GEOSCIENTIFIC INFORMATION SYSTEMS AND 3-D HYDROGELOGIC FRAMEWORK MODELS FOR THE YUCCA MOUNTAIN AREA, SOUTHERN NEVADA AND CALIFORNIA, USA

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ABSTRACT

A number of different geoscientific information system techniques were used to develop three-dimensional hydrogeologic and groundwater flow models of the complex geology of the Yucca Mountain region of Southern Nevada and California. This study, funded by United States Department of Energy as a part of the Yucca Mountain Project, focuses on an area of approximately 100,000 square kilometers (three degrees of latitude by three degrees of longitude) and extends up to ten kilometers in depth. The geologic conditions are typical of the Basin and Range province; a variety of sedimentary and igneous intrusive and extrusive rocks have been subjected to both compressional and extensional deformation. Geoscientific information systems techniques allow the synthesis of geologic, hydrologic and climatic information gathered from many sources, including satellite imagery and published maps and cross sections. Construction of a three-dimensional hydrogeologic model is possible with the combined use of commercially available software products, including traditional geographic information system products and sophisticated contouring, interpolation, visualization, and numerical modeling packages.

INTRODUCTION

Yucca Mountain at the Nevada Test Site in southwestern Nevada is being studied for a potential site to store high-level nuclear waste. The United States Geological Survey, in cooperation with the Department of Energy, is evaluating the site as part of the Yucca Mountain Project. Because of the potential for radionuclides to be transported by ground water from the repository to the accessible environment, studies are being conducted to characterize the Death Valley regional flow system of which Yucca Mountain is a part (1). Analysis of the regional flow system at Yucca Mountain will help to define the boundary conditions of the hydrologic system at the repository site. Additionally, characterization of the present, past, and future hydrologic regimes are required to adequately assess the potential for radionuclides to reach the accessible environment within the first 10,000 years after repository closure.

This study focuses on the initial phase of regional groundwater flow characterization, the development of a three-dimensional (3-D) hydrogeologic framework model. This framework model describes the geometry, composition and physical properties of the materials forming the natural hydrogeologic system. The selection of numerical modeling parameters is facilitated by using attribute data (unit thickness, hydraulic conductivity, recharge rates, evapotranspiration rates, etc.) stored in the data base that accompanies the framework model.

The study area, which is defined by the Death Valley regional ground-water flow system boundaries, lies within the area bounded by latitude 35° and 38° North and longitude 115° and 118° West (Fig. 1). The model area includes about 100,000 square kilometers and extends to depths up to ten kilometers. The study area has a semi-arid to arid climate and is located within the southern Great Basin, a subprovince of the Basin and Range physiographic province.

The geologic conditions are typical of the Basin and Range geologic province: a variety of igneous intrusive and extrusive, sedimentary, and metamorphic rocks have been subjected to several episodes of compressional and extensional deformation throughout geologic time. Topographic elevations range from 90 meters below sea level to 3600 meters above sea level; thus, the region includes a great variety of climatic regimes, and associated recharge/discharge conditions. Because of these complex geologic and hydrologic conditions and the complexity of data needed to describe them, a number of different computer based-techniques were used to

