Proposal to Test Conceptual Models using Numerical Models and to Develop an Improved Hydrogeologic Framework and Numerical Model of the Big Chino Sub-basin, Central Arizona

Formatted: Font color: Auto

A proposal from the USGS Arizona Water Science Center
July 7, 2010

Introduction

One of the main purposes of building a numerical groundwater flow model is to allow prediction of future water levels and changes in groundwater discharge based on assumptions regarding imposed stresses (changes in pumping and recharge). Another important use is to test an investigator's conceptual model of the hydrogeologic system in terms of how well it fits the observed data (Hill and Tiedeman 2007). In complex hydrogeologic systems, such as in the Big Chino sub-basin, there is often more than one plausible conceptual model. According to Hill and Tiedeman, the fact that there are "different interpretations of the incomplete data about (*hydrogeologic*) systems…. alternative models are fundamental to the study of any natural system."

The initial objective of the proposed project is to incorporate various conceptual models of the Big Chino sub-basin into numerical models and identify the conceptual flow-system model that provides the best fit with field data. This process of distinguishing the most reasonable among alternative conceptual models will help guide additional data collection that can be used to build an improved numerical model. The final objective is to use the model to make future predictions of changes in both water levels and groundwater discharge.

Formatted: Font color: Auto

Background

Concern exists regarding how past, present, and future groundwater withdrawals from the Big Chino sub-basin will affect groundwater levels in the study area as well as the future discharge at the headwaters of the Verde River, specifically at the Upper Verde Springs (UVS), which is believed to be a major discharge zone of groundwater from the sub-basin. The relation of reduced base flow to increased withdrawals is largely a function of connections between hydrogeologic (aquifer) units, aquifer storage properties and transmissivity, and proximity of withdrawal locations to discharge areas. The theoretical ultimate impact on base flow will be a reduction equivalent to the increase in groundwater withdrawal rate minus any reduction in evapotranspiration and any increase in inflow. Depending on the pumping location in the sub-basin, the period of time to reach this new equilibrium condition could be on the order of years to several decades to centuries.

A variety of hydrogeologic assessments have been conducted and published for the area; much of that work has been synthesized in the Northern Arizona Regional Groundwater-Flow Model (NARGFM; Pool, in review). This model, although regional in scope, is a useful starting point to develop more detailed tools to address concerns about the effect of groundwater withdrawals in the Big Chino sub-basin on base flow in the Verde River.

Construction of the NARGFM provided the modelers with significant insights regarding plausible conceptual models of the Big Chino sub-basin as well as the types and locations of additional data that are needed to effectively test those models. A main benefit of use of this model is that its regional nature allows the study of the effects of development in the sub-basin without imposition of artificial boundaries in a less extensive model that would degrade model accuracy.

Water users and managers who rely on the Verde River system for water supplies have an intrinsic interest in developing the best possible tools for assessing the effects of groundwater withdrawals. A group of these managers and their technical staff (hence termed the "Cooperators") have requested this proposal from the USGS to develop a numerical groundwater-flow model to aid in the understanding and effective management of water resources in the Big Chino sub-basin.

