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Plan for the Multidisciplinary Assessment of Karst and Fractured-Rock Hydrogeologic Systems and Water Resources of the Shenandoah Valley Region

SUMMARY

This plan describes the approach for a multidisciplinary study of karst and fractured-rock aquifer systems of the Shenandoah Valley Region with preliminary emphasis on the Northern Shenandoah Valley. Currently, multiple studies are ongoing in six counties within the defined study area. This plan describes the integration of these local studies into a regional synthesis of hydrogeologic information for water-resources planning.

Rapid urbanization is creating increasing dependence upon the ground-water system as a source of both public, municipal, industrial, and private water supplies. A five-year drought, from 1997 to 2002, has caused diminished water availability simultaneously with the increased demands. During this period, both private and public systems experienced shortages which required development of more reliable supplies.

Surface-water bodies also were impacted, because of their dependence upon ground water to supply baseflow to the Shenandoah and Potomac Rivers, including their tributary streams. The reduction in baseflow impacted supplies for human consumption and had ecological impacts as a result of reduced quantity and quality of in-stream flows.

Geologic, hydrologic, ecologic, and cartographic data from on-going local studies and available data from previous studies will be compiled into comprehensive regional databases. Long-term monitoring networks will be established by expanding existing local networks and additional data-collection sites. A central web-based repository of these data will be established for regional water-resources analysis. A series of comprehensive computer models of the flow system will be developed that will serve as the focal point for characterizing the ground-water-flow system. Ground-water-flow models will be developed at the local (square miles), sub-regional (10's of square miles), and regional (100's of square miles) scale to assess the flow system. The models initially will provide conceptualization of the aquifer systems, then will be used to identify anomalies and areas where more data are needed. As data are acquired, the models will be refined. This iterative process will continue until the flow models are sufficient to address local and regional- scale water-resource issues. When complete, the models will be documented and published for future use by interested stakeholders within the study area.

The key to the success of the program is the ongoing participation and support of affected stakeholders.

BACKGROUND

The Shenandoah Valley Region is located in the northwestern part of Virginia and the eastern Panhandle of West Virginia and extends from Augusta County, Virginia to Berkeley and Jefferson Counties, West Virginia (fig. 1).

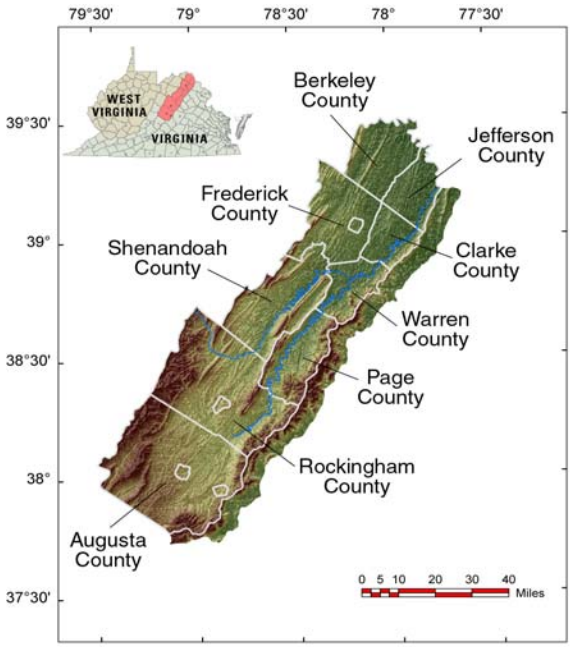


Figure 1. Map of the Shenandoah Valley Region of Virginia and West Virginia.

Steadily increasing development of ground-water supplies in the Shenandoah Valley Region of Virginia and West Virginia has prompted concerns over the availability of the water resources to support both an increasing population and sustain a healthy aquatic ecosystem. Recent sustained drought has heightened the concern of local, state, and federal agencies, as well as private citizen groups and other water-use organizations, resulting in six county studies and regional instream-flow assessment in the Northern Shenandoah Valley as part of the WRD Cooperative Water Program, and establishment of the Great Valley Water-Resources Science Forum. Drought and development have impacted ground-water levels and flows in streams and rivers, affecting the availability of water for human needs, and possibly affecting the health of aquatic ecosystems.

