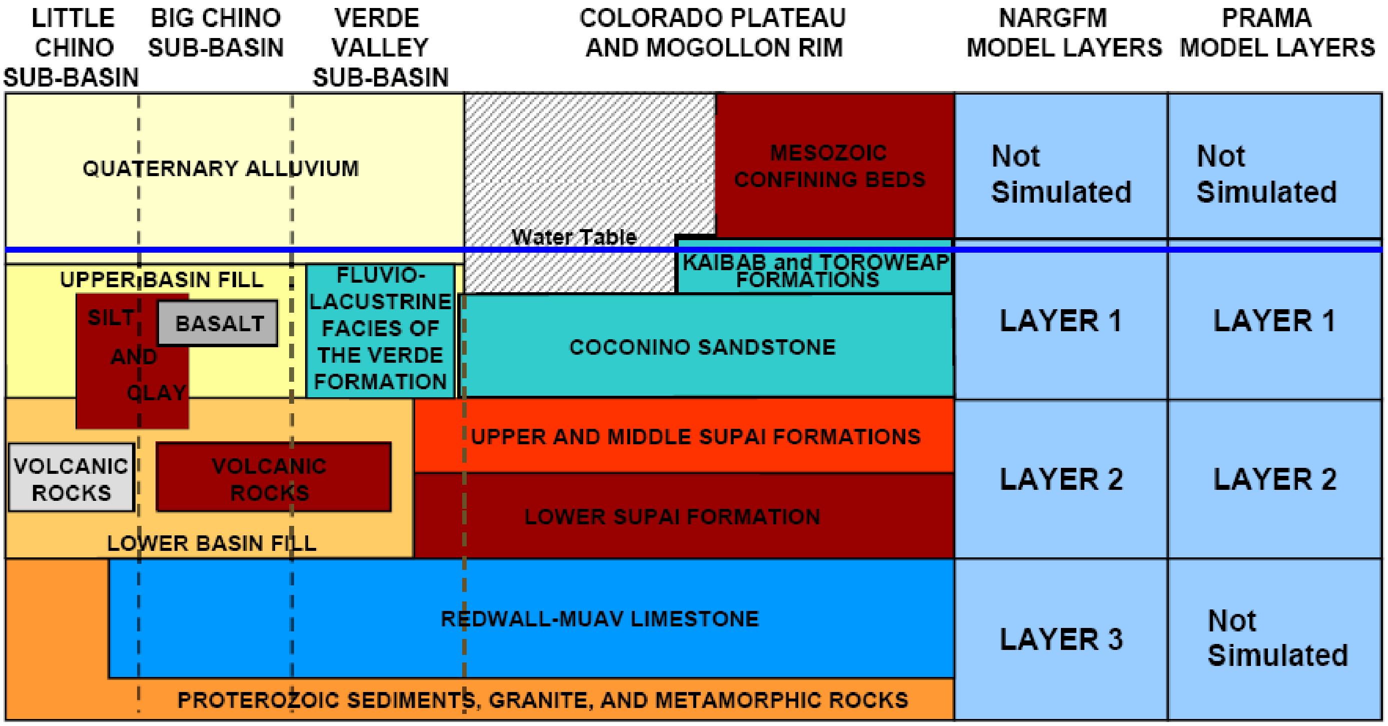
Figure 1.
Domain of the NARGFM Model and Area of Concern