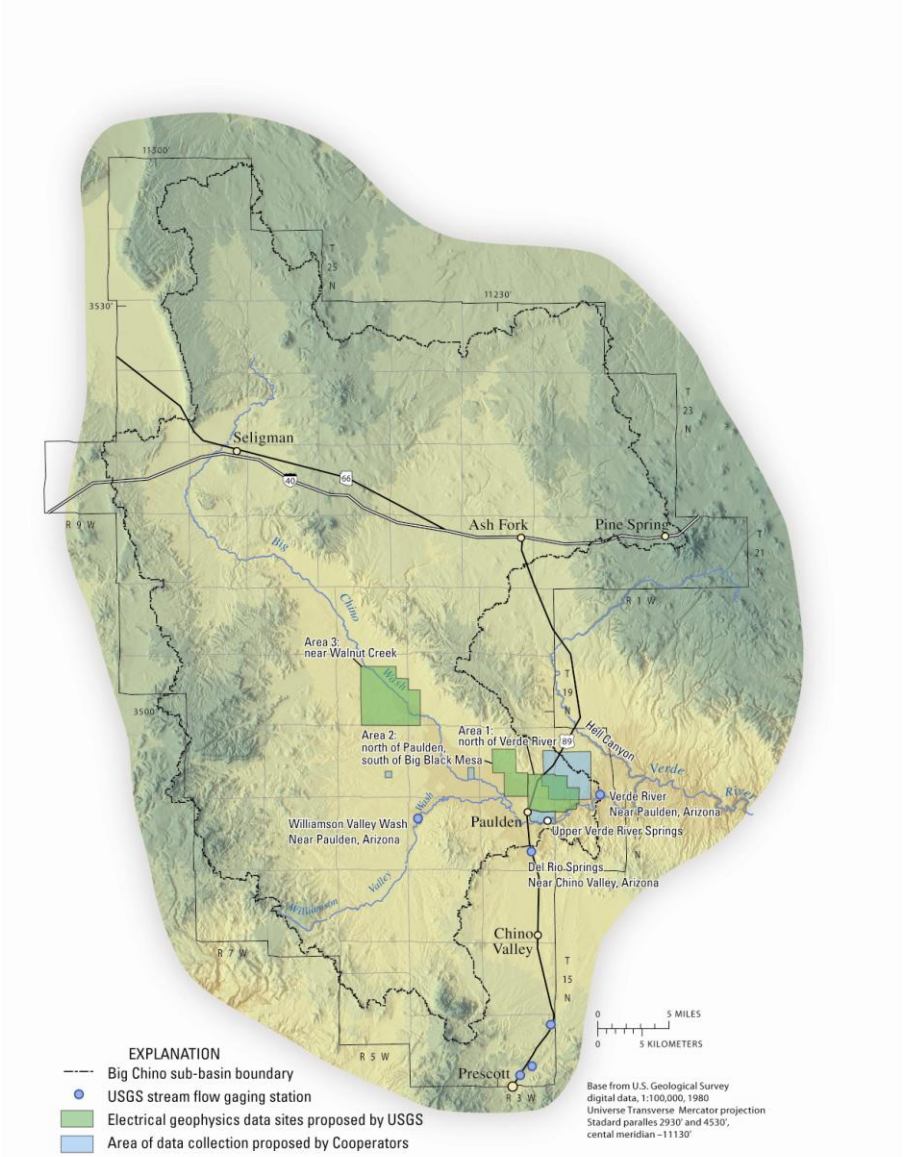

Figure 1. Approximate location of study area.

Formatted: Font color: Auto

Objectives

The overall objective of this proposal is to develop a multilayered numerical groundwater flow model of the Big Chino sub-basin and surrounding area that can inform resource managers about potential effects of groundwater pumping on the potentiometric surface, evapotranspiration, stream base flow, and spring discharge. The Cooperators and USGS believe that there are several alternative conceptual hydrogeologic models describing the groundwater system through which water flows from recharge areas to points of discharge from the Big Chino sub-basin and to the UVS. They also believe that these conceptual models could result in different distributions of water-level change and different amounts of base-flow reduction and within different time frames. Specific objectives for the project are to:

1. Test the validity of alternative conceptual flow-system models using iterative recalibration of a specified region in the Northern Arizona Regional Groundwater Flow Model.
2. Define and collect the hydrogeologic data needed to discern between ambiguous conceptual models tested during the first objective.
3. Conduct a model-based analysis of stream- and spring-discharge depletion that may result from groundwater pumping at identified locations and specified amounts in the Big Chino sub-basin and from changes in climatic conditions.
4. Determine the proportional impacts to groundwater levels and discharge to surface water sources caused by various sources of pumping in the Big Chino sub-basin.
5. Use the model to select three or more locations for monitor wells that could be used, in conjunction with the model, as alert or action indicators for alternative management of groundwater resources in the sub-basin.

Approach

The first step in this effort will be to test a series of plausible conceptual groundwater flow-system models using the existing NARGFM. The process will evaluate the plausibility of the Cooperator and USGS conceptual models and define the additional data needed to help confirm or disprove those models. The second step will identify the data needs for refining our understanding of hydrogeologic framework and aquifer properties for development of more detailed models. Where those data are collected and what types are collected will be informed by the process of testing plausible conceptual models and by existing knowledge of data gaps. The third step will be to collect and interpret the data identified as needed in step two. The fourth step will include incorporation of new information into a refined hydrogeologic framework that will be used to construct an improved numerical model of the Big Chino sub-basin.

This proposal assumes that an essential component of new data collection (the drilling of new wells, performing of aquifer tests, and collection of water-level and water quality data) will be funded and completed as part of the Cooperators' Big Chino sub-basin Data Collection and Monitoring Plan.

The USGS will cooperate and communicate closely with the Cooperators throughout the project from the data definition task through the final analysis and presentation. This communication will be essential for informing the Cooperators of project progress and, as

Comment [S1]: There is concern over what the alert should be. Should it be water levels or the model itself? What is the action that the alert will trigger? Should this be included in this report or discussed somewhere else?

Comment [JML2]: Our rationale in including both the model and water levels as alert indicators is that the water levels alone will not provide information regarding the ramifications of continuing to pump at, or beyond, the alert levels. They can, however, be used to improve the model and thus improve the ability of the model to predict implications. In addition, the alert wells alone cannot address residual effects that occur after an action to reduced or cease pumping is taken in response to the alert.

The action the result should trigger cannot be recommended by the USGS as per policy. It will be necessary to include that discussion in another document, perhaps a Cooperator management action plan.

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font: 12 pt

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

importantly, for incorporating new data collected by the Cooperators, as well as, hearing and incorporating Cooperator needs with regard to project process and analysis of results.

Task 1. Test conceptual groundwater-flow models

USGS proposes to initiate this project with an evaluation of plausible conceptual groundwater flows models rather than with a more traditional literature review and data collection effort. Much of what is currently known about system is already documented in recent and upcoming reports, and NARGFM provides an appropriate platform for quantitative tests of the various conceptual models. An advantage to this approach is that the existing model can be used to guide planning for data collection that can be specifically designed to help confirm or eliminate conceptual models where the model analysis resulted in ambiguous results.