The region contains complex hydrogeology, including karstic carbonate rocks,

siliciclastic sedimentary rocks, and crystalline basement, all of which are highly folded and faulted. The diverse lithologies result in both conduit (karst-based) and diffuse (fracture-based) ground-water flow. Ground water is a major contributor to flow in many streams and rivers and has a strong influence on river and wetland habitats for plants and animals. The interactions between ground water and surface water are difficult to observe and measure.

STATEMENT OF PROBLEM

The Shenandoah Valley aquifer systems historically served as reliable supplies for local communities and individual residences within the study area. However, in recent years, the area has been experiencing an expanding economy and rapidly growing population, especially along the I-81 corridor and the eastern margin of the Valley. Increased urbanization of these predominantly rural counties is expected to continue as the population in the Washington, D.C. commuter corridor expands.

This growth has the potential to profoundly influence the region's land, water, and biological resources. Regional and local resource managers have serious concerns over the region's ability to sustain future growth. Current resource-management concerns center on the sustainability and vulnerability of the region's water resources and their ability to provide a reliable long-term water supply.

In recent years, the region experienced an extended five-year drought, which resulted in a diminished water supply and increasing demands on the aquifer system. The prolonged drought focused attention on the quantity and sustainability of the region's water resources.

Surface-water bodies also were impacted, because of their dependence upon ground water to supply baseflow to the Shenandoah and Potomac Rivers and to their tributary streams. Reduced baseflow impacted supplies for human consumption and recreational enterprises and had ecological impacts due to reduced quantity and quality of in-stream flows. Conflicts among instream and offstream users of streamflow also have increased as flows decrease.

The aquifer systems of the Shenandoah Valley Region are likely to be developed to supplement current withdrawals and to supply water to areas with an increasing density of development. An improved understanding of the complex aquifer systems is required to effectively develop and manage them as sustainable sources of water for human and aquatic habitat. In order to assess current and future hydrologic conditions within the region, a long-term monitoring network needs to be designed and implemented, and a hydrogeologic framework needs to be developed to aid in the understanding of how water enters and moves through the aquifer system.

Local water-resources and land-use managers are in need of relevant and detailed geologic and hydrogeologic information to make informed decisions for issues such as resource sustainability, source-water protection, and land use related to subsidence. Local entities generally do not have the fiscal or technical resources available to address issues of this magnitude or at a scale appropriate for study of the regional aquifer systems.

OBJECTIVE

The overall objective of this integrated regional assessment is to better characterize the aquifer systems in the Shenandoah Valley Region and to provide relevant hydrogeologic information that can be used to guide the development and management of those water resources. This regional study of the karst and fractured-rock aquifer systems will use hydrologic, geologic, cartographic, and biologic information to improve the understanding of the aquifer systems, their relationship to surface features, and potential hazards over a multi-county area of Virginia and West Virginia.

The study has two major components: (1) long-term monitoring and (2) hydrogeologic assessment that will be conducted over the next 5 to 10 years. The first component will consist of the design and implementation of a long-term network to monitor ground-water levels, streamflow, spring discharges, and water quality as part of recently initiated and proposed projects funded through the counties and the USGS Cooperative Water Program.

The second component will consist of a hydrogeologic assessment of the karst and fractured-rock aquifer systems in the region, which will integrate research activities from projects funded by the USGS National Cooperative Geologic Mapping, Land and Remote Sensing, Cooperative Water, and National Research Programs.

