Simulation of groundwater flow in the Madison and Minnelusa aquifers, Black Hills area

16 May 2013
U.S. Geological Survey, Rapid City, South Dakota
Principle Investigator: Andrew J. Long, PhD

Executive summary

The Madison and Minnelusa aquifers are critically important water resources that were a primary focus of the Black Hills Hydrology Study of the 1990s. These aquifers have a large influence on surface-water systems and provide the most important source of groundwater for municipal, domestic, agricultural, and industrial use in the area. Rapidly increasing demand from these aquifers may affect groundwater availability and surface-water resources.

This document describes a proposed study to construct a groundwater flow model of the Madison and Minnelusa aquifers for the Black Hills and surrounding area to help address hydrologic questions on local and regional scales. Several parties in the Black Hills area, including the National Park Service and the Black Hills National Forest, have sought answers to questions concerning groundwater—the primary water supply for this area. These questions are summarized by three questions of broad scope: (1) What is the influence of the regional aquifer on local groundwater flow? (2) What is the aquifer sensitivity in different areas to pumping and drought? (3) How might future data collection efforts be planned most effectively? These questions are difficult, or impossible, to answer objectively without rigorous quantification of numerous local and regional hydrologic influences on groundwater. A three-dimensional groundwater flow model for the Black Hills area would provide these estimates better than any other known method. The U.S. Geological Survey (USGS) previously has developed site-specific models of the Madison and Minnelusa aquifers for the Rapid City and Spearfish areas. The need for updated models in these and other areas is expected to continue in the future. For example, the National Park Service recently has expressed a desire for a groundwater model of the southern Black Hills.

Developing a regional groundwater flow model that includes the entire Black Hills area will have several benefits over a continuation of site-specific modeling efforts:

1. Developing a single regional model would be more cost effective than multiple smaller models.
2. Simulation of site-specific areas (e.g., Rapid City) is more accurate when placed within a regional flow model.
3. Artesian springs are critical water sources that capture groundwater from regional areas and thus are best simulated with a regional model.
4. The model grid can be modified for high-resolution simulations in any area of special interest or to answer specific hydrologic questions (e.g., the effects of pumping in a small area).

5. As additional future questions arise, other hydrologic scenarios can be cost-effectively evaluated without the need for new site-specific models.

Until recently, the success of developing a meaningful and useful model for the entire Black Hills area would have been questionable. Fourteen years of data collection have occurred since the Black Hills Hydrology Study resulting in a wealth of available data, and this combined with our improved conceptual understanding of groundwater flow in the area and the recently developed modeling capabilities make this effort now feasible. The model will be designed to address current objectives and hydrologic questions but also will have a generic underlying structure for adaptation to future objectives and model refinement. This model is envisioned as a long-term tool that will be available for numerous future studies and will symbiotically benefit multiple interested parties. Objectives are to (1) better understand the influence of regional groundwater flow on local groundwater; (2) assess the effects of pumping and drought on groundwater availability; and (3) help guide further data collection efforts.

If multiple interested parties contribute to this effort, the cost to any one party will be minimized, and all will benefit. For 2011 and 2012, the combined contributions from the National Park Service and the Black Hills National Forest were $101,650, or 11% of the total estimated cost of $960,000. Contingent on availability of funding through its Cooperative Water Program , USGS will plan to contribute matching funds for contributions from local or state governments in a ratio of at least 40 percent USGS funds to 60 percent local/state funds. The remaining funding will be spread over the next four years (2013-2016) or more, depending on annual funding levels. Several local agencies have expressed potential interest in participation, including the cities of Rapid City and Spearfish, Lawrence County, and the West Dakota Water Development District.

Introduction

The Madison and Minnelusa aquifers are critically important within the complex hydrogeologic framework of the Black Hills area. These aquifers were a primary focus of the Black Hills Hydrology Study of the 1990s for several reasons. These aquifers have a dominating influence on area surface-water systems in several critical settings (Driscoll and others, 2001) including (1) large springs in the headwaters of many major streams; (2) sinking streams, or loss zones, along the eastern flanks of the Black Hills where substantial groundwater recharge occurs; and (3) large artesian springs that provide stream base flow downstream from the Black Hills. These aquifers provide the most important source of groundwater for municipal, domestic, agricultural, and industrial use in the area. Rapidly increasing demand in numerous communities and suburban areas may affect groundwater availability and surface-water resources. Availability of groundwater varies with annual, decadal, or longer-term changes in climate. In response to climatic changes and possibly groundwater withdrawals, water levels for the Madison aquifer have changed by more than 100 ft in some places in less than a decade, both increasing and decreasing. Understanding groundwater flow is essential for assessing and managing groundwater resources. Numerical simulation of groundwater flow is the most common method for assessing the effects of multiple influences on aquifers, including groundwater use, natural spring flow, variability in precipitation and streamflow, population growth, long- and short-term climatic changes, and contaminant transport.

This proposal describes an approach for construction and application of a numerical groundwater flow model of the Madison and Minnelusa aquifers for the Black Hills and surrounding area. The overarching approach is to develop a generalized Black Hills flow model that will help to answer current hydrologic questions as well as to serve as the underlying framework for current and future focused studies and refined flow simulation in localized areas. Such a model will benefit multiple governmental agencies and other parties interested in water management, will be available for future studies, and could be refined and updated for any particular area of interest. Until recently, the success of developing a meaningful and useful numerical model for the entire Black Hills area would have been questionable. However, the current wealth of data for the area combined with the most recent modeling and optimization software and computing power, such as cloud computing, results in a high likelihood of success.

