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Hydrologic Analyses In Support of the Navajo Generating Station-Kayenta Mine Complex Environmental Impact Statement

Open-File Report 2016–1088

U.S. Department of the Interior
U.S. Geological Survey

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By Stanley A. Leake, Jamie P. Macy, and Margot Truini

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Introduction

The U.S. Department of Interior's Bureau of Reclamation, Lower Colorado Region (Reclamation) is preparing an environmental impact statement (EIS) for the Navajo Generating Station-Kayenta Mine Complex Project (NGS-KMC Project). The proposed project involves various Federal approvals that would facilitate continued operation of the Navajo Generating Station (NGS) from December 23, 2019 through 2044, and continued operation of the Kayenta Mine and support facilities (collectively called the Kayenta Mine Complex, or KMC) to supply coal to the NGS for this operational period. The EIS will consider several project alternatives that are likely to produce different effects on the Navajo (N) aquifer; the N aquifer is the principal water resource in the Black Mesa area used by the Navajo Nation, Hopi Tribe, and Peabody Western Coal Company (PWCC).

The N aquifer is composed of three hydraulically connected formations—the Navajo Sandstone, the Kayenta Formation, and the Lukachukai Member of the Wingate Sandstone—that function as a single aquifer. The N aquifer is confined under most of Black Mesa, and the overlying stratigraphy limits recharge to this part of the aquifer. The N aquifer is unconfined in areas surrounding Black Mesa, and most recharge occurs where the Navajo Sandstone is exposed in the area near Shonto, Arizona (Lopes and Hoffmann, 1997). Overlying the N aquifer is the D aquifer, which includes the Dakota Sandstone, Morrison Formation, Entrada Sandstone, and Carmel Formation. The aquifer is named for the Dakota Sandstone, which is the primary water-bearing unit (Cooley and others, 1969).

The NGS is located near Page, Arizona on the Navajo Nation. The KMC, which delivers coal to NGS by way of a dedicated electric railroad, is located approximately 83 miles southeast of NGS (about 125 miles northeast of Flagstaff, Arizona). The Kayenta Mine permit area is located on about 44,073 acres of land leased within the boundaries of the Hopi and Navajo Indian Reservations. KMC has been conducting mining and reclamation operations within the Kayenta Mine permit boundary since 1973.

The KMC part of the proposed project requires approval by the Office of Surface Mining (OSM) of a significant revision of the mine's permit to operate in accordance with the Surface Mine Control and Reclamation Act (Public Law 95-87, 91 Stat. 445 [30 U.S.C. *1201 et seq.*]). The revision will identify coal resource areas that may be used to continue extracting coal at the present rate of approximately 8.2 million tons per year. The Kayenta Mine Complex uses water pumped from the D and N aquifers beneath PWCC's leasehold to support mining and reclamation activities. Prior to 2006, water from the PWCC well field also was used to transport coal by way of a coal-slurry pipeline to the now-closed Mohave Generating Station. Water usage at the leasehold was approximately 4,100 acre-feet per year (acre-ft/yr) during the period the pipeline was in use, and declined to an average 1,255 acre-ft/yr from 2006 to 2011 (Macy and Unema, 2014). The Probable Hydrologic Consequences (PHC) section of the mining and reclamation permit must be modified to project the consequences of extended water use by the mine for the duration of the KMC part of the project, including a post-mining reclamation period.

Since 1971, the U.S. Geological Survey (USGS) has conducted the Black Mesa Monitoring Program, which consists of monitoring water levels and water quality in the N aquifer, compiling information on water use by PWCC and tribal communities, maintaining several stream-gaging stations, measuring discharge at selected springs, conducting special studies, and reporting findings. These data are useful in evaluating the effects on the N aquifer from PWCC and community pumping, and the effects of variable precipitation.

The EIS will assess the impacts of continued pumping on the N aquifer, including changes in storage, water quality, and effects on spring and baseflow discharge, by proposed mining through 2044, and during the reclamation process to 2057.

Several groundwater models exist for the area and Reclamation concluded it would conduct a peer review of the groundwater flow model that will be used to assess the direct, reasonably foreseeable indirect, and cumulative effects of future groundwater withdrawals on the D and N aquifers in the Black Mesa area. Reclamation made this determination because of the level of controversy around the effects of continued water use and the comments received from the 2014 draft EIS scoping meetings. Reclamation requested assistance from the USGS in evaluating existing groundwater flow models of the Black Mesa Basin that can be used to predict the effects of different project alternatives on the D and N aquifers.

Purpose and Scope

The purpose and scope of these hydrologic analyses include tasks (1) performing an inventory of discharge locations (springs and perennial stream reaches) in the D and N aquifers; (2) evaluation of D and N aquifer groundwater models that could meet the needs of the NGS-KMC EIS; (3) evaluation of the technical design and calibration of the model that is most appropriate for use for the EIS; (4) evaluation of appropriate post-pumping periods for analyses of long-term aquifer effects; (5) evaluation of model projections; and (6) evaluation of existing USGS water-quality data for the Black Mesa area to quantify historical changes in water quality caused by pumping and recovery. This report outlines the results of USGS investigations for items 1–4 and 6. Model projections for item 5 were not available when this report was being prepared and will not be included in this report. Information from these analyses will be used by Reclamation in the preparation of the EIS.

Study Area

The study area is located in northeastern Arizona and contains diverse topography such as flat plains, mesas, and incised drainages. Black Mesa, a topographic high at the center of the study area encompasses about 2,000 square miles (mi^2) (fig. 1). Black Mesa has 2,000-foot-high cliffs on its northern and northeastern sides, with more gradual slopes to the south and southwest, all of which is included in the study area. For the purposes of groundwater model evaluations, spring inventories, and water-quality analyses, the area within the HDR engineering consulting firm Western Navajo Hopi N Aquifer (WNHN) groundwater model boundary was used as the largest extent of the study area and is referred to as the cumulative effects study area (CESA).

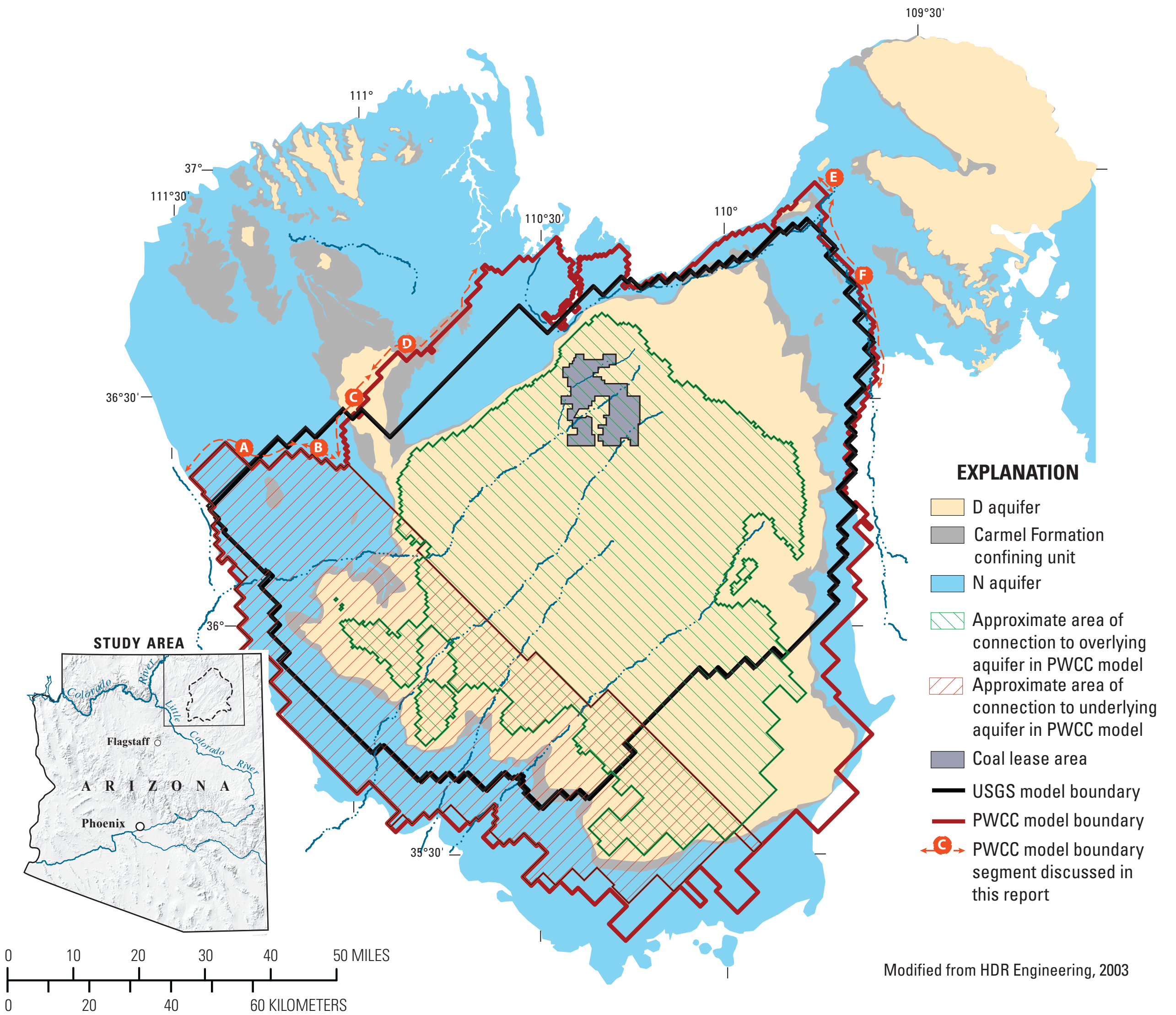

Figure 1. Study area with extents of groundwater models. The Western Navajo Hopi N aquifer (WNHN) model extends over the area of the N aquifer shown here.

Inventory of Discharge Locations in D and N Aquifers

Approach

D and N aquifer discharge locations, more commonly referred to as springs and perennial stream reaches, were inventoried as part of the USGS scope of work for the Navajo Generating Station-Kayenta Mine Complex EIS. Spring and discharge location information was retrieved from the USGS groundwater site-inventory system (GWSI) database. Spring names, locations, and contributing aquifer information were retrieved from the GWSI database using the geographic area defined by the PWCC groundwater model boundary (fig. 1) constructed by Tetra Tech. Springs that did not have contributing aquifer information in GWSI were plotted on geologic maps and, where possible, the contributing aquifer or geologic unit was identified.

In addition to springs in the GWSI database, Tetra Tech developed a separate spring dataset and provided that information to the USGS as an Excel spreadsheet. Tetra Tech's spring dataset was incorporated into the USGS spring inventory as part of Task 1, but these springs were not added to the USGS GWSI database.

After identifying D and N aquifer springs within the PWCC groundwater model in both the USGS GWSI database and in the spring dataset provided by Tetra Tech, the USGS was asked by the Bureau of Reclamation to enlarge the study area boundary to include the HDR groundwater study boundary defined by the extent of the HDR WNHN model boundary (fig. 1). All of the spring data for this larger area were compiled from GWSI in an Excel spreadsheet and plotted in ArcGIS 10.3 for visual display and further analysis.

The spring inventory consisted of identifying spring locations, the terrain surrounding each spring, and spring activity. A spring's location was designated by latitude and longitude information from the USGS GWSI database and the dataset provided by Tetra Tech and plotted in ArcGIS. The plotted springs were compared with topographic maps and aerial photography to determine if the latitude and longitude data were correct. Topographic maps used for the analysis were USGS 1:24,000, 7.5 minute quadrangle series maps. Aerial photography used for the analysis was from the Department of Agriculture National Agriculture Imagery Program (NAIP), which consists of 1-meter resolution imagery for the entire conterminous United States and is acquired as a four-band product that can be viewed as either a natural color or color infrared image. NAIP imagery from 2010 was used for this inventory. Aerial imagery from Google Earth was also used for comparison to NAIP imagery. A spring's location was determined by the presence of vegetation, found on aerial images, associated with spring sites typical of the southwestern U.S. Infrared images from the NAIP aerial imagery dataset were also used to constrain spring location sites by looking for evidence of spring flow and vegetation. Spring flow often appeared in the infrared images as a distinctly different color than the surrounding ground, and vegetation appeared as a red color. Attributes for describing a spring's location are provided below.