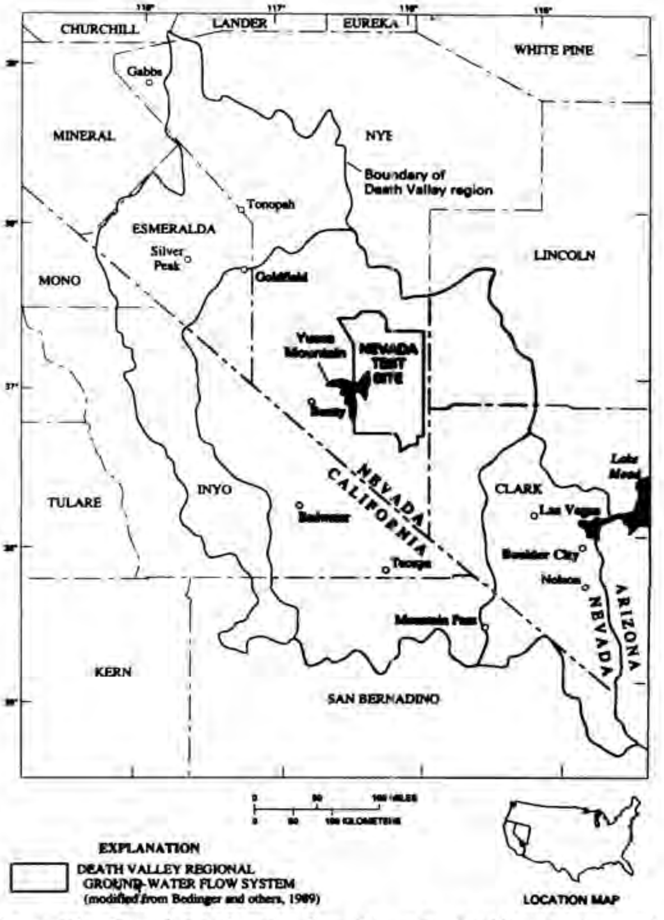

Fig. 1. The Death Valley Region, Nevada-California, located in the southwest United States.

simplify the development of the 3-D hydrogeologic framework models.

GEOSCIENTIFIC INFORMATION SYSTEMS FOR GEOLOGIC MODELING

An extension to the traditional two-dimensional (2-D) geographic information system (GIS) methods is required for hydrogeologic applications (2). These applications require representation of subsurface conditions in addition to the areal extent of geologic, hydrologic, climatic, and environmental features. All available information is linked using various data manipulation procedures. As a result, the term "Geoscientific Information System", or GSIS, is used to differentiate these hydrogeologically oriented 3-D systems from the more common 2-D GIS products (3).

GSIS's allow the use of geologic, hydrologic and climatic information gathered from sources such as satellite imagery, soil surveys, and published maps. Geologic maps and cross sections, digital elevation models, satellite imagery, and geophysical and hydrologic data were converted into a digital format utilizing 2-D GIS software. Soil surveys and digital elevation models exist in digital format and only required extraction and transformation. Geophysical, remote sensing, and terrain data, are best represented in raster file formats, while other types of mapped data are best represented as vectors.

Spatial data of a GIS can be represented as both vectors and rasters. Vectors can be stored in three different data forms including points, lines, and areas. Raster data structures consist of an array of grid cells, or pixels, that are referenced by a row number and a column number. Each pixel, point, line, or area contains an attribute number that corresponds to a characteristic being mapped.

Some geologic applications can be accomplished by reducing a 3-D subsurface volume as a quasi 2-D representation through the use of surfaces. These surfaces, which can represent bedding planes, for example, can be contoured or displayed as isometric views. However, in these cases, the elevation of the surface is not an independent variable, and so these systems are best defined as quasi-3-D, or 2.5-dimensional systems. These 2.5-dimensional systems can only accept a single elevation (z) value for any surface at any given location. Accordingly, several important geologic structures, such as folded or faulted conditions, which cause repetition of a single horizon at a given location, cannot be represented by these systems (4).

In contrast, true 3-D systems, containing three, independent coordinate axes, can accept repeated occurrences of the same surface at any given location. The need for detailed 3-D subsurface data, represented by a true 3-D system, is critical when constructing a regional hydrogeologic framework model at Yucca Mountain. This model of the geologically and hydrologically complex system is required to better assess regional vertical flow components and sub-basinal fluxes which have not been resolved by existing 2-D flow models (5,6,7).

