GEOLOGICAL SURVEY OF CANADA

OPEN FILE 6998

Three-Dimensional Geological Mapping

WORKSHOP EXTENDED ABSTRACTS

Minneapolis, Minnesota – October 8, 2011

Conveners:

H.A.J. Russell,

R.C. Berg,

and L.H. Thorleifson

2011

Natural Resources Canada
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We thank the Geological Society of America for their logistical support and working with us to achieve the best possible venue and lowest costs.

Finally, we thank all of our presenters and their respective funding agencies and sources for making this Workshop a success. Publication of this proceedings was supported by the Groundwater Geoscience Program of the Geological Survey of Canada, the Illinois State Geological Survey, and the Minnesota Geological Survey.

INTRODUCTION – THREE-DIMENSIONAL GEOLOGICAL MAPPING

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[1]Geological Survey of Canada, [2]Illinois State Geological Survey, [3]Minnesota Geological Survey.

This workshop is the seventh in an ongoing series primarily designed to share insights among geological mappers who are maximizing the use of variable and often voluminous subsurface information in order to produce 3D models that map sediment and rock, with an emphasis on the needs of groundwater management. The first workshop in this series was held in Normal, Illinois, ten years ago this past April, (Berg and Thorleifson, 2001). This year's workshop reflects the evolving focus of the series from issues of data quality, datasets, and methods for data collection to a focus at the Geological Survey Organization level on institutional implementation of modelling standards at state, provincial, and national scales.

Since the 2009 workshop in Portland two notable outcomes of the workshop series have been published. Firstly, Thorleifson et al. (2010) discussed the emergence of 3D mapping at Geological Survey Organizations (GSO). Secondly, Berg et al. (2011) edited a collection of papers on approaches to 3D geological mapping at several geological survey organizations from Europe, North America, and Australia.

This year's workshop continues the trend of increased focus on work at GSOs with 11 of 15 contributions focused on this subject. ,The four remaining papers, however, maintain the essential link to research on methods.

1. GEOLOGICAL SURVEY ORGANIZATIONS

The 11 papers from national, state, and provincial GSOs reflect the differences in organization scale, human and financial resources, and mandates. Also evident are the different challenges presented by geographic scale, population density, and breadth of natural resource issues. Mathers from the BGS provides a brief overview of the edited volume by Berg et al. (2011) and continues in more detail on activities at the BGS. BGS work on an integrated modelling environment is further detailed by Peach. Four papers from Europe highlight activities in France (Gabalda et al), Holland (Stafleu), Germany (Diepolder) and Denmark (Thomsen). Gabalda et al. highlight work in sedimentary basins and an increasing demand for deeper models to support resource decisions. Stafleu presents an up to-date account of modelling developments in Holland from existing surface models (DGM, REGIS-II) to voxel models (GeoTOP, NL3D) and database developments, as well as model dissemination via the web. Diepolder provides an overview of the responsibilities of GSOs in Germany and reviews work in various national and international modelling activities (GEOMOL, GST, and ProMine). Thomsen highlights a national program of groundwater investigation in Denmark, database development (GERDA) and the importance of data standards and geophysical data collection to provide a framework for groundwater protection .

The remaining GSO papers are from North America and review the situation at national, state, and provincial geological surveys. From the United States Geological Survey, Glynn reviews the scope and scale of demands for 3D geological information and also integrates the emerging need for data, modelling, and visualization in the fourth (time) dimension. A paper by Keller et al. highlights a collaborative effort between Manitoba and Minnesota and demonstrates what can be achieved with only minimal financial and human resources. Bajc et al. review progress in Southern Ontario and put emphasis on data collection (gravity) and modelling developments. Russell et al. provide an overview of work at the Geological Survey of Canada toward development of a hierarchal framework to support groundwater investigations in support of Canadian federal government priorities.

2. METHODS DEVELOPMENT

Four papers address methods development and concentrate on data collection and geostatistical approaches to modelling geological scenarios. Abraham and Thomason & Keefer both discuss survey design, processing, and integration of three dimensional data from airborne electromagnetic surveys, Abraham in Nebraska and Thomason & Keefer in Illinois. The value of airborne EM surveys is also discussed by Thomsen and the important contribution it is making to Danish subsurface modelling and to Russell et al. for the buried valleys in the prairie provinces of Canada. Gabalda et al. note the challenge of integrating geological heterogeneity into models and Dunkle et al. and Quinn & Moores both address this challenge through different geostatistical approaches. Dunkle presents a case study from Wisconsin applying multipoint geostatistics to map preferential flow paths, and Quinn considers a number of questions regarding spatial heterogeneity in glacial sedimentary systems and effects of data quality and geostatistical approaches.

3. SUMMARY

The proceedings content provides an overview of the rapid evolution in three-dimensional geological mapping methods at government agencies. It is becoming clear that societal needs, particularly for effective groundwater management, are leading to more research and progress in areas of 3D data collection, modelling techniques, and data management.

References

Berg, R.C., Mathers, S.J., Kessler, H., and Keefer, D. A., 2011. Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organization, edited b1. Champaign, Illinois: Illinois State Geological Survey, Circular 578, www.isgs.illinois.edu.

Berg, R. C., Thorleifson, L. H., (convenors) 2001. Geologic Models for Groundwater Flow Modeling: Workshop Extended Abstracts. Illinois State Geological Survey, Open File Series 2001-1, 62p. http://www.isgs.uiuc.edu/research/3DWorkshop/index.shtml)

Thorleifson, L. H., Berg, R. C., and Russell, H.A.J. 2010 “Geological mapping goes 3-D in response to societal needs.” GSA Today, no. 8 (August 2010): 27-29. http://www.geosociety.org/gsatoday/archive/20/8/abstract/i1052-5173-20-8-27.htm.

AIRBORNE ELECTROMAGNETIC SURVEYS FOR 3D GEOLOGICAL MAPPING

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Abstract

The U.S. Geological Survey and its partners have collaborated to create 3D geologic maps for areas of the North and South Platte River valleys, including Lodgepole Creek, in western Nebraska using airborne electromagnetic surveys. The objective of the surveys is to map the 3D configuration of aquifers and bedrock topography created by the paleochannels of the ancestral Platte River. The ultimate goal is to gain a new understanding of groundwater–surface-water relationships to improve water management decisions through the use of groundwater management models. This goal was not achievable using traditional mapping methodologies, including surface geologic maps and borehole drilling logs. Airborne electromagnetic surveys provided nearly continuous information (data is collected every 3 to 20 meters along a flight path) of the subsurface electrical-resistivity variations (immediately below the sensor) at a depth range of 2 to 300 m below ground surface. To make the geophysical data useful for 3D geologic mapping, numerical inversion is necessary to convert the measured data into a depth-dependent subsurface electrical-resistivity model. The electrical-resistivity model, combined with sensitivity analysis, geological ground truth (boreholes), and geologic interpretation, is used to characterize geologic features. The 3D map provides the groundwater modeler with a high-resolution geologic framework and a quantitative estimate of framework uncertainty. This method of creating geologic frameworks improves the understanding of the actual flow-path orientation by redefining the location of the paleochannels and associated base of aquifer highs. The improved models depict the hydrogeology at a level of accuracy not achievable using previous data sets.

1. INTRODUCTION

Water resources in the North and South Platte River valleys, inclusive of Lodgepole Creek (Figure 1), are critical to the socioeconomics of western Nebraska and the management of endangered species along the Platte River corridor. Water, both surface water and groundwater, is a heavily used and regulated resource in the project area and in the entire Platte River Basin. Agriculture and power generation are the main drivers of the socioeconomics of western Nebraska and are the largest users of water. Another priority use for water is in management activities for recovery of threatened and endangered species in the Platte River Basin.

Surface water passes through many reservoirs, canal systems, and tributaries, providing a large percentage of recharge to the aquifers within valleys; in turn, the groundwater eventually returns to the river as base flow. This process is repeated many times as water passes through the Platte River corridor. The aquifers of the area are predominately ancestral Platte River paleochannels that are filled with alluvium. The paleochannels are incised into the Tertiary White River Group siltstone and, in the western part of the area, undifferentiated Cretaceous units, both of which act as hydrologic confining units. Groundwater flow within the aquifers is restricted by the topography of the confining units creating intricate flow paths. The combination of surface water use and the geologic composition of the valleys leads to the complex groundwater–surface-water relationships of the North and South Platte Rivers and Lodgepole Creek. Resource managers need an understanding of the groundwater–surface-water system to better control the limited supplies of water. This understanding is achieved by development of Groundwater Management Models (GMMs) which replicate the hydrology of the system and test management scenarios.

The first GMMs for the North and South Platte Rivers were developed using regional, low-resolution 2-D geologic maps and borehole drilling logs. These GMMs were effective in running simulations that tested large-scale general questions relating to management scenarios. However, as demand increased for more detailed analysis of explicit scenarios from the GMMs, it was determined that the regional models were not the best tool to accomplish the task. New GMMs were developed using local, high–resolution, 3D geologic maps based on data from the 2-D maps combined with airborne electromagnetic (AEM) surveys. The AEM geophysical method acquires data sensitive to the variability in the electrical resistivity of the subsurface. Examples of these new GMMs are the USGS High Plains Groundwater Water Availability Study (Qi and Christenson, 2010) and the Cooperative Hydrology Study (COHYST) (Cannia et al. 2006). Refinement of aquifer configuration within the geologic framework from regional, low-resolution to local, high-resolution 3D maps improves the performance of these models.

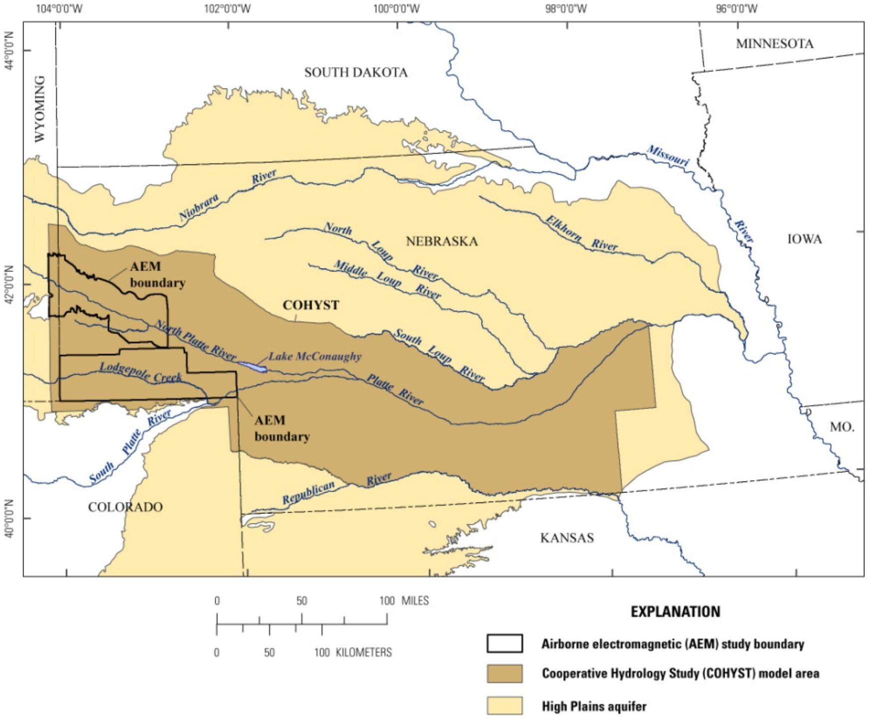

Figure 1. Location map of the AEM survey project area in western NE.

2. AIRBORNE ELECTROMAGNETIC METHOD

AEM surveys have been used recently to provide subsurface information for hydrogeological characterization (Siemon et al. 2009). Airborne surveys have the ability to cover large areas with minimal impacts to local activities and the environment. A unique value of these surveys is that data can be quickly collected without disturbing delicate environments and economically important agricultural crops. These AEM datasets are then processed, inverted, and interpreted to provide information on the structure of the geological and hydrogeological environment.

The selection of the proper AEM system to use should be based on the electrical conductivity-versus-depth relationship and the requirements for the 3D geological map. Previous knowledge of the geologic materials within the study area combined with a conceptual understanding of the geological system needs to be evaluated. Geological data gathered from boreholes is an absolutely critical part of study design and implementation, establishing confidence in the interpretation of lithology from resistivity. In addition to understanding as much as possible about the hydrogeological system, great care needs to be exercised regarding AEM system calibration and stability. A detailed and accurate calibration and inversion of AEM data to recover electrical properties with depth is an important requirement. After initial limited processing by the airborne service provider, the data goes through an advanced processing procedure where cultural couplings are removed and the calibration of the AEM system is confirmed or adjusted to remove as much systematic bias as possible. The techniques we use are the result of work done over recent years to understand and properly calibrate AEM systems (Fitterman and Deszcz-Pan 1998; Christiansen, et al. 2011).

The processed and calibrated AEM data are inverted using methods well suited for hydrogeologic mapping (Farquharson et al. 2003). After data inversion, a depth of investigation (DOI) metric is calculated in order to convey information about the depth to which the data are sensitive (Oldenburg and Li 1999). The DOI metric provides the geophysicist and geologist with a level of confidence in interpreting resistivity values related to the feature being mapped. Using stochastic parameter estimation tools, a more advanced analysis of model uncertainty has been developed as additional means of understanding and quantifying uncertainty (Minsley 2011), and is used as part of our model assessment procedure.

An interpretation for the location of a hydrogeological feature is typically completed in a Geographical Information System (GIS) that provides X, Y, and Z coordinates. Each of the interpreted locations, or picks, of the base of an aquifer, for example, is compared with the DOI metric for an AEM sounding location. A confidence value, between 1 and –1, for each feature location is calculated, with 1 being the highest confidence (picked horizon is well within the depth of investigation) and –1 being the lowest confidence (picked horizon is well below the depth of investigation) (Abraham et al. 2010).