Explanation for Spring Location Attributes

Good - The latitude and longitude data from the USGS GWSI database or Tetra Tech dataset matched topographic maps and aerial photography.
Close - The latitude and longitude data from the USGS GWSI database or Tetra Tech dataset were in close proximity to springs evident on topographic maps or aerial photography.
Bad - The latitude and longitude data from the USGS GWSI database or Tetra Tech dataset were not in the same location as a visible spring on aerial photography or a topographic map. In instances where the location data were bad and a spring was evident on aerial photography, a new revised location was established.
Unknown - The latitude and longitude data from the USGS GWSI database or Tetra Tech dataset were not in an area where a spring was evident on aerial photography or a topographic map.

Once a spring was located the nearby terrain was described using the attributes below. Explanations for spring terrain attributes were determined from personal experience by USGS hydrologists at certain spring locations and from aerial photography.

Explanation for Spring Terrain Attributes

Near_drainage - Spring is near a large wash along the banks or in a meander off of the main channel.
Near_stock_tank – Spring appeared to be flowing into a stock tank or was near a stock tank.
Surrounded_by_desert – Spring is surrounded by sand/sediment and sometimes small shrubs. There is no significant bedrock nearby.
In_canyon -Spring is along the bottom of a canyon and discharge to drainage is uncertain, spring is coming up mid-channel or along the edge of the channel.
Near_dwellings – Spring is developed and surrounded by or near modern day dwellings either in a town or one/several homesteads.
In_field_drainage - Spring is near fields alongside a drainage.
On_bedrock – Spring is on and surrounded by bedrock.
Base_of_cliff –Spring is discharging from the base of a cliff.
In_shallow_canyon – Spring is in a channel along a shallow canyon where the walls are not steep or deep.
Near_large_river – Spring plots in a river.

The final attribute for evaluating springs as part of this inventory is the activity of a spring. Spring activity was determined from personal experience by USGS hydrologists at certain spring locations, including discharge measurements, and from aerial photography. Explanations for spring activity attributes are listed below.

Explanation for Spring Activity Attributes

No_apparent_spring – Dry drainage with no upstream sign of water; sitting on bedrock with no green for many miles; desert/bedrock with nothing more than small shrubs or sand with infrared NAIP data not showing very red vegetation.
Unknown – Uncertainty of location and existence of a spring.
Flowing – Spring is clearly flowing and there is little to no vegetation nearby.
Flow_vegetation – Can see flowing water with lots of vegetation.
Seep – Location indicated damp earth with white/discolored mineral precipitation.
Developed – Location showed spring houses/troughs/storage tanks; some were based on previous knowledge of the site from having visited the location.
WWTP – Waste water treatment plant – location was near a WWTP; not always clear if the location was identified correctly because there was an existing body of water.

Spring Inventory Results

The final compilation of information from the spring inventory was provided to the Bureau of Reclamation as a single Excel spreadsheet that detailed the spring location (with revised location information), terrain surrounding the spring, and activity of the spring. Duplicate springs found in the USGS GWSI database and provided by Tetra Tech also were documented. There were 75 springs and discharge locations compiled from the USGS GWSI database and 119 springs provided by Tetra Tech. Six of the springs in the USGS GWSI database were duplicates of springs provided by Tetra Tech. Of the 75 springs found in the USGS database, 15 of those springs have recorded discharge greater than 10 gallons per minute. Discharge measurements made at those 15 springs occurred between 1948 and 2006. There are no measured discharges above 10 gallons per minute after 2006 in the USGS database.

The spring information contained in the final compilation spreadsheet is sensitive water information and is not published as part of this report. Maintaining confidentiality of spring and discharge locations is necessary because they are traditional cultural properties of historical and (or) religious significance to indigenous peoples.

Evaluation of Available Groundwater Models for the N and D Aquifers in the Study Area

The proposed Cumulative Effects Study Area encompasses the area of the N aquifer shown in figure 1. For this area, a groundwater model is needed to evaluate effects of groundwater pumping by the Black Mesa Kayenta Mine Complex, as well as pumping by communities on and around Black Mesa. Nearly all groundwater pumping in the area is from the N aquifer, which is hydraulically connected to the overlying D aquifer. Pumping effects of interest include reduction of groundwater head (drawdown), capture of groundwater outflow by evapotranspiration, capture of groundwater discharge to springs and streams, and depletion of flow in streams (streamflow depletion). Hydrologic features for which pumping effects are to be evaluated occur in both the N and D aquifers.

Three readily available MODFLOW (Harbaugh, 2005; Niswonger and others, 2011) groundwater flow models of the N aquifer exist for all or a major part of the study area. These include the U.S. Geological Survey Black Mesa model of the N aquifer (Brown and Eychaner, 1988), the Western Navajo Hopi N Aquifer model (HDR Engineering, Inc., 2003), and the Peabody Western Coal Company model (Tetra Tech, 2014). The Western Navajo Hopi N Aquifer model and the Peabody Western Coal Company model simulate flow in both the N and D aquifers, as well as in the intervening Carmel Formation (confining unit), whereas the USGS Black Mesa model simulates flow in the N aquifer only. The following sections include a brief description of each of these three models.

USGS Black Mesa Model—This model, referred to hereafter as the USGS model, was documented by Brown and Eychaner (1988). The one-layer model simulates flow in the N aquifer only. A head-dependent boundary is implemented to simulate leakage into the N aquifer from the overlying D aquifer. This arrangement of boundary conditions does not permit calculation of the effects of pumping in the N aquifer on any springs or other outflow features in the D aquifer. Select streams are simulated using the MODFLOW River Package (Harbaugh, 2005). Thomas (2002) updated the USGS model with additional simulation time and groundwater pumping for the period 1985–99; however, no recalibration of the model has been carried out. The model has been converted from an earlier version of MODFLOW to run with MODFLOW-2000 (Harbaugh and others, 2000) and MODFLOW-2005 (Harbaugh, 2005).

Western Navajo Hopi N Aquifer Model—This model was constructed by Peter Mock as a subcontractor to Southwest Ground-Water Consultants, who in turn was a subcontractor to HDR Engineering Inc. The model, referred to hereafter as the WNHN model, is documented in volume 3 of HDR Engineering, Inc. (2003). Model data sets were available to run in MODFLOW-96 (Harbaugh and McDonald, 1996). This model uses five layers to simulate groundwater flow in the D and N aquifers and intervening rock units. The areal extent of the WNHN model includes the area of the N aquifer shown in figure 1. The larger areal extent relative to the PWCC and USGS models could be an advantage because it allows for evaluation of effects of pumping in more of the N aquifer. Select streams are simulated using the MODFLOW River Package (Harbaugh, 2005). In converting the WNHN model data sets to run on a currently supported version of MODFLOW, several of the model layer-surface arrays were found to be internally inconsistent. The model cannot be directly converted for use in its present state and should not be considered for use by the NGS-KMC EIS until problems are fixed and data sets are converted for use in a current version of MODFLOW.

Peabody Western Coal Company (PWCC) Model—This model, referred to hereafter as the PWCC model, is an update of an earlier model by Peabody Western Coal Company, Inc. (1999). The model documentation was released in January 2015 (Tetra Tech, 2014). The PWCC model uses seven model layers to simulate groundwater flow in the D and N aquifers and intervening rock units. According to Tetra Tech (2014), improvements in the model over the version documented in Peabody Western Coal Company, Inc. (1999) include

1. Conversion to run with MODFLOW-NWT (Niswonger and others, 2011);
2. Modified time discretization to simulate from 1956 through 2012;
3. Implementation of the Multi-Node Well Package (Konikow and others, 2009);
4. Implementation of the Streamflow-Routing Package, version 2 (Niswonger and Prudic, 2005);
5. Simulation of evapotranspiration along washes;
6. Simulation of additional springs;
7. Implementation of a flow barrier to simulate restriction of flow across a monocline;
8. Calibration of hydraulic conductivity using pilot-point methodology;
9. Modification of storage properties; and
10. Modification of the distribution of groundwater recharge.

General Comments on Evaluated Models

The USGS model has deficiencies that preclude its use by the NGS-KMC EIS. As mentioned previously, this model cannot evaluate effects of pumping on springs and other features connected to the D aquifer. Also, the USGS model used the River Package (Harbaugh, 2005) to simulate flow between the N aquifer and streams such as Laguna Creek and Moenkopi Wash. Unless a stream or river is continuous and removes water from the aquifer domain, use of software packages such as River or Drain will result in the incorrect calculation of capture from groundwater pumping. The correct approach for streams including perennial and ephemeral reaches is simulation with the Streamflow-Routing Package (SFR1, Prudic and others, 2004; or SFR2, Niswonger and Prudic, 2005) or the Stream Package (STR) (Harbaugh, 2005). These packages were not available when the USGS model was constructed.

Of the three models evaluated, the WNHN model has the largest model domain for general use by the NGS-KMC EIS. The inconsistency problems with the layer-surface arrays, however, preclude its use in evaluating effects of pumping. This model also has the same problem as the USGS model in representation of surface-water features with a package other than STR, SFR1, or SFR2.

The PWCC model has an areal domain that is intermediate in size (fig. 1) of the three models evaluated and it has the most detailed vertical discretization of the D and N aquifers. This model has the most up-to-date calibration and it is set up to run on a relatively recent version of MODFLOW using more sophisticated boundary-condition packages than were employed for the USGS and PWCC models.

Comparison of Model-Calculated Steady-State Water Budgets

In spite of problems with the USGS and WNHN models, these models were used to help understand ranges of estimates of steady-state water-budget components for the same or similar areas of the N aquifer. Inflow water-budget items for the N aquifer part of models in the study area include recharge, net leakage from the overlying D aquifer, and specified flow. Outflow items of interest include evapotranspiration, flow to springs, and flow to streams. The WNHN model could not be run, but HDR Engineering Inc. (see volume 3, task 4.2, table 26, 2003) includes steady-state water budgets for the part of the WNHN model that is within the domain of the USGS model. Computation of water budgets for a subarea of a larger model likely will indicate lateral flow crossing the boundary into and out of the subarea. Net lateral flow out of the USGS model domain, therefore, is an additional water-budget item for the USGS subarea within the WNHN model. A comparison of steady-state water-budget components for the three models is shown in figure 2.

The range in magnitude of the three budgets—11,900 to 13,600 acre-ft/yr—indicates general agreement; however, the PWCC budget has the lowest magnitude and the largest water-budget domain in this comparison. The USGS and the WNHN models have nearly the same water budget magnitude for the sub-area encompassed by the USGS model. Some specific differences, however, exist in the individual water-budget components. The PWCC model simulates that more than half of the groundwater discharge is through evapotranspiration, whereas the other two models simulate lesser proportions of discharge to evapotranspiration. Another difference is that

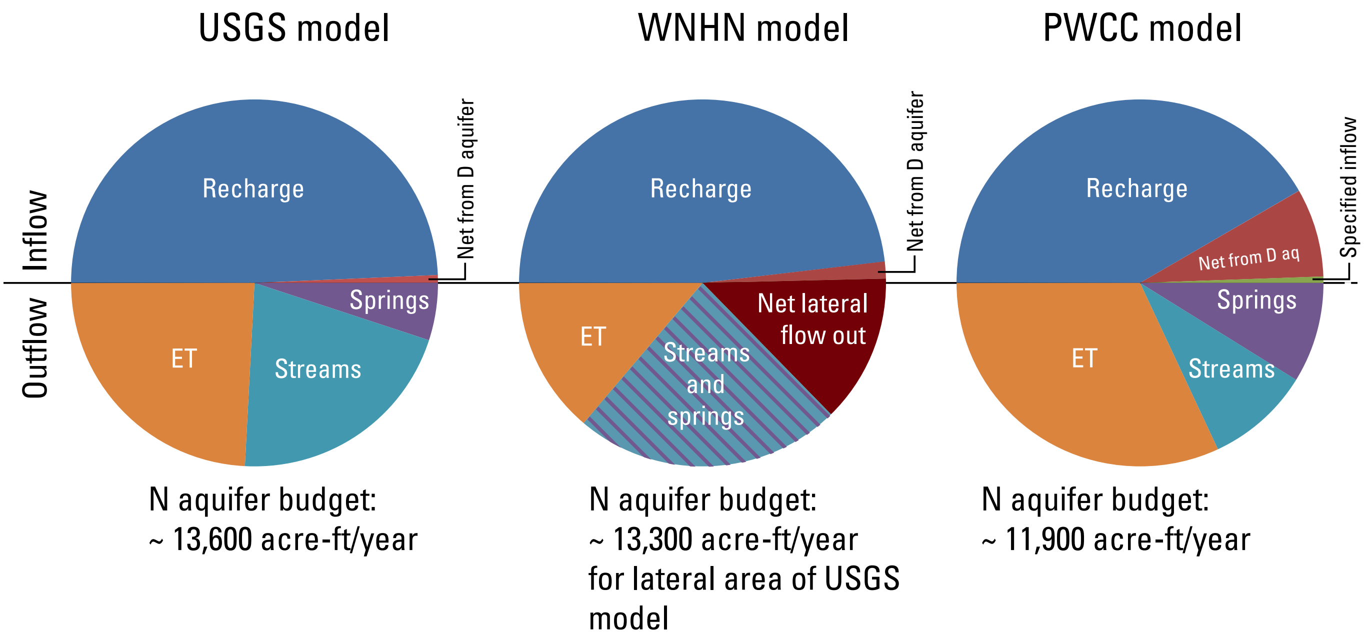

Figure 2. Comparison of N aquifer steady-state water budgets from the Peabody Western Coal Company, U.S. Geological Survey, and Western Navajo Hopi N aquifer models. The water-budget domain includes all of layers 5-7 in the Peabody Western Coal Company Model, all of layer 1 in the US Geological Survey model, and the portion of layer 5 in the Western Navajo Hopi N aquifer model that coincides with the areal extent of the US Geological Survey model.

the PWCC model simulates considerably more leakage from the D aquifer to the N aquifer for the same area as is represented by the other two water budgets. Finally, the WNHN model simulates a significant amount of net lateral flow out of the USGS model domain. Some of the no-flow boundaries of the USGS model were designed to coincide with flow lines that might have been inferred from contour maps of observed water-level data. The fact that there is a significant amount of simulated net flow out of the USGS model domain within the WNHN model indicates that the USGS model boundaries do not coincide with flow lines being calculated by the WNHN model.

