Hydrology Science Plan to Support Title II of the Northern Arizona Land Exchange and Verde River Basin Partnership Act of 2005

Prepared by the
U.S. Geological Survey Arizona Water Science Center
in cooperation with
the Verde River Basin Partnership
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Science Plan to Support Title II of the Northern Arizona Land Exchange and Verde River Basin Partnership Act of 2005

BACKGROUND

Title II of Public Law 109-110, the Northern Arizona Land Exchange and Verde River Basin Partnership Act of 2005 (S.161), authorizes the United States Geological Survey (USGS) to assist in a collaborative and science-based water-resource planning and management partnership for the Verde River Basin. Section 204 of Title II calls for the Partnership to prepare a plan for conducting water-resource studies in the Verde River Basin (fig. 1). This document is a draft of the plan and will serve as a guide for future water-resource studies in support of Title II. The water-resource studies done in support of Title II will benefit from several ongoing or completed studies relevant to water-resource planning and management. A list of publications produced from some of these studies is provided in the list of selected references.

INTRODUCTION

This document, referred to herein as the plan, describes the investigations needed in support of Title II that will fulfill water-resource planning and management needs and identify long-term water-supply management options within the Verde River Basin. The plan outlines the tasks required to meet the deliverables of Title II. As stated in the legislation, these deliverables include: (1) a water-budget analysis of the Middle Verde River Basin and a report of a preliminary analysis of potential long-term consequences of various water-use scenarios within 14 months after the date of enactment of the Act[1]; (2) a preliminary report submitted by the Partnership that sets forth findings and recommendations of the Partnership regarding the long-term availability of water supply within the Verde Valley within 16 months after the enactment of the Act[1], and; (3) a final report four years after enactment of the Act that summarizes results of water-resource assessments conducted under Title II, that identifies: (1) areas determined to have

[1]Although Title II was enacted in 2005, work on deliverables has not been initiated owing to limited resources. This revision of the Title II Science Plan includes new time lines for completion of work.

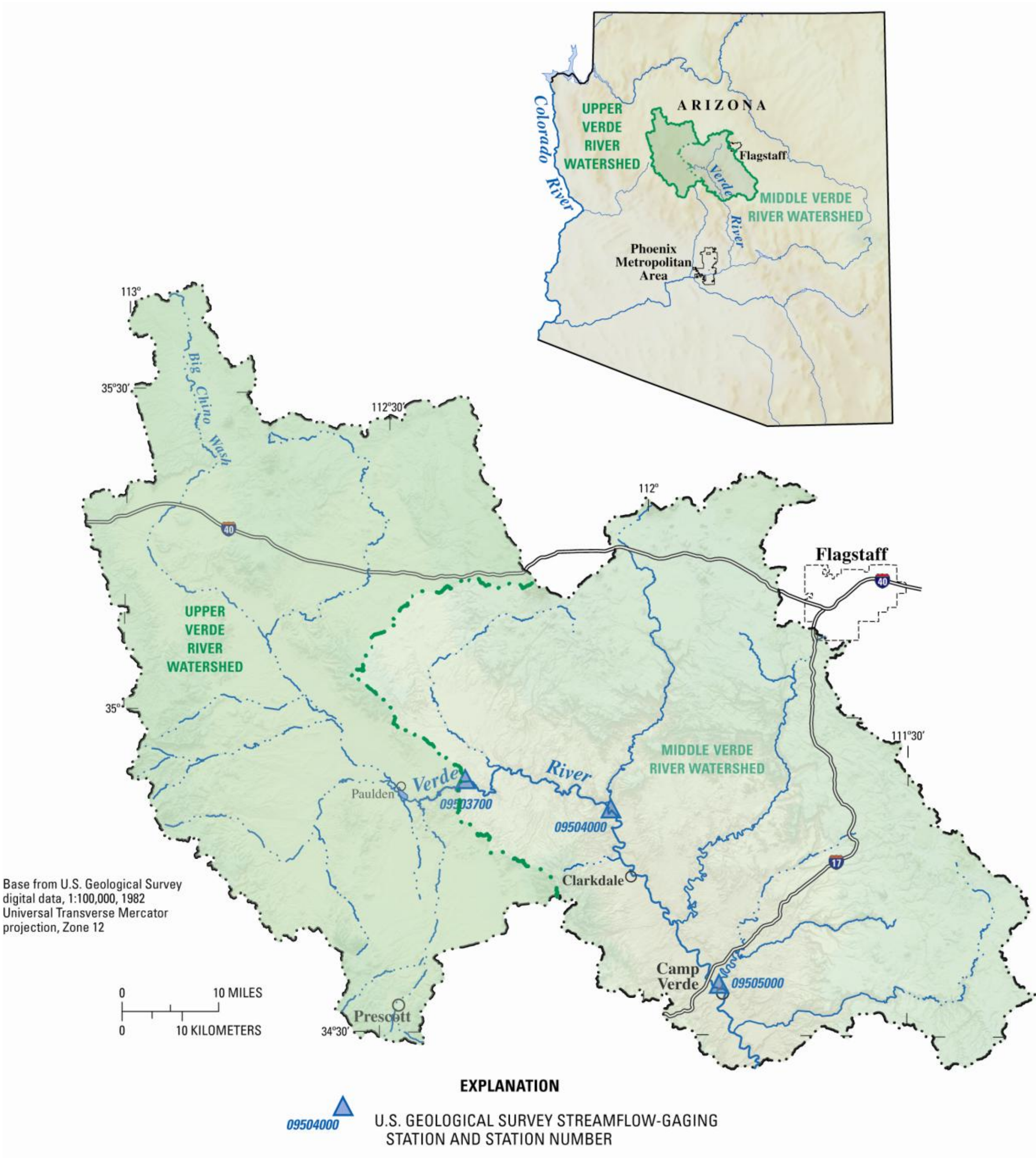

Figure 1. Area of investigations for the Title II Verde River Basin Partnership.

groundwater deficits; (2) long-term water-supply management options; and (3) analyses and monitoring needed to support implementation of management options.