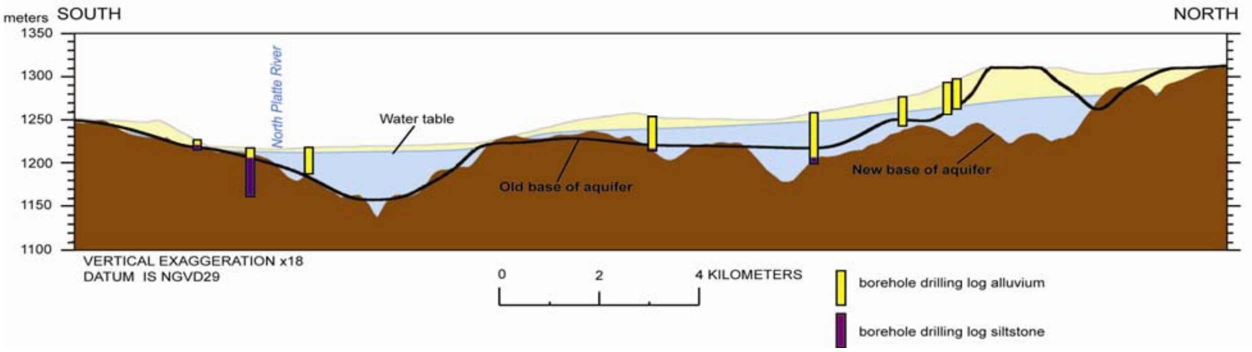

Figure 2. A selected NS profile from the 3D map, old BOA (black line), and borehole drilling logs (yellow for alluvium, purple for siltstone).

3. DEVELOPMENT OF 3D MAPS

Development of the 3D geologic maps used a process of interpretation that had the geophysicist, hydrologist, and geologist manually pick locations with elevation of the new base of aquifer (BOA) on the displayed AEM profile. These locations or "picks" of the BOA were then stored in a georeferenced database. The "pick' was made by comparing the geophysical resistivity profile from the airborne survey along a flight line to the known lithology of the area based on borehole drilling logs and other available information. GIS was subsequently used to view all of the available data at one time in a spatially correct manner; this imparts a high degree of confidence in the elevation value for the "picks".

The geodatabase of "picks", from the interpretation of the new BOA elevation, combined with the information from the borehole drilling logs and the 2-D geological maps, was used to create the new BOA contours. The large number and density of the new AEM data points along with the borehole drilling logs and surficial geology maps allowed for greater accuracy of the placement of the contour lines. Once the contour lines were generated they were converted to a grid. The BOA was combined with the digital elevation model to produce a 3D grid of the alluvial aquifer. Additionally, the new BOA was coupled with the water table to create a 3D grid of saturated thickness. Figure 2 is a selected profile from the 3D map showing the relationship between the new BOA, the old BOA (based on only regional 2-D geologic map and borehole drilling logs), borehole drilling logs (within 100 m of the profile), the water table, and land surface.

The old BOA was generated from the 2-D regional geologic map and the borehole drilling logs. As seen in Figure 2, the old BOA does not show the same complexity as the new BOA, which can only be derived from the addition of the AEM data. Both the old and new BOAs honor the geological control of the borehole drilling logs and surface geologic map. The example shown in Figure 2 illustrates the impact of the AEM data on the development of the 3D geologic map. Figure 3 is a view looking east of selected profiles from the 3D geologic map, visualizing the complex paleochannel dominated geology of the North Platte River valley.

The water table in combination with the new BOA illustrates a much more complicated system for groundwater flow and the amount of saturated thickness. There are several locations along the profile where high elevations of the BOA cause barriers or constrictions to groundwater flow from the tableland on both the north and south sides of the river. These barriers and constrictions have a direct bearing on whether a stream is hydrologically connected to the principal aquifer. The improved BOA also allows for more accurate calculations of the saturated thickness compared to the old BOA.

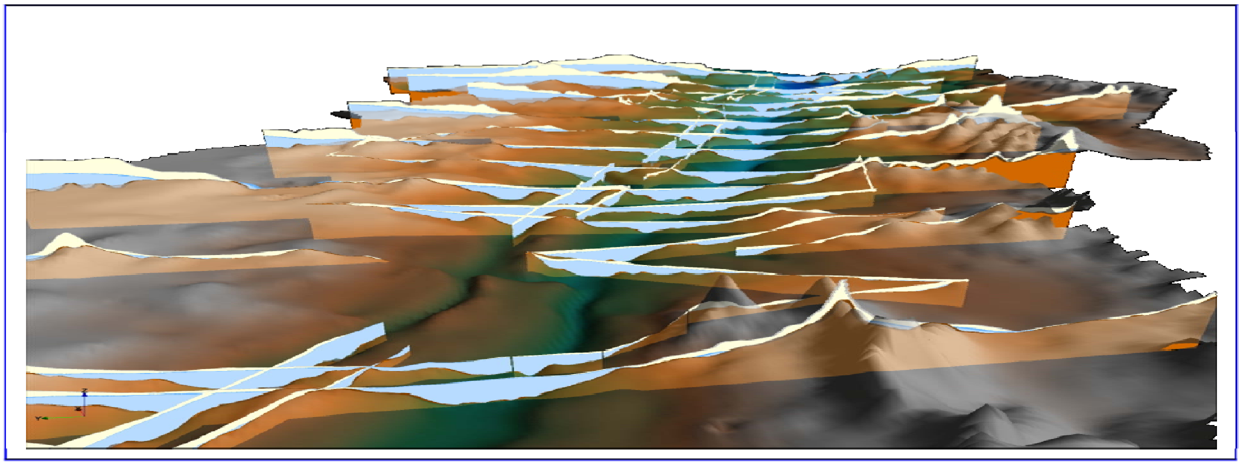

Figure 3. 3D view of the semi-transparent base of aquifer surface with selected cross sections extracted from the 3D model, looking east (down) the North Platte River Valley.

4. SUMMARY

The AEM survey provided considerable improvement to the understanding of the 3D geologic framework of the Platte River valley, and was employed to improve groundwater models of the area. This degree of accuracy was not achievable using traditional mapping methodologies, including surface geologic maps and borehole drilling logs. AEM surveys provide nearly continuous information (data is collected e very 3 to 20 meters along a flight path) of the subsurface electrical-resistivity variations immediately below the sensor at a depth range of 2 to 3 00 meters. The AEM data improved the 3D geological map of the alluvial aquifer allowing for more accurate calculations of the saturated thickness. An enhanced understanding of the complex groundwater–surface-water relationships of the Platte River allows managers to better control the limited supply of water for all uses, including endangered species.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Abraham, J.D., J.C. Cannia, S.M. Peterson, B.D. Smith, B.J. Minsley, and P.A. Bedrosian, 2010, Quantitative Hydrogeological framework interpretations using helicopter electromagnetic surveys for the North Platte valley, western Nebraska Groundwater Model, ASEG 21st Geophysical Conference and Exhibition, Sydney, Australia http://www.publish.csiro.au/paper/ASEG2010ab113.htm

Cannia, J.C., D. Woodward, and L.C. Cast, 2006, Cooperative hydrology study COHYST hydrostratigraphic units and aquifer characterization report: Cooperative Hydrology Study, http://cohyst.dnr.ne.gov/.

Christiansen, A. V., E. Auken, and A. Viezzoli, 2011, Quantification of modeling errors in airborne TEM caused by inaccurate system description: Geophysics, 76, F43-F52.Farquharson, C. G., D.W. Oldenburg, and P.S. Routh, 2003, Simultaneous 1D inversion of loop--loop electromagnetic data for magnetic susceptibility and electrical conductivity: Geophysics, 68, 857-1869.

Fitterman, D. V., and M. Deszcz-Pan, 1998, Helicopter EM mapping of saltwater intrusion in Everglades National Park, Florida: Exploration Geophysics, 29, 240-243.

Luckey, R.R., and J.C. Cannia, 2006, Cooperative Hydrology Study, Groundwater Flow Model of the Western Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) Area: Lincoln, Nebraska, COHYST, Available at http://www.cohyst.dnr.ne.gov/cohyst_preliminarydata.html/63p.

Minsley, B.J. (accepted July 2011, in press), A trans-dimensional Bayesian Markov chain Monte Carlo algorithm for model assessment using frequency-domain electromagnetic data, Geophysical Journal International.

Oldenburg, D.W., and Y. Li, 1999, Estimating depth of investigation in DC resistivity and IP surveys: Geophysics, 64, 403-416.

Olsson and Associates, 1994, Groundwater Management Plan for the North Platte Natural Resources District: Olsson and Associates, 350 p.

Qi, S.L., and S. Christenson, 2010, Assessing groundwater availability in the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming: U.S. Geological Survey Fact Sheet 2010–3008 (Revised March 2010), 4 p.

Siemon, B., A. V. Christiansen, and E. Auken, 2009, A review of helicopterborne electromagnetic methods for groundwater exploration: Near-Surface Geophysics, 7, 629–646.

THE USE OF 3D GEOLOGICAL INFORMATION IN A LARGE MANAGED AQUIFER RECHARGE PROJECT

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1. INTRODUCTION

The city of Turku and its neighboring municipalities are located in southwestern Finland. The area has a population of 300,000 inhabitants. The water supply of the region has relied on chemically treated water obtained from small local rivers and reservoirs. The surface water supply will be replaced with artificially infiltrated groundwater at the end of 2011. The cost of the project is 176,000,000 euros, and it is one of the largest managed aquifer recharge (MAR) projects in northern Europe (Figure 1).

The water for the infiltration is obtained from the Kokemäenjoki River, located 90 kilometers north of the city of Turku. Pretreatment of the water takes place 2 kilometers from the water intake plant. There, water is pretreated to remove all solid substances that may be present. Artificial infiltration is performed in the Virttaankangas Quaternary esker aquifer, 60 kilometers north of Turku. The total length of feeder pipelines is approximately 100 kilometers.

Extensive geological, sedimentological, hydrogeological, geochemical, and geophysical studies have been carried out in the Virttaankangas aquifer over the last few decades. However, most of these studies have been conducted during the last 8 years. These studies have been planned, guided, and managed with the help of 3D geological information and 3D models.

The aim of this paper is to demonstrate that the 3D geological information system and modeling tools play a key role in the successful execution of a large managed aquifer recharge project. The economic benefits of the use of this information have been substantial. Geological information and 3D models have been used to solve, for example, legislative, constructional, and land-use related issues.

Figure 1. Managed aquifer recharge system of the Turku region - Location map and photos of the facilities.

2. BACKGROUND

The Virttaankangas esker complex covers an area of approximately 50 km^2. It was formed between the sublobes of the retreating Baltic Sea ice lobe during the last deglaciation of the Scandinavian Ice Sheet (Punkari 1980, Mäkinen 2003). This sedimentary environment resulted in the deposition of a complex and highly heterogenous sand and gravel esker aquifer.

The first 3D hydrogeological model of the Virttaankangas aquifer was completed in 2001 in cooperation with the Illinois State Geological Survey (Artimo et al. 2003a,b). Subsequent models have been updated with a broader variety of research information related to hydrogeological issues. In addition to basic sedimentological and hydrogeological information, the Virttaankangas 3D hydrogeological model has seen the introduction of geochemical, isotopic, and geophysical data into the 3D modeling workflow.

The 3D hydrogeological model also works as a structural basis for the 60-layer groundwater flow model which together have been used to design the layout and configuration of the infiltration pond and production well areas of the MAR plant.

3. ENVIRONMENTAL REQUIREMENTS RELATED TO THE OPERATION AND USE OF THE MAR PLANT

Environmental permits for the artificial recharge project required at least a one-year testing phase in the Virttaankangas aquifer, during which the infiltrated and pumped water rates should not exceed 20,000 m^3/d. The full scale production is only allowed to start after the results of the testing phase provide enough information for the controlled execution of infiltration and pumping. The testing phase started in September 2010.

In addition, the whole process of obtaining the final environmental permits took seven years due to many claims. The permits were processed by all three court instances in Finland dealing with environmental permits. Turku Region Water Ltd. had to present pleas to about 100 complaints dealing with geological issues. None of the claims succeeded in court, including a few complaints made by the local EPA. By contrast, the Supreme Administrative Court has directly cited the company's geological explanations in its arguments of judgment.

4. MAR PLANT CONSTRUCTION AND GEOLOGICAL FRAMEWORK

The 3D geological information database has been available during the construction of the MAR plant. Automated updating of the 3D hydrogeological and groundwater flow models has enabled the immediate use of the newest research information in the construction of the plant.

Locations of five previously planned infiltration areas were rejected due to discovery of morphologically undetectable kettle hole systems underlying the infiltration areas. These kettle hole structures would have prevented the flow of infiltrated water into the production well areas.

The 3D groundwater flow model simulations were conducted to find an optimal layout of the infiltration and pumping locations. The precise placement of infiltration areas and production wells is crucial to obtain the needed residence times and production rates of the artificially infiltrated groundwater. The residence time of the infiltrated water in the aquifer needs to be at least eight weeks to ensure sufficient total organic carbon reduction and microbiological purification of the artificially infiltrated groundwater.

Exact locations of the production wells were decided after a vigorous examination of the available sedimentological and hydrogeological data. Interpretations were verified with additional examination of samples from test drilling. Also, groundwater monitoring wells with transparent casings were installed in each of the planned production well locations. Transparent casings were used to obtain video footage of the sediments prior to production well construction.

This approach resulted in extremely high yields of the production wells. The optimized layout of the infiltration and pumping locations also enabled the use of maximal pumping rates of these wells. As compared with the earlier pre-3D plans for pumping well locations, the amount of wells needed for full scale production of artificially infiltrated groundwater was reduced by half.