Evaluation of the Technical Design and Calibration of Model Most Appropriate for use by the EIS Team

Because of the limited areal extent of the USGS model, the inconsistencies of the layer surface arrays in the WNHN model, and because neither of these models use the STR, SFR1, or SFR2 packages to simulate streams, the PWCC model (Tetra Tech, 2014) is the most appropriate existing groundwater flow model for use by the NGS-KMC EIS team. This evaluation provides comments on the aspects of the design of this model including the MODFLOW version used; model grid dimensions and discretization; time discretization; internal and perimeter boundary conditions, including a separate section on recharge; aquifer storage properties and hydraulic diffusivity; and model calibration.

MODFLOW Version Used

The PWCC model uses MODFLOW-NWT, which is a version of the USGS MODFLOW-2005 code that uses the Newton-Raphson formulation to improve solution of unconfined groundwater-flow problems (Niswonger and others, 2011). Application of MODFLOW-NWT is appropriate in hydrogeological settings such as the combined D and N aquifer system in the area of Black Mesa. Use of the PWCC model using MODFLOW-NWT resulted in numerically stable results for any test runs done as a part of the analyses described in this report. The PWCC model using MODFLOW-NWT likely will perform well for projection runs done by the NGS-KMC EIS team.

Model Grid

The model grid in the PWCC model (Tetra Tech, 2014) is the same as was used in the earlier version of the model (Peabody Western Coal Company, Inc., 1999). The horizontal grid consists of 145 rows and 175 columns of finite-difference cells. Grid dimensions are non-uniform, with the smallest cell sizes of 1,640 ft by 1,640 ft near the PWCC well field, and the largest cell sizes of 24,606 ft by 24,606 ft in the southeastern part of the model. The grid is rotated counter-clockwise 45 degrees about the northwest corner of the grid, which corresponds to row 1, and column 1 of the grid.

The model grid consists of seven layers, each representing a different hydrostratigraphic unit (HSU) in the aquifer system. Model layer 1 represents the shallowest part of the aquifer system and layer 7 represents the deepest part. The seven model layers and corresponding HSUs are as follows:
Layer 1– Dakota Sandstone
Layer 2– Morrison Formation
Layer 3– Cow Springs Sandstone and Entrada Sandstone
Layer 4– Carmel Formation
Layer 5– Navajo Sandstone
Layer 6– Kayenta and Moenave Formations
Layer 7– Wingate Formation
Layers 1–3 make up the D aquifer and layers 5–7 make up the N aquifer. Layer 4 is a confining unit that separates the D and N aquifers. HSUs not simulated as model layers include the Mancos Shale and the Mesa Verde Group above Layer 1, and the Chinle Formation below layer 7. Both the Mancos Shale and Chinle Formation are confining layers that have an effect of restricting movement of water between adjacent aquifers.

In the horizontal and vertical dimensions, the PWCC model grid provides ample resolution to simulate groundwater flow in the aquifer system. A reasonable model probably could be constructed with coarser minimum cell sizes, but the sizes used in the PWCC model allow for more accurate representation of locations such as wells, springs, streams, evapotranspiration areas, and other features such as extents of HSUs. Similarly, fewer model layers could have been used to simulate the aquifer system. For example, the USGS and WNHN models used a single layer to represent the N aquifer. The WNHN model also used one layer to represent the D aquifer, but used three layers to represent the Carmel Formation. Possible negative aspects of the finer vertical discretizations for the D and N aquifers in the PWCC model are increased simulations times and difficulties in reaching a stable numerical solution. The PWCC model run times, however, are manageable and the original model runs and test runs made for this evaluation reached stable numerical solutions. The finer resolution of the Carmel Formation using three model layers in the WNHN model allows for a better approximation of the timing of head and storage changes in the unit and flow through the unit in response to changes such as pumping in the overlying and underlying units. The benefit of the additional vertical resolution of the confining unit, however, diminishes with time since the onset of increased pumping in an adjacent aquifer. For example, timing in release of water from an adjacent confining unit over periods of a few hours or days after the onset of pumping is best approximated using multiple layers to represent the confining unit. After longer periods, however, representation of the confining unit as a single model layer may result in reasonable estimates in release of water from the confining unit. Other than the WHNW model, no tests of effects of confining-unit vertical discretization have been run using models that include the Carmel Formation, but results of simulations of this HSU with a single model layer may be similar to results using three or more model layers for transient simulation times in the range of years to decades.

Time Discretization

Initial conditions for the PWCC model in January 1956 were assumed to be steady-state. Those conditions were obtained by running a transient model without any changes in boundary conditions for a thousand-year period. The calculated heads from that simulation were used as starting heads for the PWCC transient model run, which simulates the time period from January 1956 through December 2012. This period is broken up into 58 stress periods, all of which are 1 year in length except for two half-year stress periods that were used to simulate calendar year 1985, when there was a significant reduction in groundwater pumping in the coal-lease area. Simulation time was further broken down to four 3-month time steps within each 1-year stress period and four 1.5-month time steps within the two half-year stress periods. The time discretization appears to be adequate for the PWCC transient model run documented by Tetra Tech (2014). Simulation with a coarser time resolution may have been possible, but that would not have improved any aspect of the model other than model run times.

Recharge

Recharge from precipitation in the PWCC model was based on the recharge distribution used in the previous model (Peabody Western Coal Company, Inc., 1999), which was calculated using an approach similar to the Maxey-Eakin method. For the PWCC model, three zones were added so that multipliers could be used to reduce recharge, which reduces calculated heads, in some areas and increase recharge, which increases discharge to surface water, in other areas. The resulting distribution of recharge, shown in figure 3, was used in the predevelopment simulation and was held constant throughout the transient simulation. Total recharge within the model domain was about 12,200 acre-ft/yr.

As a part of this evaluation, recharge for the PWCC model active area was calculated using the Basin Characterization Model (BCM; Flint and Flint, 2008). The BCM is a distributed-parameter water-balance model that estimates in-place runoff and in-place recharge for 270-meter grid cells. Parameters in the equations include monthly estimates of precipitation, maximum and minimum air temperature, and potential evapotranspiration. For more details on the BCM, see Flint and Flint (2008). The 1940–2008 average in-place recharge rate calculated by the BCM for the active area of the PWCC model not overlain by the Mancos Shale was about 13,900 acre-ft/yr. That amount of recharge is distributed over the active area of the PWCC model as is shown in figure 4. Yearly BCM total in-place recharge for the PWCC model active area and precipitation at Tuba City for years 1940–2008 are shown in figure 5.

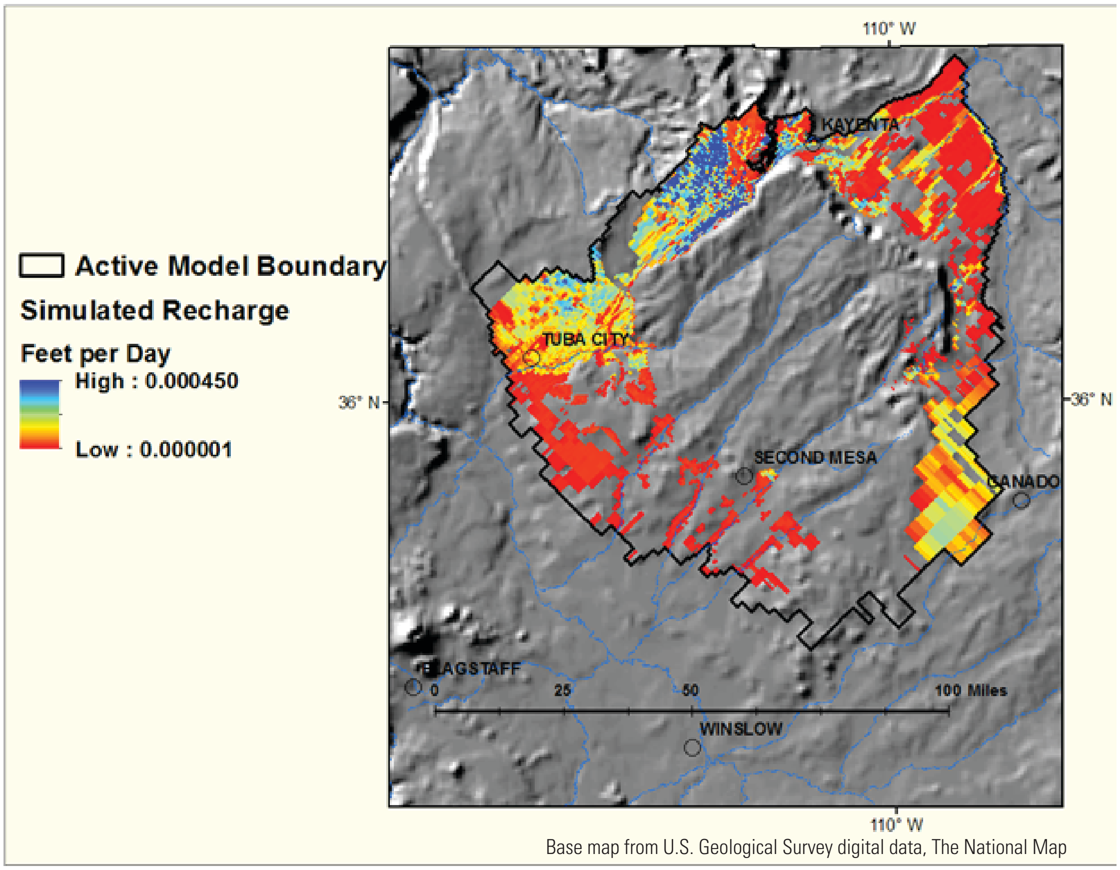

Figure 3. Distribtion of recharge from precipitation simulated in the Peabody Western Coal Company model. Areas in the active model boundary with no color in the range of the color bar have zero simulated recharge from precipitation.

These simulated results show the episodic nature of recharge in the study area.

Prior to publication of the PWCC model, Tetra Tech (2014) reran the model using the BCM-calculated recharge distribution shown in figure 4. Overall results were similar to results from the run with the recharge distribution shown in figure 3, with improvements in model fit of head and flow observations in some areas and degraded fits in other areas. Recalibration of the model with the BCM recharge distribution, however, was beyond the scope of the Tetra Tech (2014) model effort. For a more detailed comparison of results using the original PWCC model recharge and BCM recharge, see section 4.3 "Comparison to BCM Recharge" in Tetra Tech (2014). Recharge is difficult to estimate with certainty for most groundwater systems, and the total long-term average recharge estimates of 12,200 acre-ft/yr and 13,900 acre-ft/yr by Tetra Tech (2014) and BCM, respectively, are fairly close. A different recharge distribution in a model will not affect the timing of calculated responses to pumping unless the change in recharge results in a change in hydraulic diffusivity or configuration of the boundary conditions. In the PWCC model, changing from the original recharge distribution to the BCM recharge distribution likely would result in only minor differences in simulated responses to pumping. Use of the PWCC model by the NGS-KMC EIS team with the original recharge distribution therefore is reasonable. For future models of the D and N aquifers in the Black Mesa area, use of time-varying recharge distributions calculated by BCM or another water-balance model would allow for better separation of climatic and human-caused effects on groundwater levels and flow in springs and streams. Use of time-varying recharge also could help in the calibration of aquifer storage properties.