Area Of
Concern



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

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



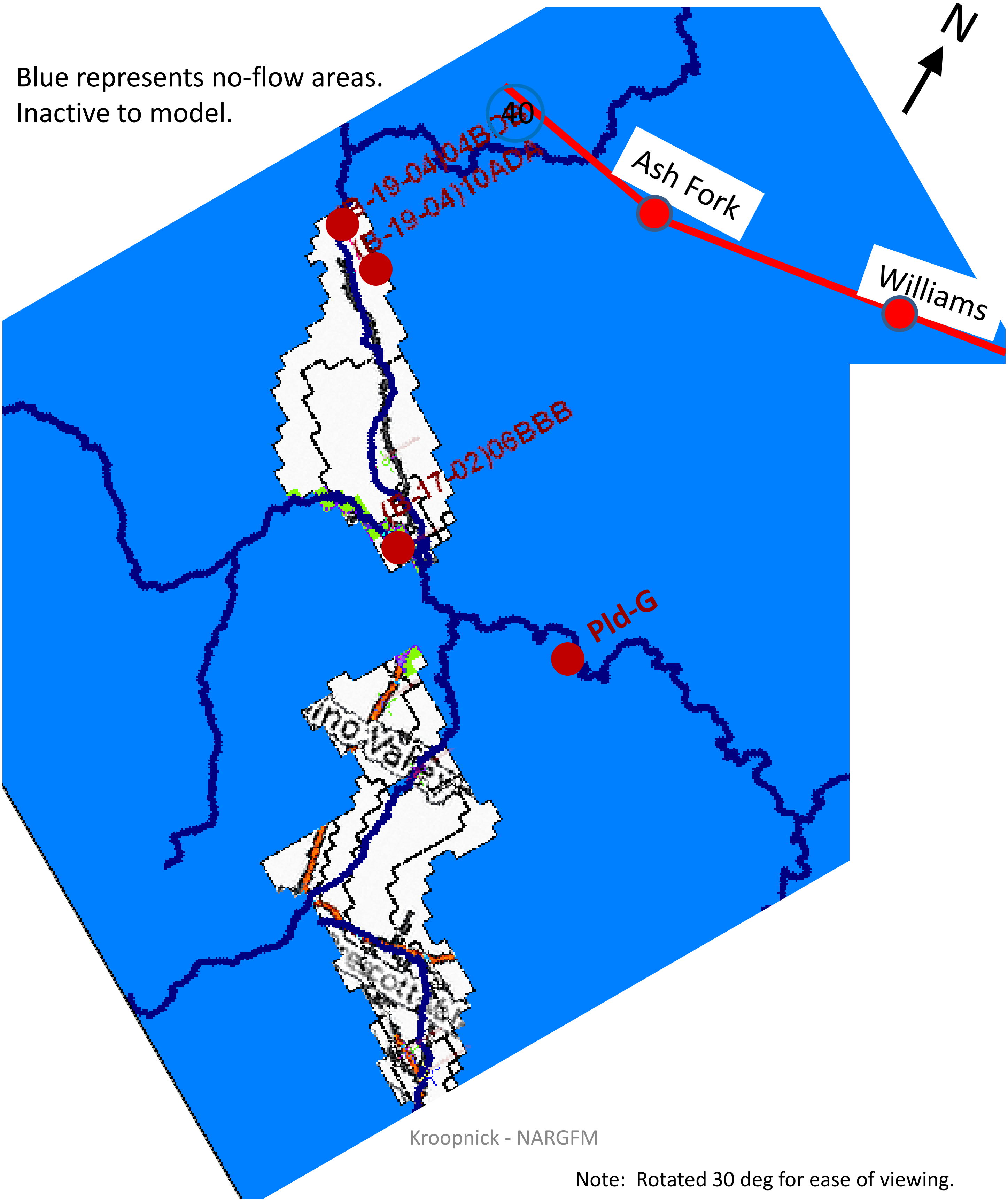
Confining beds indicated by red-brown shading

Figure 12. Conceptualized relations among major hydrogeologic units and Northern Arizona Regional Groundwater-Flow Model layers.

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

Figure 3.
Location of Wells Selected for Graphing – Layer 1

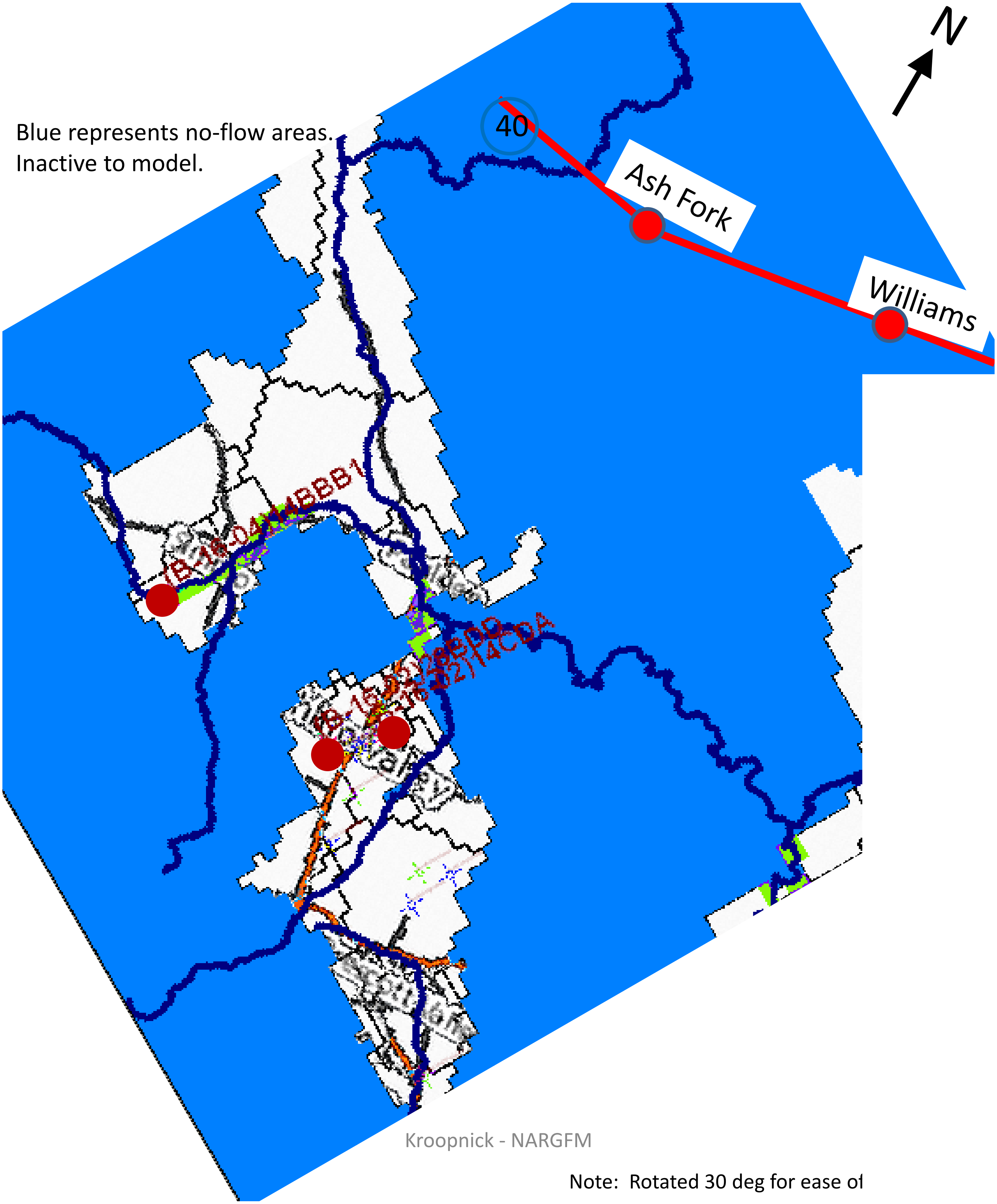
Blue represents no-flow areas.
Inactive to model.