During the one year testing phase, the observed flow paths and residence times of the infiltrated water coincided extremely well with the groundwater flow model simulations conducted prior to the testing phase. This was not the case when the earlier plans for infiltration and pumping were simulated with the same groundwater flow model that successfully predicted the obtained field observations. Had the MAR plant been built according to the earlier plans, the infiltrated water flow paths and residence times would have been unacceptable and caused severe problems for the operation of the MAR plant.

5. CONCLUSIONS

The financial benefits of having 3D geological information and models available during the construction of the MAR plant are obvious. For example, the cost of one production well is about 100,000 €. In Virttaankangas, a total amount of 80,000 m^3/d of artificially infiltrated groundwater can be produced with 12 wells (average pumping rate of 6,700 m^3/d per well), whereas the average yield of other water producers' wells within the same esker area is less than 500 m^3/d.

All of the benefits and savings resulting from the available geodatabase and 3D modeling tools are not possible to quantify. However, having the required one-year testing phase successfully completed before the entire construction work of the project was completed, resulted in savings that can be counted in millions of euros. The cost of each day of delay in water production, after the construction is completed, is about 20,000 € due to the loan interests. All of the investments in research have been less than 5,000,000 €, which is less than 3% of the total budget of this MAR project.

Most importantly, there is only one conclusion when the final layout and configuration of the MAR site is compared with the earlier plans. The required production rates of the artificially infiltrated groundwater in this 176,000,000 € project would not have been achieved without the 3D geological information and models.

6. REFERENCES

Artimo, A., R.C. Berg, C.C. Abert, and J. Mäkinen. 2003a. Constructing a Three-dimensional Geologic Model of the Virttaankangas Aquifer, Southwestern Finland: Methods Applicable to Illinois: Illinois State Geological Survey Circular 562, 9 p.

Artimo, A., J. Mäkinen, R.C. Berg, C.C. Abert, and V.-P. Salonen. 2003b. Three-dimensional geologic modeling and visualization of the Virttaankangas aquifer, southwestern Finland: Hydrogeology Journal, 11:378-386.

Mäkinen, J. 2003. Development of depositional environments within the interlobate Säkylänharju-Virttaankangas glaciofluvial complex in SW Finland: Annales Academiae Scientarium Fennicae, Geologica-Geographica 165. 65 p.

Punkari, M. 1980. The ice lobes of the Scandinavian ice sheet during the deglaciation in Finland: Boreas v. 9, no. 4, p. 307-310.

APPROACHING A DECADE OF THREE- DIMENSIONAL MAPPING OF QUATERNARY SEDIMENTS IN SOUTHERN ONTARIO; A PROGRESS REPORT FROM THE ONTARIO GEOLOGICAL SURVEY

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1. INTRODUCTION

In 2003, the Ontario Geological Survey (OGS) released a fully attributed, seamless surficial geology map of southern Ontario; the first of a series of thematic maps published in support of the Clean Water Act (2006). This provincially-mandated piece of legislation is designed to protect the safety of Ontario's drinking water. A number of other important publications in the same series, including bedrock geology, physiography, drift thickness, bedrock topography and a karst potential map were subsequently released.

Following the release of these baseline geoscience datasets, the focus of the Groundwater Program turned to subsurface mapping of Quaternary and Paleozoic strata as well as the characterization of the waters contained within them. Three-dimensional (3D) geologic mapping projects have been and are currently being undertaken primarily in areas of projected population growth that are heavily reliant on groundwater for municipal, rural and agriculture use. These include areas identified in the *Places To Grow Act* (2005) within and around the Greater Golden Horseshoe of southern Ontario. Concurrently, Conservation Authorities have been charged with developing watershed-based Source Water Protection Plans in support of the Clean Water Act (2006) to identify and assess risks to the quality and quantity of drinking water sources, develop plans as to how these risks will be addressed, implement the plans through land use planning and regulatory requirements and finally, the monitoring and ongoing assessment of the effectiveness of measures carried out to protect sources of drinking water. A good understanding of the distribution and properties of subsurface geologic materials is required if one is to develop sound, science-based plans for implementation. The activities undertaken and products developed as part of the OGS's 3D mapping program are designed primarily to meet this need for basic geoscience information. Additionally, robust exploration models are being developed as part of the 3D mapping programs to assist in the search for new municipal water supplies.

The 3D mapping and characterization of Quaternary-aged aquifers and aquitards has been ongoing for close to a decade with projects either completed or ongoing in the Waterloo (Bajc and Shirota 2007), Barrie-Oro (Burt and Dodge 2011), Brantford-Woodstock (Bajc and Dodge 2011) Orangeville-Fergus and South Simcoe areas (in progress) (Figure 1). The Brantford-Woodstock, Waterloo and Orangeville-Fergus study areas lie along an important interlobate zone along which significant stratified moraines were constructed during the final retreat of the Laurentide Ice Sheet from southern Ontario. These stratified moraines contain important aquifers capable of either meeting or contributing to the water needs of local municipalities and settlements. The Barrie-Oro project area is centred on the Oro moraine which forms both a regional aquifer recharge area and the headwaters for 4 major watersheds. Adjoining this area to the south is the South Simcoe study area, an area of thick drift underlain by the Laurentian buried bedrock valley; a bedrock depression extending from Georgian Bay in the north to Lake Ontario. All of these areas are poised to receive accelerated population growth as they have been identified in the Places To Grow Act (2005) and lie just outside of the Green Belt; a swath of land lying within the Greater Golden Horseshoe that is being protected from additional development.

The main objectives of these projects are to develop interactive 3D models of Quaternary geology that can: 1) aid in studies involving groundwater extraction, protection and remediation; 2) assist with the development of policies surrounding land use and nutrient management; and 3) help to better understand the interaction between ground and surface waters. More specifically, a better understanding of the geometry and inherent properties of the Quaternary sediments that overlie the bedrock surface within these regions will assist with the development of source water protection plans and with the development of a geoscience-based management plan for the groundwater resource.

2. EVOLUTION OF THE PROGRAM

2.1 The Waterloo Region Pilot Project

In 2002, a pilot project of 3D mapping of Quaternary deposits was initiated within the Regional Municipality of Waterloo (Bajc and Shirota 2007). This area was chosen for the initial study as the region is almost exclusively reliant on overburden and bedrock aquifers for its potable water supply and represents one of the largest municipal users of groundwater in Canada. Intense pressures are being placed on the groundwater supply as urban sprawl and population growth threaten important recharge areas and tax an already stressed groundwater system. Having a better understanding of the distribution and properties of both near surface and deeply-buried aquifers will assist with the management and protection of the groundwater resource.

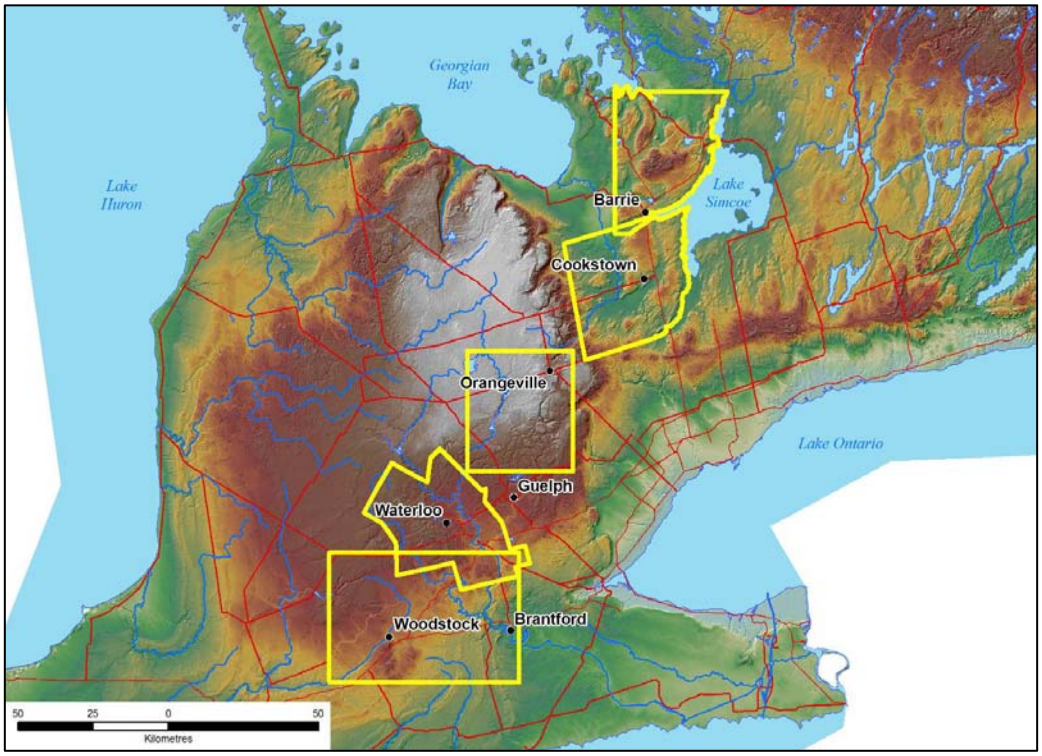

Figure 1. Location of OGS-led 3D mapping of Quaternary geology projects in southern Ontario. From north to south: Barrie-Oro, South Simcoe, Orangeville-Fergus, Waterloo Region and Brantford-Woodstock. Base map is from the provincial digital elevation model.

The Waterloo project was undertaken in 4 important stages which included: 1) data compilation; 2) acquisition of new geophysical and geological information to infill data gaps and assist with the development of a conceptual geological model for the study area; 3) data interpretation and the construction of a fully attributed 3D block model; and 4) preparation of a Groundwater Resources Study that describes the geologic setting of the region, outlines the protocols developed for the construction of the 3D block model and contains a description of the distribution and properties of the geologic units modelled. Discussions of important recharge areas and aquifer vulnerability were also included within the report. Other deliverables include structural contour and isopach maps of all modelled units, west-east and south-north cross-sections at 2.5 kilometre intervals and a depth to aquifer map that can be used to assess aquifer vulnerability and recharge areas.

Digital data also accompany the Groundwater Resources Study. The data consist of 1) portable document format (*.pdf*) versions of the contained plates; 2) comma-delimited text (*.csv*) files of both continuous and discontinuous surfaces on a 100 m grid; 3) 100 m ESRI® ArcInfo® structural contour grids of discontinuous surfaces; 4) a stripped-down version of the subsurface database (*.mdb*) containing borehole location and stratigraphic information, picks data and static water level and screen depth information; 5) new borehole information that includes graphic and written logs, grain size and carbonate data and photographs of the core; 6) a cross-section viewer (*.exe*) capable of drawing sections along user-defined lines drawn on a Microsoft® Windows® Virtual Earth® base map; and 7) a hypertext mark-up language (*.kml*) file that portrays transparent overlays of the structural contour and isopach maps as well as borehole locations and lithologic logs in a web-based (Google Earth™ mapping service) environment. This functionality allows for enhanced user interaction with the spatial data.

2.2 Modifications to the Program

Since completion of the Waterloo pilot project, a number of changes have occurred in both the field programs and to the Aquifer Mapping System developed to work with Datamine Studio software for the creation of the 3D block models. In the Waterloo area, a robust geophysical program consisting of ground penetrating radar, seismic reflection using both the GSC-owned mini-vibe and the more conventional inhole shotgun shell energy source as well as downhole geophysical profiling were all conducted to evaluate their usefulness for regional 3D modelling. Varying ground conditions within the Waterloo Moraine area resulted in marginal data quality, especially in the case of seismic imaging beneath dense, overconsolidated Late Wisconsin tills as well as in areas with depressed water tables. Conducting lengthy seismic lines for regional mapping was cost prohibitive and in most cases, was a risky proposition. In many cases, it was difficult to image the bedrock surface beneath the overconsolidated Catfish Creek Till. In the case of ground penetrating radar, depth of penetration resulted in visualization of the internal character of the upper hydrostratigraphic unit at most; most often less than 10% of the entire stratigraphic sequence. Ground penetrating radar did in some cases assist with determining the origin of landforms and with reconstructing paleoflow directions. Borehole geophysics of cored holes allowed for the development of proxies that could be used to interpret records from non-cored holes. In this regard, the downhole geophysical program had excellent value as it assisted with the interpretation of a database of subsurface geophysical profiles assembled from a series of non- cored holes within the region.

2.2.1 Field Program

As a result of these observations, it was felt that resources could be used more effectively by redirecting them to the collection of additional continously cored boreholes and more regionally-based geophysical programs. Cored boreholes are invaluable when it comes to developing conceptual geologic models and assisting with the interpretation of water well records and other lower quality sources of subsurface information. In the case of the Brantford-Woodstock study, the OGS collected continuous cores to bedrock at approximately 50 sites within an area of about 2700 square kilometers (i.e. approximately 1 hole per 54 square kilometers). In the case of the Orangeville-Fergus area, the ratio is approximately 1 hole per 37 square kilometers. These additional “golden spikes” served to greatly improve the quality of the interpretation of the subsurface data.

With regard to regional geophysical programs, the OGS has recently been undertaking and evaluating land-based gravity surveys to assist with the definition of the location and geometry of buried bedrock valleys in various study areas. There has been growing interest in evaluating deeply buried aquifers confined to bedrock valleys for their potential to host significant sources of groundwater for municipal use. Gravity surveys over the Dundas buried valley, at the west end of Lake Ontario, over the Rockwood valley within the Orangville-Fergus study area and over the Laurentian valley within the South Simcoe survey area have been completed with reasonable success. The main goals of these surveys were to better define the position of bedrock valley thalwegs (Figure 2) and evaluate their sediment infill to determine whether the bedrock valleys host significant aquifers at depth. In the case of the Dundas and Rockwood valleys, follow-up drilling clearly showed that the bedrock valleys were host to significant aquifers that were potentially capable of supporting municipal water supplies. Follow-up hydrogeologic testing of deeply buried aquifers along the trend of the Dundas valley have yielded important information regarding aquifer transmissivity and specific capacity as well as information regarding water quality and age. Drilling of significant thalwegs along the Laurentian valley are currently ongoing and seem to suggest that there may be a spatial association between thick accumulations of older stratigraphic sequences, some of which contain highly transmissive sediments, and buried bedrock channels.