Other Boundary Conditions

In groundwater models that are used to assess the effects of pumping, significant hydrologic features such as streams, springs, and groundwater evapotranspiration areas should be represented using an appropriate head-dependent boundary. MODFLOW packages commonly used to represent these features include Drain, River, Stream, Streamflow Routing version 1, Streamflow Routing version 2, and Evapotranspiration Packages. Failure to represent a groundwater discharge feature in a model would mean that calculated drawdown and the timing and locations of capture from nearby pumping would be incorrect.

In the PWCC model, streams and springs that contribute directly to streamflow are represented with the Streamflow-Routing Package, version 2 (Niswonger and Prudic, 2005);

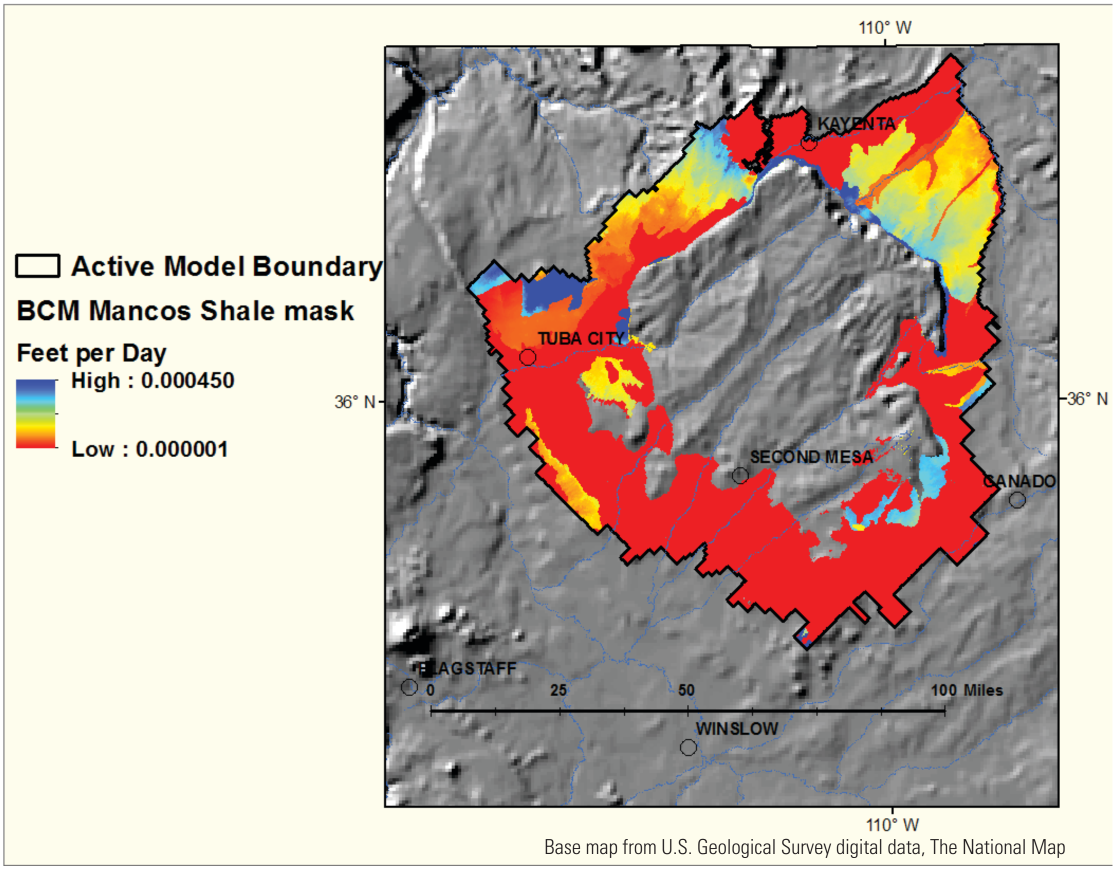

Figure 4. Distribution of 1940-2008 average recharge from precipitation calculated by Basin Characterization Model (BCM). Areas in the active model boundary with no color in the range of the color bar have zero computed recharge from precipitation.

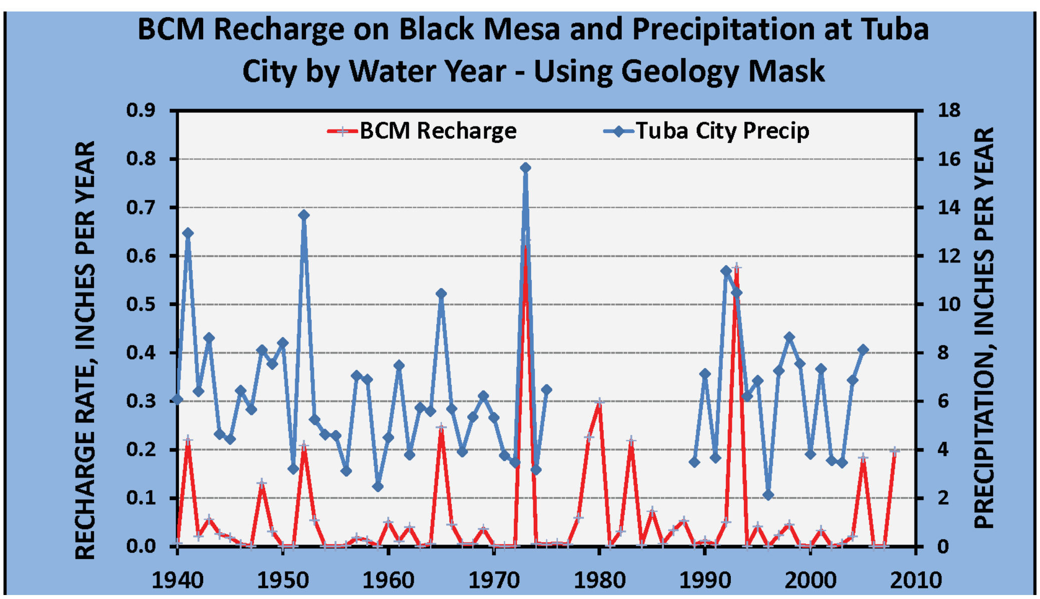

Figure 5. Yearly basin characterization model recharge in the Peabody Western Coal Company active model area and precipitation at Tuba City, 1940-2008.

other springs and seeps were simulated using the Drain Package; and evapotranspiration along washes was simulated using the Evapotranspiration Package. This combination of MODFLOW packages used to represent real hydrologic features leads to improved simulation capabilities in comparison to previous models including the original PWCC (1999) model, the USGS model, and the WNHN model. In particular, use of the Streamflow-Routing and Evapotranspiration Packages will allow for improved simulation of responses to pumping from the N and D aquifers.

In constructing a groundwater model, care must be taken to not include artificial boundaries that can affect the calculation of drawdown or capture from simulated pumping. Ideally, model boundaries should represent real features such as rocks of low permeability that are laterally or vertically adjacent to the aquifer. With many groundwater models, however, artificial boundaries are used to simulate a domain that is smaller than the actual extent of an aquifer. Reilly and Harbaugh (2004) state, "When physical hydrologic features that can be used as boundary conditions are far from the area of interest, artificial boundaries are sometimes used. The use of an artificial boundary should be evaluated carefully to determine whether its use would cause unacceptable errors in the model." Table 1 shows the types of artificial boundaries commonly used to limit the extent of a model, and the effects that those boundary conditions can have on the calculation of drawdown and storage change, and capture from real physical features such as streams, springs, wetlands, and evapotranspiration areas.

Artificial boundaries in the PWCC model have been identified on figure 1. Lateral perimeter boundary segments are denoted with red dashed line segments labeled A–F. According to Chris Gutman (Tetra Tech, oral commun., September 2015) boundary segments A and C are artificial no-flow boundaries that correspond to suspected groundwater divides or flow lines. Boundary segment B is a mixed no-flow/specified-flow boundary. Three injection wells in model layer 5 along this boundary provide additional inflow to the model to help calibrate calculated head in this part of the model. Boundary segment D is a head-dependent flow boundary in model layer 5 simulated with the Drain Package. This boundary simulates flow to springs and seeps in canyons to the northwest of this segment, outside of the model domain. Boundary segment E includes some head-dependent flow boundary cells in layers 5 and 6, simulated with the General-Head Boundary Package. The intent of this boundary is to simulate groundwater underflow across the edge of the model domain in the area of the confluence of Laguna Creek and Chinle Wash. Segment F is a mixed no-flow and head-dependent flow boundary. The lateral extent of the model in this area is defined by the edge of active cells in model layers 6 and 7. Along this segment, Chinle Wash is represented with the Streamflow-Routing Package, version 2 at select cells in layers 6 and 7. Groundwater flow and changes in groundwater flow under Chinle Wash is not allowed by the configuration of this boundary. Boundary segments not denoted with a red dashed line on figure 1 are thought to correspond with the edge of saturated parts of the N aquifer. These segments are represented as no-flow boundaries in the model. The green hachured area on figure 1 corresponds to an artificial boundary designed to simulate flow through the Mancos Shale to the D aquifer, using the River Package. For simulation of transient changes in flow, this is an artificial boundary that does not account for storage changes in the Mancos Shale or ultimate effects of changes in flow in HSUs above the Mancos shale.

Table 1. Types of artificial boundaries commonly used to limit the extents of the simulated domains in models of groundwater flow.

Type of artificial boundary	MODFLOW package(s) typically used to simulate boundary	Common justifications for using artificial boundary type	Possible negative effect(s) of artificial boundary on calculated drawdown and storage change for simulation of groundwater withdrawal	Possible negative effect(s) of artificial boundary on calculated capture and streamflow depletion for simulation of groundwater withdrawal
No-flow	Basic	A groundwater divide or flow line is an effective no-flow boundary	Overestimation within the simulated model domain	Overestimation within the simulated model domain
Specified-flow	Well	The rate of groundwater flow between a part of an aquifer and an adjacent part of an aquifer is assumed to be known	Overestimation within the simulated model domain	Overestimation within the simulated model domain
Constant-head	Constant-Head, Basic	Head along a boundary segment is assumed to be known from contours of measured groundwater levels	Underestimation within the simulated model domain	Underestimation within the simulated model domain
Head-dependent flow	General-Head, Drain, River	Flow to or from adjacent area can be approximated with function Q=f(h), where Q is flow across segment, and h is computed head at the boundary segment	Underestimation or overestimation within the simulated model domain, depending on the hydraulic conductance of the boundary	Underestimation or overestimation within the simulated model domain, depending on the hydraulic conductance of the boundary

The artificial boundaries in the PWCC model are of types that are commonly used to limit the extent of a model to a manageable size. The placement and types of the artificial boundaries do not seem to limit the usefulness of the model for evaluating effects of pumping in the coal-lease area. If this model is used for assessments of effects of pumping throughout the model domain, effects of the artificial boundaries should be assessed. Ideally, there should be little or no drawdown around artificial no-flow or specified-flow boundaries, and there should be no or small changes in flow to or from artificial head-dependent boundaries.

Aquifer Storage Properties and Hydraulic Diffusivity

Physical processes that result in increase and decrease in storage of water in the D and N aquifers and confining units in the study area include filling and draining pore spaces at the water table, expansion and compression of the sediment skeleton, and expansion and compression of water. In the MODFLOW-NWT Upstream Weighting Package used in the PWCC model, specific yield is the aquifer storage property relating to draining and filling of pore spaces at the water table and specific storage is the property relating to compression and expansion of the sediment skeleton and water.

Specific yield in the PWCC model was set to 0.1 everywhere except for a zone in layer 5 where a value of 0.13 was used. Both the USGS and WNHN models used a value of 0.1 for specific yield for all aquifers and confining units simulated. Values of specific yield in the PWCC model are largely consistent with previously modeled values and are in a reasonable range for aquifers in the study area.