Kroopnick - NARGFM

Note: Rotated 30 deg for ease of viewing.

Figure 4.
Location of Wells Selected for Graphing – Layer 2

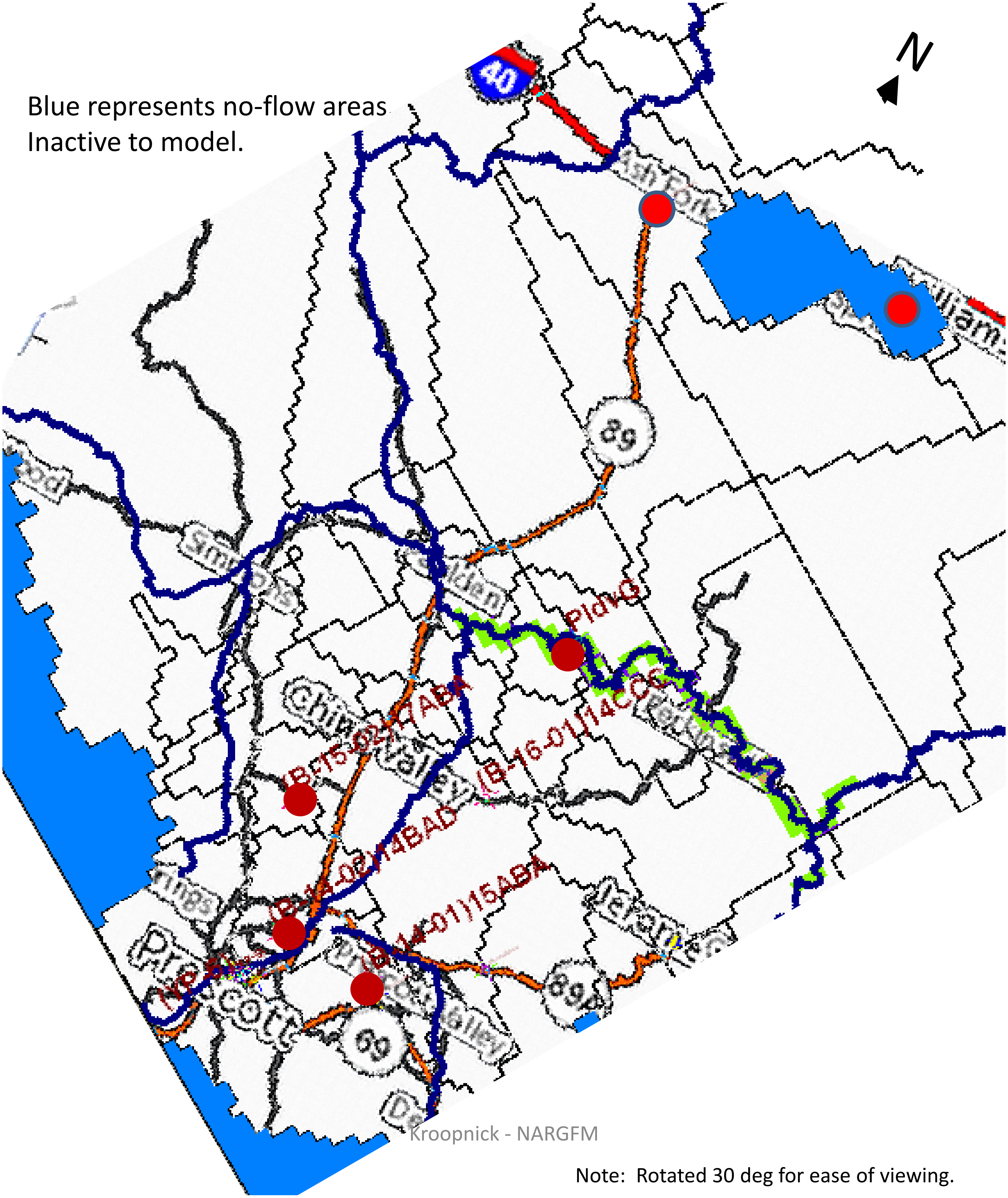


Blue represents no-flow areas.
Inactive to model.

