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A METHODICAL APPROACH TO GIS-BASED HYDROGEOLOGIC MAPPING

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ABSTRACT

This paper describes a methodical approach to hydrogeologic mapping and outlines principles of data management using Geographic Information Systems. Digital hydrogeologic maps and their underlying data base are well suited for water resources planning. The concept of the digital hydrogeologic map presented in this article focuses on the occurrence of productive aquifers and visualizes them by an "x-ray view" in the base map that outlines hydraulic conductivity at groundwater level. Additional hydrogeologic cross sections reveal the vertival distribution of hydraulic conductivity as well as the thickness of productive strata and their tectonic setting. Regional hydrogeology can be presented by at least three different layers of information that can be supplied in separate sheets: hydrogeological base map, hydrogeological cross sections, groundwater contour map. A Geographic Information System serves as a platform of integration for digital maps around which available data are centered. The application of a GIS and a subsequent georelational database allows data capture, processing, analysis, and visualization in support of decision making.

Key words: Digital hydrogeologic map, hydrogeologic cross section, Geographic Information System (GIS), ARC/INFO.

RESUMEN

El presente artículo describe una aproximación metodológica en la obtención de cartas hidrogeológicas y los principios en el manejo de los datos necesarios usando un Sistema de Información Geográfica (SIG). Cartas hidrogeológicas digitales, con sus respectivos bancos de datos, proporcionan una excelente herramienta para el buen manejo de los recursos del agua. El concepto de la carta hidrogeológica presentado en este artículo se enfoca en las formaciones acuíferas. Se muestra a los acuíferos por medio de una visualización de "rayos x" en la carta hidrogeológica base, enfocándose en la conductividad hidráulica en el nivel piezométrico. Cortes hidrogeológicos adicionales muestran tanto la distribución vertical de la conductividad hidráulica, como el espesor de las formaciones productivas y su posición tectónica. La hidrogeología regional puede ser presentada utilizando por lo menos tres diferentes capas de información: Carta hidrogeológica base, Carta de cortes hidrogeológicos, Carta isopiezométrica. Un Sistema de Información Geográfica proporciona una plataforma de integración de datos hidrogeológicos disponibles y es utilizado para la preparación de los mapas digitales. El manejo de un SIG con su respectivo banco de datos georeferenciados permite la captura de los datos, su procesamiento y su análisis, combinando estas informaciones para el soporte de la toma de decisiones.

Palabras clave: carta hidrogeológica digital, perfiles hidrogeológicos, Sistema de Información Geográfica (SIG), ARC/INFO.

INTRODUCTION

Planning engineers as well as regional and federal authorities have always relied on solid information provided by thematic maps that serve a great variety of purposes. Geologic maps outline rock types and distribution of geologic structures and provide a base for a wide range of environmental and construction activities. Similar to geologic maps, hydrogeologic maps reveal rock properties and geological settings, but additionally they focus on groundwater resources. Due to several concepts of display their information content ranges from estimations of specific yields and/or aquifer parameter distribution to hydrodynamic characteristics. An overview of hydrogeological mapping techniques and contents as well as a comprehensive proposal for an international standard legend for hydrogeologic maps are given by Struckmeier and Margat (1995).

The information displayed in hydrogeologic maps often reveal certain limitations of information to rock classification and to quantification of productivity. The approach presented in this paper is based in many aspects on the experiences of hydrogeologic mapping in Germany, where a specific concept for hydrogeologic maps considering regional geology was developed as early as in the late fifties at the Department for

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Engineering Geology and Hydrogeology at Aachen University of Technology (Breddin 1963). The outstanding features of this map concept are the visualization of transmissivity distribution by giving precise values of hydraulic conductivity for productive aquifers and less productive strata in combination with aquifer thicknesses. Hydrogeological properties are highlighted at groundwater level and additionally displayed by a series of hydrogeologic profiles relying on borehole and geophysical data. Recent increases of computational power at reasonable prices and advanced software development resulted in various attempts to rely on Geographic Information Systems (GIS) and relational database management systems (RDBMS) as the core of hydrogeologic information systems with hydrogeologic maps as a central part. The Geological Surveys of Germany are pursuing different approaches to implement digital hydrogeologic information systems. The Geological Survey of Nordrhein-Westfalen expanded and enhanced the traditional Aachen concept by focussing on the GIS aspect (Schlimm, 1996; Elfers *et al.*, 1998). The first hydrogeologic maps elaborated in the scope of this long term project are already published (Elfers, 1996; Masuch-Oesterreich, 1997). The methodical approach for hydrogeologic mapping introduced in this paper relies in great parts on these experiences.