By examining the currently available geologic, hydraulic, and geochemical data, the Cooperators have proposed specific conceptual models that will be the initial focus of the task 1 analysis. In addition, the existing NARGFM conceptual model will be included for evaluation. This analysis will include at least the following conceptual models:

1. Most recharge occurs in the uplands around the Big Chino sub-basin and flows primarily through Paleozoic carbonate aquifer across bounding faults into the basin. There, most of the groundwater flows through the basin in the Tertiary basin fill sediments and volcanic rocks. The rest of this groundwater continues to flow through the basin in the underlying Paleozoic carbonate aquifer. In addition, recharge occurs along stream channels during periodic flood events. Some of the groundwater flowing in the basin fill is consumed by evapotranspiration (native, non-native and agricultural plants). In the general vicinity of Paulden, as a consequence of a structural high that is likely fault controlled, groundwater flows from the basin fill into volcanic rocks and into the Paleozoic carbonate aquifer where it mixes with the groundwater that has flowed only through the Paleozoic carbonate aquifer. The combined flow discharges at the UVS. The flow path through the Paleozoic carbonate rocks, at least in the vicinity of Paulden, is likely controlled by fractures, faults, and fissures (such as the regional Big Chino Fault system).
2. Most recharge occurs in the western part of the sub-basin as direct infiltration to carbonate outcrops, or as mountain-front recharge. Most of this isotopically light recharge travels through the confined Paleozoic carbonate aquifer to the UVS, where it may comprise up to 70 percent of the UVS discharge. This percentage estimate is based on the isotopic and chemical similarity of the Paleozoic carbonate aquifer groundwater and that in UVS.
3. Some upper Verde River baseflow is supported by groundwater derived from recharge to Paleozoic carbonate aquifer in the Big Black Mesa and Hell Canyon watersheds on the north side of the Verde River. Movement of this groundwater is controlled largely by faults, fractures and fissures (such as the regional Mesa Butte Fault system and other local faults) in the Paleozoic carbonate aquifer. Where the faults, fractures and fissures have been enlarged by dissolution of the carbonates, springs such as the UVS, discharge groundwater directly to the Verde River both

Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto

upstream and downstream of the Paulden streamflow gage. At and upstream from the UVS, groundwater from the Paleozoic carbonate aquifer mixes with groundwater from the Big Chino sub-basin. The percent of groundwater from each source is unknown but the model should be capable of simulating at least a 50/50 mix.

4. The existing conceptual model underlying NARGFM, with the modification that a portion of the runoff from the Basin Characterization Model (BCM) is routed into an expanded streamflow network within the Big Chino sub-basin and in select surrounding areas. As such, the runoff component would be allowed to infiltrate as focused recharge, with decadal variations. This conceptual model is similar to conceptual model 1, except that flow conduits and barriers associated with fault systems are not explicitly simulated. NARGFM includes three model layers. In the study area, the uppermost layer (layer 1) represents saturated parts of upper basin fill in the Big Chino sub-basin and in adjacent areas. This layer also includes the silt and clay layer and basalt flows in the Paulden area. The middle layer (layer 2) represents sand and gravel of deposits of lower basin fill, and the lowermost layer (layer 3) represents carbonate and crystalline rocks. Discharge of groundwater at and near Upper Verde River Springs is controlled by structure and low transmissivity, resulting from lack of alluvium and discontinuous carbonate rocks. In the steady-state model, simulated groundwater discharge above the Paulden gage is 21,700 acre-ft/year.

The NARGFM will serve as the basis for distinguishing between proposed conceptual models. Rather than modifying the entire model, however, a study area pertaining to the Big Chino sub-basin and select adjacent areas will be defined (figure 1), and the rest of the model domain will provide the regional context for the study area. Within the study area, the model will be modified to represent each of the proposed conceptual models. USGS will attempt to calibrate each model by using the available water-level and streamflow datasets with the assistance of parameter estimation software such UCODE or PEST. Parameter estimation will be limited to parameter distributions in the study area, using head and flow observations from the study area. A possible tool for evaluation of alternative conceptual models is the Multiple Model Analysis (MMA) program (Poeter and Hill, 2007). MMA can evaluate results from a wide range of alternative models, provided that the observations, the observation weighting, and system being represented are the same. The goal of this analysis will be to rank the models using statistical measures provided in the MMA program, possibly eliminating some of the less plausible conceptual models on the basis of that ranking. Predictive runs can be made with one or more of the higher-ranking conceptual models, and future data collection will allow re-evaluation and re-ranking of conceptual models.

Owing to the fact that one of the ultimate concerns is how groundwater development in the Big Chino sub-basin at the Big Chino Water Ranch (BCWR) affects downgradient springs and surface water resources, an analyses of select pumping locations will be performed on each of the most plausible conceptual/numerical models to illustrate to the Cooperators the differences in model results, if any, from selecting one conceptual model vs. another. Pumping locations and time frames for analysis of effects will be selected in

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font: 12 pt

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

consultation with the Cooperators. Outputs will include, but not be limited to, model assumptions, water budgets, drawdown maps and changes in stream base flow.