APPROACH

The approach used to meet the needs of Title II will include a variety of work elements designed to take advantage of on-going studies, previously published findings, documented groundwater flow models, and other existing data. The Northern Arizona Regional Groundwater Flow Model (NARGFM), currently (March 2009) near completion, represents a valuable tool for water-resource management in the study area that can help estimate effects on Verde River flow resulting from groundwater withdrawals. The development of the model helped identify several types of information in various areas of the middle and upper Verde Watersheds that, if collected and included, would improve conceptualization of the groundwater flow system and the model. This revised Title II Science Plan targets collection of the particular data that: (1) address the named deliverables in Title II, and (2) will result in modeling tools targeted to best address water-resources in the study area. The work elements include an evaluation and refinement of the water budget and the reporting of potential long-term consequences of various water-use scenarios. Information gained from development of the NARGFM and review of recent and on-going studies and documents will be used to identify data deficiencies. This information will be used to plan and carry out new studies and develop a monitoring network designed to improve our understanding of the hydrologic setting that will assist in evaluating long-term hydrologic responses to climate and resource development.

WORK ELEMENT 1: Water-Budget Analysis

Title II stipulates delivery of a water-budget report to the Partnership within 14 months of enactment subject to appropriations. A groundwater budget consists of values derived by analysis or assumption for inflows, outflows, and change in aquifer storage. The greater the degree to which a budget relies on values derived by analysis rather than assumption the better the certainty of the budget. A variety of data compilation and data collection activities can be undertaken to generate better information to construct a water budget, some requiring only the time to compile existing information and some requiring collection of new data in the field over a period of time. Work Element 1 includes those tasks that can be accomplished and reported within the specified 14 months. Tasks that are also essential for improving water-budget calculations, such as monitoring of aquifer-storage changes, but that can not be completed in 14 months, are included in Work Elements 5 and 6.

Improved water-budget estimates will made by evaluating recently collected hydrogeologic data combined with water-budget estimates reported in historic studies. Improved estimates of recharge will made by evaluating water budgets at smaller time scales than done previously and by improving previous estimates of recharge derived from intermittent and ephemeral streams. A detailed inventory of groundwater withdrawals for municipalities, irrigation, and residential use also will be done. The specific tasks related to this work element are required to construct a rigorous water-budget analysis. These tasks are described below.

Task 1. Review of existing studies related to water budget analyses of the region and identification of data gaps.

There is considerable information in existing reports related to water-budget components of the Verde River watershed. Collectively, however, these studies demonstrate a need for improved estimates of recharge, streamflow diversions, water use, riparian water use, and storage changes. Much of this information has been compiled for and synthesized into the USGS Northern Arizona Regional Groundwater Flow Model (NARGFM) thus simplifying the task for the Science Plan. Among the reports considered are: Schwalen (1967), which described groundwater in the artesian area of Little Chino Valley and presented data for 1940 to 1965; Matlock and others (1973), which updated the work of Schwalen to include data from 1966 to 1972; Levings (1980) described groundwater availability and water chemistry in the Sedona area; Owen-Joyce and Bell (1983) presented findings of a water-resource assessment in the Verde Valley near Camp Verde, Clarkdale, and Sedona; and Owen-Joyce (1984) presented findings of a water-resource assessment in the Sedona area.

The State of Arizona's Groundwater Management Act of 1980 resulted in the declaration of five Active Management Areas (AMAs), one of which is the Prescott Active Management Area (PRAMA). Consequently, numerous studies were conducted in the PRAMA that resulted in a map of groundwater conditions (Remick, 1983); a groundwater flow model that simulates both steady-state conditions (1940) and transient conditions (1940-93); (Corkhill and Mason, 1995); and an updated groundwater flow model that extended simulation periods for examining forecasted predictions to 2025 (Nelson, 2002). Timmons and Springer (2006) updated the Nelson model by adding new hydrologic data, expanding the model from about 220 square miles to 250 square miles, and calibrating the model using water-levels and spring discharge from 1939 through 2004. Schwab (1995) constructed a synoptic water-level map for the Big Chino Sub-basin. The Bureau of Reclamation (Ewing and others, 1994, and Ostenaa and others, 1993) conducted a geohydrologic investigation of Big Chino Valley to identify potential sources of water for the city of Prescott. Knauth and Greenbie (1997) and Wirt and Hjalmarson (2000) used chemistry data to estimate groundwater flow paths and source areas to the Verde River headwaters area. The Arizona Department of Water Resources (ADWR) (2000) compiled a summary of available water-resource data in the upper and middle Verde River watersheds. Langenheim and others (2005) calculated the depth of Tertiary alluvial sediments and volcanic deposits in the Big Chino, Little Chino, Williamson, and Verde Valleys, and identified several new faults by using aeromagnetic and gravity surveys. Wirt and others (2005) describe in a detailed study the geology, hydrogeology, and geochemistry of the headwaters region of the Verde River. Most recently, Blasch and others (2006) presented a regional evaluation of the hydrogeologic setting of the upper and middle Verde River watersheds.

Task 2. Improved spatial and temporal distribution and rates of recharge estimates.