The conception of a hydrogeologic map is a crucial point that has to consider quite a lot of aspects. Figure 1 outlines only a few examples for which these maps are consulted. The conclusion that is to be drawn from these multi-purpose uses is that hydrogeologic maps have to be tailored to meet the demands of applied engineering and not only to serve scientific uses. The maps will be valued, proved, and testified simply by field testing and have to be reliable in practical engineering. To fulfill this requirement, a map concept has to be customized to regional and/or local geological conditions. Furthermore, the incorporation of GIS software, despite its undisputable advantages, adds another level of complexity to the conceptual considerations.

In the first part, this paper introduces the fundamental differences of a hydrogeologic map based on the evaluation of hydraulic conductivity to existing maps and explains the principles of visualization. The second part focuses on the underlying GIS concept.

INFORMATION CONTENT AND VISUALIZATION METHODS FOR HYDROGEOLOGIC MAPS

A concept for a visualization of groundwater conditions basically has to consider two different rock types: fractured rocks and porous media. Due to their fundamentally different hydraulic properties, distinctive display methods have to be considered. Following the commonly used methods of revealing hydrogeological properties of specific regions, a set of digital hydrogeologic maps may include at least three different sheets:

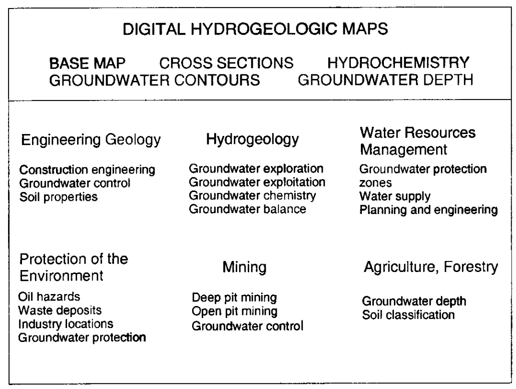

Figure 1. Applications of digital hydrogeologic maps for practical engineering.

1. hydrogeologic base map
2. hydrogeologic cross section map
3. groundwater contour map

Maps to be added optionally comprise:

1. hydrochemical map
2. depth of water table
3. groundwater fluctuations

Each of these separate layers of information has to respect local hydrogeological properties. Either way, a common parameter is needed for display in both fractured rocks and porous media. Among a variety of influencing factors, water properties (*e. g.*, dynamic viscosity, kinematic viscosity, density, compressibility), properties of the aquifer itself (*e. g.*, porosity, storage coefficient, hydraulic gradient, hydraulic conductivity, transmissivity), rock composition, and fracturing have to be considered when determining the hydrogeological characteristics of a certain area. All these features have an impact on an aquifer's capability to convey water. Consequently, most common concepts for hydrogeologic maps focus on an aquifer's hydraulic conductivity and estimations of productivity. This often results in legend explanations that describe lithological units as "highly to moderately productive" or "moderately to low productive". The approach introduced in this paper also focuses on hydraulic conductivity, but gives as precise values as possible by using the hydraulic conductivity of an aquifer as the basic vehicle of visualization. The key to the hydrogeologic map is a classification of hydrogeological units according to their characteristic hydraulic conductivity. Two different charts of classification are used for fractured rocks and porous media, respectively (Figures 2 and 3).

Hydraulic conductivity K in porous media is classified in a particle size distribution chart using grain size analyses and the Hazen formula:

$$K = 0.0116 \cdot d_{10}^{2} \cdot (0.03 \cdot \theta + 0.70) \qquad [m \cdot s^{-1}]$$

Relying on samples of certain areas of investigation, this chart has to be modified due to local geological conditions to obtain a precise classification of hydraulic conductivities of the hydraulically significant strata.

Hydraulic conductivities are outlined and verified by

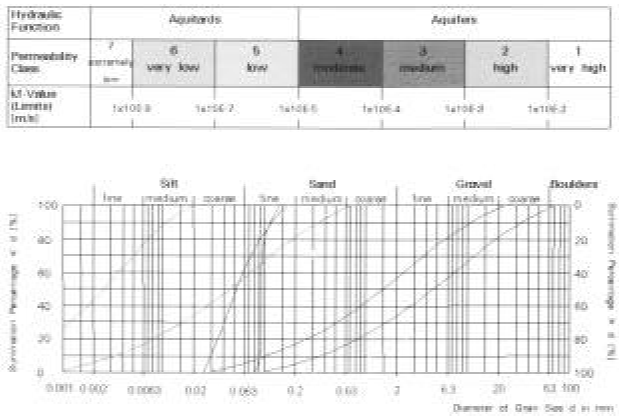

Figure 2. Hydraulic conductivity classes of porous media for the southern Muenster Basin in Germany (Masuch-Oesterreich, 1997; after the classification of Schlimm, 1996).