A wealth of new data useful for modeling has been collected since the Black Hills Hydrology Study was completed, which included data through 1998. New datasets include (1) 14 years of streamflow, spring flow, and groundwater levels for continuous gages and manual measurements, which adds an additional wet and dry cycle to the record; (2) multiple groundwater tracers (e.g., chlorofluorocarbons, stable isotopes, tritium, major ions) collected at about 70 sites and used to better characterize groundwater flow, conduit networks, and groundwater transit times; (3) microgravity measurements to estimate effective porosity and better characterize unconfined aquifer zones; and (4) several years of stable-isotope time-series data for selected wells and streams.

Problem

Local and federal agencies in the Black Hills area are seeking answers to questions regarding groundwater availability, the effects of current or future groundwater extraction or drought, the proportions of regional groundwater inflow and local recharge in particular areas, the capture zones of springs and wells, and the influence of springs and wells on flow directions and hydraulic gradients. These questions are difficult, or impossible, to answer objectively without a thorough quantification of myriad hydraulic influences and stresses on any given area. The influence of regional groundwater flow on local hydrologic responses is particularly difficult to quantify. A three-dimensional groundwater flow model would provide these estimates better than any other known method, but such a model does not exist for the entire Black Hills area. Without the availability of a calibrated regional model, smaller models would need to be developed independently to address issues in site-specific areas, which is an inefficient approach. Smaller areas for which models previously have been developed include part of the northern Black Hills (Greene and others, 1999) and the Rapid City area (Putnam and Long, 2009). Considering the complexity of the Black Hills hydrogeologic framework, the value of the water resources, and the abundance of hydrologic issues and questions, many needs for additional modeling efforts are foreseen in the near future. Developing one regional model has several advantages over developing separate smaller models for specific areas. These advantages are (1) it would be a more cost effective approach, (2) simulation of site-specific areas is more hydrologically accurate when nested within the context of regional flow, and (3) artesian springs capture groundwater flow from large, possibly regional, areas that can be simulated with a regional model but not with small-area models. The latter item is particularly important in the northern and southern Black Hills, where regional flow sweeps around the Black Hills toward the east and mixes with local recharge.

Objectives and scope

Study objectives are to (1) better understand the influence of regional groundwater flow on local groundwater; (2) assess the effects of pumping and drought on groundwater availability; and (3) help guide further data collection efforts.

The primary focus of the proposed model will be in and near the Black Hills where water from the Madison and Minnelusa aquifers is used extensively. Areas of complex hydrogeology, such as where Tertiary intrusive rocks have disrupted parts of the Madison and Minnelusa aquifers, will be simplified to a level that can be represented by the model. When constructing a model, one of the first considerations is the locations of boundaries, which frequently are set arbitrarily if a natural aquifer boundary, such as a recharge area, does not exist in proximity to the area of interest. These arbitrary boundaries generally are flux boundaries across which simulated groundwater flows horizontally through a cross-section of an aquifer. To minimize artificial boundary effects, flux boundaries will be set far from populated areas of interest and much wider than the limits of the Black Hills Hydrology Study (Figure 1). The focus area near the Black Hills (Figure 2) will have smaller model cells and will be given more weight in model calibration than other areas of the model.

Specifically, this model will be a three-dimensional numerical groundwater flow model for the Madison and Minnelusa aquifers in and near the Black Hills of South Dakota, constructed in MODFLOW (Harbaugh, 2005). The model for the Rapid City area (Putnam and Long, 2009) will be incorporated into the regional model, with a similar model cell size. Model grid cells will increase in size outside of the Rapid City area. Automated procedures for constructing the model from an independent geospatial database in ArcGIS will allow for efficient grid refinement in particular areas of interest for future focused modeling studies. These automated procedures will consist of utilities that interface between the geospatial database and MODFLOW. Hydrogeologic data or estimates, including aquifer tops, aquifer bottoms, potentiometric surfaces, well locations, recharge, and hydraulic conductivity, will be stored in the geospatial database.

The scope of the project includes a data-collection component, which will provide hydrochemical tracer data useful for calibrating the model to flow directions and groundwater mixing. The project consists of two phases: (1) a hydrogeologic framework and conceptual model and (2) a numerical groundwater flow model.

Previous investigations and available data

In developing numerical flow models, a large part of the effort involves collecting and analyzing data, constructing surfaces for aquifer tops, bottoms, and potentiometric surfaces, and so forth. However, as a result of various previous investigations, many of the basic data components necessary for developing a numerical flow model already exist. The Black Hills Hydrology Study (area shown in Figure 1) included numerous investigations that were summarized by Carter and others (2002; 2003) and Driscoll and others (2002). Other previous investigations with detailed information for focused areas of study in the northern, southern, and eastern Black Hills include Long and Putnam (2002), Putnam and Long (2007a 2007b; 2009), and Long and others (2008; 2012). Regional data beyond the Black Hills also are available from numerous other investigations listed in the "References Cited" section. Geologic maps and cross sections for the Black Hills are available from Strobel and others (1999) and Redden and DeWitt (2008).