2.2.2 Modelling Protocols

Protocols for 3D modelling have evolved as well, following the completion of the Waterloo pilot project. The main advancements are with regard to weighting of borehole information of varying quality and modelling of deeply incised valley fills. In the Waterloo study, all borehole data was weighted equally resulting in situations where both high and medium quality borehole records were not integrated into the model since there were no supporting borehole records within user-defined search radii of those holes. The new modelling scripts take data quality into account resulting in all cored borehole records as well as manually digitized picks being used to force specific geometry of units within the block model. A larger percentage of medium quality borehole records are also incoporated into the model using this new protocol as well. Maps highlighting the distribution of high, medium and low quality picks used for the creation of each modelled layer assist in visually depicting model confidence.

The new scripts also address areas where deeply incised valleys have been cut into older sediments sequences and back filled with late-glacial deposits. The previous modelling scripts resulted in steeply-dipping wedges extending from the uplands into the valleys to force pinchout of units. Graphically, these pinchouts do not appear geologically credible. Hydrogeologically, these wedges force impermeable barriers between aquifers that in reality are juxtaposed along valley walls. The new scripts allow the user to model the uplands and valley fill sequences separately then recombine them into a single model during the final model creation step resulting in the removal of these wedges.

3. WHERE DO WE GO FROM HERE?

The OGS has moved from program development to production mode as it strives to model priority areas of the province. An improved conceptualization of glacial history and depositional environments associated with important aquifer complexes has resulted from recently completed and ongoing studies. This knowledge has translated into improved predictive capability and associated efficiencies. To date, the OGS has mapped approximately 5400 square kilometers with an additional 2850 square kilometers in progress. Two full-time Quaternary geologists are dedicated to this program with support staff available to assist with geophysical surveying, database management and GIS mapping functions. With limited staffing and funds, completion of detailed 3D mapping of all of southern Ontario will likely take several decades. There has been an attempt to produce a standardized product that will allow for merging of models. With this in mind, it is important to create models with similar conceptualizations of geology and easily correlatable units. Detailed sampling of cored boreholes for grain size analysis will assist with the assigning of hydraulic properties to the modelled units and hence more reliable groundwater flow models. The OGS has attempted to partner with municipalities and conservation authorities to convert as many cored boreholes as possible into long term monitoring wells. Static water levels, water chemistry and isotope analysis to determine water age will assist with better understanding groundwater flow paths and identifying windows in aquitards. Short term pump tests to better characterize transmissivity of aquifers and their associated recovery rates will undoubtedly assist with the modelling of aquifer extent in the subsurface. The OGS continues to pursue alternative subsurface imaging and characterization technologies to assist with 3D mapping. Refinements to the modelling protocols developed to work with Datamine Studio software are ongoing as well. New visualization products carrying a wider appeal to a diverse client base continue to be developed.

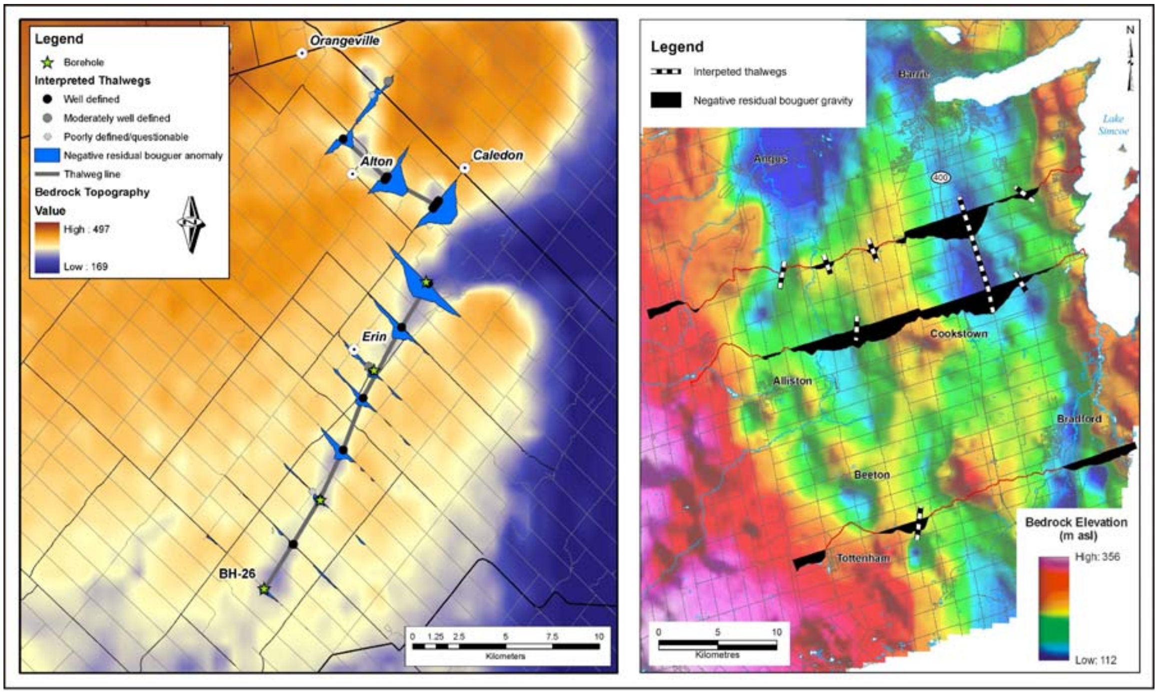

Figure 2. Residual Bouguer gravity profiles superimposed on regional bedrock topographic surfaces derived from water-well records for the Rockwood buried bedrock valley (left) (Burt and Rainsford, 2010) and the Laurentian buried channel (right) (Bajc and Rainsford, 2010). Anomalous negative residual responses are shaded in blue (left) and black (right).

4. REFERENCES

Bajc, A.F. and Dodge, J.E.P. 2011. Three-dimensional mapping of surficial deposits in the Brantford–Woodstock area, southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 10, 86p.

Bajc, A.F. and Rainsford, D.R.B. 2010. Three-Dimensional Mapping of Quaternary Deposits in the Southern Part of the County of Simcoe, Southern Ontario in Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6220, p.30-1 to 30-10.

Bajc, A.F. and Shirota, J. 2007. Three-dimensional mapping of surficial deposits in the Regional Municipality of Waterloo, southwestern Ontario; Ontario Geological Survey, Groundwater Resources Study 3.

Burt, A.K. and Dodge, J.E.P. 2011. Three-dimensional modelling of surficial deposits in the Barrie–Oro moraine area of southern Ontario; Ontario Geological Survey, Groundwater Resources Study 11.

Burt, A.K. and Rainsford, D.R.B. 2010. The Orangeville Moraine Project: Buried Valley Targeted Gravity Study in Summary of Field Work and Other Activities 2010, Ontario Geological Survey, Open File Report 6220, p.31-1 to 31-6.

3D MODELLING AT THE BAVARIAN STATE GEOLOGICAL SURVEY – EXAMPLES FOR COOPERATION TOWARDS 3D STANDARDS

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1. INTRODUCTION AND BACKGROUND

Germany's federal structure manifests itself in an aggregation of 16 independent regional Geological Survey Organisations (GSOs) in addition to the federal Institute for Geosciences and Natural Resources (BGR) and the Leibniz Institute for Applied Geophysics (LIAG), all of which vary considerably in terms of responsibilities and organisational structures. Regional geological surveying and mapping is generally assigned to the State Geological Surveys, whereas the BGR is the central geoscientific authority providing advice to the German Federal Government concerning all geo-relevant issues, including international projects and consultancy. LIAG is a research institution mainly engaged in the implementation of geophysical methods.

Like all State Geological Surveys of Germany, the Bavarian GSO, now part of the Bavarian Environment Agency (LfU), originally was founded to produce an inventory of the subsurface resources to advise the territorial government on energy and raw material supply issues. Although, as a consequence of changing societal needs, the focus substantially shifted to natural resources in general and environmental concerns such as water, waste, land contamination, and ,more recently, the enhanced use of renewables to mitigate climate change. Nonetheless, the core function of all GSOs remains unchanged: to make the best coherent geological information accessible to the clients. As geology is inherently a 3D science, 3D models are crucial for this purpose as they transform abstract geoscientific information into tangible products, enabling an understanding of complex geological findings to non-geoscientists and policy makers.

Figure 1. Map of Germany indicating location of Bavaria

3D modelling at the Bavarian State Geological Survey, in charge of a territory of about 70,500 km^2, started a holistic mapping project covering 2,850 km^2 in 2000. In the meantime, 3D subsurface modelling is a standard tool in assisting hydrogeological investigations and in planning sustainable geothermal energy generation. It is well on its way to establishing itself as an integral part of standard geological mapping. Several examples of 3D subsurface modelling and methodologies implemented are described and illustrated in Pamer and Diepolder (2010). However, most of the practical modelling is carried out by temporary project staff with little capacity to contribute to the further development of the agency's 3D modelling concept. The conceptual advancements for safeguarding the future of 3D modelling are managed by a very limited staff. Thus, to operate a complex and continuously evolving technology such as 3D modelling successfully, a continuous exchange and cooperation with other GSOs is crucial.

2. INTER-STATE AND FEDERAL COLLABORATION: THE STUDY GROUP 3D MODELLING

Of the 16 German regional GSOs, 11 currently are actively engaged in 3D subsurface modelling and 2 have assigned 3D modelling to local universities. The 3D modelling concepts and infrastructures within the surveys are very diverse. Staffs range from one-person enterprises to well-equipped sections comprising several geoscientists and IT-specialists implementing elaborate workflows for all steps of modelling as well as the pre- and post-processing. This diversity and the differing emphasis of scope offer many options for cooperation and increasing know-how. Thus, the main objective of the Study Group 3D Modelling (Kommunikations forum 3D, Kf3D) of the German GSOs, founded in 2005, is to exchange knowledge and developments concerning workflows and best practices and to agree on common standards for data and data access (Diepolder 2011). Another focus of the Study Group – at present comprising 10 regional GSOs and the two federal institutes BGR and LIAG – is to enhance software development, especially for Paradigm's® Gocad® and plug-ins, as this software is a standard tool for all study group members.

Using the same modelling software at all regional GSOs enables the sharing of model independent routines of workflows and customizing them to individual databases. Also conceptual parts of workflows and routines covering more general steps of pre- or post-processing are exchanged on demand. As a voluntary panel without budget, however, the Kf3D has no empowerment for awarding contracts in order to meet common requirements. Thus, the Study Group confines itself to channel developments defined and assigned by study group members and fosters the share of the outputs in accordance with the relevant inter-state agreements. Linchpin of all R&D services for Gocad and beyond is the Mining Academy of Freiberg, Saxony, which features a long-term and profound expertise in geo-informatics research and education, and also hosts the annual German Gocad User Workshop. Tendering of BSc and MSc theses on specific modules and plug-ins required by GSOs has led to a successful cross-fertilizing cooperation of mutual benefit.

All recent developments at the member GSOs are discussed regularly at the biannual meetings of the study group, where, in addition, the compilations of workflows and plug-ins used at the member GSOs are updated. All information, agreements and results of the Study Group meetings are disseminated via InfoGEO (http://www.infogeo.de/), the joint internet portal of the German GSOs. Extensions including a thematic webpage featuring the state of 3D modelling at the German GSOs, linked to the respective homepages, are under development. Furthermore, the Study Group organizes workshops for the German 3D modelling community every three years.

3. INTERNATIONAL COLLABORATION: THE PROJECT ‘GEOMOL’

Due to their geological evolution, foreland basins feature a multitude of geogenic potentials. Until recently, the exploitation of these natural resources was focused on extraction of groundwater from regional aquifers, oil and gas production, stockage and mining. In the context of recent developments for the mitigation of climate change, additional demands such as exploitation of deep geothermal energy, underground storage of sequestered CO_2, and compressed air (hydrogen or methane) energy storage will strongly rival the current utilizations (Diepolder et al. 2010, Diepolder and Schulz 2011). The prioritized exploitation of these geo-potentials and the sustainable management of the subsurface as a finite resource are key issues for geoscientists and land use administration and have a high societal relevance.

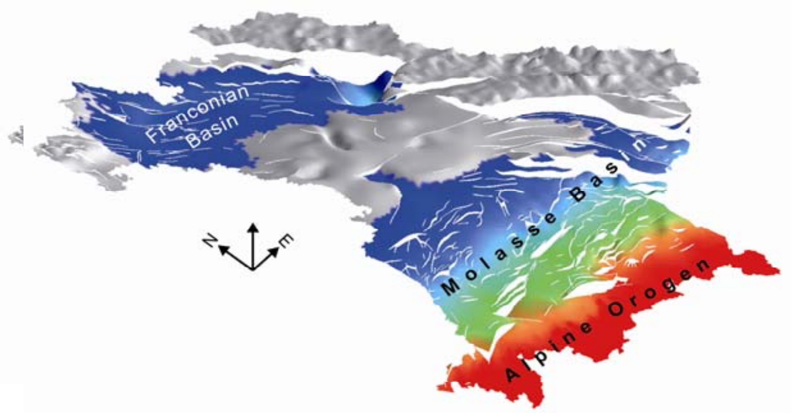

Figure 2: Surface of the crystalline basement in Bavaria (Sattler & Pamer 2009), perspective view from south-west. The colouring shows areas with a sedimentary cover between 800 m (blue) and > 5000 m (red). The white

In Bavaria, the deeper parts of the North Alpine Foreland Basin (Molasse Basin), underlain by the Upper Jurassic limestone aquifer dipping southward to depths greater than 5000 m, build up the most important hydrothermal reservoir in Central Europe (e.g. Kayser and Kaltschmitt 1998) and are tapped by several drillings to supply district heating and combined heat and power plants. The increasing number of utilizations and the increasing drilling depths for exploration and extraction, however, enhance the risk of failure. Thus, 3D modelling of the relevant aquifers, their structure and facies distribution, in order to provide a cross-regional structural inventory for defining productive zones and areas of possible mutual flow interference, is presently the main focus of 3D subsurface modelling at the Bavarian GSO.