A specific storage value of 3.05×10^{-7} ft^{-1} was specified for all active cells in the PWCC model. MODFLOW-NWT uses this storage property for any cells in which head is above the top of the cell—otherwise, specific yield is applied. The WNHN model used a value of 1×10^{-7} ft^{-1} throughout that model domain. The specific storage in the USGS model cannot be readily obtained because the storage property specified in that model is the product of specific storage and aquifer thickness. Specific storage can be broken up into skeletal and water components as follows:

$$S_s = S_{sk} + S_{sw} \, ,$$

where S_s is total specific storage, S_{sk} is skeletal specific storage, and S_{sw} is water specific storage. S_{sw} can be calculated as follows:

$$S_{sw} = \theta \gamma_w / E_w \, ,$$

where θ is porosity; γ_w is the unit weight of water, 62.4 pounds per cubic foot (lb/ft^3);and E_w is the bulk modulus of elasticity of water, 3.5×10^{7} pounds per square foot (lb/ft^2). Using the above equation with an assumed porosity of 0.2 results in an S_{sw} of 2.77×10^{-7} ft^{-1}, and a porosity of 0.25 results in an S_{sw} of 3.47×10^{-7} ft^{-1}. Assuming that 0.2–0.25 is a reasonable range for porosity of unweathered rocks in the model domain, the total specific storage value in the PWCC model, 3.05×10^{-7} ft^{-1}, accounts for the process of expansion and compression of water, but not of the sediment skeleton. A slightly larger value that accounts for some compressibility of the sediment skeleton in aquifers and confining units as well as of water may have been better. An effect of a storage property that is too low is that drawdown from pumping will propagate faster than it would with a correct higher storage property. If, on the other hand, porosity is lower than 0.2, the specific storage value used in the PWCC model will account for compressibility of the sediment skeleton as well as of water in the pore spaces.

Hydraulic diffusivity is the key parameter that controls the rate of propagation of drawdown and other changes in head from system stresses such as removal or addition of groundwater. In a system dominated by horizontal groundwater movement, hydraulic diffusivity is defined as

$$D = K_h b / S_s b \, ,$$

where D is hydraulic diffusivity, K_h is horizontal hydraulic conductivity, and b is aquifer thickness. The product of K_h and b, transmissivity, is commonly estimated by aquifer tests. The diffusivity equation applies where head in the aquifer is above the top of the aquifer. In areas where unconfined conditions exist, $S_s b$ in the denominator should be replaced with S_y (specific yield). Where vertical flow exists, the ratio K_v / S_s, where K_v is vertical hydraulic conductivity, also may be an important parameter that affects the rate of propagation of changes in head in the vertical direction. For this study, an evaluation of simulated aquifer diffusivity in the PWCC and USGS models was carried out for cells within a 20,000-ft radius of well NAV8 in the coal lease area (table 2 and fig. 1). In table 2, values are given for layers 1–7 of the PWCC model, and values of certain properties are summed for layers 5, 6, and 7, which make up the N aquifer in that model. The row in table 2 that sums PWCC-model properties for layers 5–7 can be compared to the last row in the table, which corresponds to the N aquifer in the USGS model. The Elastic storage coefficient for the PWCC model is calculated as the product of specific storage and aquifer thickness. In the USGS model, the elastic storage coefficient was read directly into the Block-Centered Flow Package. The 20,000-ft radius encompassed 460–466 active cells for each of layers 1–7 of the PWCC model and 58 active cells for layer 1 of the USGS model. The two models indicate some differences in transmissivity and storage coefficient in this region, but the average diffusivity values of about 1.58×10^{6} ft^2/day and 1.46×10^{6} ft^2/day for layers corresponding to the N aquifer in the PWCC and USGS models, respectively, are fairly close.

Model Calibration

The PWCC model was calibrated using both manual and automatic methods. For details on the calibration procedures

Table 2. Arithmetic averages of select aquifer properties within a 20,000-foot radius of well NAV 8.

[ft, feet]

Model layer	Aquifer thickness (ft)	Horizontal hydraulic conductivity (ft/day)	Transmissivity (ft^2/day)	Specific storage (ft^{-1})	Specific yield, dimensionless	Elastic storage coefficient, dimensionless	Diffusivity (ft^2/day)
PWCC							
1	153.18	0.152974	23.43	3.05×10^{-7}	0.1	4.67×10^{-5}	501,554
2	509.91	0.001773	0.9	3.05×10^{-7}	0.1	1.56×10^{-4}	5813
3	428.32	0.027836	11.92	3.05×10^{-7}	0.1	1.31×10^{-4}	91,266
4	134.78	0.01303	1.76	3.05×10^{-7}	0.1	4.11×10^{-5}	42,721
5	791.58	0.431983	341.95	3.05×10^{-7}	0.1	2.41×10^{-4}	1,416,338
6	223.1	0.0003	0.07	3.05×10^{-7}	0.1	6.80×10^{-5}	984
7	290.73	0.05	14.54	3.05×10^{-7}	0.1	8.87×10^{-5}	163,934
5+6+7	1,305.41		356.56[1]			3.98×10^{-4}	1,581,256
USGS							
1	981.9	0.588453	576.38		0.1	3.94×10^{-4}	1,462,893

[1]Transmissivity shown here is the sum of average transmissivity values for layers 5, 6, and 7.

and statistical results of matching targets of head and flow quantities, see section 3 of Tetra Tech (2014). Sensitivity analyses are detailed in section 4 of that report. Automatic calibration was carried out using programs PPEST (Doherty, 1998) and PEST (Doherty, 2013). For this procedure hydraulic property zones throughout the model domain were used. For the Navajo Sandstone, hydraulic conductivity was estimated with 19 pilot points at locations with prior information and an additional 20 or 21 pilot points at other locations. Quantitative calibration targets included hydraulic head in the D and N aquifers, drawdown in the N aquifer, particularly in and around the coal lease area, flow in streams and springs, and evapotranspiration rates inferred from a greenness index obtained from a Land Remote-Sensing Satellite (LANDSAT) image taken on June 13, 2005. Other information used in calibration included observations of flow patterns, lack of wet channels in areas devoid of phreatophytes, and locations of interaction of groundwater and surface water in Moenkopi Wash, Laguna Creek, Dinnebito Wash, Polacca Wash, and Begashibito Wash.

Given the complexity of the N and D aquifer system in the study area and the amount and types of data available, the calibration of the PWCC model described in Tetra Tech (2014) seems to be reasonable. Some general comments on the calibration are as follows:

1. As Tetra Tech (2014) points out, other combinations of parameters, zone geometries, and HSU configurations could have been evaluated. The model as configured is not unique. That, however, could be said about any model constructed with currently available data in the study area. Uniqueness of future models can be improved by continued data collection that helps define HSU geometry, aquifer and confining unit properties, and flow rates into, out of, and within the model domain.
2. As shown in figure 3.1-1 in Tetra Tech (2014), the calibrated Navajo Sandstone horizontal hydraulic conductivity distribution shows high and low values centered on some pilot points. The variation across the model domain, however, is smooth, with most values of the parameter within the relatively narrow range of 0.05–10 ft/day.
3. The average calibrated horizontal hydraulic conductivity in layer 5 within a radius of 20,000 ft of well NAV8 is about 0.43 ft/day (table 2). For comparison, the average horizontal hydraulic conductivity in this area in the USGS model is about 0.58 ft/day.
4. Observed streamflow in most of the major washes is simulated reasonably well. Of four major springs with observed discharge, two do not have simulated outflow in the calibrated model. In groundwater models, simulated water-table altitudes and hydraulic heads often are too high in some areas and too low in other areas. Where simulated heads are too low, simulated springs may not flow enough or may not flow at all. As noted in the section "Internal and Perimeter Boundary Conditions," springs need to be represented to properly simulate propagation of drawdown and changes in groundwater outflow from groundwater pumping. Any future work on the model should focus on getting all known simulated springs to flow in reasonable amounts.

According to Tetra Tech (2014) the recharge multiplier is the most sensitive parameter in the PWCC model. Other important parameters include the evapotranspiration multiplier, various horizontal and vertical hydraulic conductivity pilot point and zone values, and specific storage of the Navajo Sandstone. Future data collection that improves knowledge of aquifer properties and flow rates will allow the model to be improved. It would be possible to use the PWCC model to help guide data collection that would be the most efficient in improving the model.

Evaluation of Appropriate Post-Pumping Period for Analyses of Long-Term Aquifer Effects

The USGS and PWCC models were used for this evaluation. Two hypothetical analyses were carried out to help understand long-term effects of groundwater pumping in the PWCC coal-lease area. The extended-pumping analysis involved simulating effects of pumping for a period of 1,000 years, and the limited-pumping analysis involved pumping for a period of 80 years. For both analyses, all PWCC wells simulated in the PWCC model (Tetra Tech, 2014) were pumped at equal rates totaling 10,000 ft^3/day. The effects evaluated are changes in groundwater outflow, or "capture." Results and insights from these analyses are included in the following sections.

Jim Burrell (AECOM, written commun., September 12, 2014), stated that the interest is in a target duration that is defined by the maximum impact of pumping in the coal-lease area, rather than a period of time that includes further impacts after project pumping ceases. Project impact is presumed to include drawdown of water levels and capture of water from features including streams, springs, and evapotranspiration areas. In general, capture can include pumping-induced increased inflow to an aquifer as well as reduced outflow from an aquifer. In most aquifers, including the ones in the study area, there is little opportunity for groundwater pumping to increase inflow to an aquifer; most of the capture, therefore, is in the form of decreased outflow from the aquifer. The first type of capture that can be evaluated is referred to here as "global capture." For any given time, global capture is the rate at which groundwater pumping is supplied from reduced outflow and increased inflow from all simulated features such as springs, streams, and evapotranspiration areas. "Components of global capture" refer to capture from all of a particular type of boundary in a model, such as all springs, all streams, and all evapotranspiration areas. "Local capture" is the rate at which groundwater pumping is supplied from a particular feature or group of features of interest. It is important to realize that the timing of capture is strongly influenced by the distance from the pumping location to a feature from which capture can occur. The timing of local capture from any individual feature may be faster or slower than the timing of global capture, depending on the location of the feature relative to the location of groundwater pumping.

Extended-Pumping Analysis

The objective of this analysis is to see which groundwater outflow features will eventually be affected by pumping in the PWCC coal-lease area and to get a general sense of timing of those pumping effects. The timing of capture from a pumping well is a function of the aquifer geometry, hydraulic conductivity, storage properties, and geometry of features from which reductions in groundwater outflow can occur, including distances of those features from the pumping well. If an aquifer system responds linearly to groundwater pumping, the timing of capture is not a function of the well pumping rate and capture can be expressed as a fraction of the pumping rate (Barlow and Leake, 2012).

Results from this analysis in terms of global capture, expressed as a fraction of pumping rate, and major components of global capture for the PWCC and USGS models are shown in figures 6 and 7, respectively. A direct comparison of global capture for the two models is shown in figure 8. Both models indicate that the process of changing from groundwater storage to capture as the source of pumped water is a long process. After pumping for 1,000 years, the PWCC model indicates that slightly more than 50 percent of the pumping rate will come from capture, and the USGS model indicates that more than 60 percent of the pumping rate will come from capture (fig. 8). Although faster capture is indicated by the USGS model, both indicate that large rates of capture do not occur in short time periods such as one or two decades. In addition to different rates of capture, the relative rates of capture coming from different sources are dissimilar for the two models. For the PWCC model, most of the capture comes from reduced evapotranspiration, with a minor amount coming from reduced discharge to streams (fig. 6). With the USGS model, capture from streams is slightly more than capture from evapotranspiration (fig. 7). A reason for the difference is that streams in the PWCC model are simulated with the Streamflow-Routing Package and streams in the USGS model are simulated with the River and Drain Packages. If streams consist of isolated perennial reaches, then no capture of streamflow in these reaches can occur, even though streamflow depletion can occur. Simulating these configurations of streams with the River or Drain Package will result in unrealistically high calculated capture. If any streams are not continuous and through-flowing to the edges of the aquifer, the simulation approach taken by the PWCC model is correct. Neither model calculates an appreciable amount of capture from springs that are represented with the MODFLOW Drain Package.