Major work elements of the hydrogeologic assessment include:

- formulate a comprehensive hydrogeologic framework that describes aquifer geometries, hydraulic properties, and water levels that are consistent with the best available hydrogeologic information;
- develop a complete, accurate, and maintainable database of ground-water and related hydrologic information, including ground-water withdrawals, stream and spring flows, and land and water-use data. These data are needed to describe the water budget of the basin to provide required model-input datasets for ongoing simulation efforts;
- develop a complete, accurate, and maintainable database of ground- and surface-water quality data that can be used to evaluate aquifer susceptibility to contamination and to help characterize interaction among ground and surface water;
- develop geographic information system coverages that depict critical aspects of geologic, hydrologic, and land-surface features within the basin; and
- develop and calibrate a series of ground-water-flow models for the Shenandoah Valley Region to be published in a transferable format for use by interested stakeholders.

Information gained from this research will be assessed on an ongoing basis and updates will be provided to stakeholders through a variety of outreach mechanisms, ranging from workshops to a series of USGS-approved publications.

APPROACH

Geology

The hydrogeologic framework will be determined through geologic mapping, fracture analysis, conduit analysis, and a karst inventory. To aid in the karst inventory and geologic analyses of karst features in the Shenandoah Valley, various remote-sensing tools will be used to locate karst features and fracture traces.

Maps of karst features will be analyzed with the geologic maps to evaluate geologic controls on karst development. A digital three-dimensional map will be constructed of the topography and geology of the Shenandoah Valley region, using a new digital elevation model map (DEM), which will be prepared for the region, and existing geologic data, new cross sections, and new maps of sinkhole and major surficial deposits.

A geologic map of the Winchester 30' X 60' quadrangle will be produced by compiling the detailed 1:24,00-scale geologic maps. The geologic maps will be used, along with fracture analysis and karst inventories, to determine structural and stratigraphic relations between karst features and geology.

Bedrock lithology, structure, and surficial deposit maps of the western Blue Ridge

province which forms the eastern divide to the basin also will be prepared. The study area basin defined by using the DEM, lithologic map, and cross sections will be among the early inputs for the conceptual regional flow model. Subsequent field mapping in the Blue Ridge will provide data for the flow model and will be incorporated and published with Shenandoah Valley data.

Karst hazards maps will be produced as derivative products. Sinkhole distribution analyses will define areas for potential entrance points of contaminants and areas of potential subsidence hazards. Derivative maps showing these karst features and internal drainage basins will be produced that will aid in source-water protection.

Hydrology

Current cooperative investigations of the ground-water resources of the counties of Clarke, Frederick, and Warren in Virginia are focused on characterizing the carbonate and fractured-rock aquifer systems in the region and providing relevant hydrogeologic information that can be used to guide the development and management of this important water resource. These investigations are being uniformly conducted as detailed hydrogeologic appraisals with evaluations of the (1) hydrogeologic framework, (2) ground-water flow system, (3) water balance, and (4) water quality, and also include the establishment of long-term monitoring networks.

Berkeley County, West Virginia, is cooperating with USGS in a water-resource assessment to determine aquifer properties throughout the karst aquifer within the county and to conduct lineament and fracture trace analysis. This study will identify zones where greater-than- average well yields may be expected, areas with sustainable yield, and areas that may be especially vulnerable to contamination. A similar investigation has been proposed in Jefferson County. Previous USGS ground-water investigations of these counties provided data on hydrogeologic framework, ground-water flow systems, water budgets, and water quality.

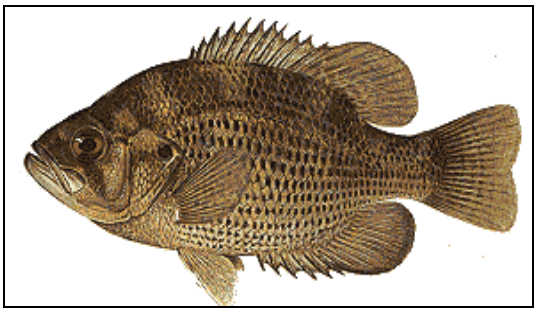
A detailed on-going hydrogeologic assessment of the Leetown Science Center and adjacent properties will use a variety of techniques to evaluate ground-water flow and availability within the complex fractured karst bedrock aquifer on which the Center and the adjacent USDA aquaculture research facility rely for their primary source of water. Activities planned for the assessment include (1) detailed karst, geologic, and sinkhole mapping including an analysis of fracture distribution, (2) installation of a series of ten monitoring wells and associated borehole geophysical surveys to determine the nature and extent of fracturing and solution development within the bedrock aquifer, (3) aquifer tests to determine hydraulic properties of the aquifer including transmissivity, hydraulic conductivity, storativity, and saturated thickness, (4) development of a ground-water flow model for ground-water flow system characterization and evaluation, (5) collection of water quality samples to determine background quality of ground water and to evaluate potential contamination from nearby point sources, (6) current and historical land-use analyses, (7) and establishment of a long-term monitoring network. Current plans are to utilize the USGS Leetown Science Center as a long-term research site to develop and evaluate methods for karst ground-water investigations and to study hydrogeologic