Depths of relevant aquifers, facies interpretation, and fault geometries are derived from seismic sections and scattered borehole evidence of the 1960s to 1970s hydrocarbon exploration campaigns (Pamer and Sieblitz 2009).

The resulting basic 3D models are updated permanently using the 3D seismic surveys carried out by the hydrothermal exploration industry in certain licensed areas. Drill logs and samples supplied afterwards allow for further improvement of the model and the calibration of the velocity model for a revised time to depth migration.

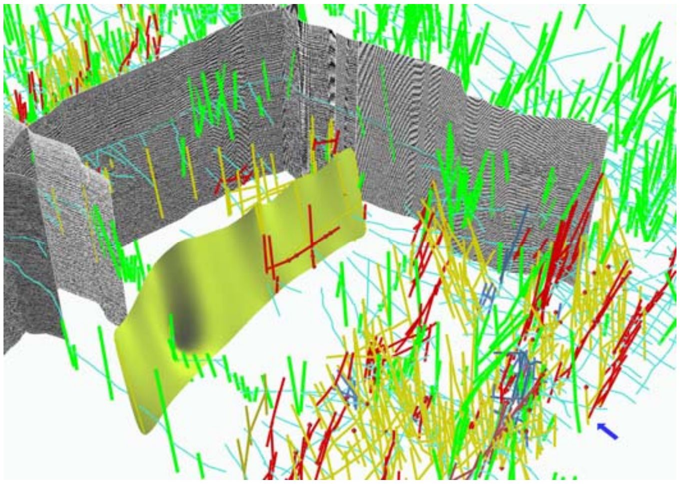

Figure 3: Fault stick network of the Greater Munich model area, classified by synthetic (yellow), antithetic (red) and non-distinctive (green), exemplifying one fault surface and three seismic sections of which several thousand kilometres have been scanned and geo-referenced for interpretation based on prominent seismic reflectors. An array of seismic cross-sections and a regionalized velocity model is used for correlating seismic and borehole data (from Pamer and Sieblitz 2009).

However, the reach of impact of many subsurface utilizations is much larger than the respective licensed areas and, as geology in general, does not respect political boundaries. The sustainable management and impact assessment of the multiple uses of geo-potentials, thus, inevitably requires a transnational approach: The Molasse Basin, stretching over more than 1.200 km along the northern pre-alpine regions from the Rhone river south of Lyon, France, to Brno, Czech Republic, is homeland of several million people and features a vast variety of 21st century key industries. Homemade, decentralised green energy exploiting geo-potentials and subsurface storage capacities play a crucial role in future development and the competitiveness of this area. However, currently no harmonized information base exists for coordinated planning, evaluation and sustainable utilization of these geo-potentials.

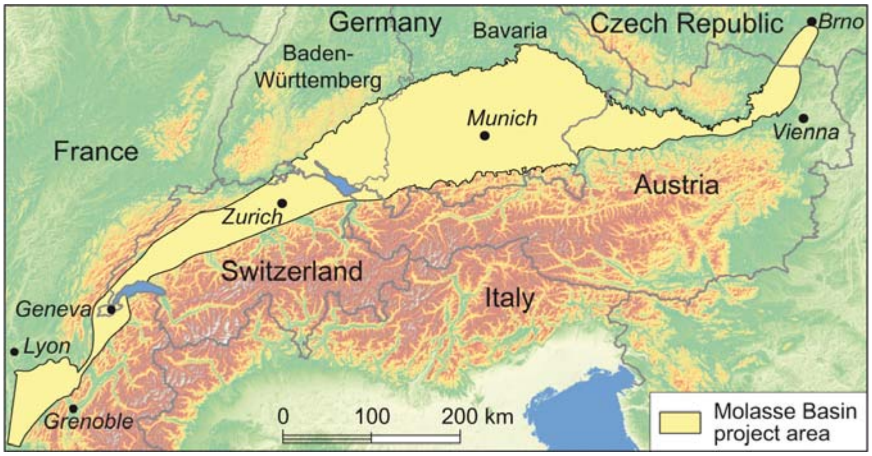

Figure 4: Outline of the Molasse Basin project area covering 61,700 km^2 in front of the Alpine orogen. About 80% of the area coincides with the EU Alpine Space cooperation area, thus a corresponding EU grant is aspired.

Based on existing 3D models as nuclei, the manifold experience of the project partners in seismic interpretation and modelling deep basin structures (e.g. http://www.geopotenziale.org/) will be combined with modelling the entire basin trans-nationally under the project titile 'GeoMol – Subsurface Potentials of the North-Alpine Foreland', coordinated by the Bavarian GSO. The main objective of this project is to develop a trans-nationally harmonized digital information base on the Molasse's geo-potentials. The involvement of stakeholders from at least five countries requires a comprehensive semantic harmonization, the alignment of different standards and terminologies as well as an evaluation using common criteria. The project is designed to combine researchers and users from different areas of technical and organisational expertise. It presents an innovative partnership model for cross-cutting application of 3D modelling that will address strategic issues as well as the user's needs. Special emphasis will be put on the transferability of the elaborated methods and best practice to other deep basins, thus establishing proved standards.

In case of funding by the EU's Alpine Space Programme in the eligible areas, GeoMol will be implemented within a 3 year timeframe as a trans-nationally coordinated coherent 3D geological framework model, incorporating detailed small-scale models in areas of special interest that will be suitable for testing subsequent applications such as assessing regional aquifer dynamics or impact assessments, e.g. the risk of induced seismicity. Decision guidance to support authorities will be derived directly from the 3D models thus offering a high quality of information towards spatial planning and the evaluation, development, and sustainable management of geo-potentials. In the course of project preparation a cluster of excellence among the stakeholders has been established to ensure a cross-sectoral integration and long-term cooperation in 3D modelling efforts which will go beyond GeoMol. However, one of the crucial issues for the success of GeoMol is the feasibility of integrating 3D data from individual databases in an efficient and comprehensive way.

4. WITH 'GST' TOWARDS AN INTEROPERABLE 3D GEOSCIENCE INFORMATION NETWORK

Even though many proprietary databases and information systems as well as web-based tools have been developed, the 3D geological community still lacks the ability to exchange 3D geoscience data efficiently across the various systems. Considering the steadily growing diversity of 3D subsurface models with respect to extent, detail, and populated properties, a platform independent exchange of 3D geo-information, beyond the current practice of file-based bilateral interchange, is indispensable. For the success of cross-border modelling projects on a national or trans-national level, as discussed, semantic and technical interoperability is of utmost importance. The data model and the appropriate cyberinfrastructure required must be designed highly flexible and adjustable to the proprietary databases, the national data policies and the mandatory requirements of the EU regulatory framework.

Conceptualized within the scope of the pan-European project ProMine (http://promine.gtk.fi/), GST, Geo Sciences in Space and Time (http://tu-freiberg.de/fakult3/IS4GEO/), meets these basic prerequisites. GST is developed by the Mining Academy of Freiberg, Saxony, as a framework for spatial and spatio-temporal geoscience data, giving access to geoobjects for viewing and manipulating using open standards. It is aimed at the generation of geomodels which will use thematic geo-information gathered at various scales to model and visualize the key spatial, geological, geophysical and geochemical parameters. Beyond the deliverables of ProMine, comprising the concept and the first prototypical implementation of the geodata model, the major concern is the management of large models, i.e. models of large regions, and the ability of 3D tiling into spatially restricted models with refined resolution of large regions.

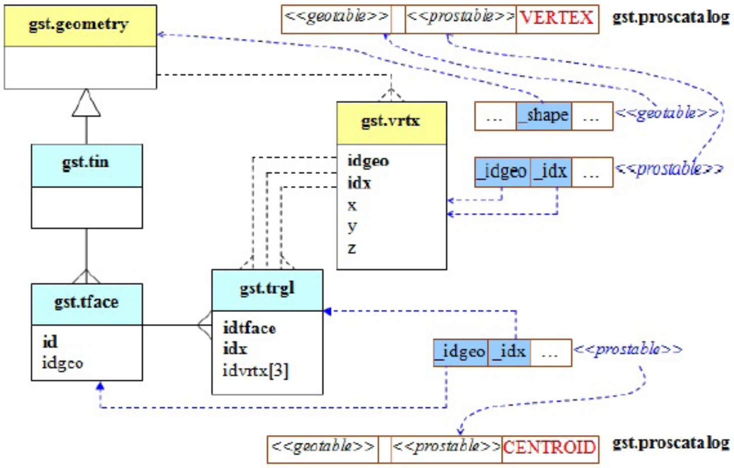

Figure 5: The internal structure of a triangulated irregular network (TIN) object in GST v.0.1 (from Gabriel et al. 2011).

GST is based on simplex structures, allowing to store point sets, linesets, facesets (where a face is a single triangle), and tetrahedron sets, thus enabling to store geoobjects that originate from geomodelling software like Gocad®, Petrel®, MOVE® or AutoCAD®. Additionally properties can be attached to the objects, stored either on a vertex level or a cell level, for example, that a triangle network has a property stored for each triangle. The stored geometries are transported via the OGC standard Simple Feature SQL (SFS) ensuring that not only the developed client software can be used to retrieve the data, but any client understanding SFS can be used for data access to the database. The basic principle of GST is to model classes, e.g. base horizons or faults. These classes are made up of one single basic type, e.g. triangle network. Each class has its own properties which could be of any data type supported by the involved database system. The properties can be discrete, like rock type, or continuous like porosity. GST enables the user to query just the geometry as SFS or to query the properties without any geometry or, to retrieve both; geometry and property. Thus GST comprises some basic GIS functions, e.g. query of specific objects with a particular property.

Due to its advanced stage of development, the successful check of GST prototypes in different test beds and its capability of being expanded and adapted to individual databases, GST is the designated tool to guarantee interoperability in collaborative projects of the German GSOs. Thus, exploiting the achievements of the ProMine 3D developments is a logical consequence regarding the scope of GeoMol and inter-state collaboration of the German GSOs. Incorporating the Mining Academy of Freiberg into GeoMol ensures continuity in further development towards more general applications and international standards in storage and dissemination of 3D subsurface information. With respect to interoperability and easy communication of 3D geological models, developing a viewer for the next browser generation supporting WebGL technology is also considered.

5. REFERENCES

Diepolder, G.W. 2011. German Geological Surveys: Federal-State Collaboration for 3-D Geological Modeling: Illinois State Geological Survey Circular 578, 48-52

Diepolder, G.W., and U. Schulz. 2011. Tiefliegende Speicher- und Barrieregesteinskomplexe in Bayern – ein Überblick: Schriftenreihe der Deutschen Gesellschaft für Geowissenschaften 74, 118-136.

Diepolder, G.W., U. Schulz, and S. Sattler. 2010. 3D geological modelling of potential CCS settings in the Molasse Basin of Bavaria – first step towards spatial planning of subsurface rights?: CCS: bridging the transition from fossil fuels to renewables, Abstracts, 33: Dublin, Royal Irish Academy. http://www.ria.ie/getmedia/12727428-f9ba-45bd-a4bc-02d2043684bb/book-of-abstacts-090310-FINAL.pdf.aspx

Gabriel, P., J. Gietzel, H.H. Le, and H. Schaeben. 2011. A network based datastore for geoscience data and its implementation: Proceedings of the 31st Gocad Meeting, June 7-10 2011, Nancy, France, 7 p. http://tu-freiberg.de/fakult3/IS4GEO/gOcad2011.pdf

Kayser, M., and H. Kaltschmitt. 1998: Potentiale hydrothermaler Erdwärme in Deutschland: Geothermie Report 98/1, 7-26: Potsdam, GeoForschungsZentrum.

Pamer, R., and G.W. Diepolder. 2010. 3D geological modelling in Bavaria – state-of-the-art at a State Geological Survey: Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 161/2, 189-203.

Pamer, R., and S. Sieblitz. 2009. Subsurface modelling using scanned 2D-seismics: 6th European Congress on Regional Geoscientific Cartography and Information Systems (EUREGEO), Munich, June 9-12 2009, Proceedings I, 314-316: München, Bayerisches Landesamt für Vermessung und Geoinformation.

Sattler, S., and R. Pamer. 2009. A 3D Structural Model of the Bavarian Basement: 6th European Congress on Regional Geoscientific Cartography and Information Systems (EUREGEO), Munich, June 9-12 2009, Proceedings I: 202-203: München, Bayerisches Landesamt für Vermessung und Geoinformation.

MULTIPLE-POINT GEOSTATISTICS FOR CREATION OF 3D HYDROSTRATIGRAPHIC MODELS, OUTAGAMIE COUNTY, WI

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1. INTRODUCTION

Three-dimensional hydrostratigraphic models created using multiple-point geostatistics promise to help quantify the role of preferential flow paths in a heterogeneous glacially-deposited aquitard. The preferential flow paths allow for faster transport of fluids and solutes than in the surrounding matrix. Transport in preferential flow paths is governed by the hydraulic properties within the flow path and connectivity among flow paths. Preferential flow paths are difficult to detect and quantify, especially in aquitards. They may be created by fractures or connected bodies of sediment with high hydraulic conductivity (K), such as sand within a clay matrix. Even thick aquitards (greater than 150 ft) may have fractures that are capable of transporting contaminants (Cherry *et al*., 2006; Gerber *et al*., 2001). Few researchers have documented preferential flow paths created by connected sand bodies. Techniques to delineate preferential flow paths in aquitards are key to protecting underlying aquifers.