Regional hydrogeologic modeling efforts at Yucca Mountain utilize GSIS's for each of the following six stages:

a. development of a hydrogeologic framework model of the Death Valley region which characterizes the 3-D subsurface geologic structures and materials;
b. analysis of selected framework model components to define the physical boundaries and flow parameters of the system;
c. evaluation of the mechanisms of regional ground-water recharge, discharge and flow to characterize hydraulic boundaries and flux conditions;
d. development of a series of numerical model input arrays using an interface between the GSIS data base and the numerical model;
e. numerical simulation of ground-water flow and evaluation of the model predictions through GSIS visualization; and
f. repetition of the above stages to achieve numerical model calibration.

DATA GATHERING AND PREPARATION PROCEDURES

Construction of a true 3-D hydrogeologic framework model is possible only with the combined use of many available software products, including traditional GIS, and sophisticated contouring, interpolation, and visualization packages (Fig. 2). Existing geologic maps and cross sections, digital elevation models, satellite imagery, geophysical data, and hydrologic data were converted into a consistent digital format utilizing the 2-D ARC/INFO* GIS (Fig. 2). Some data already exist in digital formats and only required extraction and transformation. Manuscript map data were scanned using a raster-to-vector Tektronix scanner and the resulting vector files were further processed to remove artifacts of the scanning process, transformed to a convenient geographic coordinate system, and edited to achieve accurate topology. The digital files were then moved to the Intergraph Corporation Modular GIS Environment (MGE) which allows the integration of raster and vector 3-D data sets and associated data base files.

HYDROGEOLOGIC FRAMEWORK MODEL DEVELOPMENT

Construction of the 3-D hydrogeologic framework model involves several steps. The digital geologic maps and cross sections are accurately placed in their correct 3-D spatial relationships and their features attributed using MGE (Fig. 2). The Radian Corporation's CPS-3 gridding system and fault handling package is then used to interpolate the fault planes and geologic horizon surfaces between existing cross sections and boreholes. The hydrogeologic system is then graphically displayed, or visualized. After visualization, the data are re-entered into MGE for use in 3-D ground-water flow modeling utilizing the MGE Environmental Resource Management Applications (ERMA) MODFLOW interface. Throughout the above steps, the geometrical model components are supported by a complex sequence of attribute information describing the hydrogeologic properties of all components. This information is organized and stored in a relational data base in over one hundred tables organized into the data categories shown in Fig. 3.

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* Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

INTERPRETATION OF THE FRAMEWORK MODEL

The GSIS procedures allow the 3-D hydrogeologic framework model to be repeatedly analyzed and interpreted. Alternative strategies for evaluating the hydrologic systems within the faulted terrains can be explored, for example, they may be analyzed and interpreted as either heterogeneous porous media or equivalent porous media systems. For each case, the distribution and values of numerical flow model parameters are determined directly from the 3-D hydrogeologic data contained in the data base. These data include attributes gathered from aquifer test results, lithologic and geologic logs, and published reports. The heterogeneous distribution of the flow parameters is estimated using stochastic procedures and probability distributions. Additionally, these hydraulic properties can be changed using parameters generated from multiple probable likelihood simulations.

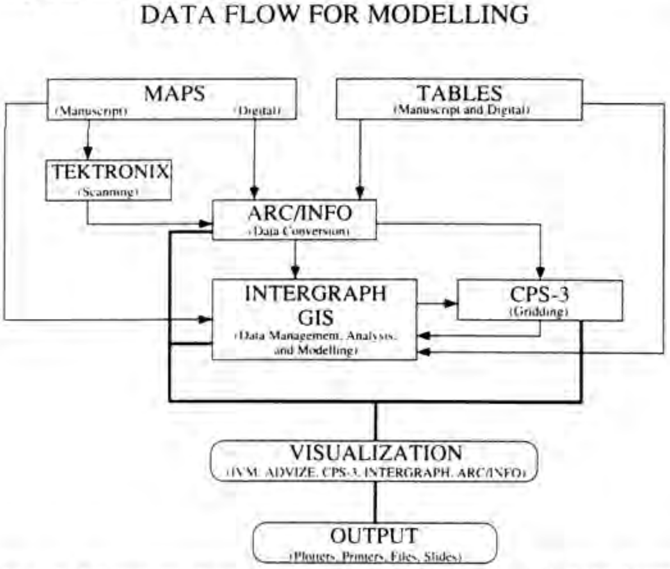

Fig. 2. Diagram showing the logical movement of data from raw format, through data conversion and analysis, and ultimately to model visualization.