A. Recharge investigations in the southwestern United States show that recharge in arid basins does not occur in all years or at all locations (Flint and others, 2004). In the desert southwest, potential evapotranspiration exceeds precipitation on a yearly basis. However, on shorter time scales and in certain areas of a basin, precipitation and (or) snowmelt exceed the infiltration capacity of the soil and become runoff. If storage capacity of the soil is exceeded water may percolate below the root zone in deeper soils. To evaluate the spatial and temporal variability of net infiltration Flint and others (2004) developed a deterministic water-balance model with use of GIS coverages including a digital elevation model and maps of geology, soils, vegetation, and time-varying climatic conditions of air temperature and precipitation. Other required surficial properties for the model, such as permeability, porosity, and water-retention functions, are calculated from associated data sets. The deterministic model, termed a Basin Characterization Model (BCM), identifies the areas and climatic conditions that allow for excess water, quantifies the amount of water available either as runoff or in-place recharge, and allows intra-basin comparison of recharge mechanisms (i.e. mountain front, mountain block, ephemeral stream) and potential recharge for current, wetter, and drier climates.

A generalized version of the BCM provided valuable information during NARGFM development with respect to distribution and magnitude of regional recharge. To evaluate the timing, locations, and magnitude of recharge in the upper and middle Verde River Watersheds, the USGS will create a BCM specific for the study area that includes representation of ephemeral-channel recharge processes—a process not captured during the NARGFM development. An example of the product a BCM produces is shown in figure 2 where monthly time steps are used to produce annual runoff and recharge distributions for the upper and middle Verde watersheds. Separate process models are used to develop spatial distributions of potential evapotranspiration, snow accumulation, and snowmelt. When combined with surface properties of soil-water storage and bedrock permeability, the potential water available for in-place recharge and runoff will be calculated. The calculations will be made in daily to monthly time steps at a grid scale of 270 meters. The BCM will be used with transient historic climatic inputs. A report summarizing the results of this analysis will be produced in the second year of the project.

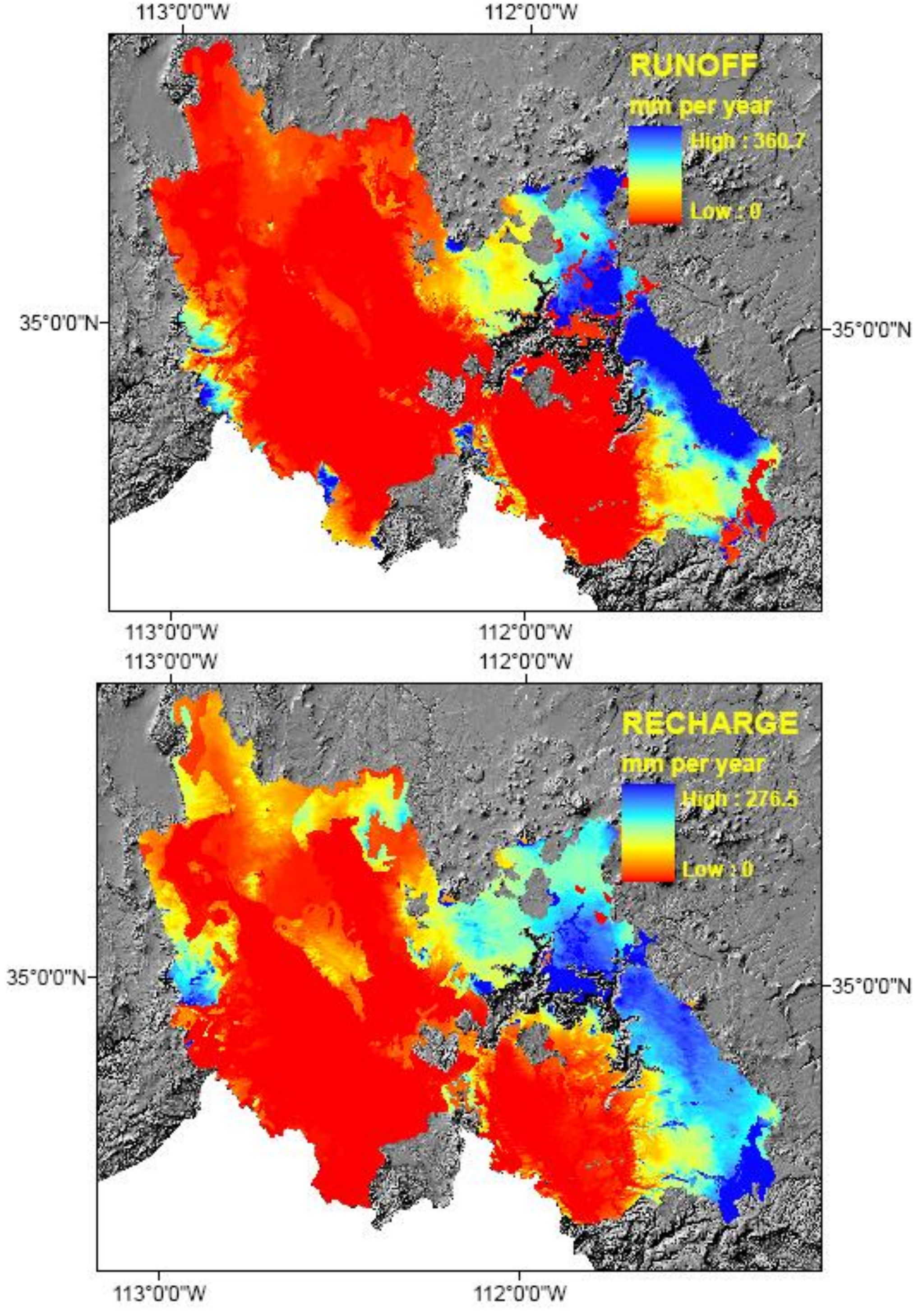

Figure 2. Annual runoff and recharge estimates from a Basin Characteristic Model for the middle and upper Verde Valley based on monthly time steps.