processes in karst aquifers. The purpose of this research is to provide technology which may then be applied to similar fractured rock karst aquifers within the Great Valley and other regions.

Long-term monitoring networks will be established by expanding the existing local networks to provide areal coverage of the region. These monitoring networks will facilitate the collection of ground-water, surface-water and water-quality data. Data from the networks will represent current hydrologic conditions and will be used to compare these conditions with historic data.

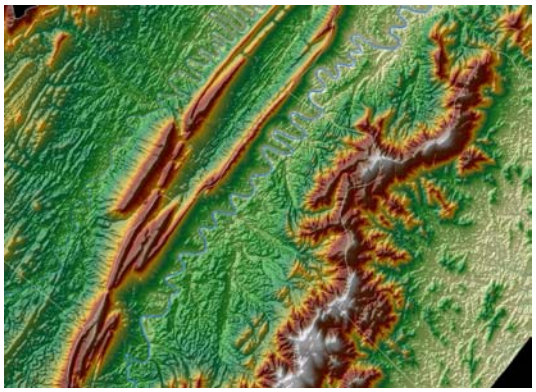
In addition to water availability, water quality is an emerging concern throughout the region. The water resources of this region are highly susceptible to contamination because of the nature of the aquifer systems. Assessment of water quality and age of the ground-water is needed to document trends and contamination potential. Bacterial contamination is a significant problem within the Shenandoah Valley Region. Viability of existing techniques for tracking the sources of bacteria within the karst aquifer in Berkeley County are being evaluated and new technology and methods are being proposed for future use.

Information provided by the detailed hydrogeologic appraisals, regional instream flow assessments, and the regional ground-water-flow modeling will provide useful information to better address questions about (1) the quantity of water available for use, (2) the effects of increased pumpage on ground-water levels and instream flows, (3) the relation between karst features and the hydrology and geochemistry of the surface- and ground-water flow systems, and (4) the quality of the ground-water supply and its vulnerability to current and potential future sources of contamination.



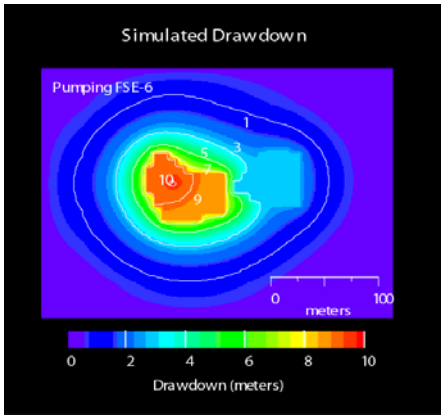
Ecology

A current, cooperative regional instream flow assessment sets the stage for the identification and compilation of the major instream-flow users in the Shenandoah River Basin, and development of basin specific habitat and flow requirements for fish species, species assemblages, and various water uses. The current investigation focuses on the North Fork Shenandoah River. The intent is to expand this research, and also incorporate the South Fork Shenandoah River and Opequon Creek. As a result of the study, the counties and communities in the Shenandoah Valley should have a better knowledge of the water resources in the region, the regional ground-water and surface-water hydraulic systems, and the potential effect of withdrawals and conservation measures on the ecology, agriculture, industry, and water supplies of the region. The knowledge and long-term monitoring data gained from this cooperative investigation will provide an important endpoint for the regional ground-water-flow modeling efforts, as the models are used to evaluate the regional effects of ground-water withdrawals on instream flows.