Hydrologic questions to be addressed

What is the influence of the regional aquifer on local groundwater flow? The model will be used to assess and better understand regional groundwater flow in relation to the Black Hills area and the relative mixture of local recharge and regional flow, which might originate from as far away as the eastern flanks of the Rocky Mountains in Wyoming. This is of particular importance at the northern and southern tips of the Black Hills, where local and regional flow converges. The capture zones of artesian springs, the influence of these springs on the mixing of regional and local flow, and the relative proportions of regional and local spring flow will be assessed. Also, the converging and mixing of recharge on the western flank of the Black Hills with regional flow from farther to the west will be assessed.

What is the aquifer sensitivity in different areas to pumping and drought? The effects of increased groundwater demand as a result of potential population growth will be evaluated by simulating additional pumping from existing or hypothetical production wells. One transient simulation will be executed for each of 5 to 7 areas on the eastern side of the Black Hills between Spearfish and Hot Springs. Potential evaluation areas include Spearfish, Sturgis, Rapid City, Hermosa, Hot Springs, or other areas between these cities (e.g. near Whitewood, Summerset, or Buffalo Gap). The final selection of evaluation sites and pumping rates will be determined by consulting with project cooperators. A pumping period of 10 to 30 years will be simulated for each area (not to exceed the length of the transient calibration period). Declines in hydraulic head and spring flow as a result of the additional pumping will be evaluated. Artesian springs to be evaluated are described by Driscoll and Carter (2001, fig. 12 and table 2). Water table springs for the Madison aquifer to be evaluated include springs at the headwaters of streams on the western outcrop of the Madison Limestone (limestone headwater springs; Driscoll and Carter, 2001). At the end of the pumping periods, the simulated aquifers will be allowed to recover, and the recovery time for hydraulic head and spring flow will be evaluated for each of the pumping areas. Aquifer recovery will be simulated until full recovery is achieved. GWM is groundwater management process (Ahlfeld and others, 2005) developed for MODFLOW that might be useful for this purpose.

One or more drought periods similar to those that occurred in western South Dakota between 1930 and 1960 (Driscoll and others, 2000) will be simulated, and the resulting declines in hydraulic head will be shown on a map of the focus area, and spring-flow declines will be evaluated.

How might future data collection efforts be planned most effectively? Because data collection can be costly, an objective assessment of future groundwater data collection scenarios would be useful. Model predictive uncertainty analysis, as described in Doherty (2010) and Fienen and others (2010), will be used to assess possible scenarios. Specifically, this will indicate what new data would reduce the model's uncertainty if these data were acquired at some future time. Future revisions of the model, as well as other future hydrologic studies, will benefit from this assessment. GWM might be useful in this application.

Approach

The MODFLOW finite-difference groundwater flow modeling software will be used to construct the model and simulate groundwater flow (Harbaugh, 2005). The grid will be coarse near model boundaries (~15-km spacing) and finer within the focus area (300-500-m spacing; Figure 2). The highest resolution will occur in the Rapid City area, with a grid spacing of about 150 m. The coarse-gridded areas will have few model cells with a small effect on execution times but will minimize artificial boundary effects. One method for varying the size of grid cells is to vary the widths of model rows and columns in the desired area, as described in Harbaugh (2005). This method was used by Long and Putnam (2008) and Putnam and Long (2009). Another method is to use the Local Grid Refinement (LGR) capability that is now available for MODFLOW-2005 (Mehl and Hill, 2007). This option allows nested grids of fine resolution within an otherwise coarse-gridded model. Also, the USGS soon plans to release a new version of MODFLOW that allows for much more freedom in the structure of the model's grid and will allow grid cells to be almost any shape desired. For example, small triangular grid cells could be used for the Rapid City area and could increase in size outward in all directions. This versatility would easily accommodate small cells in any area of interest where high resolution simulation is desired.

The full extent of the Madison and Minnelusa aquifers in the model area will be simulated, each with two model layers, similarly to the approach of Putnam and Long (2009). Outside of the focus area, the Madison and Minnelusa aquifers each will be simulated as one layer unless additional information indicates benefits to simulating them with two layers each. The Englewood Limestone underlies and has similar properties to the Madison Limestone, and this formation will be combined with the lower Madison aquifer layer. Upward flow into the Madison aquifer layer from underlying aquifers will be simulated, but the model will not be calibrated for these underlying aquifers, which consist of the Whitewood, Winnipeg, and Deadwood aquifers. This method was used in the numerical model by Putnam and Long (2009). These three aquifers will be combined into one model layer, hereafter referred to as the *sub-Madison* layer and will be included in the model for the purpose of providing a lower model inflow boundary only. The rate of this flow component will be estimated by the method used by Long and Putnam (2002) for the eastern-central Black Hills, which was also was used in the numerical model by Putnam and Long (2009). This method uses Darcy's law and the difference in hydraulic head between the Madison and Deadwood aquifers to estimate a flow rate. This estimated flow rate will be assigned as recharge to outcrops of the Whitewood, Winnipeg, and Deadwood aquifers and allowed to leak upward into the Madison aquifer. As a minimum areal extent, the sub-Madison layer will be included below exposed areas of the Madison aquifer, with the option of a larger areal extent if necessary for upward flow.

Some of the Phase 1 tasks have been completed or are in progress. This proposal describes the project in its entirety, including completed tasks.