B. NARGFM development underscored the importance of better characterizing recharge to the regional aquifer from stream systems for robustly simulating groundwater flow. Recharge from perennial, intermittent and ephemeral streams occurs episodically and seasonally, and often is related to high-magnitude flood flows when available water exceeds potential evapotranspiration for sustained periods of time. To better estimate streamflows that could provide water for potential recharge, the USGS will conduct an analysis of the magnitude and frequency of streamflows within the watersheds. To do this, methods for estimating streamflow statistics will be developed, updated, and improved by using new data, information, and technology that have become available since the last methods were developed (Thomas and others, 1997; Pope and others, 1998). This proposed study will (1) update streamflow statistics at gaged sites, and (2) develop regional methods for estimating streamflow statistics at ungaged watersheds. This study will use the regional-regression approach for estimating streamflow statistics in ungaged watersheds. In the regression approach, streamflow statistics at gaged sites are transferred to ungaged sites using multiple-regression equations. GIS techniques, new information on basin and climatic characteristics, and new automated techniques will be used to improve and expand the capabilities of regional streamflow methods. The analyses will be done for both annual and seasonal flows. Although this information will not provide specific recharge values, it will provide relative distributions of recharge from infiltration of streamflow throughout the area. A report summarizing the results of this analysis will be produced in the second year of the project.

C. Although water may be available for recharge, certain geomorphological and vegetation conditions are required for recharge to occur. To evaluate the potential for recharge along ephemeral and intermittent washes in and downstream of the areas of likely recharge as determined from Tasks 2A and

2B above, the USGS will use the method developed by Callegary and others (2007). This method classifies recharge potential (RCP) in ephemeral-stream channels, incorporating information about channel geometry, vegetation characteristics, and apparent electrical conductivity (σ_a) of bed sediment. Seven data types will be collected along each wash: σ_a at two depth intervals, channel incision depth and width, diameter-at-breast-height (DBH) of the largest tree, density of woody plants, and density of grasses. Apparent electrical conductivity is measured in the channel thalweg during the month of June, the hottest, driest month of the year. At this time, bed-sediment water content would be expected to be at an annual minimum, maximizing the contrast between high and low clay content. Because σ_a is proportional to clay content and clay is the primary factor affecting permeability during saturated flow in unconsolidated media, σ_a values are inversely proportional to permeability. Apparent electrical conductivity is measured by using a low-induction-number frequency-domain electromagnetic-induction instrument at two intervals bracketing 0-3 m and 0-6 m depths. Vegetation characteristics will be measured in 10 by 10 meter plots on each bank. As DBH, woody plant density and grass density increase, evapotranspiration also increases. Increases in any of these three factors should, therefore, decrease RCP. Incision depth and width will also be measured in reference to the break in slope between the channel and floodplain or first major terrace. An increase in channel width provides greater area for infiltration, and greater incision depth allows for increased flow depth. Increases in these two factors increase RCP. A two-tiered system is used to classify a transect's RCP. In the first tier, transects are categorized by the permeability of near-surface sediments based on measurements of 0 to 3 m depth σ_a. Each of the permeability categories is further divided in the second tier into three classes indicating low, medium, or high RCP by applying the same ranking approach to the remaining six data types. Local trends and variations in RCP will be used to better estimate variations in the distribution of recharge. An example of electromagnetic measurements used in ephemeral reaches in southern Arizona is shown in figure 3. A report summarizing the results of this analysis will be produced in the second year of the project.

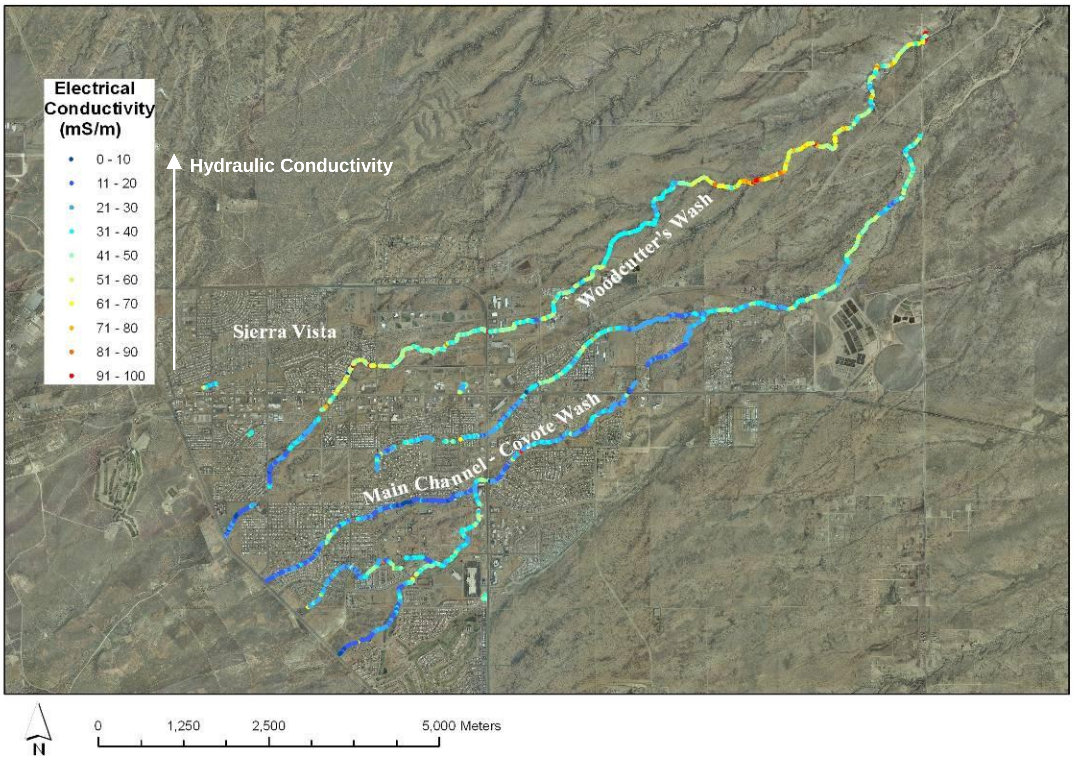

Figure 3. Electrical conductivity measurements in ephemeral streams in southern Arizona made with an electromagnetic induction instrument. The values are considered in the first tier of the classification of the recharge potential.