A critical component of all project tasks will include a close working relation between the Cooperators and USGS. As details regarding conceptual models are formulated and those models are implemented into numerical models, regular communication will be essential to guide USGS staff in representing the Cooperators' concepts appropriately. Similarly, USGS will work with the Cooperators to fully communicate the results obtained.

Task 2. Identify Data Needed to Distinguish Conceptual Models

The purpose of Task 1 is to constrain plausible conceptual models using numerical test models. A possible outcome of that analysis is that multiple conceptual models will be feasible that cannot be distinguished with existing field data. The second project task will be to identify the types and locations of additional data that will be required to discern between multiple plausible conceptual models.

Additional data needs have been identified by the Cooperators and documented in a Big Chino Sub-basin Data Collection and Monitoring Plan. This proposal is written in reference to that plan. Some aspects of proposed data collection are already described, planned, and budgeted in the Data Collection and Monitoring Plan, while others, such as geophysical surveys, will be conducted as part of this proposed work.

Work completed to date has identified specific data gaps and has provided tools that can guide the data collection associated with this effort. It is expected that while some data collection can be defined and initiated immediately (Task 3), other aspects will be subject to modification over time in response to knowledge gained from analysis of collected data, development and calibration of the groundwater flow model, and from research by others. Specifically, elements that will guide the data collection planning include:

- Previously published data and analyses. Among these sources is the NARGFM, SRP model, BCWR model of the upper Big Chino sub-basin and BCWR Wellfield Design Investigation. The construction process of the NARGFM model included the consideration of various conceptual models of flow and highlighted many data deficiencies that limited the ability to constrain framework and conceptual models

- The Cooperators' Data Collection and Monitoring Plan. The Plan includes the installation of new hydrologic data collection points (wells, streamflow stations and weather stations) as well as the continuation and, as appropriate, expansion of existing monitoring networks. Data collected as part of the Cooperators' Plan will be incorporated into the current effort. Conversely, the outcome of data collection planning effort described here will be communicated back to the Cooperators for consideration.

Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto

- Observation prediction and parameter prediction statistics applied to the multiple numerical models constructed during Task 1. These models provide an opportunity to better understand the importance of improving knowledge about specific parameters and data within the model domain through an analysis of sensitivity. The test numerical models will be used to guide data collection for the development of the enhanced Big Chino model. Knowledge gained during the development of the regional model will provide insight into the types and locations of additional data that are most needed to improve and constrain conceptual models of the flow system. Software tools such as those developed by Tonkin and others (2007) that calculate Observation-Prediction (OPR) and Parameter Prediction (PPR) statistics will be used to evaluate the sensitivity of the models to new or existing observations. The tools can then be employed to evaluate the relative importance of various kinds and locations of data to improve simulated predictions. The results of this analysis will be communicated to the Cooperators for consideration in honing their monitoring plan.

Task 3. Collect New Data

Aspects of new data collection will be initiated immediately after the joint funding agreement is signed and will focus on remedying known deficiencies and on providing field evidence to support or reject the proposed conceptual flow-system models. As Task 1 results are realized, the specific types and locations of data collection may be adjusted. In the project timeline, new data are collected longer than can be incorporated into the improved numerical model in order to increase the period of record for future utility. The specific data collection categories defined are:

- **Groundwater levels and aquifer storage change**. Definition of groundwater level collection locations and drilling needed for this effort is described in detail in the Cooperators' Data Collection and Monitoring Plan. Aspects are restated here for the purpose of emphasizing the data necessary to meet the stated objectives of the proposal; however, other data collection defined in the Monitoring Plan will also benefit the project.

  Collection of water-level data will serve several purposes. Monitoring of levels through time at targeted locations and depths will provide insights regarding how different aquifers respond to natural variability in recharge as well as to withdrawals. Appropriately selected wells will provide data for calculation of horizontal hydraulic gradients in key areas. Wells designated for long-term monitoring will provide information on trends resulting from human and natural stresses and a subset will serve the "alert" function requested by the Cooperators. Where important, and if possible, water-level data will also be collected from nested piezometers colocated geographically, but separated vertically in different aquifer units. To facilitate this, USGS recommends that the site-selection process for Cooperator-installed wells consider the utility of also monitoring nearby existing wells that will compliment data collected at new wells. Preferably, the nearby existing and new wells will be screened in different vertically adjacent

Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto

aquifers and vertical gradients will be defined to help define the flow system and the connectivity between critical aquifers. Designation of some specific well locations will, in many cases, depend on the results of Task 2. Water levels in all wells should be measured by using installed continuously recording pressure transducers and (or) at least semi-annually by field personnel~~, and or by using installed continuously recording pressure transducers~~.