Phase 1—Hydrogeologic framework and conceptual model

A hydrogeologic framework will be assembled primarily on the basis of existing data from numerous sources (see References cited). The first step is to define the model area and hydrogeologic boundary conditions (e.g., head-dependent, no-flow, specified-flux, or constant-head boundaries). Figure 2 shows the approximate model area. The exact model area and focus area will be finalized after further examination of data and literature. The second step is to define altitudes of the tops and bottoms of the hydrogeologic units as they will be represented by model layers. The third step is to define general potentiometric surfaces for the hydrogeologic units. Fourth, recharge from direct precipitation and sinking streams, evapotranspiration, and discharge to springs and streams will be estimated on the basis of available data. Groundwater pumping will be obtained from publically available water use data (U.S. Geological Survey, 2011). If necessary, data on water permitting for South Dakota, Wyoming, and Montana will be acquired. Manual flow measurements will be made at selected springs and streams where continuous gages do not exist one or more times during the study and will be used as model calibration data. Geochemical data consisting of stable isotopes of oxygen and hydrogen ($\delta^{18}O$, $\delta^{2}H$) and major ions will be collected at sinking streams, wells, and springs for use as natural tracers. Samples will be analyzed at the USGS Isotope Laboratory in Reston, Virginia and the USGS National Water Quality Laboratory in Denver, Colorado. Sampling will consist of about 50-70 samples, collected either once at each site or multiple times at few sites. These data, together with existing geochemical data, will be used to better characterize groundwater flow directions and mixing and also in model calibration or to help assess model uncertainty (e.g., how well does the model simulate flow directions and mixing determined by natural tracers). Hydraulic conductivity estimates will be assembled where available from aquifer tests and previous groundwater flow models. Because these estimates are sparse, hydraulic conductivity will be estimated primarily during the model calibration phase. All assembled data and estimates will be used to describe the groundwater flow system conceptually, which will then become the basis for a numerical flow model.

Groundwater recharge will be estimated using the method of Westenbroek and others (2010), which is a soil-water-balance (SWB) model that uses precipitation, temperature, land-use, and soil-type data. Methods similar to SWB also are available and possibly will be used as a comparison to SWB.

Recharge near sinking streams and hydrologic processes in semi-saturated cavernous aquifer zones in the Black Hills are poorly understood because of lack of data and complexity of these areas. A pilot project to test the capabilities of microgravity measurements for assessment of transient groundwater storage processes in recharge areas of the Black Hills currently is near completion. Results indicate that microgravity methods are useful for characterizing physical properties and flow processes in recharge areas of the Madison and Minnelusa aquifers (Koth and Long, 2012 *in review*), and this information could not be obtained from previously applied methods. Microgravity investigations will continue in previously studied areas because longer data records for these areas will better constrain gravity-based effective porosity estimates and other flow characterizations. Microgravity investigations may be applied to areas not previously studied if, at some time, this is determined to be more useful than continuation at current measurement locations.

Nuclear magnetic resonance (NMR) is a geophysical method that has been used successfully in karst aquifers. This is the same technology that is routinely used in medical imaging; i.e., magnetic resonance imaging (MRI). NMR can be used to determine the depth and volume of groundwater, particularly in aquifers with large porosity and large voids, such as karst aquifers. NMR can be applied over an area of the land surface, imaging to depths of 150 meters in some cases, or as a down-hole tool in boreholes. NMR initially will be tested in areas where microgravity methods have been applied, and the combination of these two methods to characterize recharge areas will be tested. Additional NMR work may be used with or without microgravity, depending on what is found to be useful.

Some combination of microgravity and NMR investigations will be conducted at existing microgravity survey areas, and additional measurement areas may be added. The number of measurement areas and the relative effort invested in the two methods will be determined as data are collected and analyzed. Effort will be allocated according to what is most efficient for obtaining useful data to characterize recharge areas.

Phase 1 tasks

1. *Identify and assemble existing data sources* – Several categories of data have been previously described.

2. *Define model area and boundary conditions* – The approximate model area shown in Figure 2 will be revised as necessary after further examination of previous studies, which describe the geology and hydrology of the model area. Particular attention will be given to the southern model extent, at or near the limit of the Madison aquifer.

3. *Construct datasets for aquifer tops and bottoms* – Several contour maps of formation tops and thicknesses cover different parts of the model area. These will be merged or matched at the edges of the individual map extents for continuous surfaces across the model area. These will be checked for consistency in the three-dimensional hydrogeologic framework.

4. *Construct datasets for potentiometric surfaces* – Several contour existing maps of potentiometric surfaces cover different parts of the model area and will be merged similarly to what is described for the aquifer tops and bottoms.

5. *Construct datasets for hydraulic conductivity* – Estimates from previous modeling studies and aquifer tests will be assembled. These will provide initial values that will be refined during model calibration.

6. *Interpolate spatial and temporal precipitation for Black Hills* – Data from precipitation gages will need to be interpolated between gages. This has been completed for 1931-1998 (Driscoll and other, 2000) but will need to be updated for 1999-2012.

7. *Apply the soil water balance (SWB) method to estimate areal recharge from precipitation* – This method is described by Westenbroek and others (2010).

8. *Estimate groundwater recharge from sinking streams* – This will involve assembling streamflow records for existing gages and estimating recharge rates on the basis of maximum streamflow loss rates indicated by Hortness and Driscoll (1998). Recharge rates also will need to be estimated for ungaged streams and when maximum loss rate estimates are not available.

9. *Estimate and construct datasets for spring and stream discharge* – Discharge records for springs and gaining streams will be assembled when available. In some cases, these will be determined by estimating stream base flow at gages downstream from springs or gaining streams.

10. *Acquire or estimate groundwater-use data*

11. *Collect hydrochemical and flow data* – Stable isotopes of oxygen and hydrogen ($\delta^{18}O$, $\delta^{2}H$) and major ions will be collected. Flow rates will be measured at selected springs and streams.