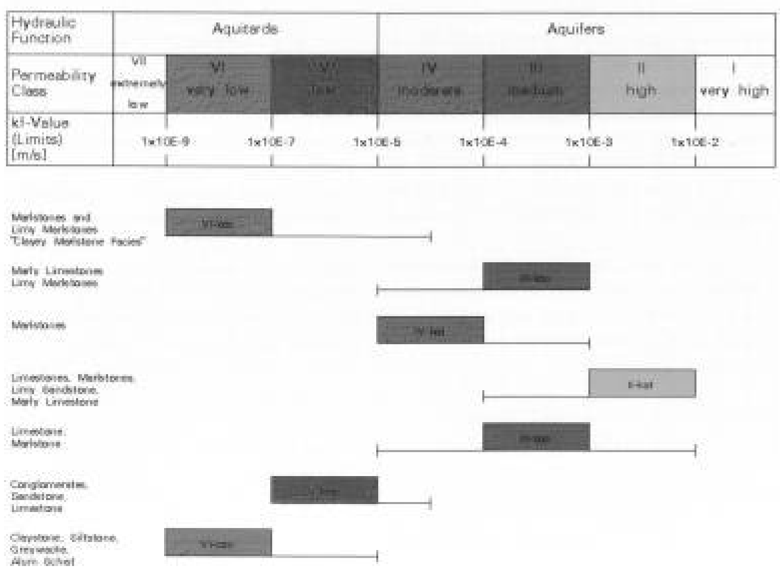

Figure 3. Hydraulic conductivity ranges in the loosened zone of fractured rocks in the southern Muenster Basin in Germany (Masuch-Oesterreich, 1997; after the classification of Heitfeld, Krapp and Stoltidis, 1974; and Schlimm, 1996)

available data obtained from field and laboratory tests. Geologic formations are then classified according to hydraulic conductivity. If necessary, stratigraphic units are split up and are separately visualized. The colors viewed in the base map then correspond to the classes of hydraulic conductivity as given in Figure 2. The parameter directly visualized is the resulting vertical hydraulic conductivity.

Among the first layers to be elaborated is the groundwater contour map. In porous media, groundwater elevations measured at one specific date are used as the level of visualization. Basically, there are two possibilities for a level of reference: a long-term high level or a long-term low level. It will depend on local conditions and the information preferably in demand to choose which one to use. Planning waste deposits and construction activities will require the knowledge of the highest groundwater level possible whereas groundwater exploration, among many other requirements, has to consider the lowest level as well. Groundwater fluctuations can be visualized in an additional map.

All strata above the groundwater level are not displayed in the base map. Contour lines of the exploitable aquifer thickness are added and subsequent polygons are indicated by variations of color intensity representing the aquifer thickness. Since transmissivity is the product of the hydraulic conductivity and the saturated thickness of an aquifer, the result is a map displaying the distribution of transmissivity at groundwater level. Transmissivities can be obtained for each polygon through a table accompanying the map.

Less permeable strata covering an aquifer are shown by hatching with the colors of their respective hydraulic conductivity. Areal extent of silt and clay intercalations significantly reduce vertical hydraulic conductivity and therefore are represented by colored lines.

The basic principle of visualization consistently is an “x-ray view” through the geological strata that focuses on the display of the permeable strata. That way, productive aquifers, even those hidden by a less permeable cover, and non-productive strata are clearly highlighted.

Whereas flow conditions in porous media are determined basically by the effective porosity of the material, groundwater content and groundwater flow in fractured rocks are controlled by their tectonic inventory. Weathering, fracturing, cleavage, and karstification are the most influential factors with an impact on hydraulic conductivity. Capture and representation of flow conditions are more complicated and less predictable. Stress release and weathering commonly result in a loosened zone of higher permeability of varying thickness. Below this loosened zone hydraulic conductivity can rapidly decrease. The same strata is liable to have different hydraulic properties in its loosened zone and in the unaltered rock. Hydraulic conductivity is less determined by rock properties but the tectonic structure of the massives. Field data can vary to a great extent and are less precise to be obtained and determined.