A representative site was selected in Outagamie County, Wisconsin, where a bedrock valley is filled with more than 300 feet of sediment; mostly lake sediment with some glacial till and sand bodies of uncertain deposition. The sediment appears to form an extensive aquitard of very low conductivity and occasional sand bodies of unknown extent and continuity. Multiple-point geostatistics (Guardino & Srivastava, 1993) were used to create hundreds of three-dimensional hydrostratigraphic models of the representative site, using as input data a combination of well logs, geophysics, drilling logs, hydraulic conductivity (K) measurements, and depositional histories. In future work, quantitative comparisons of all hydrostratigraphic models will be performed using CONNEC3D (Pardo-Igúzquiza & Dowd, 2003), which calculates a number of connectivity statistics. Results of the statistics will aid in selecting a representative set of 3-5 models for input into groundwater flow and transport models.

Multiple-point geostatistics uses training images, either 2D or 3D, that represent the general features of the subsurface (i.e., channels, lenses). Training images have advantages over variograms, the more traditional geostatistical approach, because training images can include soft data, such as observations from outcrops or geophysics, and can maintain geologic structure and continuity. Additionally, the problems associated with a single variogram producing widely varying images of heterogeneity (i.e., connected channels, disconnected spheres) are avoided. Despite these advantages, multiple-point geostatistics is computationally intensive and was not used much until the single normal equation simulation (*snesim*) algorithm was developed by Strebelle (2002), which reduced the computation time. Feyen and Caers (2005) used a synthetic case to compare variogram based methods with multiple-point geostatistics. Using MODFLOW-2000 (Harbaugh *et al.*, 2000) and MT3DMS (Zheng & Wang, 1999) they showed that variogram based methods did not reproduce head and underestimated solute movement, while multiple-point geostatistics reproduced the head field and correctly estimated solute transport. Another comparative study by Bastante *et al.* (2008) looked at slate deposits for mining applications. They found that not only did multiple-point geostatistics best reproduce the structure of the deposits, but also provided slate percentages closer to observed values than variogram methods.

2. GEOLOGIC DATA AND INTERPRETATION

Hooyer *et al*. (2008) studied groundwater recharge through the fine-grained glacial deposits in our project area. Four rotosonic boreholes were drilled along the axis of the valley and multilevel wells were installed in two of them (RS-17 and RS-18). Two other boreholes were drilled where the fine-grained sediment was much thinner over bedrock (<50 ft). These boreholes, located at the Riehl and Lorenz Farms (Figure 1), were drilled using a hollow-stem auger. Three multilevel wells were installed in each borehole. With the exception of RS-17, water Leveloggers® were installed and have continuously recorded pressure head in the aquitard in every well since 2007. The RS-18 location contained a sand body at a depth of 40-60 feet, and sand bodies of similar thicknesses have been noted in multiple private well logs in the study area. Intact core samples from RS-18 and other rotosonic boreholes drilled through the fine-grained sediment were collected for consolidation testing to measure preconsolidation stress, hydraulic diffusivity (D), and specific storage(S_s) (Grisak and Cherry, 1975; Hooyer *et al*., 2008). The vertical K can then be calculated from D and S_s. Slug tests performed in the wells at RS-18, Riehl, and Lorenz Farms show that K values range from 1 x 10^{-8} to 5 x 10^{-14} m/s for the fine-grained sediment, and 2.5 x 10^{-4} to 6.0 x 10^{-5} m/s for the sand bodies.

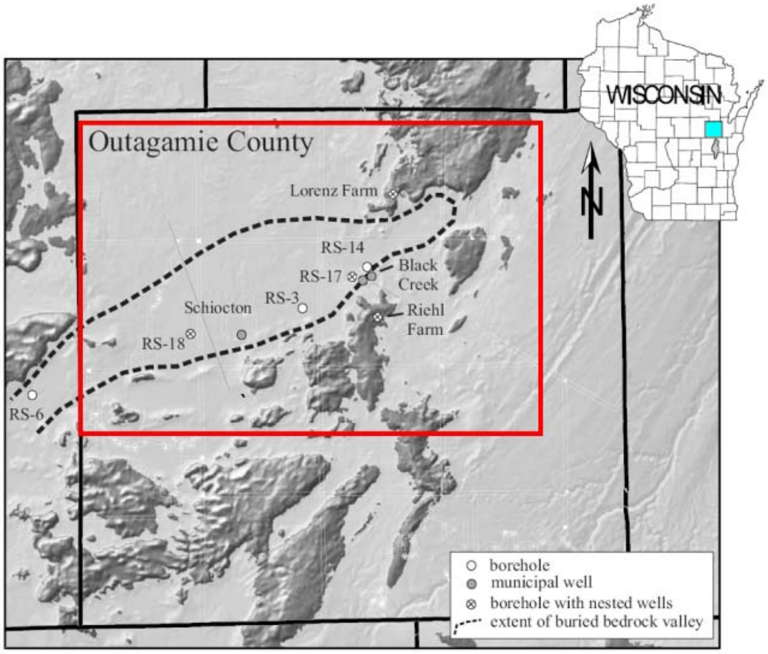

Figure 1. Shaded relief map of Outagamie County showing the lateral margins of the buried bedrock valley and locations of boreholes and wells drilled by the WGNHS. The red box indicates the approximate location of the hydrostratigraphic and groundwater flow models. The light gray regions approximate the area covered by glacial Lake Oshkosh during the last glaciation. The inset shows the location of Outagamie County in WI. (modified from Hooyer et al., 2008)

Approximately 2,200 Wisconsin Well Construction Reports (WCRs) with driller described lithologies and locations accurate to within 250 ft were used to analyze the unconsolidated sediment, in order to identify distinct hydrofacies ranging from dominantly clay or silty clay to coarse sand or gravel. Most drillers lack formal geologic training and often subtle differences in sediment are not reflected in cuttings. Thus the quality of these data varies considerably. For example, terms such as " hardpan" usually refer to glacial till, but so can “stoney clay” or “clayey gravel”, among other designations. Considerable effort was made to be consistent and as accurate as possible in transforming the drillers’ descriptions into geologic categories. Analysis of the WCRs indicated the presence of four distinct units and their corresponding percentage of unconsolidated material by thickness as: 55.9% clay/silt, 24.6% till, 11.8% sand, and 7.7% gravel. Fogg *et al*. (2000) introduced the idea of a connected network paradigm in which small volumes (<20%) of higher K materials form a fully connected network within a formation. The WCR analysis indicates 19.5% high K material by thickness; thus it is plausible there may be a fully connected network of sand and gravel acting as preferential flow paths in this aquitard. Analyzed WCR data was then displayed in 3D (Figure 2).

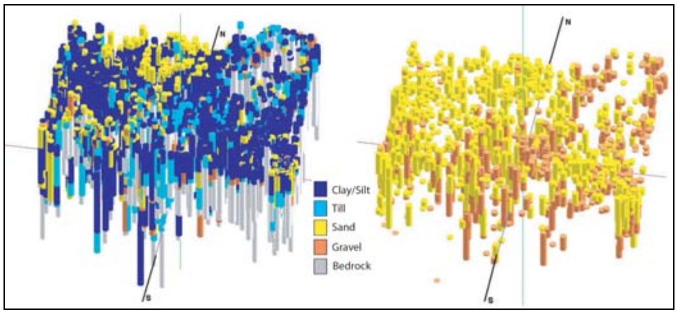

Figure 2. WCRs displayed in 3D. All units displayed on left, high K units only displayed on right (created in Rockworks®, 2006).

Geophysical methods (seismic, radar, time-domain electromagnetics, and electrical resistivity) were tested at the RS-18 site, which has a known sand body. Electrical resistivity gave the best image of the sand body. Electrical resistivity imaging (Figure 3) was used at an additional 8 sites, with analysis of the imaging used to determine the average and range of sizes of the sand bodies. Geoprobe sampling at two of the sites confirmed the geophysical interpretations.

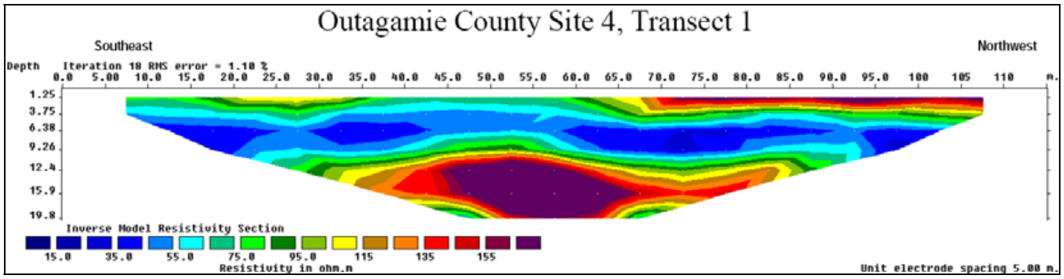

Figure 3. Electrical Resistivity Image for one of the additional sites located in the northern central portion of the buried bedrock valley. Note the higher resistivity units at the surface and at depth, most likely sand. Hand augering to a depth of 5 ft confirmed sand in the near surface. Geoprobe sampling to a depth of 55 ft confirmed sand at depth.

3. HYDROSTRATIGRAPHIC MODELS

The 3D hydrostratigraphic models were created using the Stanford Geostatistical Modeling Software (SGeMS) (Remy *et al*., 2009), which is the only software available that has algorithms for multiple-point geostatistics and the necessary training images. The hydrostratigraphic models all have 400 x 400 ft horizontal grid spacing, and 5 ft vertical grid spacing. The training images were based on the sand body information determined by well logs, geophysics and drilling throughout Outagamie County. The training images were created in SGeMS with the TIGENERATOR program, which is an object-based image generator. The input for the program is the shape, dimensions, orientation, and proportion by volume of one or more geobodies (i.e. channels, lenses). Shapes were selected based on the geophysical images and the depositional environment. Several plausible shapes, including elliptical, sinusoidal and cubic were tested. Dimensions for each of these were based on geophysics and the WCR analysis. For example, the mode thickness for the WCRs is 10 ft. Each dimension can have either mean, max/min, or max/min/mode values assigned. Orientations are based on Laurentide ice sheet advance/retreat directions during the last glaciation and proportion based on the WCR thickness percentages. SGeMS output can be manipulated visually so only the sand bodies can be viewed in 3D, making it possible to visualize the interconnectedness between the sand bodies (Figure 4).

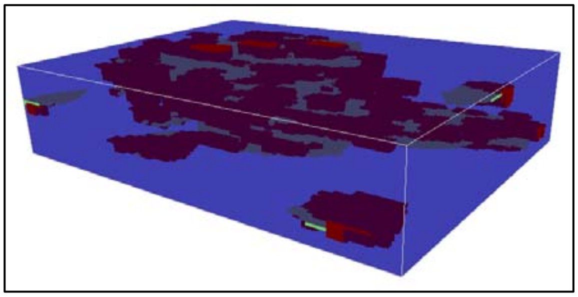

Figure 4. Training Image displayed to view interconnectedness of sand bodies within the aquitard (blue region).

The *snesim* algorithm (Strebelle, 2002) was then used to calculate the statistics from the training images and create the hydrostratigraphic models. The *snesim* algorithm works by first constructing a grid and assigning all hard data points to the closest grid cells. Then the training image(s) are scanned and conditional probability distributions are saved in a search tree. Finally, a random path is defined: at each cell along the path the algorithm searches for nearby data and cells already simulated. The algorithm gets the probability distribution from the search tree, and assigns a value of sediment type to the cell based on the probability. Parameters include which training image to use, search ellipsoid (size of nearby data area) and direction, and target volumes for each of the geobodies and the matrix. For each training image, 10 realizations were created. In future work, each hydostratigraphic model will be compared qualitatively to the 3D WCR images (Figure 5) and evaluated quantitatively with CONNEC3D (Pardo-Igúzquiza & Dowd, 2003).

Preliminary modeling results indicate that multiple-point geostatistics, combined with a combination of hard and soft field data, are able to create models of aquitards with preferential flow paths. The use of a quantitative measure of connectivity for these models allows for determining the possible range of connectivity of sand bodies occurring in the aquitard. These techniques could be a very powerful tool for characterizing preferential flow in aquitards.

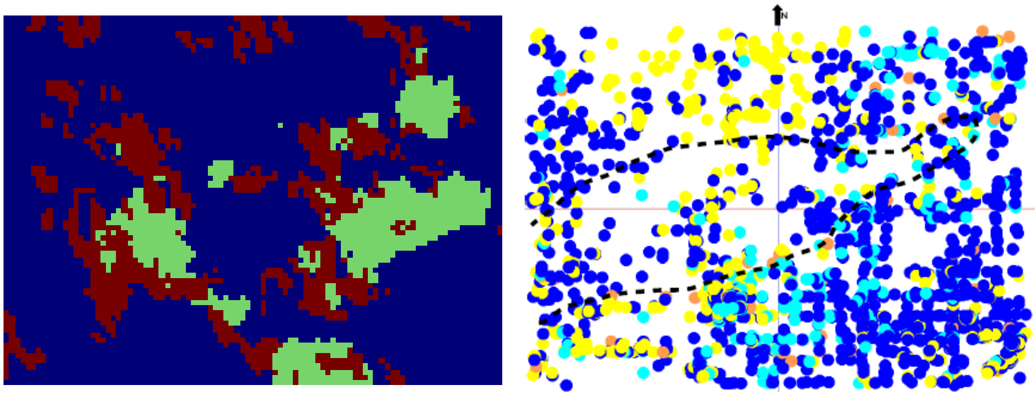

Figure 5. Layer 1 of one hydrostratigraphic model (red and green are sand bodies) compared to map view of WCR data (see Figure 2 for legend).