Note: Rotated 30 deg for ease of

Figure 5.
Location of Wells Selected for Graphing – Layer 3

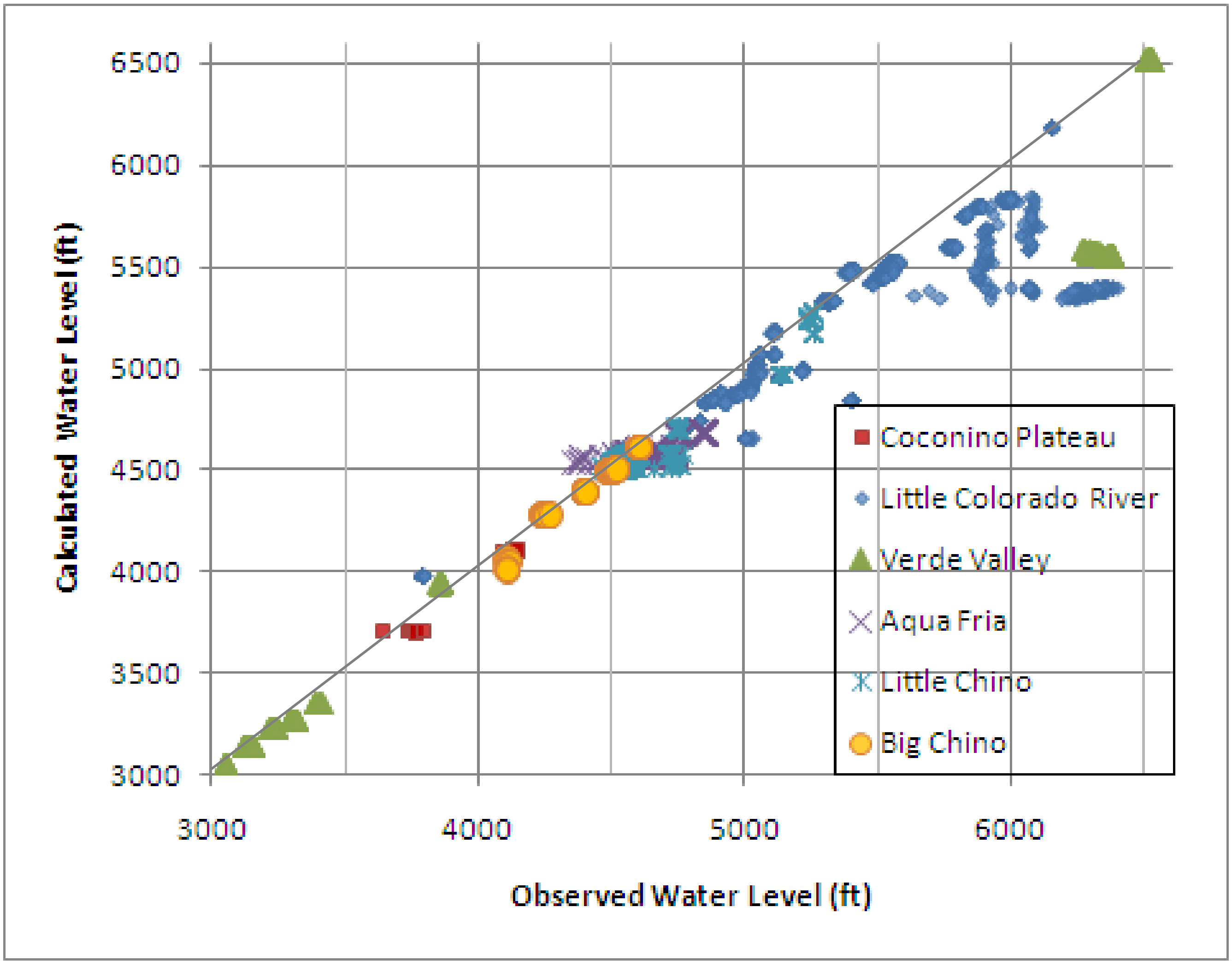
Blue represents no-flow areas.
Inactive to model.



Note: Rotated 30 deg for ease of viewing.

Figure 6.