Task 3. Inventory of surface-water diversions and returns.

Within the Verde Valley there are approximately 50 diversions of surface water for the irrigation of nearly 5,000 acres. The diversions range from river pumps and small ditches that divert 0.5 ft^3/s to large ditches that divert up to 60 ft^3/s. The diversions move water from the main stem of the Verde River and its tributaries to agricultural fields and residential yards in the vicinity of, but varying distances from the river. Some of the diverted water is consumptively transpired, some is returned to the river as surface flows, while some is recharged back into the aquifer. For the purpose of improving NARGFM, understanding the fate of the recharged water and the speed with which it returns to the river are important considerations in determining the importance of knowing diversions and returns versus simply knowing the consumptive use. To better understand the behavior of recharged diversion water, several piezometers will be instrumented and monitored along the Middle Verde River starting in year 1 of the project. Interpretations of piezometer data will be included in the final report rather than the Water Budget report owing to the time required for collection of sufficient period of record.

Understanding diversion volumes, consumptive use, and return volumes will improve the water budget within the Verde Valley and support efficient water management. To this end, USGS or other qualified personnel will inventory, map, and measure flow for diversions and returns from the Verde River and its tributaries. Previously, ADWR attempted to quantify diversions for the 2000 Verde River Watershed Report. The experience gained by ADWR during investigation suggests that it may be very difficult to quantify how much surface water is being diverted from the river. During that study it was observed that no irrigation systems had measurable structures or recorders to determine how much is actually being diverted. To compound difficulties many of the larger irrigation districts divert the entire river and use what is needed and then let the remainder return back to the river as much as a mile or more in some cases downstream. ADWR ultimately determined a consumptive use value for the crops that were identified and assumed any water diverted above the consumptive use of the plant ended up back in the river either by percolation or return flow. Therefore, given prior experience, it will be important to build flexibility in the possible approaches used to determine water use from diversions.

Prior to field work, an initial effort will be made to review available information on surface-water diversions at the Arizona Department of Water Resources adjudications and planning support section, from pertinent Northern Arizona University (NAU) researchers, and from USGS data collected during summer 2007 (Bills, 2008). A significant amount of information collected during the mid to late 1990's from the study area is stored in ADWR's Watershed File Reports. These ADWR and USGS data will be used to design a preliminary field campaign to measure diversions in the area. The new campaign will build on current and planned monitoring of diversions by NAU. In addition, the USGS will work with the Verde Natural Resources Conservation District and area researchers in obtaining contact information on diversion ownership for the purpose of securing access permission. Field work to measure diversions and return flows will be scheduled during periods of maximum and minimum diversions (summer and winter). Because diversions are expected to vary seasonally and over time with climatic variations, this preliminary effort will be used to design a long-term program to inventory diversions and return flows in the entire basin. Diversions will be inventoried for the duration of the project. If NAU researchers have successfully implemented diversion monitoring at important locations at the initiation and through the duration of Title II work, then USGS will focus on characterizing the groundwater portion of return flows.

Task 4. Improved estimates of groundwater withdrawal.

Most of the study area is outside the PRAMA; therefore, requirements for reporting groundwater withdrawals outside of an AMA are less stringent within an AMA (note: requirements for reporting withdrawal, however, increased in April 2007 for community water providers, as per Arizona HB2277). Various methods of analyses will be pursued with the goal of improving estimates of current groundwater withdrawal by wells. It is expected that local cooperation will be needed for this task. A valuable local-cooperation element would consist of an effort, using volunteer well owners, to better characterize withdrawals of groundwater by exempt wells. Note: Improvements to this water budget component are likely to come after the initial 14-month delivery date for the water-budget analysis. Even so, improvements to this water budget component are needed and should be addressed for the longer term needs of Title II.

Estimates of, and methods to determine, groundwater withdrawals will be evaluated for the duration of the project.

WORK ELEMENT 2: Analysis of potential long-term consequences of various water-use scenarios on groundwater levels and Verde River flows

The USGS will use the NARGFM for this task. Initial water-use scenario formulation for the Verde River Basin is currently underway and will be completed in cooperation with Yavapai County. For the purpose of Title II, more detailed and specific water-use scenarios will be identified by the Partnership or other appropriate party on the basis of what is learned in the initial scenarios. Scenarios will be delivered to the USGS within 6 months after initialization of Science Plan work. The scenario analysis may include various representations of streamflow capture such as published for the San Pedro River by Leake and others (2008) and evaluate other water-budget components as deemed most beneficial to the Partnership.

WORK ELEMENT 3: Reporting of the water budget and water-use scenario analysis

The USGS will provide a draft report to the Partnership within 14 months of initiation of the Science Plan work that:

1. Summarizes the hydrologic information available for the Middle Verde River between the U.S. Geological Survey streamflow gages at Clarkdale and Camp Verde.
2. Estimates aspects of the water budget including inflow and outflow of surface and groundwater, and consumptive water use.
3. Describes potential changes to the system (water level and stream flow) resulting from the water-use scenarios

The draft report will be subsequently published as a USGS-series report.

WORK ELEMENT 4: Preliminary report

The Partnership shall submit a preliminary report that sets forth the findings and recommendations of the Partnership regarding the long-term available water supply within the Verde Valley within 16 months after enactment of the Act.