USGS will rely on Cooperator-furnished water-level data. This proposal budgets sufficient resources for USGS to inventory selected existing wells and newly installed monitoring wells and to manage QA/QC and archiving of tape-down and transducer-collected water level data in the national USGS National Water Information System database. The USGS will rely on the Cooperators to communicate with well and property owners, install equipment, and collect data. The USGS will, however, will assist with identification and selection of appropriate monitoring wells and locations. Specific subtasks related to well monitoring are:

- Subtask 3a. Survey existing wells (location, access, video, water sampling) in the area of the basin-fill/carbonate aquifer interface north and east of Paulden and near the UVS to determine their suitability as long-term monitoring wells.
- Subtask 3b. Install a deep monitor well in the Paleozoic carbonate aquifer near the southern margin of the upper Big Chino sub-~~Sub~~basin (well BMW-2 in BCWR Monitoring Plan).
- Subtask 3c. Depending on the results of Subtask 3a and the OPR/PPR analysis, select existing or install one or more monitor wells to define hydrogeologic units and measure water levels and hydraulic gradients near the UVS.
- Subtask 3d. Install vertically distributed piezometers in the Paulden area to record hydraulic gradients and water-level responses in the Paleozoic carbonate aquifer, alluvium overlying the carbonates, basalt units, and the shallow aquifer units overlying the basalt.
- Subtask 3e. Quantify aquifer storage properties using microgravity observations. Aquifer storage properties are a poorly constrained, but highly important, variable that have a direct effect on the predicted timing of changes in stream base flow due to groundwater pumping. Repeated measurements of changes in gravity at wells and corresponding measurement of water levels provide a means to calculate aquifer storage properties. A subset of wells monitored as part of this effort will also be monitored for microgravity changes. There are currently 6 wells within the study area that are being monitored for water-levels and seasonal groundwater storage (3 times per year). The existing network will be augmented with 15 to 20 additional storage-monitoring stations, many of which will be co-located with observation wells and others that will be in

Formatted: Font color: Auto

Formatted: Font: 12 pt, Font color: Auto

Comment [S3]: This paragraph needs clarification. Who will talk with and alert well owners? Who will budget?

Formatted: Font color: Auto

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

areas where storage change information would be helpful but are lacking observation wells.

- **Perform geophysical surveys.** Geophysical techniques will be employed to gather data regarding the subsurface environment in locations, with a distribution, and at a budget not possible using monitor wells.

  - Subtask 3f. Electrical geophysical methods (ground-based transient electromagnetic (TEM) and controlled source audio-magnetotelluric (CSAMT)) will be used in 3 areas to address specific questions in Big Chino sub-basin. The USGS Arizona Water Science Center will use Center equipment and experienced staff to carry out these surveys. Targets of the electrical surveys will include the aquifer extent and lithology and geologic structures such as horsts and grabens. In particular, the distributions of productive aquifer materials (coarse-grained sediments and limestone), and poor aquifer materials (fine-grained sediments and crystalline rock), will be mapped. Depths of investigation of will range from a few tens of meters to several hundred meters. Data processing will include subsurface electrical models. Additional methods that may be used to refine the electrical survey results, such as 2-dimensional electrical resistivity surveys and seismic reflection, will be considered after evaluation of the initial surveys.

    The 3 areas of interest for electrical geophysical surveys include:

    1. Paleozoic carbonate aquifer that lies to the north of the Verde River above the Paulden gage T18N R2W sec 26 to T18N R1W sec 30, T18N R2W sec 35 to T18N R1W sec 32, T17N R2W sec 2 to T17N R1W sec 5. The Cooperators are planning well drilling in this area. The electrical geophysical surveys for this area will be completed during the first 2 quarters of the project in year 1 so that interpretation will be available to aid well siting.

    2. North of Paulden and south of Big Black Mesa including areas within T18N R2W sec 16, 17, 20, 21, 26, 27, 28, 33, 34. The purpose of electrical geophysical surveys in area 2 is to gain structural and lithologic information for the improved groundwater flow model. The surveys of area 2 will be completed during the first 3 quarters of year 2.

    3. The region of steep hydraulic gradients near Walnut Creek that appear to hydraulically compartmentalize the upper and lower parts of the alluvial basin including an area within the following region T19N R4W sec 9, 10, 11, 13, 14, 15, 16, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 33, 34, 35, 36 and T19N R3W sec 19, 30, 31. The purpose of

Formatted: Font color: Auto

Formatted: Font: 12 pt

Formatted: Font color: Auto

Formatted: Font: 12 pt

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

Formatted: Font: 12 pt

electrical geophysical surveys in area 3 is to gain structural and lithologic information for the improved groundwater flow model. The surveys of area 3 will be completed during the first 3 quarters of year 2.

The target of surveys north of the Verde River include the thickness and extent of the Paleozoic carbonate aquifer including geologic structures such as the Mesa Butte and Big Chino Fault systems that may limit or transmit groundwater flow. Detailed CSAMT profiles will be needed to map geologic structure in sufficiently useful detail. The specific location of profiles will be determined after evaluating available geologic information, drill logs, other geophysical data, the hydrogeologic framework model of Fry (NAU Master's Thesis, 2006), and access to lands in the region. At least 3 profiles are planned, 2 approximately W-E and 1 N-S. The distribution of CSAMT soundings along profiles may be as small 500 ft or as great as 1 mile between stations along multiple profiles.