Comparison of observed and calculated groundwater elevation for all observation wells in the NARGFM USGS model

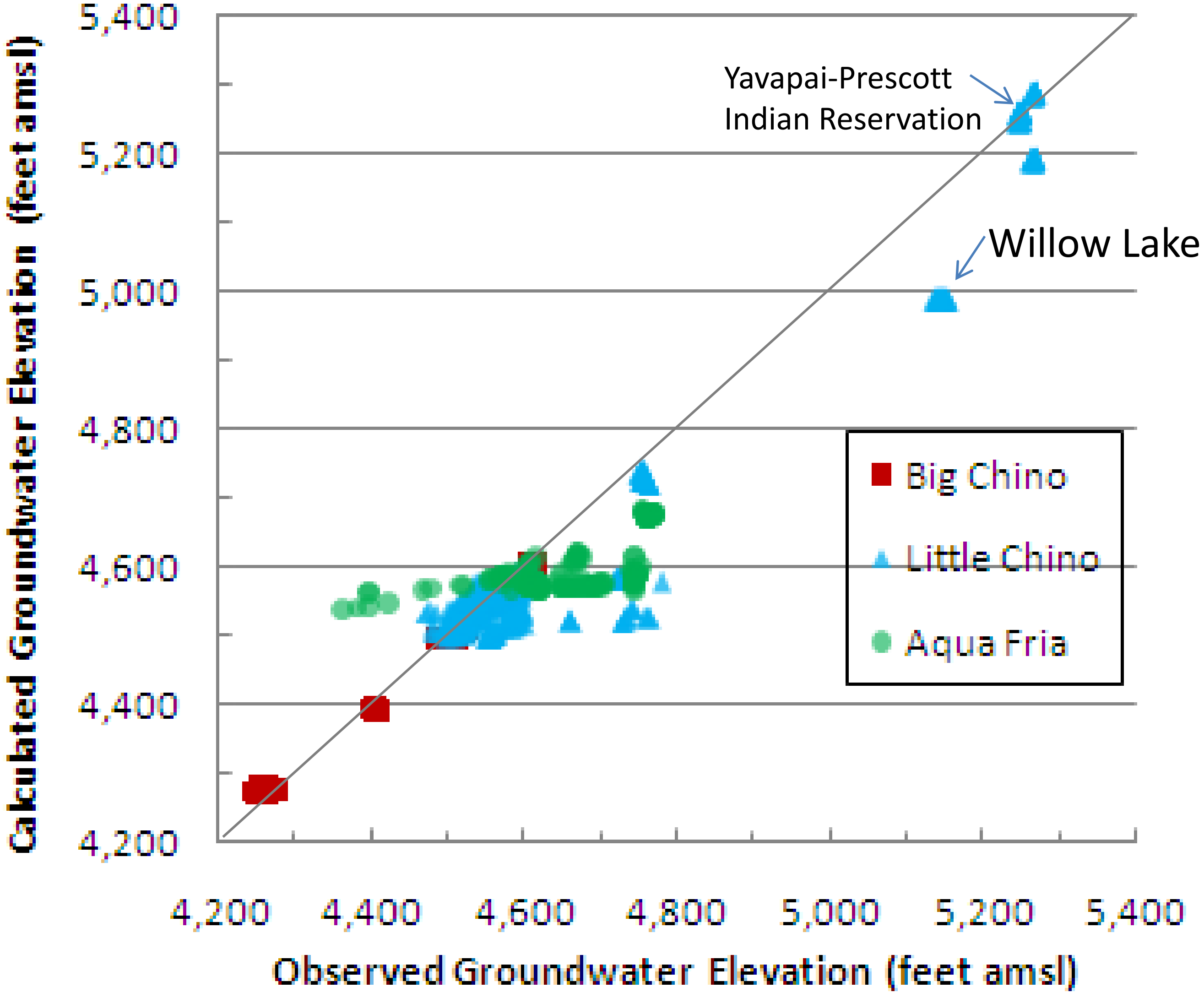


Summary of statistics
For Residuals
(obs. – calc., feet amsl)

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

Residual Statistics (feet)	
Average residual	44.5
Absolute average	57.0
Standard Deviation	66.7
Number of Obs.	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.
Comparison of observed and calculated Groundwater elevation for selected observation wells in the Area of Concern