Ground-water recharge and discharge information gathered from satellite imagery, digital soils surveys, and climate data reports are compiled and interpreted using traditional 2-D and 2.5-D surface modeling techniques. Regional vegetation maps, created using Intergraph's Imagestation Imager software, are used with maps describing surface hydrology, soils, and climate to estimate potential regional recharge and discharge rates.

These data are then integrated to supply a series of layered input arrays suitable for processing by the numerical flow model. The model results are returned to the GSIS data base and visualized. The numerical model is then calibrated to water levels and regional discharge rates. Model calibration is performed by modifying input arrays on a node-by-node basis, or by revising components of the hydrogeologic framework model, or the physical and hydraulic boundaries, fluxes, and flow parameters.

FUTURE WORK

After model calibration of the present-day hydrologic system, information on past geology, structure, climate, and

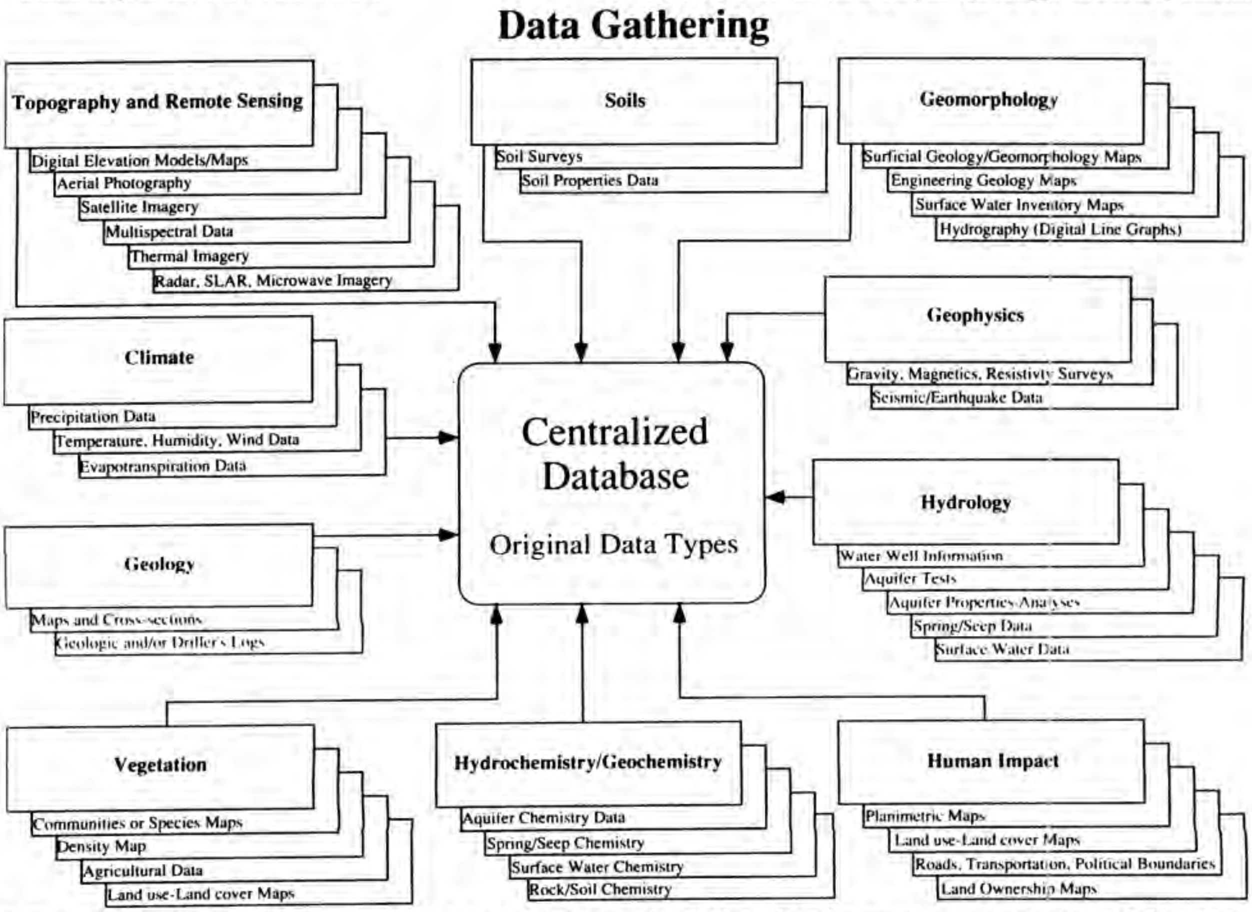

Fig. 3. Data categories and types stored in relational database that is linked to the graphical components of the 3-D model.

hydrology will be used in the same manner as described and the hydrologic flow model will be developed that estimates paleohydrologic conditions at the close of the last full glacial period *approximately* 23,000 years ago (8). Ultimately, information gathered from YMP's climate program will be incorporated into these models in an attempt to simulate a future hydrologic regime that may potentially exist in the region 10,000 years after repository closure. While model results of past and future hydrologic regimes will be estimates at best, the models are more accurately assessed and easily constructed with GIS techniques. Critical to this modeling method is the premise that present-day geologic and hydrologic data are the key to entering past geologic, climate, and hydrologic conditions. The past and present data can then be synthesized to help in the prediction of the future hydrologic conditions.