12. *Analyze geochemical samples* – Samples will be sent USGS laboratories

13. *Apply geophysical methods* – Geophysical methods will include microgravity, direct-current resistivity, and nuclear magnetic resonance (NMR), which will help characterize aquifer properties in recharge areas. Also, water wells will be site visited when necessary for quality control of elevation or water-level data.

14. *Report writing, including figure and table preparation for a report to document the hydrogeologic framework and conceptual model.*

15. *Respond to review comments and reciprocate reviews* – The review process is essential to a quality scientific report.

Phase 2—Steady-state and transient numerical flow model

Data and estimates from Phase 1 will be used to develop a numerical groundwater flow model for the regional area shown in Figure 2 using MODFLOW-2005 (Harbaugh, 2005) or an updated version of MODFLOW if available. The model of the Rapid City area (Putnam and Long, 2009) and the model of the Spearfish area (Greene and others, 1999) will be incorporated into the regional model. Hydraulic conductivity values used in these models will be used as initial, or pre-calibration, values for the regional model. These values may change during calibration of the regional model because of differences in boundary conditions between the small models and the regional model. The regional model first will be calibrated to steady-state flow conditions, where all inflows and outflows are constant in time. Initial estimates of model parameters, such as hydraulic conductivity values, will be refined by adjusting these values to achieve similarity between observed and simulated hydraulic-head and flow values. The abundance of hydraulic-head values makes this an effective method for estimating hydraulic conductivity. The parameter optimization software PEST will be used to achieve this calibration (Doherty, 2005). This state-of-the-art software eliminates the need for inefficient trial-and-error parameter adjustment. A relatively new and powerful method known as *pilot points* described in Doherty (2005) will be used in model calibration. This method interpolates hydraulic conductivity values in each model cell between pilot points, where the optimization occurs.

Once the steady-state calibration is complete, the model will be executed in transient mode, which will simulate a specific historical time period of up to 20-30 years of record for annual data. Model calibration will be refined in this mode to achieve optimum similarity between temporal changes in observed and simulated hydraulic-head and flow values on an annual basis.

Phase 2 tasks

1. *Format all data for MODFLOW input files and construct model* – Data stored in ArcGIS will be exported to populate model cells. Data stored in other formats will be formatted for MODFLOW input.

2. *Link MODFLOW model to PEST optimization software* – PEST runs as a parent program to MODFLOW. Several instruction files need to be created so that PEST can read MODFLOW output. Debugging the PEST instruction files generally is part of this process.

3. *Calibrate steady-state model to measured data* – The model is calibrated to average flow conditions in this step. This is a lengthy process with many stages of increasing model complexity and parameter definition and categorization.

4. *Execute and calibrate transient model to historical data* – This process is similar to Task 3, except that the model is calibrated to long-term records. Parameter estimates from the steady-state calibration will be used as initial estimates.

5. *Define spring capture zones and ratio of regional flow* – Backward particle tracking from spring discharge points will be conducted on the calibrated model to determine spring capture zones. The point of origin for these particles will determine the ratio of regional flow for each spring.

6. *Assess spatial aquifer sensitivity to pumping and drought* – A series of model executions will be conducted, where one simulated well will be pumped for each execution. Average drawdown in proximal cells will be determined for each pumped well, and a map of relative drawdown will be created. An extended drought period will be simulated as previously described, and a map showing the resulting hydraulic-head decline at the end of this period will be created.

7. *Determine the focus of future data collection efforts – A model predictive uncertainty analysis will be conducted to determine areas and types of data that, if collected, would decrease the model's predictive uncertainty.*

8. *Report writing, including figure and table preparation for a report documenting the numerical model results.*

9. *Respond to review comments and reciprocate reviews*

Potential future studies

Hydrologic scenarios related to increased water use, additional pumping wells, or extreme climatic conditions, such as drought, could be simulated for particular areas of interest. Refined model calibration for these areas might be necessary, and grids with finer resolution could be nested into these areas. Contaminant-transport simulations could be conducted to investigate water-quality issues. One potential approach for these investigations might be to simulate flow in discrete conduits in the Madison aquifer for areas where knowledge of conduit locations exist. The conduit-flow process for MODFLOW-2005 (Shoemaker, 2008) could be applied in this case. Plans for the new version of MODFLOW include pipe-flow simulation capability, which also could be used for this purpose. Hypothesis testing for conduit flow and conduit locations could be applied in areas for which knowledge of conduit locations is lacking. The model will be constructed such that flow in the Precambrian aquifer in the Black Hills also could be simulated in the future. GWM might be useful in many future studies involving this model.

The proposed model will be available and useful for studies long into the future, both within and outside of the USGS. The USGS South Dakota Water Science Center consistently has had experienced staff with groundwater modeling expertise for more than 25 years, and is committed to continuing this past record. For most of this time, there have been at least two hydrologists with groundwater modeling experience on staff, with additional assistance from several part-time students. Kyle Davis, a recent graduate with groundwater modeling experience, has recently been hired as a permanent employee. All numerical models are archived electronically according to USGS protocol for the purpose of future use. These archives include all model input files, the executable program (e.g., MODFLOW), model input and output data in ArcGIS format, and documentation describing how to execute the model. All archived models are available upon request to the public. For example, the groundwater flow model for the Rapid City area (Putnam and Long, 2009) currently is being used by Colorado State University for research in karst aquifers. Another example of a USGS model that was first documented and published but later updated is a groundwater flow model of the Ogallala and Arikaree aquifers in South Dakota. The model first documented by Long and others (2002) was later updated with improved estimates of recharge, current hydrologic conditions, higher grid resolution, and an assessment of potential future hydrologic scenarios (Long and Putnam, 2008).