Limited-Pumping Analysis

This analysis also was run with the PWCC and USGS models. A comparison of global capture calculated by the two models is shown in figure 9. Those results show the timing of the maximum effect in terms of global capture. Given

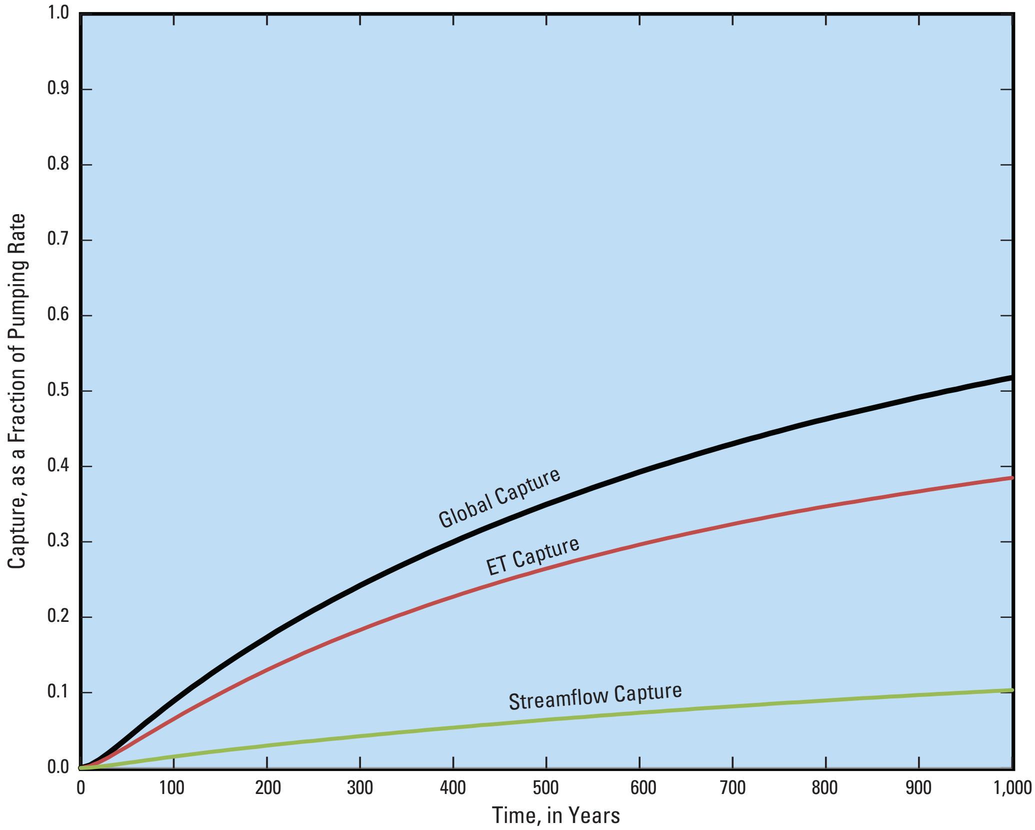

Figure 6. Capture results for the Extended-Pumping Analysis using the Peabody Western Coal Company model. Evapotranspiration (ET).

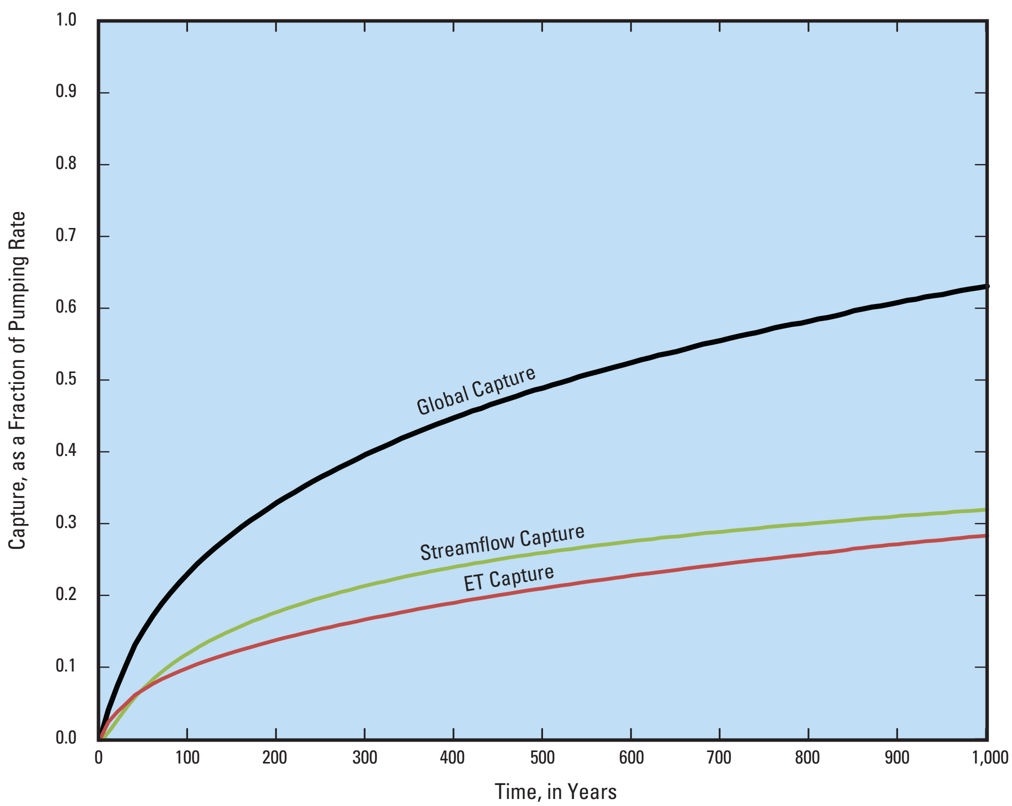

Figure 7. Capture results for the Extended-Pumping Analysis using the U.S. Geological Survey model. Evapotranspiration (ET).

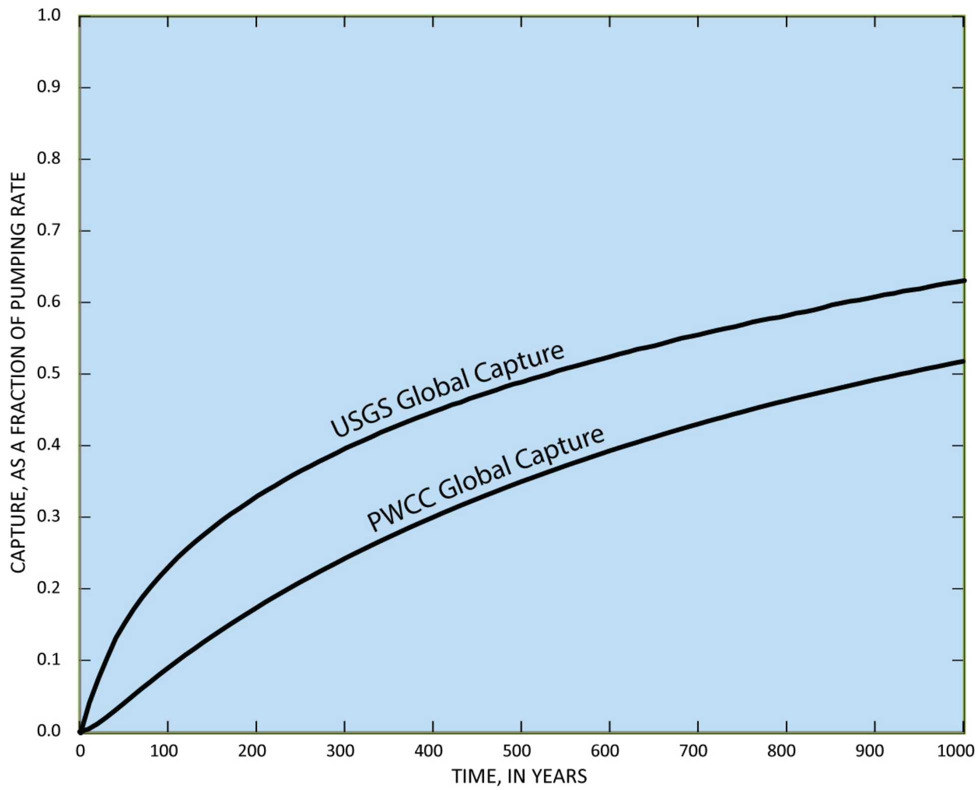

Figure 8. Comparison of global capture computed by the Peabody Western Coal Company and U.S. Geological Survey models for the Extended-Pumping Analysis.

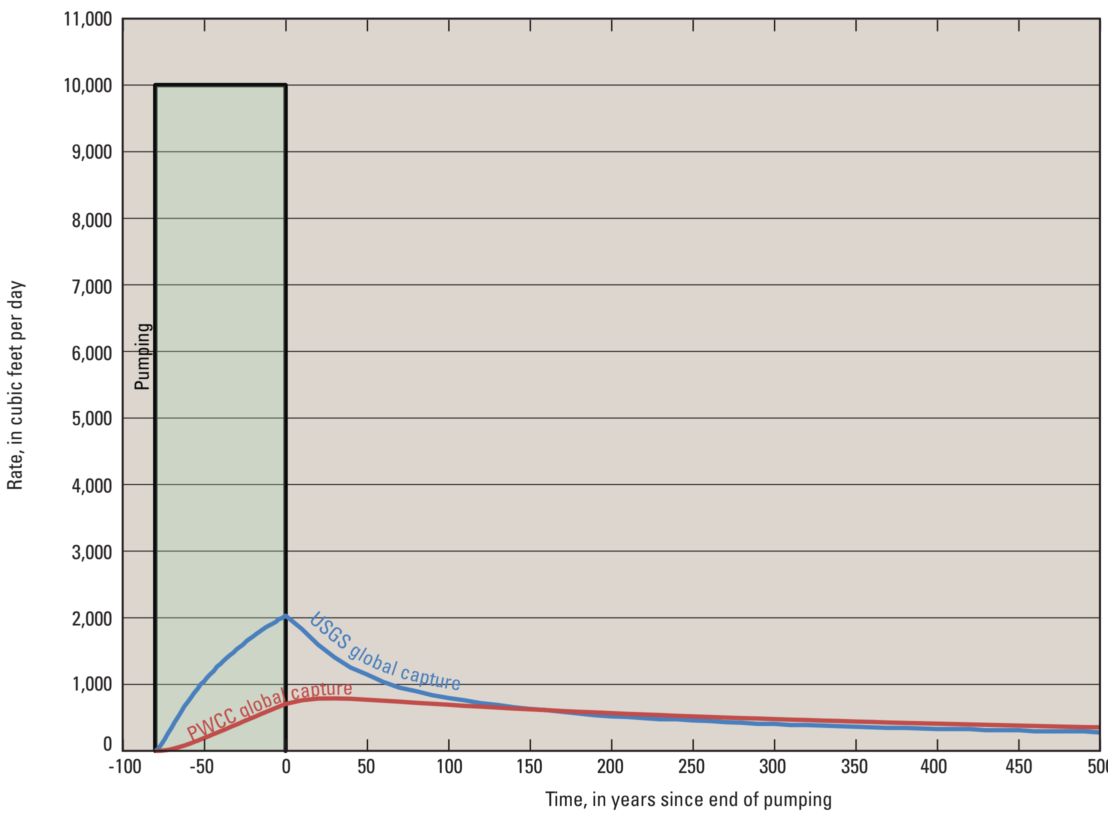

Figure 9. Comparison of global capture computed by the Peabody Western Coal Company and U.S. Geological Survey models for the limited-pumping analysis. In this scenario, all Peabody Western Coal Company mine wells were pumped at a total rate of 10,000 cubic feet per day and then shut off.

enough recovery time, the total volume of global capture will equal the total volume of groundwater pumped. For this analysis scenario, that volume was 292,200,000 ft^3 (about 6,700 acre-ft). For the PWCC model run of this scenario, the total volume captured through time was calculated (fig. 10). After 1,000 years since pumping stopped, slightly half of the volume pumped was accounted for as reduced outflow volume. This means that reduced outflow of almost half of the pumped volume will occur after 1,000 years beyond the cessation of pumping. To counterbalance the long time of residual effects of pumping (reduction of groundwater outflow), the calculated effects for any given time is a small fraction of the quantity of groundwater pumped (fig. 9). As was mentioned previously, the timing of local capture for any given stream, spring, or ET area can be different than the timing of global capture. For example, the maximum capture from a stream that is far from the pumping wells may occur at a much longer time than the time to maximum global capture. There is, however, an inverse relation between the magnitude of maximum capture and distance from the pumping wells. Features closest to the pumping wells are most likely to have significant amounts of capture. Evaluation based on timing of global capture is reasonable because effects on all streams, springs, and ET areas are integrated into a single value. In addition to that measure, analyses of effects of pumping also should look at pumping-induced changes in streamflow at key locations in the simulated stream network.

In the USGS model, maximum global capture occurs when pumping ends. This fast time to maximum capture likely is a result of the unrealistic boundary conditions used for streams. In the PWCC model, maximum global capture occurs about 30 years after pumping ends (fig. 9). If the intent of NGS-KMC EIS model runs is to determine maximum global capture from PWCC mine pumping, a post-pumping (recovery) analysis period of 50–100 years likely would be sufficient. Community pumping occurs at various locations within the model domain, and unlike mine pumping, community pumping is not likely to cease in the future. Evaluations of effects of community pumping on groundwater outflow will involve making model runs with projected pumping rates at known pumping locations and subtracting calculated outflow quantities from corresponding outflow quantities in a model run with community pumping set to zero.