Consequently, a different way of presentation has to be considered for a map concept for fractured media. Values of hydraulic conductivity are rather an estimation than a precise data source. The classification chart proposed thus considers the variation of hydraulic conductivity occurring in a certain hydrogeological unit while attempting to focus on the most precise data that can be determined (Figure 3).

A detailed geologic and tectonic map is necessary to extrapolate hydraulically active structures into a three-dimensional image. Since exploitable groundwater resources are most likely to occur in the loosened zone, the presentation of hydraulic conductivity focuses on this specific zone of interest. The reference level for visualization in this case is the ground surface, omitting soils, hydraulically insignificant porous media, and weathering residues of minor thickness. Hydrogeological boundaries are defined due to similar hydraulic properties and do not have to coincide with the geologic or stratigraphic limits. The elaboration of a groundwater contour map is not always recommendable, though piezometric heads of existing wells can be included in the base map.

The hydrogeologic base map is accompanied by a map of hydrogeologic cross sections (Figure 4). Following a certain equidistance and a direction perpendicular to tectonic structures, this map displays the vertical distribution of hydraulic conductivity. In combination with the hydrogeologic base map, the cross section map provides a nearly three-dimensional view of the covered area by adding a transparent visualization of hydraulic properties into depth. The colors used coincide with those of the distribution charts of hydraulic conductivity. However, the groundwater level is marked by a blue line, followed by the unsaturated zone indicated with a yellow color. Confined piezometric heads and groundwater levels in fractured rocks are indicated by interrupted lines with short interruptions indicating confined levels, and long interruptions indicating groundwater levels in fractured rocks, where possible.

The most important basis for the construction of the cross sections is provided by available borehole data. Geophysical logs, geoelectric and seismic data, if available, are also considered. Lithologic boundaries serve to construct base maps of significant hydrogeologic units. Thrust and fault settings, especially those causing major dislocations, thus can be determined. The dislocations and base maps serve as the framework for the correlation of boreholes. The construction of profiles in poorly perforated areas additionally relies on tectonic surface data and assumes geometrically and genetically probable positioning between the closest boreholes. Unsecurities in this construction can be displayed in an optional map of data density.

The hydrogeologic cross section map provides information about the tectonic framework and the geologic setting of the hydrogeologic units as well as their composition, thickness, hydraulic conductivity, and groundwater levels. Due to the geometric construction of the cross sections along

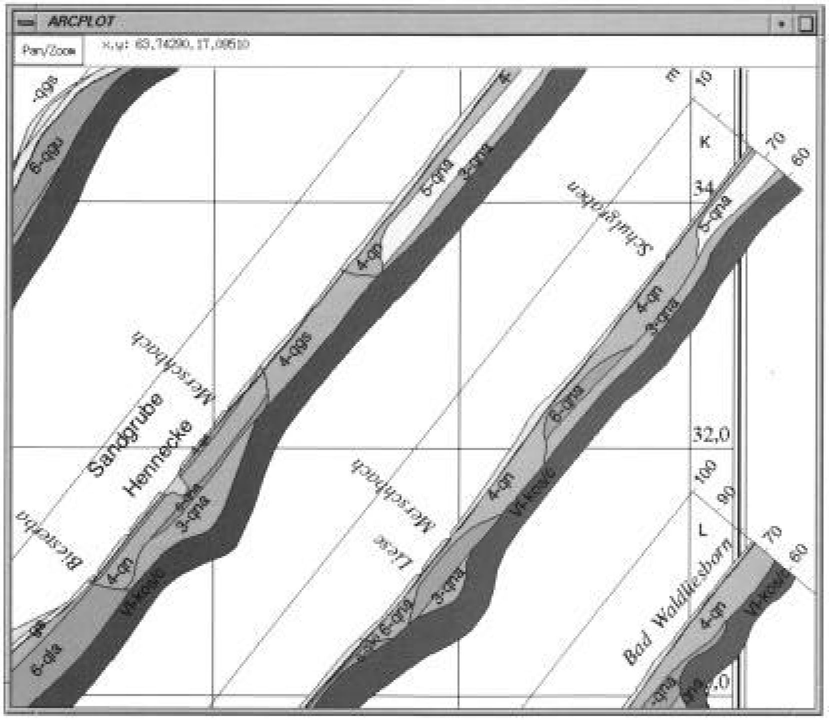

Figure 4. Clip of a draft of the Hydrogeologic Map of Nordrhein-Westfalen (cross section map), sheet L4314 Beckum.

equidistant lines, it is possible to derive a lithologic profile for any given location between adjacent cross sections by assuming geometrically logical stratification.