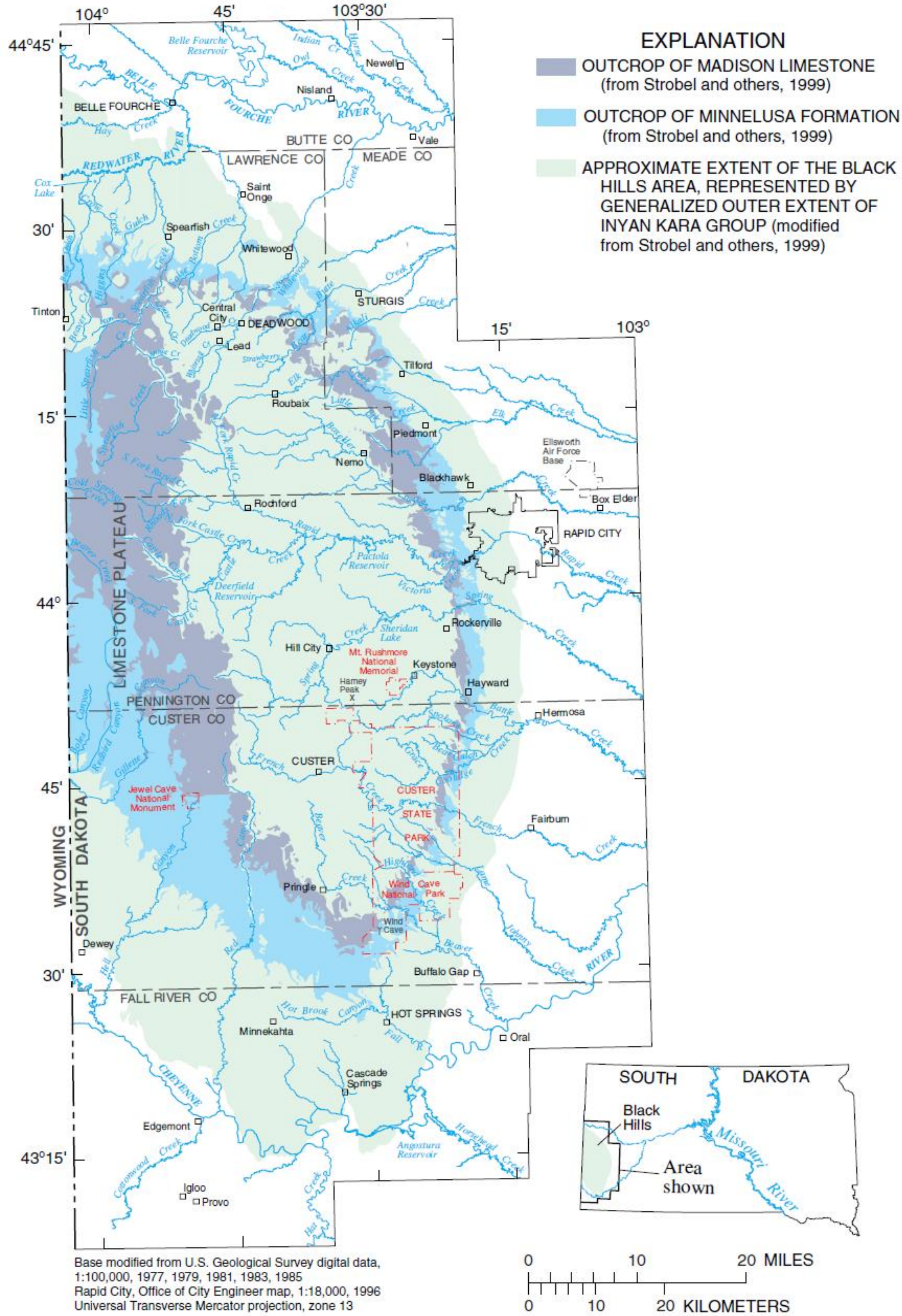
EXPLANATION
OUTCROP OF MADISON LIMESTONE (from Strobel and others, 1999)
OUTCROP OF MINNELUSA FORMATION (from Strobel and others, 1999)
APPROXIMATE EXTENT OF THE BLACK HILLS AREA, REPRESENTED BY GENERALIZED OUTER EXTENT OF INYAN KARA GROUP (modified from Strobel and others, 1999)
104°
45'
103°30'
15'
103°
44°45'
30'
15'
44°
45'
30'
43°15'
BELLE FOURCHE
Newell
Nisland
Vale
BUTTE CO
LAWRENCE CO
MEADE CO
Saint Onge
Spearfish
Whitewood
STURGIS
Tinton
Central City
DEADWOOD
Lead
Tilford
Roubaix
Piedmont
Nemo
Ellsworth Air Force Base
Blackhawk
Box Elder
Rochford
RAPID CITY
LIMESTONE PLATEAU
Rockerville
Hill City
Mt. Rushmore National Memorial
Keystone
Harney Peak
Hayward
PENNINGTON CO
CUSTER CO
Hermosa
CUSTER
Jewel Cave National Monument
CUSTER STATE PARK
Fairburn
WYOMING
SOUTH DAKOTA
Pringle
Wind Cave National Park
Wind Cave
Dewey
Buffalo Gap
FALL RIVER CO
HOT SPRINGS
Minnekahta
Oral
Cascade Springs
Edgemont
Igloo
Provo
Angostura Reservoir
Belle Fourche Reservoir
Pactola Reservoir
Deerfield Reservoir
Sheridan Lake
Cox Lake
REDWATER RIVER
BELLE FOURCHE RIVER
CHEYENNE RIVER
SOUTH DAKOTA
Black Hills
Area shown
Missouri River
Base modified from U.S. Geological Survey digital data, 1:100,000, 1977, 1979, 1981, 1983, 1985
Rapid City, Office of City Engineer map, 1:18,000, 1996
Universal Transverse Mercator projection, zone 13
0 10 20 MILES
0 10 20 KILOMETERS