WORK ELEMENT 5: Improved conceptual model of the hydrologic system

Development of the NARGFM has resulted in a two-fold benefit. First, it will provide a valuable tool for informing water-resource management. The second aspect is that the model provides a systematic and comprehensive means to identify types of data and areas from which additional data will significantly improve future models—by creating the initial model, much more is known about what is not fully understood. The types of information necessary to improve the current model and thus improve confidence in model predictions are: (1) hydrogeologic framework information such as layering and thickness of aquifer materials, storage properties, and hydraulic conductivity, and (2) long-term hydrologic information such as groundwater levels, streamflow, spring flow, and aquifer storage change. Collection of these two types of data in key locations represents an essential part of addressing Title II Science Plan goals. Work Element 5 consists of the tasks that improve the understanding of the physical hydrogeologic framework, while Work Element 6 addresses establishment of long-term monitoring.

Existing concepts of the groundwater flow system in the middle and upper Verde watersheds are evolving. Additional investigations are needed including subsurface investigations using geophysical methods and test-well drilling to better define aquifer geometry, geochemical sampling to define groundwater flow paths and distributions and rates of recharge, and aquifer tests to better evaluate aquifer properties. The data collected will include:

Task 1. Vertical head gradients.

These data help identify the upward or downward movement of water in the aquifer and define the connection between aquifer layers. Currently data are needed to improve the understanding of vertical connection in the upper and lower Big Chino Valley between the basin fill deposits and the underlying Martin Formation. Two piezometer nests, each having a deep and a shallow monitoring point, will be installed; one in the upper valley and one in the lower valley.

Vertical gradient data are also needed in the middle Verde area to better define the hydraulic connection between the Verde Formation, and underlying alluvial deposits and Paleozoic rocks. Understanding this connection is important to improving simulation of the relation between the regional aquifer and Verde River in this area. Two piezometer nests will be installed in the middle Verde for this purpose.

Task 2. Aquifer storage properties.

Knowledge of the magnitude and variability of storage properties of the regional aquifer are essential for realistically simulating effects of groundwater withdrawals on groundwater levels, aquifer storage, and depletion of streamflow.

A. To address a current deficiency in knowledge, two test wells will be drilled in proximity to the piezometer nests (see Work Element 5, Task 1) installed for vertical gradient monitoring in the upper and lower Big Chino Valley. Aquifer tests will be long-term (weeks duration) and intended to determine storage properties including specific yield.
B. A network of gravity monitoring stations will be established at monitoring wells. Measurements of changes in gravity can be related to changes in the mass of water, or storage, in the aquifer. Simultaneous measurements of changes in gravity and water levels provide a mechanism for calculating aquifer storage properties.

Task 3. Playa deposits in the Big Chino Valley.

Steep hydraulic gradients are observed near the upstream limit of a low-permeability playa deposit in the Big Chino Valley. Knowledge of the cause of these gradients would improve the ability to simulate the effect of withdrawals in the upper Big Chino on Verde River flow. Electrical geophysical methods (transient electromagnetic and CS-AMT) will be used to define the underlying structure in this area. The electrical geophysical lines will run between existing wells along the long axis of the valley.

Task 4. Connection of saturated limestone to basin fill.

A key, but poorly understood component of groundwater flow in the Big Chino Valley is the nature of connection between saturated limestone and saturated basin fill deposits. Electrical geophysical methods will be employed to investigate and identify areas of connection.

Task 5. Horizontal gradients north of Paulden gaging station.

Owing to lack of data in the area north of the Paulden streamflow gaging station (09503700), uncertainty exists regarding the amount of groundwater flow that bypasses the Upper Verde river in that area and enters the stream further downstream. The uncertainty limits the ability to accurately calibrate the numerical model to actual flow conditions in the area. Three wells will be drilled in the area north of Paulden gaging station to establish horizontal gradients driving groundwater flow through the area.

Task 6. Connection of middle Verde River to permeable underlying units.

The middle Verde River between Clarkdale and Camp Verde has been shown (Zlatos, 2008; Bills, 2008) to gain water from the regional aquifer system in constrained reaches. A key part of properly simulating stream-aquifer interactions is identifying and characterizing the connections between the regional aquifer and streams in these areas. Electrical geophysical mapping will be used to delineate zones where permeable regional aquifer materials (most likely limestone intervals within the Verde Formation) are in connection with the stream alluvium of the middle Verde River.

Task 7. Stream-aquifer interactions in the middle Verde.

Simulation of the effects of groundwater pumping on streamflow depletion requires a good understanding of the character and spatial relation of stream-aquifer interactions. The NARGFM is built using the best current information including the geochemical work of Zlatos (2008), and seepage data of Bills (2008). These works provided valuable information to improve the understanding of stream-aquifer interactions in the middle Verde, but did not include the simultaneous collection of groundwater level data. To supplement the existing data, about 10 existing wells screened in the stream alluvium between streamflow gages at Clarkdale and Camp Verde will be monitored over the course of the project.

Task 8. Age of regional aquifer water.

Knowledge of the age of water in the regional aquifer system provides additional constraint on numerical groundwater flow models. When combined with estimates of recharge amounts, water age provides an estimate of the average flux of water through the aquifer system. Additionally, age dating of water will help constrain the physical routing, or flowpaths, along which water moves.

Task 9. Quantification of distributed recharge.

The installation of monitoring wells provides an excellent opportunity to collect a variety of data in addition to long-term water levels. Core samples taken during drilling can be used to measure the accumulation of chloride in the soil profile which provides a means of estimating how much recharge occurs through the land surface (as opposed to through ephemeral stream channels). Samples of soil moisture and shallow groundwater can also be used to measure ages of water which can also provide information regarding recharge occurrence and rate.

Installations of monitoring wells are indicated in several tasks of this Science Plan (such as Work Element 5, tasks 1 and 5). Soil core samples will be collected from an appropriate subset of installed wells and analyzed for the chloride concentrations and tritium levels in the contained soil moisture. Sieve analyses for grain size distribution will be completed on collected cores. These data will help constrain the distribution and amounts of areally distributed recharge that occurs in the Big Chino and Verde Valleys.