Geography

New digital elevation models (DEM) of the region will be produced at a 10-meter resolution that will provide a framework for construction of a digital three-dimensional map of the topography and geology of the Shenandoah Valley Region. A comprehensive and unified geographic information system (GIS) will be established. The GIS will be used for the dissemination of data and interpretive products, as well as input to the ground-water flow models.



Numerical ground-water models

The USGS will develop a series of comprehensive numerical models of the Northern Shenandoah Valley flow system. Preliminary models will help identify areas where more data are needed. A preliminary regional model will be developed and will be refined throughout the investigation as relevant data are acquired. This initial model will provide a basis for a conceptual model of the hydrogeologic setting, which will help scientists conceptualize the regional ground-water-flow system. As additional data are acquired through the various investigations that are planned, they will be incorporated into the model. As a result, the modeling effort will be refined iteratively throughout the life of the program. This iterative process will continue and additional models will be developed to address more local and sub-regional scale water-resource issues.

MODFLOW (McDonald and Harbaugh, 1988), a modular finite-difference-model program code will be used to develop the Shenandoah Valley regional ground-water model. The program reads input data files that specify the aquifer layers, individual cells, transmissivities and storativities, initial hydraulic heads, and sources or sinks, along with vertical leakances between the aquifer layers and conditions of specified head or flow along model boundaries. Systems of partial differential equations that approximately represent ground-water flow in three dimensions are then iteratively solved to calculate values of hydraulic head and flow rate for each cell. Simulated flow rates can then be analyzed to examine the behavior of the flow system. Model development will be ongoing, beginning with a conceptual model, followed by refinements leading to a working model.

Existing data will be used as the basis for development of the conceptual regional model. Historical hydrologic data are available in the USGS National Water Inventory Summary. Digital elevation models, geologic, and hydrographic data will be used as available.

As improved hydrologic and geologic data are generated by various investigators, they will be incorporated into the conceptualization of the numerical model. As the model is tested, feedback regarding data needed to appropriately refine the

model will be provided to investigators and stakeholders. To the extent that those additional data can be obtained, they will be used to refine the model. The model will first be used to simulate steady state conditions. Once refinements are complete, a transient model will be developed to evaluate impacts of changing patterns in land and water use, and climatic conditions.

Advanced data pre- and post-processing techniques will be applied in conducting the model evaluations. The model will include a GIS-based Graphical User Interface (GUI) for efficient compilation and spatially referenced examination of model input and output data. Particle- tracking techniques (Pollock, 1989) and analysis of model cell-by-cell flow data will distinguish directions of horizontal flow and vertical leakage, and rates of recharge and discharge, among various areas. In addition, parameter estimation techniques (A.W. Harbaugh, U.S. Geological Survey, oral commun., 1999) will provide a means to quantitatively assess various sources of uncertainty in model-input data and simulation results. The magnitude of effect (sensitivity)of the various inputs on simulated heads and flow rates will be analyzed and the most critical inputs thereby identified. Accordingly, parameter estimation will be applied to the diagnostic tests as appropriate to address each need; alternative conditions will be imposed to represent the various hydraulic controls, and calibration and sensitivity analysis will be performed to examine the resulting effects on simulated heads and flow rates. In particular, hydraulic interaction among the aquifer system and surface-water bodies (streams and springs) will be evaluated to determine the interdependency of ground water and surface water within the regional system. If particularly sensitive areas of ground-water and surface-water interactions are identified at a sub-regional or local scale, proposals will be developed for further investigation at the appropriate scale.

BENEFITS

This project will produce data needed to assess local as well as regional issues related to aquifers within the Shenandoah Valley region and will provide data and methodology which may be applied to similar primarily fractured rock karst aquifers in other regions. The data will be used to develop the conceptual and numerical models of the Shenandoah Valley Region. Published data and analyses, particularly the models, will provide scientists and resource managers in Virginia, West Virginia, and local communities with scientifically based tools to guide effective management and sustainability of this regionally important resource. Current plans are to develop a ground-water atlas for the Shenandoah Valley region which will compile all available data and provide a better understanding of ground-water flow processes both conceptually and quantitatively throughout the region.