Evaluation of Water Quality

Several USGS scientific reports have summarized water-quality monitoring in the Black Mesa study area for about the

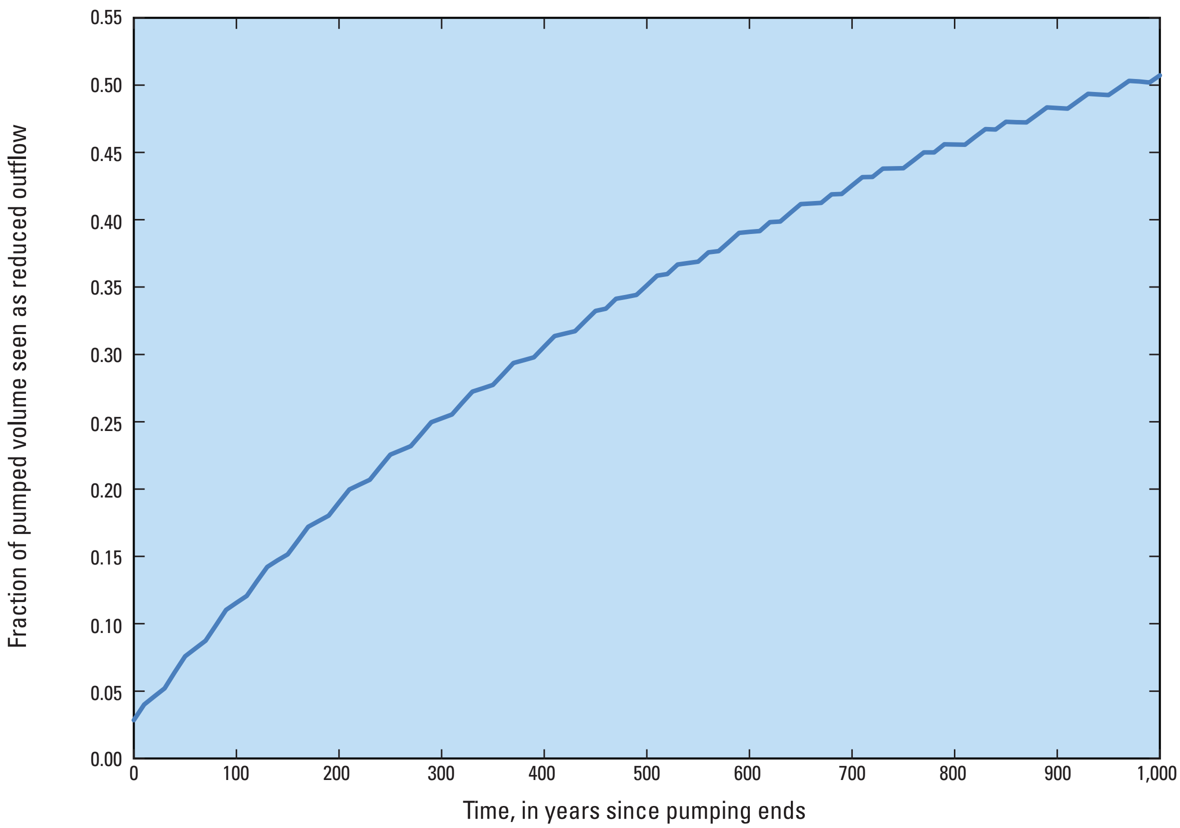

Figure 10. Fraction of the ultimate global caoture volume computed by the Peabody Western Coal Company model for the limited-pumping analysis.

past 40 years (appendix). Annual USGS reports as part of the USGS Black Mesa N Aquifer Monitoring Project document water-quality sampling on an annual basis. Specific conductance, dissolved solids, chloride, and sulfate are monitored on an annual basis because increased concentrations of these constituents in the N aquifer could indicate induced leakage from the overlying D aquifer caused by pumping in the N aquifer. The area of highest leakage occurs in the southern part of Black Mesa, where the N aquifer is thin, the confining layer (Carmel Formation) is less than 120 ft (37 m) thick, and the lithology of the Carmel Formation is more of a sandy-siltstone than a clayey-siltstone (fig. 11). Induced leakage from groundwater development during the last several decades could take centuries to detect geochemically because of the increased vertical difference between the potentiometric surface of the D and N aquifers, and possibly because of increases in the hydraulic gradient in the N aquifer that would increase flow rates, causing dilution (Truini and Longsworth, 2003). On average, the concentrations of dissolved solids in water from the D aquifer is about 7 times greater than that of water from the N aquifer; concentration of chloride ions is about 11 times greater, and concentration of sulfate ions is about 30 times greater (Eychaner, 1983). Long-term data for specific conductance, dissolved solids, chloride, and sulfate for the wells and springs sampled each year for the USGS Black Mesa monitoring project are presented in the annual reports. Additional USGS studies and accompanying reports have also documented water-quality conditions in the D and N aquifers. All water-quality information from USGS projects are stored in the USGS Water-Quality System (QWDATA) database and are available through the USGS National Water Information System website (available at http://waterdata.usgs.gov/nwis).

For this investigation, water-quality information that pertains to the PWCC Tetra Tech and HDR WNHN groundwater model boundaries was retrieved from the USGS QWDATA database and from USGS reports so that the data could be analyzed for trends. Increasing trends in specific conductance, dissolved solids, chloride, and sulfate in water samples from wells or springs in the N aquifer could indicate induced leakage from the overlying D aquifer due to pumping in the N aquifer. A site was analyzed for water-quality trends if 5 years of specific conductance, dissolved solids, chloride, and sulfate data were available for that site. Data for these sites were retrieved from the USGS GWSI and QWDATA databases and compiled in an Excel spreadsheet. Water-quality data were examined for completeness when compared to additional USGS reports to ensure that all available water-quality data are presented in the reporting of this task.

Water-quality data for total dissolved solids, chloride, and sulfate were plotted over time to look for potential trends and twenty-five well sites and four spring sites met the criteria that could indicate induced leakage from the D aquifer to the N aquifer. Statistical analyses used to determine if trends are present in the data included simple linear regression and Kendall's tau. If any trends were found within wells completed in the D and N aquifers, then further investigation using existing data occurred to determine the potential for vertical flow between aquifers, well installation, screening intervals and grouting, and changes in aquifer flow patterns.

Twenty-five well sites met the criteria of a minimum of 5 years of total dissolved solids, chloride, and sulfate data (table 3). Simple linear regression and Kendall's tau statistical analyses for these 25 wells revealed appreciable trends for increased total dissolved solids, chloride, and sulfate in well Shonto PM2, and increased total dissolved solids and chloride in well Keams Canyon PM2. Shonto PM2 is located in the unconfined part of the N aquifer (fig. 12) and, therefore, increasing trends would not indicate induced leakage from the overlying D aquifer. Keams Canyon PM2 is located in the southeastern part of the study area in the confined portion of the N aquifer. The confining layer, the Carmel Formation, in the area of Keams Canyon is between 80 and 100 ft (24 to 30 m) thick, and composed of a more sandy-siltstone rather than the clayey-siltstone observed in the northern part of the study area, where leakage has not been detected (fig. 11; Truini and Macy, 2005). Areas where the Carmel Formation is 120 ft (37 m) thick or less coincide with areas where isotopic ratios of $^{87}Sr/^{86}Sr$ and major-ion data for groundwater indicate that D aquifer water has mixed with N aquifer water as a result of leakage (Truini and Longsworth, 2003). Both the lithologic difference in, and the thickness of, the Carmel Formation near Keams Canyon indicate that leakage could be possible without effects from pumping.

Four spring sites met the criteria of a minimum of 5 years of total dissolved solids, chloride, and sulfate data (table 3). Burro Spring is the only one of the four springs that is found in the confined part of the N aquifer where the D aquifer is overlying, and therefore the only spring where effects from induced leakage of the overlying D aquifer from pumping could be expected. There are no appreciable trends found for sulfate, chloride, or specific conductance at Burro Spring based on simple linear regression and Kendall's tau (fig. 12).

Summary and Conclusions

The Lower Colorado Region of the Bureau of Reclamation is preparing an environmental impact statement for the Navajo Generating Station-Kayenta Mine Complex Project. The EIS includes evaluation of various groundwater-related alternatives that may have effects on the N aquifer, which is the principal water resource in the Black Mesa Basin. Groundwater from the N aquifer is used by the Navajo Nation and Hopi Tribal communities, as well as the Peabody Western Coal Company (PWCC). The USGS was asked by the Bureau of Reclamation to provide technical assistance to the NGS-KMC EIS team in several areas including spring inventory, evaluation of groundwater models, and evaluation of water-quality information. Some key conclusions from this study are outlined in the following paragraphs.

Three groundwater models evaluated for possible use by the NGS-KMC EIS team include the USGS model (Brown and

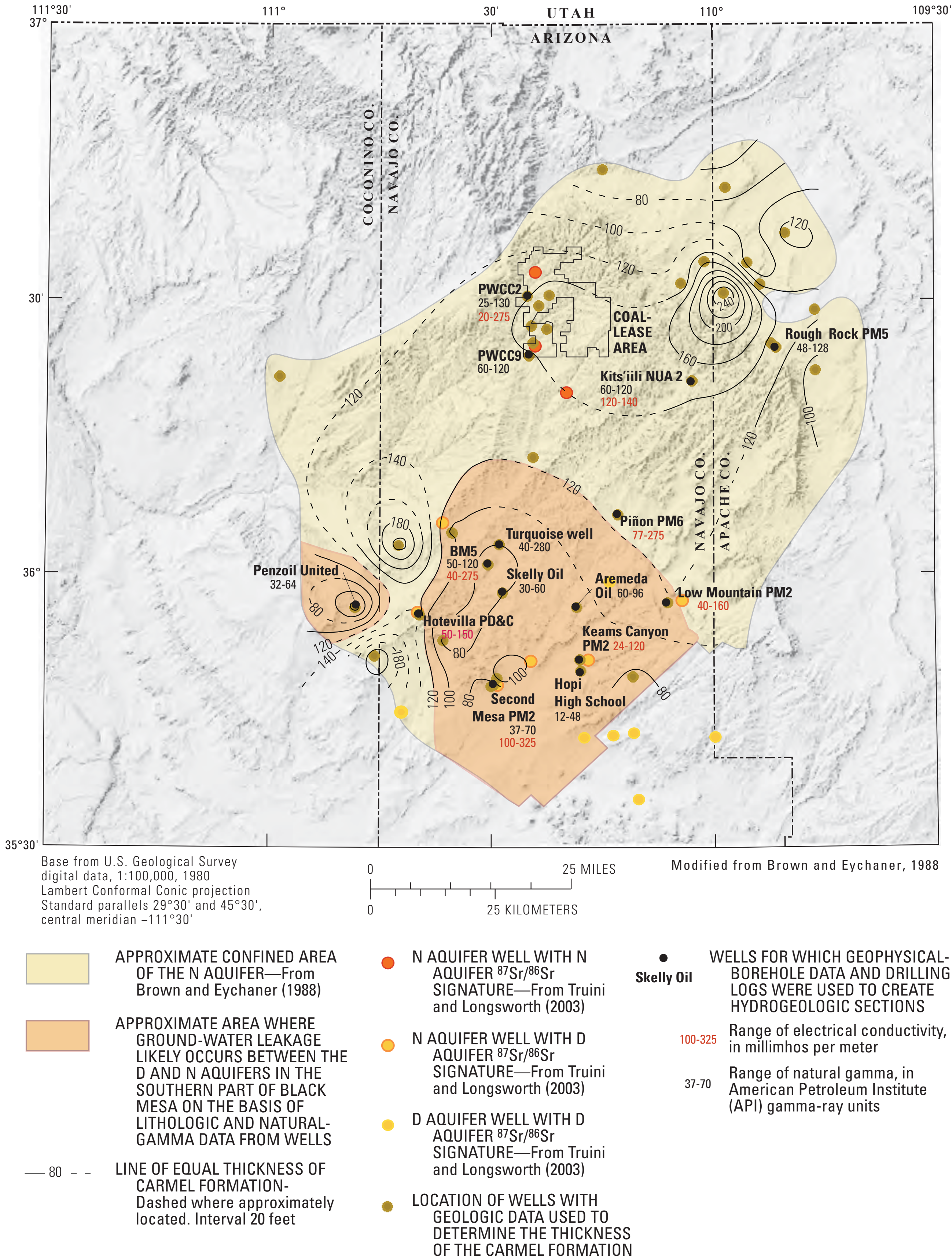

Figure 11. Thickness of the Carmel Formation, ranges of natural gamma and electrical conductivity from borehole-geophysical logs, and relative $^{87}Sr/^{86}Sr$ signatures, Black Mesa, Arizona (modified from Truini and Macy, 2005).