Formatted: Font: 12 pt

The target of surveys north Paulden and south of Big Black Mesa include the thickness and extent of the Paleozoic carbonate, basalt and alluvial aquifers including the Big Chino Fault. Detailed CSAMT or TEM profiles will be use to map geologic structure. The specific location of profiles will be determined after evaluating available geologic information including drill logs, other geophysical data, and access to lands in the region.

Formatted: Font: 12 pt

The targets of surveys near Walnut Creek include the thickness, extent, and continuity of the alluvial and Paleozoic carbonate aquifers and the extent and thickness of the silt and clay body. Detailed CSAMT or TEM profiles will be use to map aquifer lithology and geologic structure. The specific location of profiles will be determined after evaluating available geologic information including drill logs, other geophysical data, and access to lands in the region.

Formatted: Font: 12 pt

- **Geochemical data.**

Formatted: Font: 12 pt

The Cooperators' Data Collection and Monitoring Plan includes collection of geochemical data including stable isotopes of water and major cations and anions. The USGS believes that these data may prove useful for constraining conceptual models through limited flow-path analysis and will use these data to the greatest degree possible.

Formatted: Font: 12 pt

Formatted: Font color: Auto

Task 4. Construct improved hydrogeologic framework and numerical model

Formatted: Font: 12 pt, Font color: Auto

Formatted: Font color: Auto

The time-invariant data collected in Task 2 (well logs, geophysical assessments) will be considered in the context of the conceptual underpinnings of NARGFM and other existing work, such as a geologic framework model created by Northern Arizona University researchers for most of the Big Chino sub-basin, the SRP model, and the BCWR numerical model of the upper Big Chino sub-basin, to define a refined hydrogeologic framework model and alternative conceptual models. These various concepts will then be built into numerical models that will be used to test whether each model fits the time-variant data (water levels, streamflow, spring discharge) collected in Task 2 or compiled from other sources and databases.

A new improved model will be constructed from NARGFM, results of the conceptual analysis from Task 1, and new data collected in Task 3. The improved model will be either an inset model that derives boundary conditions from NARGFM or a new version of NARGFM that incorporates the updated conceptual model in the area of interest. In either case, the area of interest will encompass, at a minimum, the Big Chino sub-basin and the Big Black Mesa and Hell Canyon watersheds.

The 1-km spatial discretization of the NARGFM domain is believed to be adequate to address the Cooperators' objectives, but the layering, distribution and magnitude of aquifer properties, use of conduits, and spatial extent will be modified using the conceptual models constructed in Task 3 to create a suite of numerical models that can be used to test and constrain the range of conceptual models into a plausible subset.

Task 5. Assess potential Impacts of Big Chino Groundwater Development

The USGS will use the final numerical model to assess the location and timing of impacts to regional groundwater outflow including natural discharge locations in the Verde River headwaters. The locations examined will include the UVS and other key discharge locations as identified by the USGS and the Cooperators. Data for the analysis of impacts will derive primarily from forward scenario runs performed using the updated numerical model and scenarios provided by the Cooperators. It is anticipated that at a minimum the scenarios will include withdrawals (existing and future) by the following:

- Big Chino Water Ranch (BCWR)
- Agriculture
- Municipal and other public suppliers (existing and anticipated)
- Exempt wells

The details of analysis and presentation of results from the scenario runs will be determined through close communication with the Cooperators throughout the project. Scenario results can readily be expressed as composite effects from many stresses, or as effects from individual stresses. It is likely that the primary scenario analysis will focus on the predicted depletion of key surface-water resources and of evapotranspiration (at fixed locations) resulting from groundwater development for select pumping locations

Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto

and times. The analysis will also predict water-table surface changes through time and relate those changes to depletion of surface water.

The USGS will work with the Cooperators to understand the implications of the predictions as well as the limitations and uncertainties inherent in the modeling process. The Cooperators have an interest in establishing a well-monitoring network that would allow water managers to set alert levels based on changes in water levels. There are several considerations for use of wells for this purpose. First, effects of pumping must be large enough to be separated from other signals from variability in climate and barometric pressure. Second, it must be understood that there are residual effects after management action (such as reduced pumping) that can only be understood by running the model. The best approach for establishing monitoring wells is to use the model and pre-established management constraints. In addition to use as alert indicators, water level data from the wells should be used as points for refining the calibration of the model in the future.

Task 6. Communication (Deliverables)

Several aspects of this project—for example, that the Cooperators will be responsible for collection of some components of essential data and that Cooperator-conceived conceptual models are to be tested by USGS—require close communication between the Cooperators and USGS. This will be accomplished through informal and formal communications. Informal communications will be via telephone and email and will include exchange of data, clarification of previous work products, discussion of conceptual models, etc.

Informal Cooperator interaction will be welcomed throughout the project. Formal communications will include progress updates and reports, as described below.