DATA ARCHIVAL

Geologic data will be input into the USGS National Geologic Map Database where it will be archived for future use. Hydrologic data will be input into the USGS National Water Information Summary (NWIS) where it will be archived for use and public accessibility. A central web-based repository of these data will be established for regional water-resources analysis. As an example, the National Biological Information Infrastructure (NBII), if funded, could provide a user-friendly web-based linkage among the various databases in a central location.

PUBLICATIONS

Each of the individual studies is expected to publish results in a format appropriate for the discipline and the scope of the study. Hydrologic data will be published annually in state Data Books of the respective WRD Districts. Interpretive results typically will be published as USGS Water Resources

Investigations Reports and Open-file Reports, Journal Articles, and digital layers including geologic maps of 1:24,000 and 1:100,000 scale quadrangles. All published investigative results will be available for public access. The proposed final product is a hydrogeologic atlas which comprehensively documents the hydrogeologic flow system of the Shenandoah Valley Region.

PRELIMINARY PROJECT TIMELINE

TASK	FEDERAL FISCAL YEAR									
	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Project design. *Includes input from multidisciplanary team of USGS geologists, hydrologists, geophysicists, biologists, cartographers; State and local regulatory and resource management agencies; other Federal agencies; non-governmental organizations; and other stakeholders*										
Review of existing data and generation of new data										
Establish and maintain long-term monitoring networks										
Hydrogeologic framework revision										
Numerical model development										
Data analysis and conclusions *Completion in accordance with individual project schedules*										
Data archival *Ongoing archival in accordance with established procedures*										
Publications o *Results published in appropriate outlet and in accordance with individual project schedules* o *Regional ground-water flow model published in format for future use by stakeholders* o *Proposed final publication will be a hydrogeologic atlas for the Shenandoah Valley Region published in approximately 2012.*										

Phase I Planned Assessment
Phase II Assessment
Continuing Assessments

SUMMARY OF USGS PROGRAM ACTIVITIES IN THE SHENANDOAH VALLEY REGION

USGS has several complementary investigations that are currently underway, or have been proposed for the Northern Shenandoah Valley. Each of these studies has a well-defined purpose and scope of its own, yet each will yield important information that can contribute to integrated regional assessments of the Valley's land, water, and biological resources.

National Cooperative Geologic Mapping Program

- Karst Applied Research Studies Project (KARST)
- Bedrock Regional Aquifer Systematics Study (BRASS)
- Digital elevation mapping (SIR)

National Landslide Hazards Program

- Debris-Flow Hazards in the Blue Ridge of Virginia

Land and Remote Sensing Program

- National Civil Applications Project (NCAP) - mapping of karst features

Cooperative Water Program

Virginia

- North Fork Shenandoah River Instream Flow Study
- Frederick County Carbonate Aquifer Appraisal
- Clarke County Aquifer Appraisal
- Warren County Siliciclastic and Crystalline Aquifers Appraisal

West Virginia

- Berkeley County Karst Aquifer Fracture Trace Analysis
- Jefferson County Karst Aquifer Fracture Trace Analysis – proposed
- Bacterial source tracking technique evaluation

Federal Program

- Leetown Science Center, W. Va. Karst Aquifer Assessment

National Research Program (NRP)

Kinetic Modeling (*Ground-Water Age Dating*)

- Shenandoah National Park
- Karst Springs

Transport Phenomena in Fractured Rock

- Leetown Science Center

National Water-Quality Assessment (NAWQA) Program

- Potomac-Delmarva (PODL) Study Unit

National Biological Information Infrastructure

- Shenandoah NBII node - proposed

Water Availability for Human and Ecological Needs

- Integrated Science Study

West Virginia Water Research Institute

- Age-Dating Regional Karst Waters - proposed