INTEGRATION OF HYDROGEOLOGIC DATA IN A GEOGRAPHIC INFORMATION SYSTEM

Digital hydrogeologic maps fundamentally differ from their conventionally elaborated counterparts. As soon as a GIS is part of a project, we are leaving the traditional way of storing, analyzing, accessing, and presenting data. A GIS is not exclusively applied for the task of map production and data visualization. It does not store maps—it holds a spatial database from which views can be derived to suit particular user requests. A GIS means creating and maintaining a digital information system with its internal geospatial and/or an external relational database as one interface of access to its information. This central aspect insists on a thorough and detailed conception of the GIS application before launching a major project.

One can be of the opinion that this is just a question of project management. However, this point of view neglects the complexity of these systems. A smooth interaction of hardware, software, personnel, and available budget always requires a scientific concept as well. This concept will be of crucial significance to the success of a GIS project. A short definition of a GIS may describe it as a computer system capable of storing and accessing spatial data. Reality, however, is much more complex. Consequently, Esri (1995a) defines a GIS as an "organized collection of computer hardware, software, geographic data, and personnel designed to efficiently capture, store, update, manipulate, and display all forms of geographically referenced information". Thinking about the continuity of long term projects, two aspects are of significant importance: data and personnel. Availability and quality of input data and trained specialists working on the task are part of the considerations that may finally manifest themselves in a concept for a digital hydrogeologic map.

The possibilities offered by the system, but also its application limits, have to be well known. The system needs to be tailored to local hydrogeologic conditions. Often enough, hydrogeologists preparing a map have to deal with predefined goals and natural conditions that are sometimes impossible to achieve together. A seemingly simple example like the construction of a groundwater contour map already outlines GIS limits that sometimes have ill-fated results. Assuming that the problem of feeding the system with local geology has been sufficiently solved, and a groundwater contour map was created from well registrations, the map calculated by GIS algorithms may come close to nature. Though considering that a surface model is just that, a model, in this specific case it is not even correct in the mathematical sense. The fundamental equation of hydrogeology, Darcy's law, is not implemented in GIS software. Tauxe (1994) incorporated tools for two dimensional groundwater flow in a GIS that allow the generation of a Darcian flow field and particle tracking. But these extensions do not come standard with GIS software.

The example mentioned above describes one of the principal problems that hydrogeologists have to solve when establishing digital information systems and preparing adequate data output: GIS software does not cover all the functions needed to analyse hydrogeologic data. Even more so, no GIS software was ever designed for that particular purpose.

Hydrogeological mapping requires the regionalization of hydrogeologic conditions. The data that have to be processed fall into one of the following three categories, all of which can principally be described in either the raster or vector data model of hybrid GIS software (Plum *et al.*, 1997):

1. Point data: data belonging to objects that can be pinpointed on the earth's surface. Wells, well galleries, groundwater monitoring wells, and springs, for instance, fall into this category. Data related to point objects are, among others, borehole logs, groundwater level registrations, or hydrochemical analyses.

2. Line data: data referring to linear objects. Faults, geoelectric or seismic profiles, and water conduits may serve as examples of this group.

3. Polygonal data: polygonal data can be either polygonal objects or the spatial distribution of hydrogeological parameters and/or properties. Polygonal objects are homogeneous areas defined by the same properties and can be, for instance, well head protection zones or the projection of the extent of a certain hydrogeologic unit at surface level. In hydrogeologic maps these data are separated by closed polygons indicated by a certain signature or color. Spatial distributions and their according variations are, for instance, distribution of groundwater potential, groundwater depth, hydrochemical characteristics, or top and base levels of aquifers. They are commonly displayed by contour lines or related methods of visualization.

Hydrogeologists have to deal with three-dimensional structures of aquifers and their lateral and vertical differentiation of parameters. Hoewever, certain hydrogeological data highly vary with time. GIS software is quickly stretched to its limits when processing, even capturing, these data. At this point, two different approaches following different concepts of realising data management are pursued.

The first approach is the attempt to manage all necessary data and operations of data processing and analysis with the tools provided by the respective GIS software as presented in Figure 5. Additionally to the GIS spatial database, a relational database management system (RDBMS) is often incorporated to hold data that are unconvenient or simply impossible to capture in the GIS database itself. A typical hardware and software setup for this solution may be Sun or Silicon Graphics workstations running their respective Unix operating systems, an Oracle or Informix relational database, and the ARC/INFO GIS package. In this example, the ARC/INFO database integrator links the RDBMS to the GIS. The ArcTools graphical user interface facilitates quick access to the GIS itself. Applications can be customized and automized by programming routine tasks in the software's AML language. Considering the hydrogeologic map as the major goal to achieve, this setup already provides the routines needed by supplying the tools for data processing for each of the steps shown in Figure 6. The processing heavily relies on both the raster and the vector data models.