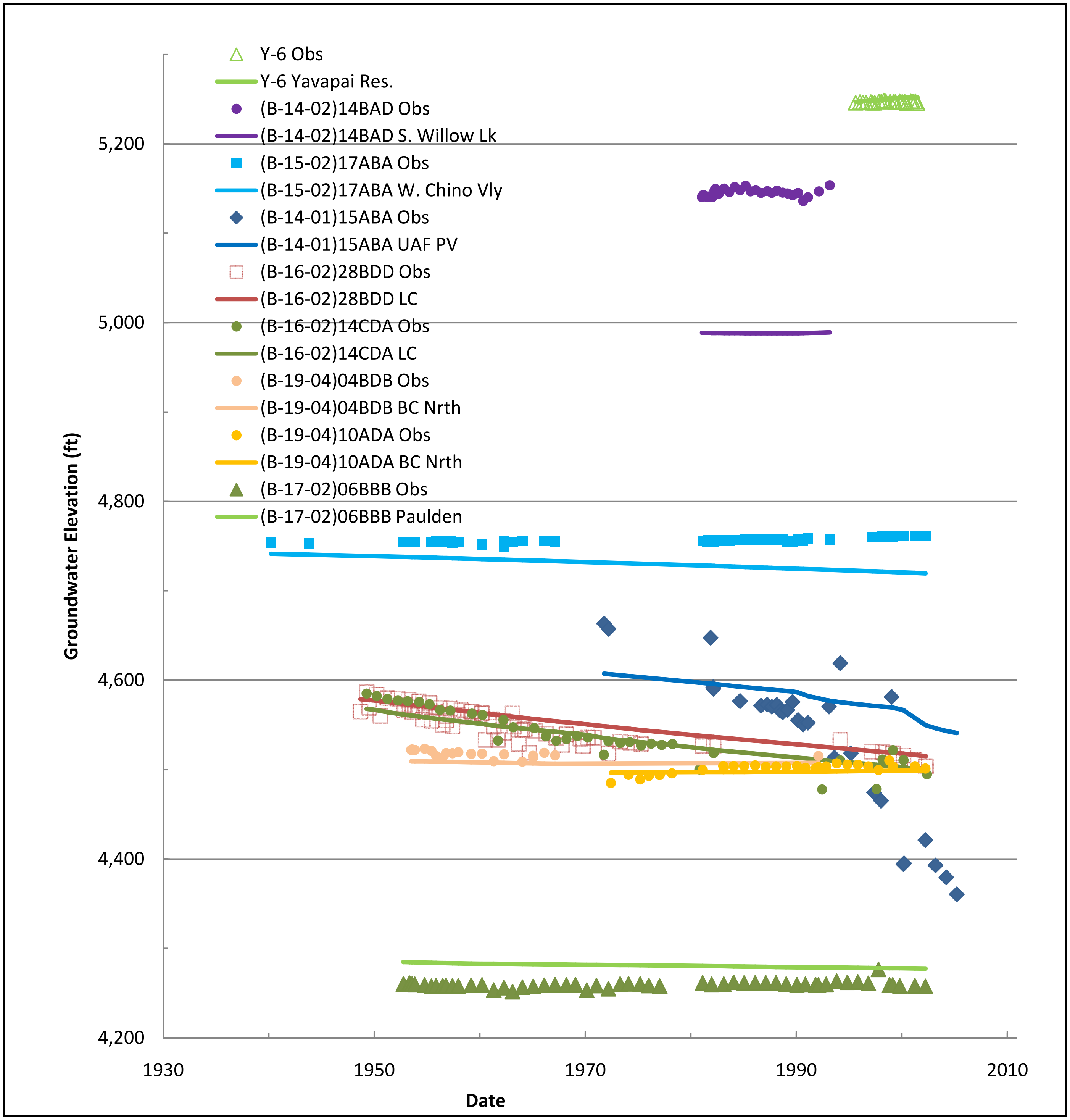


Summary of statistics for residuals (obs. – calc., feet amsl)

Residual Statistics (feet)	
Residual Mean	20.0
Root Mean Square Deviation	31.2
Res. Std. Dev.	46.9
Number of Observations	1568
Range of Observations	1024
Scaled RMS Deviation	5%

Figure 8.

Hydrographs for Wells in the Area of Concern



Note:
Symbols represent the observed values.
Lines represent the model calculated values