Task 10. Recharge in ephemeral-stream channels.

Measurements of ephemeral-channel flow, groundwater responses and storage changes in the vicinity of stream channels will be used to directly monitor recharge attributed to selected ephemeral channels. Several locations will be selected from the upper and middle Verde Watershed areas for monitoring. Streamflow will be monitored using the Continuous Slope Area (CSA) technique. This method allows continuous monitoring of flows in otherwise difficult-to-gage channels at a relatively low cost. About 10 CSA installations will be used to monitor stream inflows and outflows in the 5 selected locations. Tripod LiDAR surveys will be performed at each installation to establish baseline channel morphology. One or more shallow monitoring wells will be continuously monitored at each ephemeral-channel location to observe groundwater responses to flows. Existing wells will be instrumented where possible. Otherwise, new shallow wells will be drilled. In addition, gravity will be monitored at each monitor well for the purpose of estimating aquifer specific yield and volumes of recharge.

Task 11. Quality assurance at existing monitoring locations.

Many wells are currently used to collect groundwater levels throughout the upper and middle Verde areas. Some of these wells indicate anomalous behavior of the groundwater. For this task, USGS personnel would field check multiple wells to ensure they are properly connected to the aquifer system.

WORK ELEMENT 6: Identify and initiate a network for the long-term monitoring of the hydrologic conditions that affect the middle and upper Verde watersheds

Knowledge of how the hydrologic system responds over short and long time scales to stresses such as climate variability and human water-resource development is critical for improving the understanding of the system as well as providing data for model calibration and reducing error in model-based projections.

Long-term hydrologic monitoring will provide data sets for evaluation of current status of the hydrologic system, long-term trends, and to improve understanding of how the system responds to changes in climate and human development of water resources. Hydrologic monitoring will include streamflow, water levels in wells, aquifer storage, riparian water use, and withdrawals for agricultural, domestic, and industrial use. Many long-term monitoring sites currently exist including several stream gages (USGS), a network of index wells measured on an annual or quarterly basis (ADWR), and real-time water-level monitoring at several wells (USGS). A preliminary network of storage-monitoring sites has been established (USGS), and some monitoring of evapotranspiration has been completed (USGS). Existing monitoring networks will be evaluated for adequacy and will be expanded where needed using Title II resources. Current issues with state resources may limit ADWR capacity to maintain all ongoing monitoring.

Many hydrologic conditions occur in the middle and upper Verde watersheds, and each should be monitored. The different hydrologic conditions are defined by the many aquifers in the area, different rates of recharge and discharge, and the water use drawn from each aquifer. In a general sense, hydrologic conditions that should be monitored include major recharge areas, natural discharge areas (springs, streams, riparian), and major areas of groundwater withdrawal. Development of the NARGFM, however, has helped identify specific areas and types of data that are needed and will be collected as part of this plan including:

Task 1. Vertical head gradients.

The piezometer nests installed as part of Work Element 5, Task 1 in the upper and lower Big Chino Valley and in the Middle Verde area will be fitted with recording pressure transducers for long-term monitoring. These data help identify the upward or downward movement of water in the aquifer and define the connection between aquifer layers.

Task 2. Horizontal gradients north of Paulden gaging station.

The three monitoring wells installed in Work Element 5, Task 5 to establish horizontal gradients north of the Paulden streamflow-gaging station (09503700) will be instrumented with recording transducers as part of the long-term monitoring network.

Task 3. Effect of climate variability on groundwater.

Natural variability in annual precipitation causes variable responses in groundwater levels. Understanding the relation between variable precipitation and groundwater responses in the absence of any pumping effects is critical information for calibrating the groundwater model. Approximately 5 wells will be monitored in locations in the upper and middle Verde watersheds sufficiently distant from pumping to not be affected and close enough to recharge zones to observe responses to precipitation.

Task 4. Storage-change monitoring.

Storage-change estimates are commonly made by combining water-level changes with assumed aquifer storage properties. However, information on water-level change and aquifer-storage properties in the upper and middle Verde Valleys is insufficient to make storage-change estimates without a large degree of uncertainty. Estimation of aquifer-storage change from water-level changes in monitored wells entails significant assumptions about the storage properties of the aquifer system. One difficulty is the heterogeneity of storage properties of the aquifer; the alluvial sediments of the aquifer vary substantially in lithology, both laterally and with depth. Accordingly, data from individual wells cannot reliably be assumed to represent aquifer characteristics some distance away from the well. A second difficulty is monitor-well design; many water levels are measured in wells that tap multiple aquifer layers. When these composite water levels are used to estimate storage changes, the storage properties used in the calculation typically do not reflect the range of aquifer materials that the well samples. Because of these complexities and requisite assumptions, use of water-level variations as indicators of storage change can be highly misleading, and cannot be reliably extrapolated beyond the well location.

Groundwater storage change will also be determined directly by periodically measuring very small changes in gravity at the Earth's surface that are directly related to total mass change. Microgravity measurements are generally sufficiently precise to detect a change of 5 inches of free-standing water. Where water-level and gravity measurements are both measured at a well, a specific yield value may be estimated by linear correlation of gravity-indicated storage change with measured water-level change. A significant advantage of gravity measurements is that measurements can be made with equal ease in developed and undeveloped areas thereby allowing comparison of changes between these two area types. New stations can be established at a low cost allowing easy adaptation of the gravity-monitoring network. Also, gravity stations do not require specific permitting and are noninvasive. A typical gravity station consists of a benchmark set in a concrete pad. Measurements are made by temporarily occupying the station with a portable gravity meter. Occupations may last for several minutes to an hour depending on type of meter used and required survey accuracy. Surveys with portable gravity meters are manpower intensive and therefore can only be completed periodically. Continuous or near continuous monitoring would be cost prohibitive. The frequency of gravity surveys for this project will be based on the expected magnitude and timing of storage change; adjustments to the frequency of measurements will be evaluated throughout the duration of the project.