4. REFERENCES

Bastante, F.G., Ordóñez, C., Taboada, J., and Matias, J.M., 2008. Comparison of indicator kriging, conditional indicator simulation and multiple-point statistics used to model slate deposits. Engineering Geology, vol. 98, p. 50-59.

Cherry, J.A., Parker, B.L., Bradbury, K.R., Eaton, T.T., Gotkowitz, M.G., Hart, D.J., and Borchardt, M., 2006. Contaminant Transport through Aquitards: A State-of-the-Science Review. Denver, Colorado: American Water Works Association Research Foundation.

Feyen, L. and Caers, J., 2005. Multiple-point geostatistics; a powerful tool to improve groundwater flow and transport predictions in multi-modal formations. Proceedings-European Conference on Geostatistics for Environmental Applications, vol. 5, p. 197-207.

Fogg, Graham E, Carle, Steven F., and Green, Christopher, 2000. Connected-network paradigm for the alluvial aquifer system in Theory, Modeling, and Field Investigation, in Hydrogeology: A special Volume in Honor of Shlomo P. Neuman's 60th Birthday, eds. Zhang and Winter. Geological Society of America Special Paper 348, p. 25-42.

Gerber, Richard E., Boyce, Joseph I., and Howard, Ken W.F., 2001. Evaluation of heterogeneity and field-scale groundwater flow regime in a leaky till aquitard. Hydrogeology Journal, vol. 9, no. 1, p. 60-78.

Guardiano, F. and Srivastava, M., 1993. Multivariate geostatistics: Beyond bivariate moments, in Geostatistics Troia'92, ed. A. Soares, p. 133-144.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G. 2000. MODFLOW-2000, the U.S. Geological Survey modular ground-water model- user guide to modularization concepts and the ground-water flow process. U.S. Geological Survey Open-File Report 00-92.

Hooyer, T.S., Hart, D.J., Bradbury, K.R., and Batten, W.G., 2008. Investigating groundwater recharge to the Cambrian-Ordovician Aquifer through fine-grained glacial deposits in the Fox River Valley: Final Report to the Wisconsin Department of Natural Resources.

Pardo-Igúzquiza, Eulogio and Dowd, Peter A., 2003. CONNEC3D: a computer program for connectivity analysis of 3D random set models. *Computers and Geosciences*, vol. 29, p. 775-785.

Remy, Nicolas, Boucher, Alexandre, and Wu, Jianbing, 2009. Applied geostatistics with SGeMS; a user'sguide,Cambridge University Press, New York, 110 p.

Strebelle, 2002. Conditional simulation of complex geological structures using multiple-point statistics. Mathematical Geology, vol. 34, no. 1, p 1-21.

Zheng, C., and Wang, P., 1999. MT3DMS: A modular three-dimensional multispecies transport model for simulation of advection, dispersion, and chemical reactions of contaminants in groundwater systems; documentation and user's guide. US Army Corps of Engineers, Contract Report SERDP-99-1, 220 p.

GEOLOGICAL AND PETROPHYSICAL 3D MODELLING OF SEDIMENTARY BASINS FOR GROUNDWATER APPLICATIONS, BRGM

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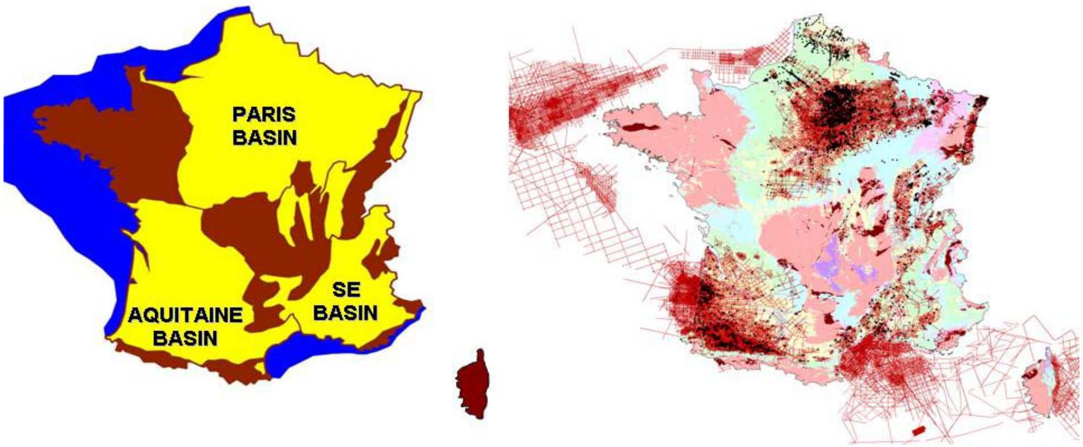
1. INTRODUCTION

During the past 50 years the Bureau de Recherche Géologiques et Minières, (BRGM) has collected a large amount of diverse data during projects for water and hydrocarbons exploration and underground storage investigations (methane, nuclear-waste, etc.). Societal and environmental issues have had a significant influence on research applied to groundwater exploration and characterization. During this period, methodological improvements have allowed the investigation of new targets, such as deep reservoirs and aquifers that have delineated new geothermal targets, alternative water resources and potential CO_2 storage sites. Most of this data comes from sedimentary basins (Figures 1 & 2) and provides an excellent opportunity for developing new methodologies in deep geology 3D reconstruction.



Figures 1 & 2: Fig 1 (left): Geographic location of France's three main sedimentary basins, i.e. the Paris Basin, Aquitaine Basin and Southeast Basin. Fig 2 (right): Location of seismic lines (red segments) and deep wells (black points) available for study of France's sedimentary basins.

2. GEOLOGICAL DATA MANAGEMENT AND ENHANCEMENT

BRGM is the unique public organisation in France which is in charge of the management of the large amount of geological data acquired in the field, development of geological maps, and archiving of data from major exploration programs (seismics, deep drilling, airborne geophysics, gravity) in sedimentary basins. For the past two decades BRGM has done extensive work on database management, which is essential for producing integrated geological models.

Since 2006 BRGM has managed 350,000 line km of petroleum industry seismic data and the 6000 boreholes collected in sedimentary basins (Figs. 1 & 2). Raw data are accessible to the public via a public "front office" (guichet.H@brgm.fr) and dedicated re-processing is possible on request. Aside from data management and delivery, BRGM has launched a vast data enhancement program. The seismic lines are gradually being reprocessed and interpreted and then assembled to provide regional reference transects. The borehole data set consists of a suite of downhole geophysical logs (e.g. gamma ray, density, and resistivity) and petrophysical logs (e.g. porosity, permeability) that are being systematically digitized, thus enabling stratigraphical and petrophysical calibration of the geological models (Figures 3 & 4). The methodologies are also being implemented internationally for geological syntheses and basin modelling.

Taking advantage of easy access to data and a renewal of activity in the sedimentary basins, BRGM is now in a position to update existing geological syntheses and to produce digital models in support of various applications. Consequently, the geological models must be constructed in a numeric 3D environment compatible with the dynamic software used downstream by hydrogeologists and reservoir engineers. One of the most studied sedimentary basins in France is the Paris basin, which is currently the focus of this data analysis and model construction.

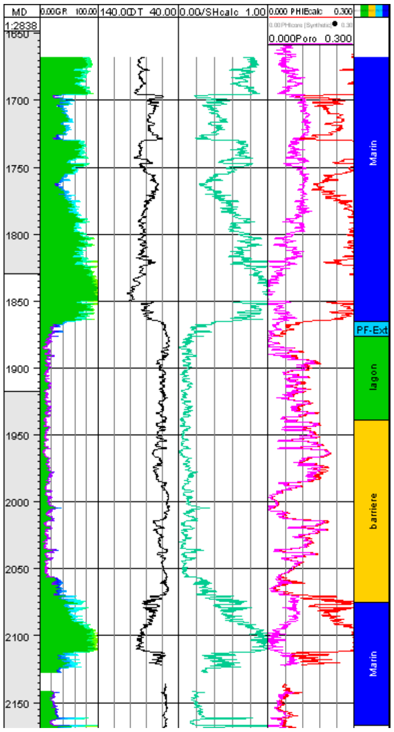


Figure 3: Example of digitized well logs (Dogger aquifer, Paris basin), from the left to the right: Gamma Ray, density, volume of shale in carbonate system (VSH), equivalent porosity (without and with shale effect), facies rocks descriptions

3. UNDERGROUND APPLICATIONS IN PARIS BASIN

Following the 1973 and 1979 oil crises, the development of deep geothermal energy exploded in France between 1980 and 1986. The Dogger carbonate formations of the Paris Basin have been the principal targets for such exploration. Today, in anticipation of a decrease in the thermal potential of the Dogger aquifers, the underlying Triassic aquifers are being studied.

The potable water resources of the shallow aquifers are vulnerable to contamination. It is thus necessary to identify alternative water resources, and thus to explore the deep water reservoirs. Several projects exploring major fracture and/or karst systems in Dogger formations are currently underway in France's three main sedimentary basins. There is also interest in the role of aquifers for underground storage of methane, which has been in constant development since the 1960s, and CO2. Major French and European research programs have led us to reconsider the principal deep reservoirs of each basin in order to study storage capacities on a regional scale (unlike the storage of methane, localized on anticlinal structures).

4. GEOLOGICAL AND PETROPHYSICAL MODEL PRODUCTION: OUR INTEGRATED METHODOLOGY

The models constructed to date for groundwater applications postulated model layers consisting of homogeneous geological formations. The challenge currently is to model the reservoir heterogeneity so that the 3D models are more geologically realistic. This is an enormous challenge because the characteristics of the geological formations of the reservoir (porosity, permeability) vary greatly from place to place in the sedimentary basin.

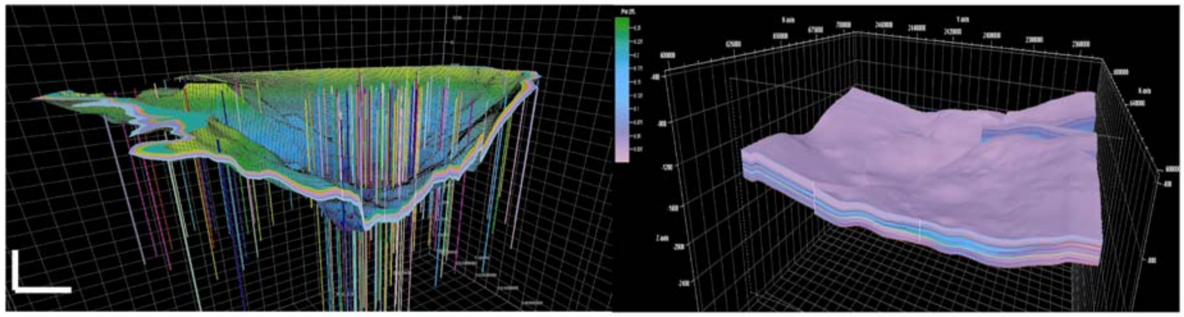


Figure 4: 3D gridded geological and petrophysical models (with Petrel®). On the left: surface and boreholes from geological model of the Paris basin (LogIso project, Author: S.Gabalda). On the right: regional model of the Dogger aquifer (ANR-SHPCO2, Author: S.Gabalda, Geology division, BRGM).)

To build these models, we relied on a methodology developed by petroleum engineers, working at oilfield's scale (a few square kilometers). We have transposed the same approach to a regional and basin system scale (several hundred square kilometers, Figure 4). Models are constructed by integration of deep data (seismic lines and boreholes) and geological map data (limits on geological outcrops) that are then interpreted within a sequence stratigraphic framework (i.e. subdivision of the sedimentary pile into layers bounded by isochronous surfaces) and depositional facies models. Based on this approach we are then able to produce paleogeographic maps and 3D digital models suitable for geodynamic reconstruction of the basins. Prediction of favourable zones for the exploitation of target formations is evaluated by petrophysical modelling. For each type data analysis of boreholes (logs and core data) is completed. These petrophysical data are then interpolated and simulated in the geological model using geostatistical tools.

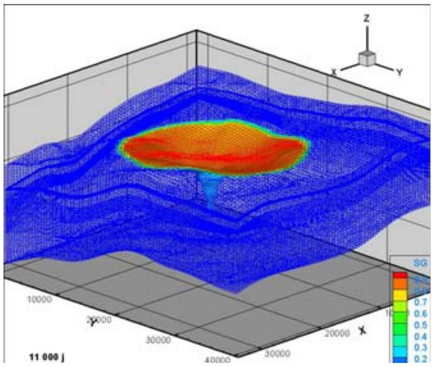


Figure 5: Simulation of CO_2 injection (with Tough 2) into the Dogger aquifer (Paris basin, ANR-SHPCO2, Author: C. Chiaberge, Water division, BRGM).

The large scale models allow delineation of areas within sedimentary basins that are potentially suitable for CO2 storage or exploitation of geothermal resources. For zones of interest in the aquifer more detailed models can be constructed by upscalling of the preliminary models. In the example below (Figure 4), we produced a gridded 3D geological model at the basin scale, that here highlights the petrophysical properties (Figure 4). After potential areas for CO_2 storage are identified, a regional model is built (downscaling). Both scales of models allow dynamic simulations of flow and injection of CO_2, and permit assessment of the impact of the respective fluid on the reservoir with time. Finally, these methodological results are now transferable to other aquifers in the Paris Basin and to others sedimentary basins in France (ie. the Aquitaine basin, South East Basin or, the Upper Rhine Valley, Figure1).