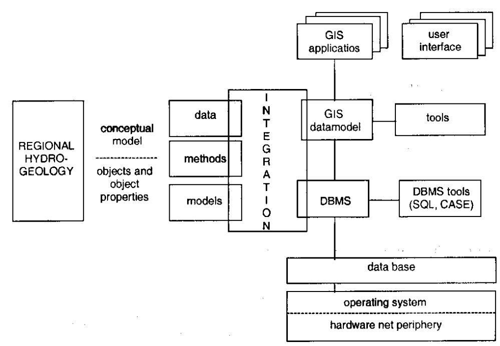

Figure 5. Managing hydrogeologic data in a GIS (modified after Schilcher *et al.*, 1996).

The second approach to managing hydrogeologic data tends to a modular concept for data analysis using additional and specific software for specific data and tasks. The results then have to be transferred into the GIS by suitable means of data interchange. This approach relies on the GIS as merely one of several components, but with the GIS taking over the role of the integrating platform. Obviously, all hydrogeologic data are related to certain locations. At this point, the GIS takes full advantage of its capability to manage spatial data and functions as the core of this complex setup of analysis tools.

The results of data collection and subsequent analysis for the purpose of hydrogeological mapping, in any case, are thematically separated. The GIS layer concept coincides with reasonable data capture by storing each theme in its own layer. Since the results of the raster analyses have to be prepared in vector format for output, attributes are labeled to the coverages. The link between spatial and tabular data used by ARC/INFO is outlined in Figure 7.

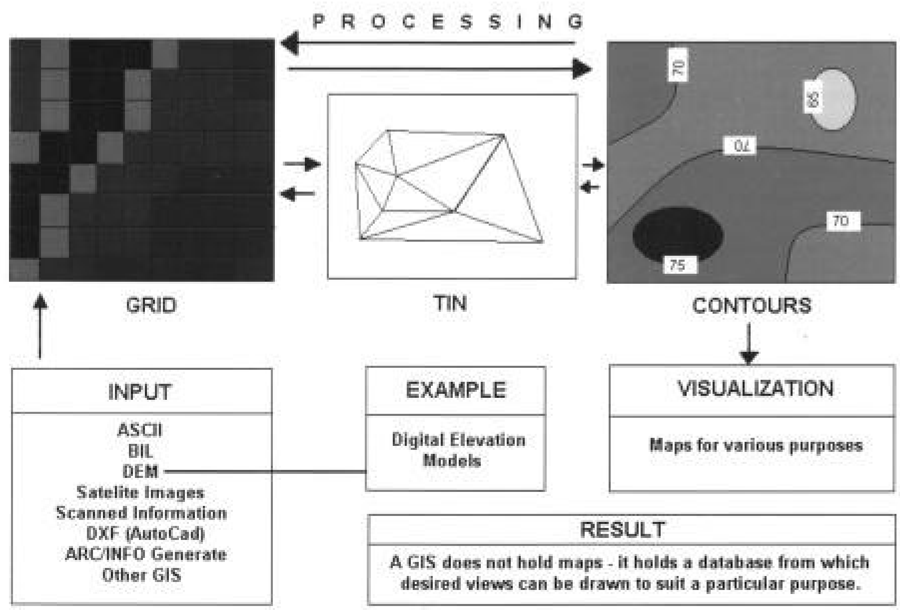

Figure 6. Data flow within the ARC/INFO GIS.

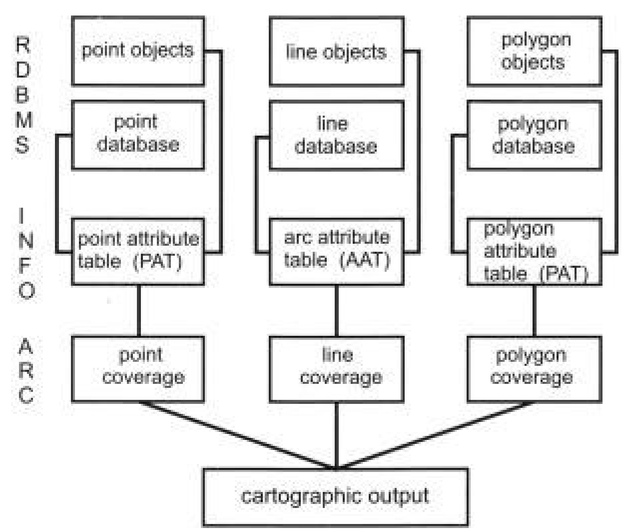

Figure 7. Link between descriptive data and spatial data in ARC/INFO.