REFERENCES

1. BEDINGER, M.S., SARGENT, K.A., and LANGER, W.H., 1989, Studies of geology and hydrology in the Basin and Range Province, Southwestern United States, for isolation of high-level radioactive waste - characterization of the Death Valley region, Nevada and California: USGS Professional Paper 1370-F.
2. TURNER, A.K., 1989, The Role of Three-dimensional Geographic Information Systems in Subsurface Characterization for Hydrogeological Applications, in Three-dimensional Applications in Geographic Information Systems (J.F. Raper, editor), Taylor and Francis, London, pp. 115-127.
3. RAPER, J.F., 1989, The 3-dimensional geoscientific mapping and modelling system: a conceptual design, in Three-dimensional Applications in Geographic Information Systems (J.F. Raper, editor), Taylor and Francis, London, pp. 11-19.
4. TURNER, A.K., 1991, Applications of Three-dimensional Geoscientific Mapping and Modeling Systems to Hydrogeological Studies, in Three-Dimensional Modeling with Geoscientific Information Systems (A.K. Turner, editor), NATO ASI Series C: Mathematical and Physical Sciences, vol. 354, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 327-364.
5. WADDELL, R.K., 1982, Two-dimensional, steady-state model of ground-water flow, Nevada Test Site and vicinity, Nevada-California: USGS Water-Resources Investigations 82-4085, 72 p.
6. CZARNECKI, J.B., and WADDELL, R.K., 1984, Finite-element simulation of ground-water flow in the vicinity of Yucca Mountain, Nevada-California: USGS Water-Resources Investigations Report 84-4349, 38 p.
7. RICE, W.A., 1984, Preliminary two-dimensional regional hydrologic model of the Nevada Test Site and vicinity: Richland, Washington, Pacific Northwest Laboratory Report SAND83-7466, 44 p.
8. SPAULDING, W.G., 1985, Vegetation and climates of the last 45,000 years in the vicinity of the Nevada Test Site, South-Central Nevada: USGS Professional Paper 1329, 83 p.