WORK ELEMENT 7: Final report

The USGS shall provide a final report, with a focus on the knowledge gained from results of Work Elements 5 and 6, to the Partnership that summarizes results of the water-resource assessments conducted under Title II within 4 years after the initiation of work.

Table 1. Timeline of work elements and tasks in support of Title II

WORK ELEMENT/TASK	YEAR 1 (FY11)				YEAR 2 (FY12)				YEAR 3 (FY13)				YEAR 4 (FY14)			
	Q1	Q2	Q2	Q4	Q1	Q2	Q2	Q4	Q1	Q2	Q2	Q4	Q1	Q2	Q2	Q4
WORK ELEMENT 1: Water Budget Analysis																
Task 1. Review existing studies	■	■														
Task 2A. Basin Characterization Model		■	■	■	■	■										
Task 2B. High-flow frequency analysis		■	■	■	■	■										
Task 2C. Mapping recharge potential		■	■	■	■	■										
Task 3. Inventory of diversions	■	■	■	■	■	■	■		■		■		■			
Task 4. Estimate ground-water withdrawals	■	■	■	■	■	■		■		■		■		■		
WORK ELEMENT 2: Analysis of pumping scenarios		■	■	■												
WORK ELEMENT 3: Report of scenario analysis			■	■	■	■										
WORK ELEMENT 4: Preliminary report by Partnership					■	■										
WORK ELEMENT 5: Improved Conceptual Model																
Task 1. Vertical hydraulic gradients					■	■	■	■								
Task 2. Aquifer storage properties					■	■	■	■	■	■	■	■	■	■		
Task 3. Playa deposits in Big Chino									■	■	■	■	■	■		
Task 4. Connection of saturated limestone to basin fill									■	■	■	■	■	■		
Task 5. Horizontal gradients north of Paulden gage					■	■	■	■								
Task 6. Connection of middle Verde River to underlying units									■	■	■	■	■	■		
Task 7. Stream aquifer interactions	■	■	■	■	■		■		■		■		■			
Task 8. Age of regional aquifer water									■	■	■	■	■	■		
Task 9. Quantification of distributed recharge					■	■	■	■					■	■		
Task 10. Recharge in ephemeral stream channels			■	■	■	■	■	■	■		■		■			
Task 11. Quality assurance at existing monitoring locations			■	■												
WORK ELEMENT 6: Long-term monitoring																
Task 1. Vertical hydraulic gradients					■	■	■	■	■		■		■		■	
Task 2. Horizontal gradients north of Paulden gaging station					■	■	■	■	■		■		■		■	
Task 3. Effect of climate on variability of groundwater					■	■	■	■	■		■		■		■	
Task 4. Storage-change monitoring			■	■	■		■		■		■		■		■	
WORK ELEMENT 7: Final Report											■	■	■	■	■	■

BUDGET

Table 2 contains estimates of costs associated with each work element of the plan. The costs may be adjusted over time to account for changing conditions and needs.

Table 2. Preliminary estimated budget by fiscal year and work element/task for Title II of S.161.

Work Element/Task	FY11	FY12	FY13	FY14
WORK ELEMENT 1: Water Budget Analysis				
Task 1. Review existing studies and identify data gaps	55,000			
Task 2A. Improve spatial and temporal distribution and rates of recharge estimates—Basin Model Char.	65,000	35,000		
Task 2B. Improve spatial and temporal distribution and rates of recharge estimates—High flow frequency	75,000	35,000		
Task 2C. Improve spatial and temporal distribution and rates of recharge estimates—Recharge potential.	85,000	35,000		
Task 3. Inventory surface-water diversions and returns	160,000	55,000	55,000	25,000
Task 4. Improve estimates of groundwater withdrawal	55,000	55,000	55,000	55,000
WORK ELEMENT 2: Analysis of potential long-term consequences of various water-use scenarios	70,000			
WORK ELEMENT 3: Reporting of the water-use scenario analysis	50,000	15,000		
WORK ELEMENT 4: Preliminary Report (note: this will be done by Partnership and therefore does not have an associated cost in this budget)	0			
WORK ELEMENT 5: Improved Conceptual Model				
Task 1. Vertical hydraulic gradients - includes drilling		1,380,000		
Task 2. Aquifer storage properties		145,000	30,000	32,000
Task 3. Playa deposits in the Big Chino Valley			40,000	10,000
Task 4. Connection of saturated limestone to basin fill			40,000	10,000
Task 5. Horizontal gradients north of Paulden gage - includes drilling		160,000		
Task 6. Connection of middle Verde River to underlying units			45,000	10,000
Task 7. Stream-aquifer interactions in the middle Verde	45,000	15,000	15,000	27,000
Task 8. Age of regional aquifer water			60,000	55,000
Task 9. Quantification of distributed recharge		62,000		25,000
Task 10. Recharge in ephemeral-stream channels - includes drilling	210,000	610,000	120,000	120,000
Task 11. Quality assurance at existing monitoring locations	$10,000			
WORK ELEMENT 6: Long-term monitoring				
Task 1. Vertical hydraulic gradients		25,000	12,000	12,000
Task 2. Horizontal gradients north of Paulden gage		15,000	5,000	5,000
Task 3. Effect of climate on variability in groundwater		22,000	7,000	7,000
Task 4. Storage-change monitoring	285,000	110,000	110,000	115,000
WORK ELEMENT 7: Final report	0	0	15,000	130,000
FY Totals	$1,165,000	$2,774,000	$609,000	$638,000

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