Figure 1. Area of investigation for the Black Hills Hydrology Study (From Driscoll and others, 2002).

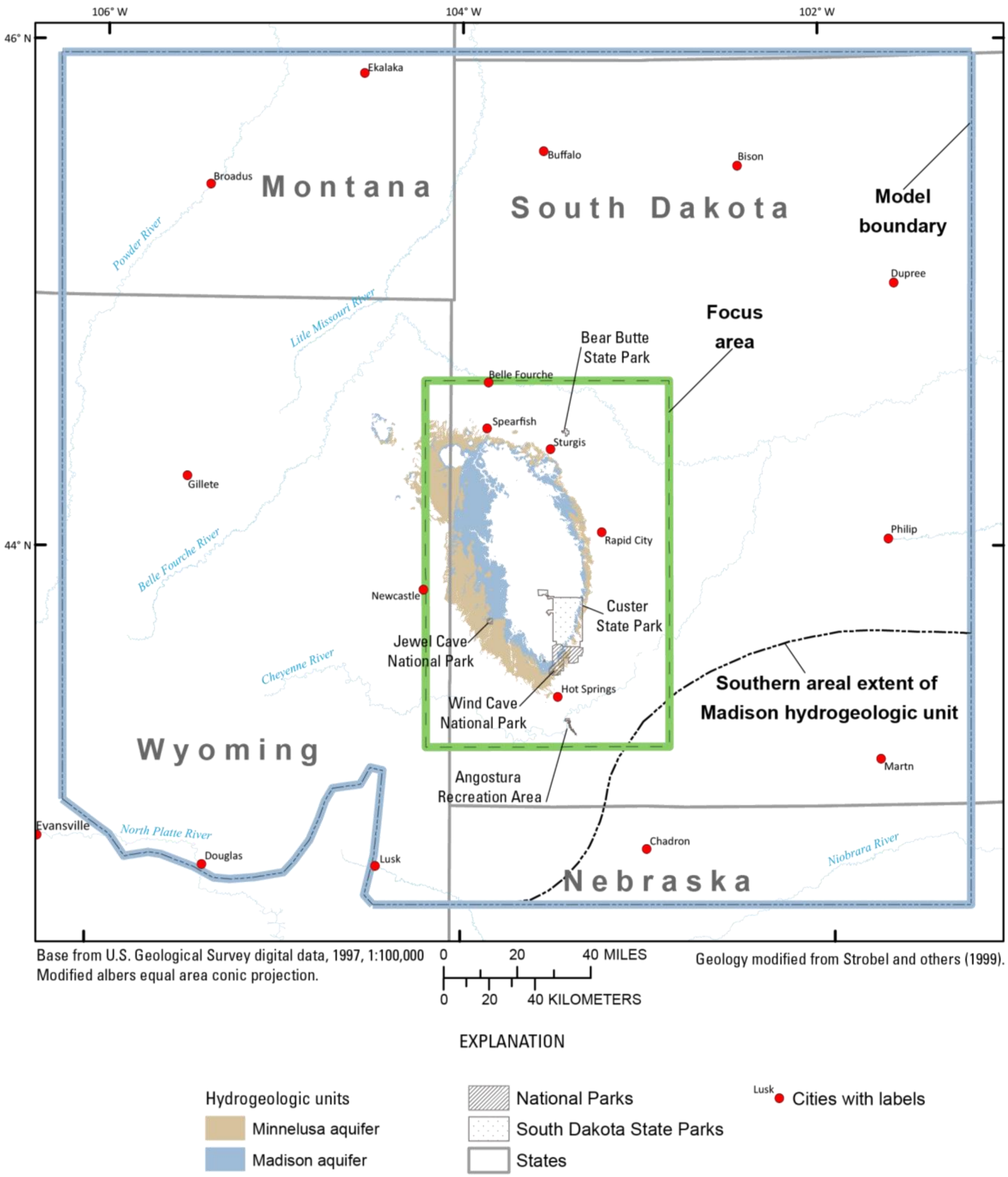

Figure 2. Potential model boundaries and focus area for groundwater flow simulation.

References cited

Carter, J.M., Driscoll, D.G., and Sawyer, J.F., 2003, Ground-Water Resources in the Black Hills Area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 03-4049, 36 p.

Carter, J.M., Driscoll, D.G., Williamson, J.E., and Lindquist, V.A., 2002, Atlas of water resources in the Black Hills area, South Dakota: U.S. Geological Survey Hydrologic Atlas 747, 120 p.

Doherty, J., 2005, Pest: Model-Independent Parameter Estimation, User Manual 5th ed. (5th ed.), Watermark Numerical Computing, variously paged p.