Figure 9.
Details of Wells in Big Chino and Little Chino Aria

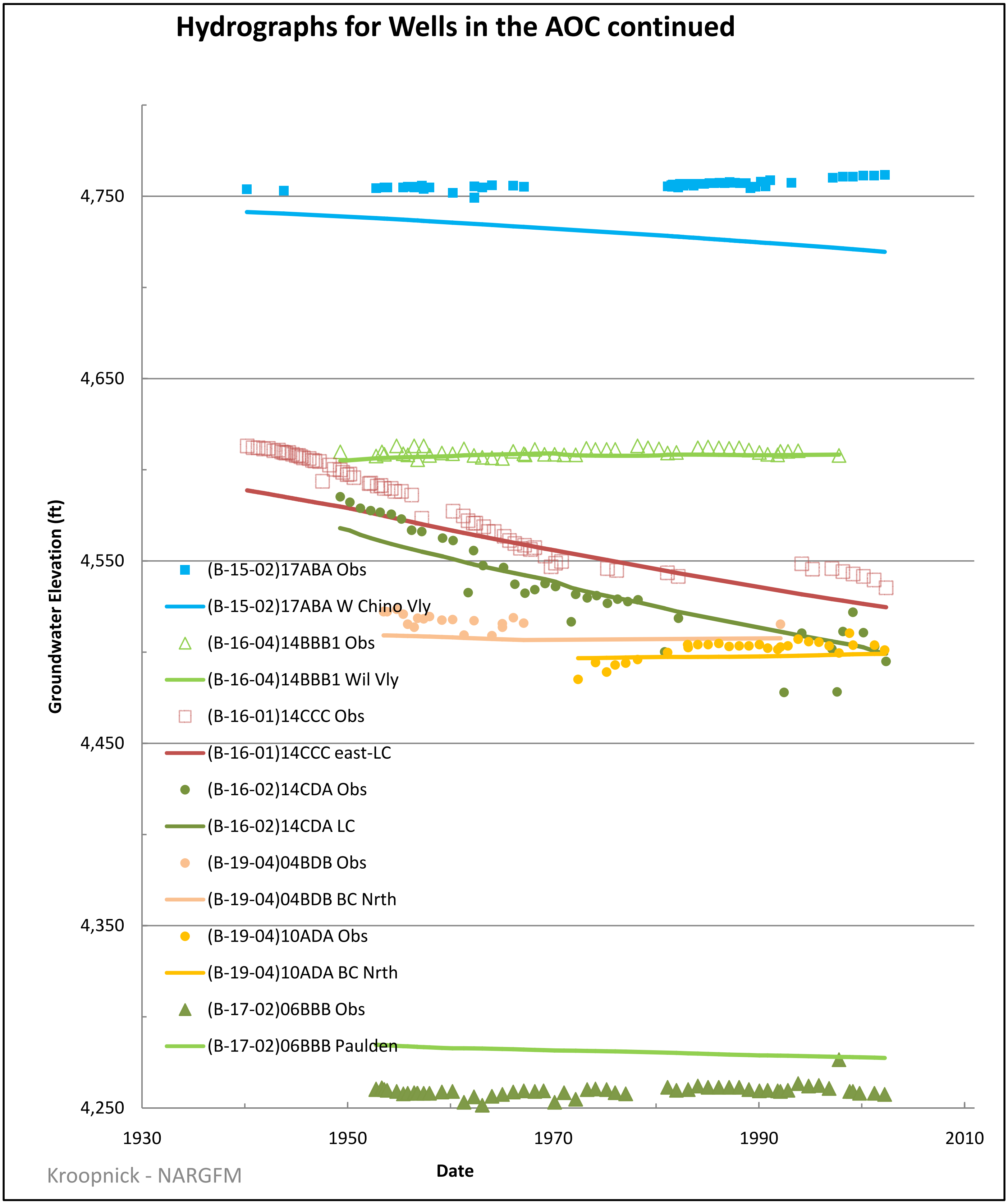


Figure 10.
Simulated and estimated base flow discharge at Del Rio Springs as modeled by the USGS and ADWR.