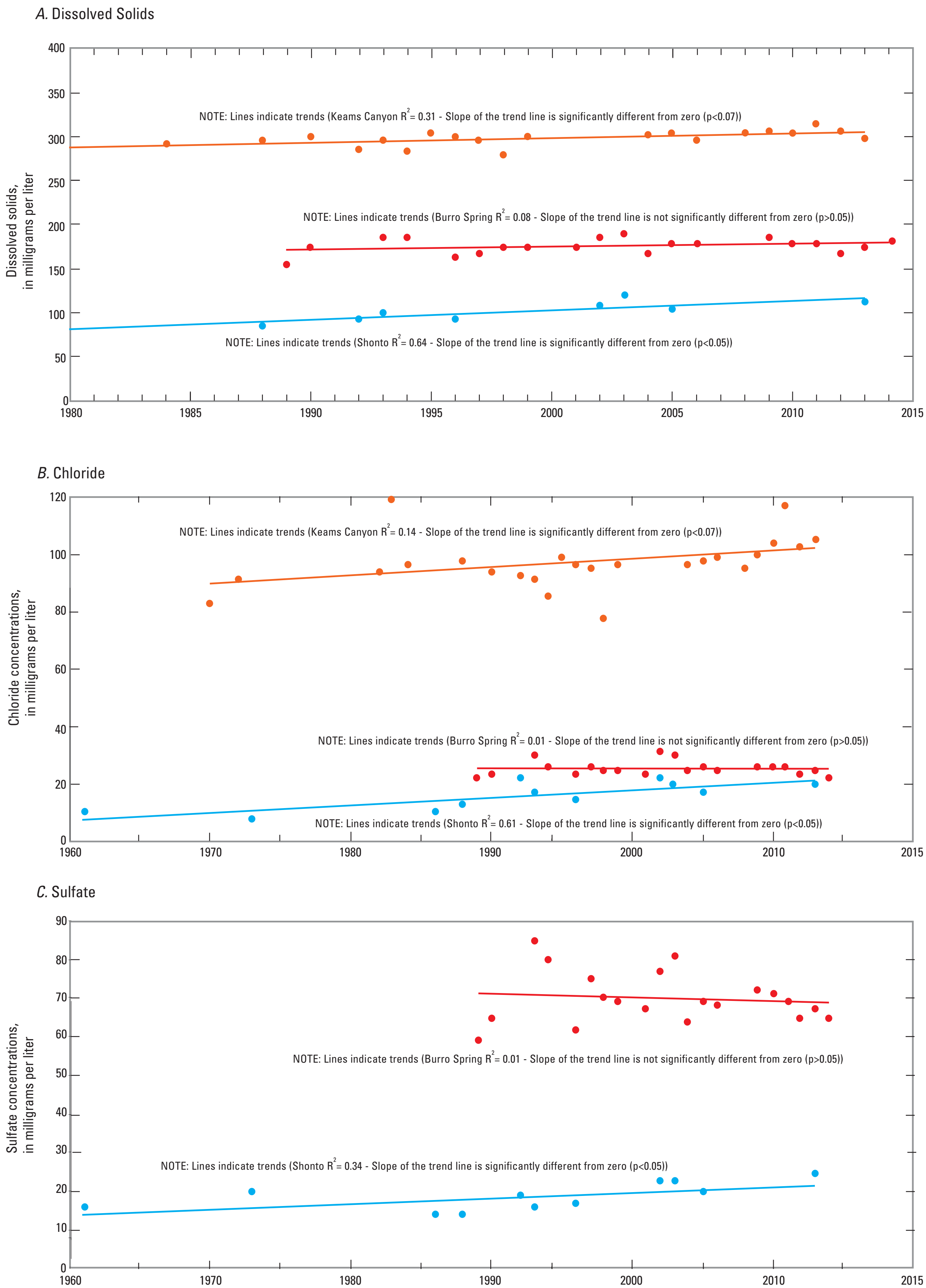

Figure 12. Concentrations of dissolved solids, chloride, and sulfate for water samples from Burro Spring, 1982–2013 *A*, Dissolved solids; B, Chloride; and C, Sulfate. Trend lines were generated by using the method of least squares.

Table 3. Site name and U.S. Geological Survey site ID for wells and springs with a minimum of 5 years of total dissolved solids, chloride, and sulfate water-chemistry data.

Site name	USGS site ID
Wells	
Second Mesa Day School	354749110300101
Keams Canyon PM2	355023110182701
Kykotsmovi PM1	355236110364501
Kykotsmovi PM2	355215110375001
Hotevilla	355518110400301
Low Mountain PM2	355638110064001
Rocky Ridge	360418110352701
Rocky Ridge PM3	360422110353501
Pinon PM6	360614110130801
Forest Lake NTUA1	361737110180301
Red Lake PM1	361933110565001
Kitsillie NTUA2	362043110030501
Chilchinbito PM3	363137110044702
Shonto PM2	363558110392501
Kayenta PM2	364344110151201
Dennehotso PM2	365045109504001
Glen Canyon National Recreation Area	365723111302801
PWCC 2	363005110250901
PWCC 3	362625110223701
PWCC 4	362647110243501
PWCC 5	362901110234101
PWCC 6	363007110221201
PWCC 7	362456110242301
PWCC 8	363130110254501
PWCC 9	362333110250001
Springs	
Moenkopi School Spring	360632111131101
Pasture Canyon Spring	361021111115901
Burro Spring	354156110413701
Unnamed Spring near Dennehotso	364656109425400

Eychaner, 1988), the WNHN model (HDR Engineering Inc., 2003), and the PWCC model (Tetra Tech, 2014). The USGS model was eliminated from consideration for use by the EIS team because it does not simulate groundwater flow in the D aquifer. The WNHN model cannot be used at present because of some problems with layer-surface arrays. The PWCC (Tetra Tech, 2014) model is a recently calibrated model that can simulate the effects of past groundwater development in the D and N aquifers in the Black Mesa area. In the horizontal and vertical dimensions, the PWCC model grid provides ample resolution to simulate groundwater flow in the aquifer system. This model has some artificial boundaries that limit its areal extent within the area of the N aquifer. Because of the limited areal extent of the USGS model, the inconsistencies of the layer surface arrays in the WNHN model, and because neither of these models uses the STR, SFR1, or SFR2 packages to simulate streams, the PWCC model is the most appropriate existing groundwater flow model for use by the NGS-KMC EIS team. The combination of MODFLOW packages used in the PWCC model to represent real hydrologic features leads to improved simulation capabilities in comparison to previous models including the original PWCC (1999) model, the USGS model, and the WNHN model. In particular, use of the Streamflow-Routing and Evapotranspiration Packages will allow for improved simulation of responses to pumping from the N and D aquifers. The placement and types of the artificial boundaries do not seem to limit the usefulness of the model for evaluating effects of pumping in the coal-lease area. Use of the PWCC model by the NGS-KMC EIS team, however, should include evaluations of the effects of these artificial boundaries on calculated drawdown and capture in areas of interest.

Evaluation of the PWCC model (Tetra Tech, 2014) involved consideration of aspects of the model including the MODFLOW version used, model grid, time discretization, recharge, internal and perimeter boundary conditions, aquifer storage properties and hydraulic diffusivity, and model calibration. This evaluation found no problems with the PWCC model that would preclude its use by the NGS-KMC EIS team. Given the complexity of the N and D aquifer system in the study area and the amounts and types of data available, the calibration of the PWCC model described in Tetra Tech (2014) seems to be reasonable. Observed streamflow in most of the major washes is simulated reasonably well.

An evaluation of long-term effects of hypothetical pumping in the coal-lease area was carried out to understand possible timing of capture. An extended-pumping analysis simulated pumping wells in the coal-lease area for a period of 1,000 years. The effect evaluated was "global capture," which is the reduced groundwater discharge to all springs, streams, and evapotranspiration. A limited-pumping analysis also was carried out. For those simulations, wells in the coal-lease area were pumped for 80 years and then shut off. Global capture was calculated for the period during pumping and for a period of 1,000 years after pumping stopped. Both the extended and limited pumping analyses were run with the PWCC and USGS models for comparison of the timing of effects. The USGS model calculated faster capture in both cases, most likely because of the boundary conditions used to represent streams. For the limited-pumping analysis, the PWCC model indicates that maximum capture occurs about 30 years after pumping stops. If the intent of NGS-KMC EIS model runs is to determine maximum global capture from PWCC mine pumping, a post-pumping analysis period of 50–100 years likely would be sufficient.

For future models of the D and N aquifers in the Black Mesa area, use of time-varying recharge distributions calculated by BCM or another water-balance model would allow for better separation of climatic and human-caused effects on groundwater levels and flow in springs and streams. Use of time-varying recharge also could help in the calibration of aquifer storage properties.

Analyses of trends in water quality were carried out for select sites in the study area. Sites were selected where 5 years of specific-conductance, dissolved-solids, chloride, and sulfate data were available. These data were plotted over time to look for potential trends. Twenty-five well sites and four spring sites met the criteria and were analyzed for trends in sulfate, chloride, and total dissolved solids that could indicate induced leakage from the D aquifer to the N aquifer. Statistical analyses to determine if trends exist included simple linear regression and Kendall's tau. A total of 25 wells had sufficient data for analysis, and of those, water-quality data from 3 wells indicated appreciable trends for increased total dissolved solids, chloride, and sulfate. The remaining 22 wells had no statistically significant trends in these constituents. Of four springs that had sufficient water-quality data for analysis, only one was in an area subject to pumping-induced increased leakage of poorer quality water into the N aquifer. Data from that spring did not indicate a trend in total dissolved solids, chloride, and sulfate.

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Appendix. U.S. Geological Survey Black Mesa Monitoring Reports

Year Published	Author(s)	Title	USGS Report Type and Number
1978	U.S. Geological Survey	Progress report on Black Mesa monitoring program—1977	Open-File Report 78–459
1985	Hill, G.W.	Progress report on Black Mesa monitoring program—1984	Open-File Report 85-483
1986	Hill, G.W., and Whetten, M.I.	Progress report on Black Mesa monitoring program—1985–86	Open-File Report 86-414
1987	Hill, G.W., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987	Open-File Report 87–458
1988	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1987–88	Open-File Report 88–467
1989	Hart, R.J., and Sottilare, J.P.	Progress report on the ground-water, surface-water, and quality-of-water monitoring program, Black Mesa area, northeastern Arizona—1988–89	Open-File Report 89–383
1992	Sottilare, J.P.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1989–90	Water-Resources Investigations Report 92–4008
1992	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1990–91	Water-Resources Investigations Report 92–4045
1993	Littin, G.R.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1991–92	Water-Resources Investigations Report 93–4111
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-quality monitoring, Black Mesa area, northeastern Arizona—1992–93	Water-Resources Investigations Report 95–4156
1995	Littin, G.R., and Monroe, S.A.	Results of ground-water, surface-water, and water-chemistry monitoring, Black Mesa area, northeastern Arizona—1994	Water-Resources Investigations Report 95–4238
1996	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1995	Open-File Report 96–616
1997	Littin, G.R., and Monroe, S.A.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1996	Open-File Report 97–566
1999	Littin, G.R., Baum, B.M., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1997	Open-File Report 98–653
2000	Truini, Margot, Baum, B.M., Littin, G.R., and Shingoitewa-Honanie, Gayl	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—1998	Open-File Report 00–66
2000	Thomas, B.E., and Truini, Margot	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona–1999	Open-File Report 00–453
2002	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2000–2001, and performance and sensitivity of the 1988 USGS numerical model of the N aquifer	Water-Resources Investigations Report 02–4211
2002	Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2001–02	Open-File Report 02–485
2004	Truini, Margot, and Thomas, B.E.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2002–03	Open-File Report 03–503
2005	Truini, Margot, Macy, J.P., and Porter T.J.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2003–04	Open-File Report 2005–1080
2006	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2004–05	Open-File Report 2006–1058
2007	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2005–06	Open-File Report 2007–1041
2008	Truini, Margot, and Macy, J.P.	Ground-water, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2006–07	Open-File Report 2008–1324
2009	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2007–2008	Open-File Report 2009–1148
2010	Macy, Jamie P.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2008–2009	Open-File Report 2010–1038
2011	Macy, Jamie P., and Brown, C.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2009–2010	Open-File Report 2011-1198
2012	Macy, Jamie P., Brown, C.R., and Anderson, J.R.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2010–2011	Open-File Report 2012-1102
2014	Macy, Jamie P. and Unema, Joel A.	Groundwater, surface-water, and water-chemistry data, Black Mesa area, northeastern Arizona—2011–2012	Open-File Report 2013-1304

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