- **Project progress updates**

The USGS proposes to hold quarterly meetings in person or via remote-communication technology with the Cooperators to regularly update progress made and, as importantly, to seek input regarding the Cooperators' intent. Anticipated information exchanged in quarterly meetings includes:

  - Status and issues regarding planning of USGS-conducted field data collection
  - Feedback from USGS to the Cooperators regarding the planning and implementation of Cooperator-conducted field data collection
  - Collected data
  - Assumptions made regarding implementation of Cooperator-derived conceptual models into numerical test models
  - Details regarding USGS-derived conceptual models to be tested
  - Results of the conceptual model testing

Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt

- Development of refined framework using field data
- Development of improved numerical model
- Progress of improved numerical model calibration
- Inquiry to Cooperators regarding the model scenarios development
- Initial results and implications of scenario runs
- Results of well alert-level analysis
- Progress on final report publication

When feasible, material to be presented at quarterly meetings should be furnished to the Cooperators at least one week in advance of the meeting.

In addition, a fundamental part of Task 1 will be a numerical-model analysis of the implications of selecting one conceptual model vs. another from the perspective of depletion of Upper Verde River source water. Results will be communicated with the Cooperators by using presentations.

- **MODFLOW model files**

The USGS will provide all model files from the improved numeric model to the Cooperators for review. The model files will, however, be considered preliminary and for the purpose of cooperator review until final publication.

- **Reports publication**

Publication of peer-reviewed and publically released reports documenting methods and results will play an essential role in building confidence in project results for the Cooperators and for the public as a whole. Study results will be formally released in USGS series reports and become publically available upon release; however, through the quarterly meetings described previously, the Cooperators will be engaged in the process throughout and will be aware of findings. The Cooperators will be asked to review model files during the course of the project and will also be asked to review draft report products. In addition to Cooperator reviews, report products will have two independent colleague reviews. Until final USGS approval of reports, results cannot be publically released.

Two USGS series reports will be published as part of this project. The first will summarize the results of Task 1—the conceptual model testing and elimination. The second will discuss the results of the geophysical surveys, data from well drilling and monitoring that are used in the project, and will document the final improved numerical model. A web page for the project will be maintained for the duration of the project. At the discretion of project staff, scientific journal articles may also result from this work. Such articles, although not a requirement of this project, would serve to strengthen the scientific integrity of the work. Cooperators will be given the opportunity to review and comment on articles prior to submission to the scientific journal.

Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font color: Auto

Schedule

The proposed project timeline spans 4 years, which represents a one-year extension relative to earlier discussions regarding this work. The primary reason for the addition of a year is that that adequate time will be needed to:

1 – Complete the Task 2 analysis of highest priority data needs such that the results can inform and influence the type and location of geophysical and hydrologic data collected.

2 – Implement data collection and collect a sufficient period of record to provide useful information that will be built into the final improved numerical model.

The proposed work will be carried out in stages by task. A Gantt chart (Table 1) shows the proposed project timeline by tasks. Tasks are timed such that each completes in an appropriate sequence to provide needed results and interpretations to the next tasks. An exception of the collection of water level and aquifer storage change data. Those tasks are continued through year 4 to increase the period of record; however, the data that will inform the enhanced model development will by necessity of timing end early in project year 3. Data collected in year 4 that will not be included in the improved numerical model are represented as a cross-hatched pattern. The USGS feels the continued collection of data to extend the period of record at least through the fourth project year is of high value.

Table 1. Proposed project timeline by task and project year

	Project Year 1				Project Year 2				Project Year 3				Project Year 4			
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1: Conceptual model testing																
2: Identify needed data																
3 a-d: Assess/manage water level data																
3 e: Aquifer storage change monitoring																
3 f: Geophysical field surveys - area 1																
3 f: Geophysical field surveys - areas 2-3																
3 f: Geophysical data analysis																
4: Improved model development																
5: Assessment of impacts																
6a: Report results of task 1 and 2																
6b: Report results of tasks 3-5																
Report review and publication																

Budget and personnel

The preliminary project budget is presented by task and by fiscal year in Table 2. The proposed project requires a wide variety of skillsets for successful implementation. USGS will pursue a project-management goal to keep key modeling staff dedicated to the project through completion. USGS will assemble a project team that reflects expertise in the hydrologeology of the area, in numerical modeling, and in geophysical field data collection and analysis. Although USGS cannot firmly commit specific staff members to

Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto

the project until negotiations are completed, we currently expect to assign three experienced numerical modelers, Jesse Dickinson, Don Pool, and Stan Leake, to work on the project as needed throughout. Proposal budgeting included these individuals plus field support from students, hydrologic technicians, and hydrologists.

It is important to note that some data collection tasks, specifically the geophysics and aquifer storage change monitoring, will be performed by USGS personnel and are specifically budgeted in this proposal. Well drilling, groundwater level data collection, aquifer testing, and certain ephemeral channel flow modeling are critical to the success of this effort but are budgeted and staffed through the Cooperators' Monitoring Plan. Success of the proposed work relies on the successful and timely implementation of those data collection efforts. The proposed budget does include resources for USGS personnel to inventory wells installed by the Cooperators' as well as perform standard USGS QA/QC on Cooperator-collected data. In addition, data used by the USGS in the analysis, regardless of source, will be archived in the USGS National Water Information System database.

USGS will commit federal Cooperative Water Program matching funds to the proposed project. Although data regarding specific funding amounts are not currently available, USGS expects to commit no less than $50,000 and up to $100,000 annually.