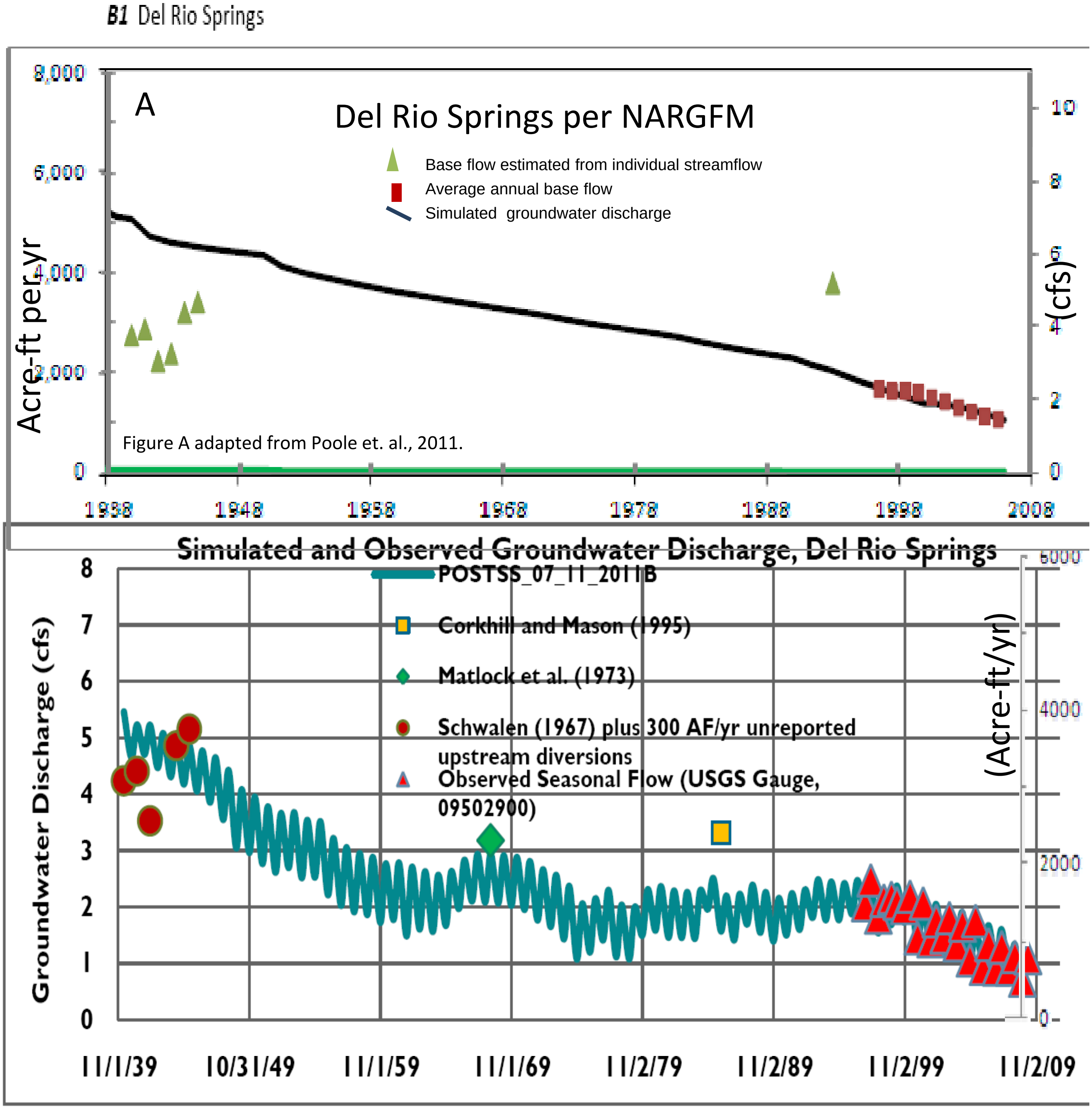


Figure B adapted from Nelson, 2011.

Figure 11.
Simulated and observed base flow at the Verde River
and at Well (B-17-02)06BBB near Paulden.

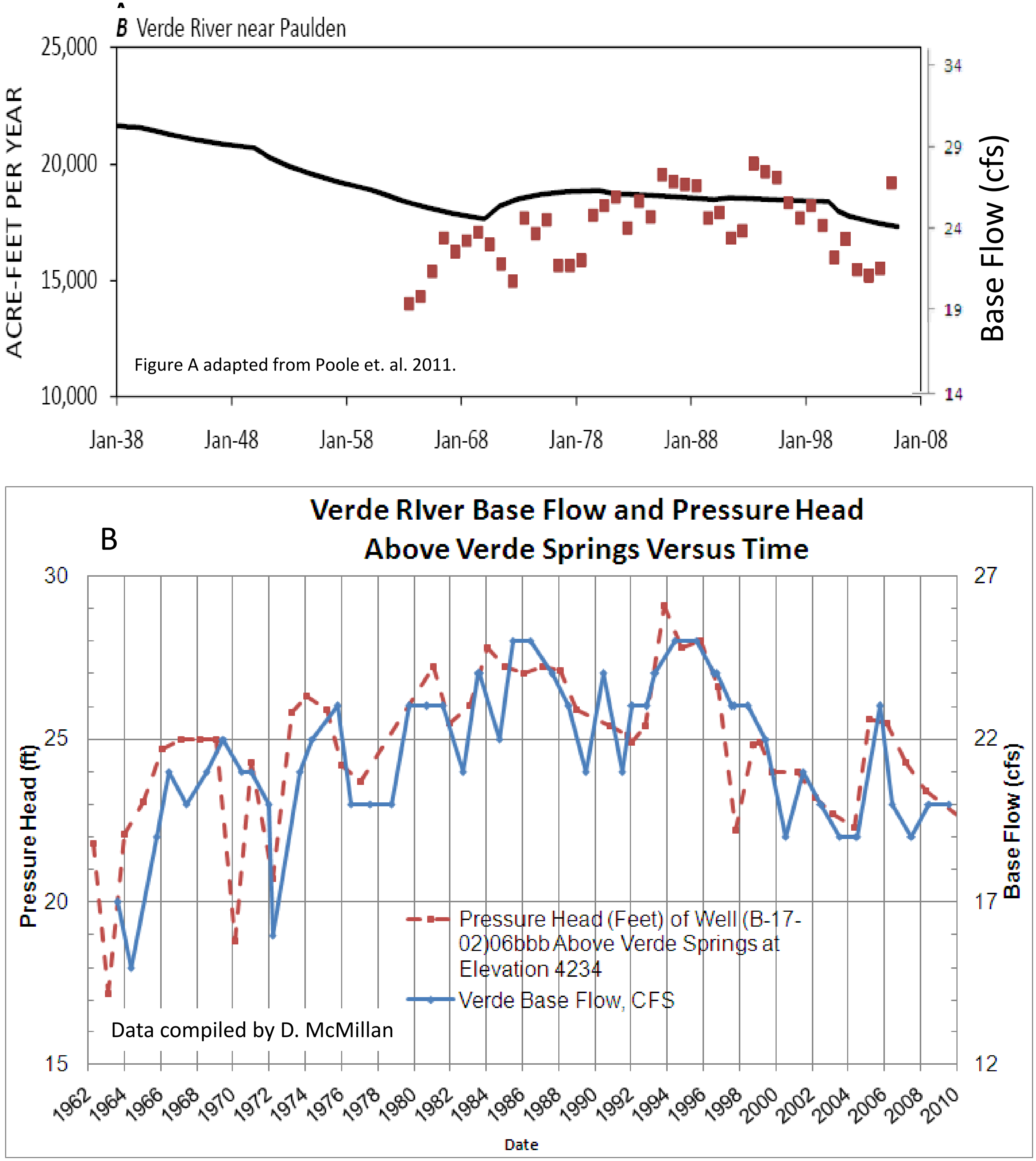


Figure A adapted from Poole et. al. 2011.

Verde RIver Base Flow and Pressure Head Above Verde Springs Versus Time

Data compiled by D. McMillan