ARC/INFO georelational model gives access to the descriptive attribute data held in an RDBMS. The software database integrator associates data created and managed externally with coverages and grid data sets. A "relate" operation establishes a connection between corresponding records in tables using a common key item. Hydrochemical analyses, groundwater levels, or borehole registrations are data typically held in the RDBMS and are linked to point coverages. Data describing contour lines or tectonic elements are related to line coverages while the spatial extent of hydrogeological units or any other objects defined by polygonal surroundings are associated to polygon coverages. In any case a common database-ID in the INFO module and the RDBMS is used to establish the link between attribute and geometry data. The content of information of the proposed digital hydrogeologic map is structured according to this concept of data handling with each theme of data being captured in a separate layer.

The implemented data structure has to be an open system that allows to add recently obtained data at any time. However, a steadily growing system requires to be very well organized in order to prevent losing control of the project. Table 1 presents an example of a hierachical structure for holding the data for the compilation of a digital hydrogeologic map. Data management is organized into four different levels with each level serving a particular purpose. The system is designed to easily allow adding and updating data. Access to the project is limited to the project staff and the system administrator, beginning at the second level of data storage.

The root directory (1st level) splits up into the subdirectories of the maps presently in elaboration. The directories of the respective hydrogeologic maps (2nd level) point to the thematically separated data sets of the respective maps. The 3rd level is equally structured for each of the projects and contains all the coverages necessary for map generation. The subdirectories of the 4th level hold the maps that are already edited, revised, and prepared for publication.

AML files written for the ARCPLOT module are held in the 3rd level and join the several coverages together to compose the base map. Selecting specific data and creating new themes of information is accomplished at this level by editing the AML files. The AMLs patch the coverages together using absolute pathnames. Thus, the implemented data structure is fixed and should not be altered. AMLs for ARCPLOT held in the 1st level are used to run the map generating AMLs in the 3rd level. That way, specific map views of ongoing projects can be selected and automatically generated (Masuch et al., 1997). The process of map production is recorded either on the UNIX standard-out or is written to a log file. Metadata about the coverages are contained in the respective directories in the 3rd level. Metadata standards may follow the specifications given by Esri (1995b) or by the US Geological Survey at http://mapping.usgs.gov/standards/.

In a growing system, the project documentation is a crucial point that has to be handled with great accuracy. The data structure has to be ultimately transparent and easy to follow to ensure monitoring of the proceedings of the project. A documentation written in HTML and maintained by responsible supervision staff provides an easy way of access to the project status to both, the involved specialists and the management.

CONCLUSIONS

A modern concept for hydrogeologic maps has to consider a wide range of possible uses (Figure 1). Environmental protection and securing of groundwater resources are among the most pressing issues for which a hydrogeologic map will be consulted. A suitable principle to fulfil these needs is the visualization of extent and thickness of the aquifers by displaying the horizontal and vertical distribution of hydraulic conductivity. Geographic Information Systems are highly useful tools for the analysis and the cartographic presentation of hydrogeologic data. The raster and vector data models provide an adequate projection of the real world data. However, certain restrictions of GI Systems have to be considered when modelling groundwater dynamics. A GIS delivers its major advantages when coupled with mathematical groundwater models. The digital approach to hydrogeologic mapping demonstrates its flexibility by taking advantage of the GIS´s analytical tools. The open data structure facilitates data updates and the automation of the process of map production. The generation of new thematic views in rapid response to specific problems helps in water resources management and decision making.

DISCLAIMER

When talking about GIS methodology it is almost inevitable to mention certain hardware and software products. Users have a particular interest in knowing which programs and hardware platforms were used to achieve certain results. The products named in this paper are trademarks of their respective companies. The author is not affiliated with any of them and does not endorse certain products.

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Table 1. Example of a data structure for a project of three hydrogeologic maps in four hierachical levels.