Table 2. Preliminary project budget by fiscal year and task for the purpose of predicting the magnitude and timing of groundwater pumping effects on Upper Verde River source waters

	Project year			
Task	Year 1	Year 2	Year 3	Year 4
Task 1: Conceptual modeling	$162,966	--	--	--
Task 2: Identify data needs	$62,265	--	--	--
Task 3 a-d: Management of WL data	$56,688	$14,098	$14,521	$14,957
Task 3e: Aquifer storage	$58,000	$40,000	$40,000	$40,000
Task 3f: Geophysics data collection	$58,382	$107,614	--	--
Task 3f: Geophysics data analysis	$16,507	$27,385	--	--
Task 4: Improved model development	--	--	$124,731	--
Task 5: Implications analysis	--	--	$58,506	$63,237
Task 6: Report - author aspects	$18,779	$76,677	--	$168,318
Report - publication	--	$10,320	--	$13,760
Drilling, testing wells, collecting WL data	†	†	†	†
Total	$433,587	$276,095	$237,759	$300,272

†Well drilling, logging, aquifer testing, and water-level monitoring are assumed to be completed outside this scope of work; the timeliness of the work proposed here depends on completion of well drilling and monitoring.

Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt

Selected References

Arizona Department of Water Resources, 2000, Verde River Watershed Study: Arizona Department of Water Resources, Phoenix, Arizona, vp.

Blasch, K.W., Hoffmann, J.P., Graser, L.F., Bryson, J.R., and Flint, A.L., 2006, Hydrogeology of the upper and middle Verde River watersheds, central Arizona: U.S. Geological Survey Scientific Investigations Report 2005–5198, 101 p., 3 plates.

Ewing D.B, Osterberg J.C., Talbot W.R., 1994, Groundwater study of the Big Chino Valley, Technical Report, Section I of III, Perspective, United States Bureau of Reclamation.

Glover, R. E., and Balmer, G. G., 1954, River depletion resulting from pumping a well near a river. EOS Trans. Am. Geophys. Union, 35(3), 468–470.

Hill, M. C., and Tiedeman, C. R., 2007, Effective groundwater model calibration: New Jersey, John Wiley and Sons, 455 p.

Jenkins, C.T., 1968, Computation of rate and volume of stream depletion by wells: U.S. Geological Survey Techniques of Water-Resources Investigations, Ch. D1, Bk 4, 17 p.

Knauth, L.P., and Greenbie, M., 1997, Stable isotope investigation of groundwater-surface-water interactions in the Verde Rivers headwaters area: Arizona State University Department of Geology report in fulfillment of Arizona Water Protection Fund Grant #95-001, administered by Arizona Department of Water Resources, 28 p.

Langenheim, V.E., DeWitt, Ed, and Wirt, Laurie, 2005, Geophysical framework based on analysis of aeromagnetic and gravity data, upper and middle Verde River Watershed, Yavapai County, Arizona: U.S. Geological Survey Scientific Investigations Report 2005—5278, 25 pp. 1 pl.

Ostenaa, D.A., U. Schmischal, C.E. King, Jr., and J.W. Wright, 1993, Groundwater Study of the Big Chino Valley, U.S. Bureau of Reclamation, Denver, CO.

Poeter, Eileen P., and Mary C. Hill, MMA, A computer code for Multi-Model Analysis: U.S. Geological Survey Techniques and Methods 6-E3, 113 p.

Pool, D.R., Blasch, K.W., Callegary, J., and Graser, L., (in review), Groundwater Flow Model of the Redwall-Muav, Coconino, and Alluvial Basin Aquifer Systems of Northern and Central Arizona, U.S. Geological Survey Scientific Investigations Report.

Schwab, K.J., 1995, Maps showing groundwater conditions in the Big Chino sub-basin of the Verde River basin Coconino and Yavapai Counties, Arizona-1992, ADWR Hydrologic Map Series Report No. 28.

Theis, C.V., 1940, The source of water derived from wells: essential factors in controlling the response of an aquifer to development. *Civil Engineer* 10:277-280.

Theis, C.V., 1941, The effect of a well on the flow of a nearby stream: *American Geophysical Union Transactions*, 22, part 3, 734-738.

Tonkin, M.J., Tiedeman, C.R., Ely, M.D., and Hill, M.C., 2007, OPR-PPR, a computer program for assessing data importance to model predictions using linear statistics: Reston Virginia, USGS, Techniques and Methods Report TM-6E2, 115 pages.

Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font: 12 pt
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt, Font color: Auto
Formatted: Font color: Auto
Formatted: Font: 12 pt

Wirt, Laurie, and Hjalmarson, H.W., 2000, Sources of springs supplying base flow to the Verde River headwaters, Yavapai County, Arizona: U.S. Geological Survey Open-File Report 99-0378, 50 p.

Wirt, L, E. DeWitt, and V.E. Langenheim, 2005, Geologic Framework of Aquifer Units and Groundwater Flowpaths, Verde River Headwaters, North-Central Arizona. U.S. Geological Survey Open-File Report 2004-1411.

Formatted: Font: 12 pt

Formatted: Font: 12 pt