Doherty, J., 2010, Methodologies and Software for PEST-Based Model Predictive Uncertainty Analysis, Watermark Numerical Computing, 157 p.

Driscoll, D.G., Carter, J.M., Williamson, J.E., and Putnam, L.D., 2002, Hydrology of the Black Hills area, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 02-4094, 150 p.

Driscoll, D.G., Hamade, G.R., and Kenner, S.J., 2000, Summary of precipitation data for the Black Hills area of South Dakota, water years 1931-98: U. S. Geological Survey Open-File Report 00-0329, 151 p.

Driscoll, D.G., and Carter, J.M., 2001, Hydrologic conditions and budgets for the Black Hills of South Dakota, through water year 1998: WRIR 2001-4226, 143 p.

Fienen, M.N., Doherty, J.E., Hunt, R.J., and Reeves, H.W., 2010, Using prediction uncertainty analysis to design hydrologic monitoring networks: Example applications from the Great Lakes water availability pilot project: U.S. Geological Survey Scientific Investigations Report 2010–5159, 44 p.

Greene, E.A., Shapiro, A.M., and Carter, J.M., 1999, Hydrogeologic characterization of the Minnelusa and Madison aquifers near Spearfish, South Dakota: U.S. Geological Survey Water-Resources Investigations Report 98-4156, 64 p.

Harbaugh, A.W., 2005, MODFLOW-2005 : the U.S. Geological Survey modular ground-water model--the ground-water flow process: U.S. Geological Survey Techniques and Methods 6-A16, variously paged p.

Hortness, J.E., and Driscoll, D.G., 1998, Streamflow losses in the Black Hills of western South Dakota: U. S. Geological Survey Water-Resources Investigations Report 98-4116, 99 p.

Koth, K.R., and Long, A.J., 2012, Microgravity Methods for Characterization of Groundwater Storage Changes and Aquifer Properties in the Karstic Madison Aquifer in the Black Hills of South Dakota: U.S. Geological Survey Scientific Investigations Report XX-2012, *in review*

Long, A.J., Ohms, M.J., and McKaskey, J.D.R.G., 2012, Groundwater Flow, Quality (2007-2010), and Mixing in the Wind Cave National Park Area, South Dakota: U.S. Geological Survey Scientific Investigations Report 2011-5235

Long, A.J., and Putnam, L.D., 2002, Flow-System Analysis of the Madison and Minnelusa aquifers in the Rapid City area, South Dakota - Conceptual model: U.S. Geological Survey Water-Resources Investigations Report 02-4185, 100 p., 3 plt.

Long, A.J., and Putnam, L.D., 2008, Simulated groundwater flow in the Ogallala and Arikaree aquifers, Rosebud Indian Reservation area, South Dakota—Revisions with data through water year 2008 and simulations of potential future scenarios: U.S. Geological Survey Scientific Investigations Report 2010–5105, 64 p.

Long, A.J., Sawyer, J.F., and Putnam, L.D., 2008, Environmental tracers as indicators of karst conduits in ground water in South Dakota, USA: Hydrogeology Journal, v. 16, no. 2, p. 263-280.

Mehl, S.W., and Hill, M.C., 2007, The U.S. Geological Survey modular ground-water model—Documentation of the multiple-refined-areas capability of local grid refinement (LGR) and the boundary flow and head (BFH) package: U.S. Geological Survey Techniques and Methods 6-A21, 13 p.

Putnam, L.D., and Long, A.J., 2007a, Analysis of Ground-Water Flow in the Madison Aquifer using Fluorescent Dyes Injected in Spring Creek and Rapid Creek near Rapid City, South Dakota, 2003-2004: U.S. Geological Survey Scientific Investigations Report 2007-5137

Putnam, L.D., and Long, A.J., 2007b, Characterization of Ground-Water Flow and Water Quality for the Madison and Minnelusa Aquifers in Northern Lawrence County, South Dakota: U.S. Geological Survey Scientific Investigations Report 2007-5001, 61 p.

Putnam, L.D., and Long, A.J., 2009, Numerical Groundwater-Flow Model of the Minnelusa and Madison Hydrogeologic Units in the Rapid City Area, South Dakota: U.S. Geological Survey Scientific Investigations Report 2009-5205, 81 p.

Redden, J.A., and DeWitt, E., 2008, Maps showing geology, structure, and geophysics of the central Black Hills, South Dakota: U.S. Geological Survey Scientific Investigations Map 2777, 44 p., 2 sheets p.

Shoemaker, W.B., Kuniansky, E.L., Birk, S., Bauer, S., and Swain, E.D., 2008, Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005: U.S. Geological Survey Techniques and Methods, Book 6, Chapter A24, 50 p.

Strobel, M.L., Jarrell, G.J., Sawyer, J.F., Schleicher, J.R., and Fahrenbach, M.D., 1999, Distribution of hydrogeologic units in the Black Hills Area, South Dakota: U.S. Geological Survey Hydrologic Investigations Atlas HA-0743

U.S. Geological Survey, 2011, Water use in the United States: U.S. Geological Survey database, accessed December 2, 2011, at *http://water.usgs.gov/watuse/.*

Westenbroek, S.M., Kelson, V.A., Dripps, W.R., Hunt, R.J., and Bradbury, K.R., 2010, SWB-A modified Thornthwaite-Mather Soil-Water-Balance code for estimating groundwater recharge: U.S. Geological Survey Techniques and Methods 6-A31, 52 p.