1. Level (root directory)

/usr/local/hydrogeol_maps

2. Level (directories of the respective hydrogeologic maps)

/sheet_beckum	/sheet_bueren	/sheet_soest	/tmp
(Hydrogeologic Map 1:50,000 L 4314 Beckum)	(Hydrogeologic Map 1:50,000 L 4516 Bueren)	(Hydrogeologic Map 1:50,000 L 4514 Soest)	(temporary files)

3. Level (thematically separated data sets of the respective maps)

/photographs	/images	/base_map	/cross_sections	/raster_data	/vector_data	/templates

4. Level (completed maps in zipped plotter file formats)

/maps
(edited maps ready for hardcopy)

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BIBLIOGRAPHIC REFERENCES

Breddin, H., 1963, Die Grundrisskarten des Hydrogeologischen Kartenwerkes der Wasserwirtschaftsverwaltung von Nordrhein-Westfalen: Aachen, Germany, Geologische Mitteilungen, v. 2, p. 393-416.

Esri, 1995a, Understanding GIS - the ARC/INFO Method: Self-study workbook, version 7 for UNIX and OpenVMS: New York, John Wiley and Sons.

Esri, 1995b, Metadata management in GIS.- Esri White Paper, available at http://www.esri.com

Elfers, H., 1996, Blatt L 3912 Lengerich der Hydrogeologischen Karte von Nordrhein-Westfalen 1:50,000 (HK50): Krefeld; Germany, Geologisches Landesamt Nordrhein-Westfalen.

Elfers, H., Masuch-Oesterreich, D., Schetelig, K., Schlimm, W. and Wimmer, G., 1998, The Hydrogeological Map of Northrhine-Westphalia - A new concept and its realization— Experiences on applied geological mapping: Zentralblatt für Geologie und Paläontologie, Teil 1, Heft 9/10 - Sedimentologie, Natural Resources and Environmental Protection; Sammelband 9, und 11. Kontaktwochenende Sedimentologie in Aachen, Schweitzerbart´sche Verlagsbuchhandlung; Stuttgart, Germany.

Heitfeld, K.-H., Krapp, L. and Stoltidis, I., 1974, Die Grundgebirgskarten des Hydrogeologischen Kartenwerkes von Nordrhein-Westfalen (Teilbereich Nordeifel und Bergisches Land): Geologische Mitteilungen, v. 12, p. 413-430.

Masuch, D., Hellweg, F., and Schmela, M., 1997, ARC/INFO-gestützte hydrogeologische Karten als Grundlage für wasserwirtschaftliche Planungen, in Esri, 1997, Tagungsband der 5. Deutschen ARC/INFO-Anwenderkonferenz, 11.-13.03.1997; Kranzberg, Germany.

Masuch-Oesterreich, D., 1997, Die Blätter L 4314 Beckum und L 4514 Soest der Neuen Hydrogeologischen Karte von Nordrhein-Westfalen: Mitteilungen zur Ingenieurgeologie und Hydrogeologie, Vol. 67, Lehrstuhl für Ingenieurgeologie und Hydrogeologie der Rheinisch-Westfälischen Technischen Hochschule Aachen; Germany.

Masuch-Oesterreich, D., 1999, Blatt L4314 Beckum der Hydrogeologischen Karte von Nordrhein-Westfalen 1: 50 000 (HK50): Geologisches Landesamt Nordrhein-Westfalen; Krefeld, Germany.

Plum, H., Sokol, G., and Watzel, R., 1997, GIS-Einsatz bei der Konzeption einer digitalen hydrogeologischen Karte, in Esri, 1997, Tagungsband der 5. Deutschen ARC/INFO-Anwenderkonferenz, 11.-13.03.1997; Kranzberg, Germany.

Schilcher, M., Kaltenbach, H., and Roschlaub, R., 1996, Geoinformationssysteme - Zwischenbilanz einer stürmischen Entwicklung, in ZfV, Heft 8/1996, Wittwer Verlag, Germany.

Schlimm, W., 1996, Generallegende zur Hydrogeologischen Karte von Nordrhein-Westfalen 1:50,000: Krefeld, Germany, Geologisches Landesamt Nordrhein-Westfalen, Interner Report.

Stahl, R., and Henneberg, F., 1995, Internet- und Gistutorial— Available at the Web Site of the Institute of Geography, University of Salzburg, Austria, at http://www.sbg.ac.at/geo/gisnet/start.htm (1995).

Struckmeier, W. F., and Margat, J., 1995, Hydrogeological Maps - A Guide and a Standard Legend: Hannover, Germany, International Contributions to Hydrogeology, IAH publication, v. 17, Verlag Heinz Heise.

Tauxe, J. D., 1994, Porous media advection-dispersion modeling in a geographic information system: Center for Research in Water Resources Technical Report no. 253, Bureau of Engineering Research, University of Texas at Austin; Austin, Texas.

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