5. ON-GOING CHALLENGES: COMPATIBILITY BETWEEN GEOMODELLING AND SIMULATION SOFTWARES

Due to the diversity of the geology of France and variety of sedimentary basins, we made the choice of using several different software options. This reflects the fact that no software possesses all the required facilities for 3D geological modelling and simulation. Consequently, we take advantage of the complementary software features in commercial software (ISATIS®, Earth Vision®, PETREL®, etc.) and in-house software (GDM Multilayer, Geomodeller 3D, etc.). One or the other is chosen on the basis of the complexity of geology being modelled and the aim of the 3D modelling. For example, Petrel® (©Schlumberger) software is mainly used for 3D gridded models of sedimentary basin and subsequent flow simulations with Eclipse or Tough. More complex geology, such as the margin of basins within the deformation front of of orogenic belts (i.e. non-tabular structures, folds, diapirs, etc) are modelled using Geomodeller 3D (in house software, see an example in Figure 6).

One of our research objectives is to improve compatibility between geomodelling and simulation software (see Figure 7). The workflow integrating multiple software options and facilitating data transfer between one another, and successive projects, needs to be as fluent as possible. Major challenges are faced with model compatibility between software formats and in maintaining the timely delivery of results. Models need to be as complete as possible (geometry, petrophysical information, etc.) and their integrity has to be preserved between software options.

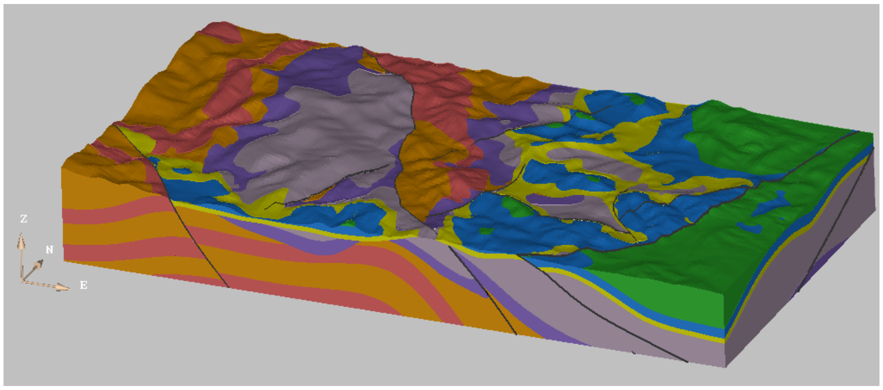


Figure 6: Example of complex geological features in a groundwater study area (with Geomodeller, Author: G. Courrioux, Geology division, BRGM)

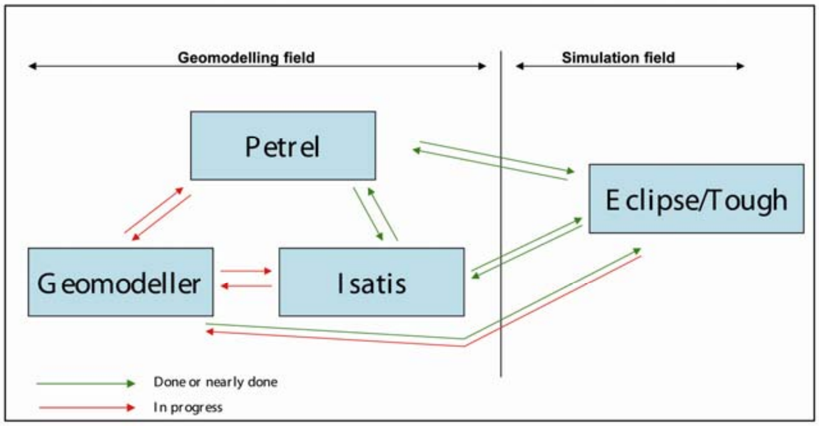


Figure 7: Links between software improvement at BRGM, Geomodeller (©Brgm-Intrepid): models at large scale with few data, Petrel (©Schlumberger): reservoir characterization, Isatis (©Geovariance): complex geostatistics, Eclipse / Tough2 / ToughReact: to compute simulation.

3D/4D MODELLING, VISUALIZATION AND INFORMATION FRAMEWORKS: CURRENT U.S. GEOLOGICAL SURVEY PRACTICE AND NEEDS

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Abstract

Progress is being made in the ability to visualize and model geologic data and information in 3 spatial dimensions (3D) and sometimes adding time for 4 dimensions (4D). These abilities are enriching the conceptual models and process simulations constructed by geologists and hydrogeologists. Computer technology is also enhancing the visualization and modeling of landscapes and the hydrodynamic simulations of surface waters. Progress needs to be made in visualizing and coupling geologic, hydrologic, atmospheric, and biologic processes together into 3D/4D information frameworks that encompass and integrate observations and simulations across a diversity of spatial and temporal scales and data types. Achieving progress in these areas will also enhance the relevance and effective communication of USGS science to policy makers and to the lay public.

1. INTRODUCTION

We need to gain abilities to visualize and model our dynamic multi-dimensional earth. Natural processes are 3D/4D in character, yet many people increasingly access the natural world through 2D screens and visualize and simulate reality through 2D or 1D representations. Current 3D modelling and visualization efforts often consist of 2D map/GIS overlays stacked in 3D space that only provide a limited extension of the geological realities perceived by Nicholas Steno in 1669. Static block diagrams and other 2D visuals do not allow efficient exploration of the rich multi-dimensional datasets and knowledge that they portray. Why should we, and how can we, advance our visualization and modelling of information frameworks to a new level of perceived reality? Plato described this need in his allegory of the cave, referring to the "philosopher" as someone who was able to escape a 2D world of shadows. Current capabilities and practice in using 3D/4D visualization/modelling tools vary widely across the U.S. Geological Survey (USGS). Our presentation (1) considers different types of 3D/4D visualization and modelling efforts currently conducted in the USGS, (2) highlights some interdisciplinary possibilities for future efforts and science applications, including the more effective communication of USGS science and the implications of alternative management scenarios to policy makers and to the lay public and finally (3) comments on desired software capabilities of a general information framework for 3D/4D modeling and visualization.

2. 3D/4D GEOLOGIC APPLICATIONS

Current USGS geologic applications for 3D/4D visualization and modelling include:

- Paleoseismic frameworks and tectonic models to assess past tectonic displacements, earthquake potential, and fault-slip scenarios;
- Geologic models to define, assess, and bound resources and/or lithologic properties (water, oil, gas, minerals, porosity, rock chemistry...);
- Geophysical inverse models to visualize/characterize anomalous properties in the earth's crust;
- Volcanic models to describe magmatically driven bulging or to predict eruption types and timing;
- Deformation models showing landform subsidence or rebound caused by removal or addition of resources;
- Geomorphic analyses to detect/quantify landscape changes and structural features (e.g., faults, landslides, debris flows, paleo-floods, glaciers, impact craters).

Recently published USGS 3D geologic maps and databases (e.g. Phelps et al., 2008; Faith et al., 2010; Pantea et al., 2011) go beyond traditional geologic mapping. They provide a more complete characterization of features (e.g., units, faults, unconformities, structures, physical and chemical properties) and also describe the methods and techniques used. The descriptions are needed because 3D geologic mapping updates and adds to the conventional scientific methods for 2D mapping. 3D maps and models also define some features solely on geophysical expressions and include a discussion of the data and model(s) used in constructing the map.

3. 3D/4D SURFACE-MAPPING APPLICATIONS

3D and 4D analyses and visualization of LiDAR (**Li**ght **D**etection **A**nd **R**anging) imagery are frequently used in the USGS. LiDAR data are displayed, checked and corrected in immersive, virtual-reality, environments that comprise hardware 3D display technology (e.g., Keck[1] Caves) and LiDAR viewing softtware. LiDAR and remote-sensing measurements and analyses can help determine the impact, frequency of occurrence and the future impacts of earthquakes, debris flows, fires, floods and other disturbances that have modified, or could modify, the land surface, its vegetative cover, water resources, and/or human infrastructure. For example, repeat ultra-high resolution (sub-centimeter) 3D ground-based LiDAR imagery was collected in the days and months following the magnitude 6.0 Parkfield earthquake in central California. Immersive, virtual reality 4D analysis (Kreylos et al., 2006, Kellogg et al., 2008) of the land surface and engineered structures illuminated small active tectonic geomorphic features that would have been overlooked in a 2D analysis.

Airborne and ground-based LiDAR are also commonly used in the detection of potentially hazardous faults and to assess structure and surface stability after landslides, rockslides, and debris flows. Detailed 3D/4D analyses are used to characterize these events, understand their driving mechanisms, and provide rapid feedback to local authorities regarding post-event stability of the land surface. Visualization tools, coupled with “before and after” landscape surveys, through remote sensing or LiDAR, are being used to benchmark current landscape conditions and help characterize and model the magnitude and extent of atmospheric events in terms of natural hazards, water availability, ecosystem response, and long-term climatic variability. At local scales, these technologies are used with biomorphic imaging of trees, roots or forest canopies to improve understanding of subsurface and surface relations between species, soils, geomorphic changes, solar fluxes and ecological productivity.

4. SURFACE HYDROLOGY APPLICATIONS

The USGS conducts work visualizing and predicting the impacts of sea level rise and salinity intrusion on coastal habitats. Although fixed-level 3D flood maps provide a first cut interpretation of the consequences of floods or sea level rise, 4D renderings are used to describe/model flood waves, storm surges, tsunamis, tidal surges, and outflows. Deterministic, predictive models based on mathematical descriptions of both, the operative physical processes and mass and energy conservation relations, are often displayed using advanced visualization systems to enhance dynamic patterns that would not otherwise be apparent. These models are vital to understanding the effects of storm surges on coastal wetlands or in predicting the potential impact and movement of hazardous spills or biomass (e.g., red tides). Numerical simulation models, often with associated 3D/4D visualization tools, have also been used to understand the dynamics of contaminant transport in Boston Harbor and Massachusetts Bay (Blumberg et al., 1993); and to simulate and understand water transport, nutrient cycling and ecological responses in the San Francisco Bay/Delta estuary (Lucas et al., 1999, 2009; http://cascade.wr.usgs.gov/index.shtm), in Upper Klamath Lake (Wood et al., 2008), and in the Florida Everglades (e.g., Larsen and Harvey, 2010).

The dynamically changing cryosphere presents complex environments, including permafrost and surging glaciers, with significant challenges to our understanding. The rapidly changing landforms, vegetation, and hydrology of arctic landscapes with warming temperatures and disappearing permafrost offers an example of the need for more integrated 3D/4D modeling, visualization and interpretations across traditional disciplines in the physical and

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

biological sciences and also coupling surface and subsurface processes. As the areal distribution of permafrost decreases, there is increased hydrologic connectivity between surface water and groundwater that in turn changes the landscape, the distribution of vegetation, and the fluxes of nutrients and carbon to the rivers, sea, and atmosphere. The USGS also has a long-standing study of the Bering Glacier, which surges approximately every 20 years (e.g. Molnia and Post, 2010). Repeat 4D ground-based Tripod-LiDAR imagery of pressure ridges and on the glacier toe were collected to help understand and show the dynamic processes of the 2011 Bering Glacier surge.

5. GROUNDWATER APPLICATIONS

The USGS extensively uses 3D/4D visualization (e.g., Model Viewer: Hsieh and Winston, 2002) and modelling tools to simulate subsurface flow and contaminant transport. These tools are essential in:

- Representing and checking the primary data and information in a geologic context;
- Visualizing lithologic units and the spatial distribution and temporal evolution of hydrogeologic and chemical properties associated with lithologic properties (e.g. primary and secondary porosities, permeability, mineralogy) and/or with structural features such as active faults, fractures, joints, channels, and folds;
- Integrating hydrologic, chemical, or geophysical response information to help determine the spatial distribution of hydrogeologic or lithologic properties in various subsurface zones through “inverse modelling” numerical simulations;
- Using predictive or “forward” modelling to numerically simulate the potential movement of water, solutes, contaminants, colloids, viruses, or bacteria in the subsurface, and the coupled evolution of the hydrogeologic environment.

Both groundwater availability and groundwater contamination studies in the USGS focus mostly on the shallow subsurface, which is usually the source of groundwater resources for irrigation or drinking water. Hydrogeologic studies of deeper environments are mostly confined to sites that might be suitable for the disposal of nuclear wastes or the injection of other industrial wastes; however, this situation is rapidly changing. Developments in energy resource extraction increasingly necessitate geologic/hydrogeologic studies of the deep subsurface. These developments include: (1) the extraction of shale gas through the use of hydrofracking, (2) the potential development of oil shale resources through in-situ retorting, and (3) the deep-injection of waste fluids associated with energy resource extraction. There is also the potential for using deep geologic formations, specifically former oil and gas reservoirs, coal seams, and saline aquifers for geologic carbon sequestration. Finally, brackish and saline groundwater is increasingly recognized as a potential source of water, due to technical advances and cheaper costs of desalination technology (Alley, 2003).

There are a number of remote sensing approaches that are useful to assess groundwater fluctuations, water withdrawals, and their associated impacts at both global and local scales. At regional to global scales, terrestrial water storage-change observations from the NASA GRACE (Gravity Recovery and Climate Experiment) satellites have been used to estimate groundwater depletion in the US and in the Indian states of Rajasthan, Punjab and Haryana (Rodell et al, 2009). Groundwater withdrawals not only impact water sustainability in semi-arid environments but also can adversely impact surface water resources in humid climates, produce substantial land subsidence, damage infrastructure, and irreversibly decrease an aquifer’s ability to store water. At smaller regional scales, repeat satellite InSAR (Inferometric Synthetic Aperture Radar) imagery of active hydrocarbon fields shows how the land surface responds to hydrocarbon removal and CO2 and water injection over time. At local scales, high resolution imagery from a suite of observational technologies including InSAR, airborne LiDAR, ground-based Tripod LiDAR, and GPS can be fused to characterize the surface deformation through time associated with pumping of groundwater at depth. In all these studies, 3D/4D visualization can help us understand what areas are at the greatest risk, what areas are being most depleted of groundwater or an energy resource, and can also be used in optimization modelling to more efficiently manage and distribute pumping and recharge in a given area. More generally, 3D/4D visualization tools can also be used to effectively communicate the implications of scientific research and assessments, and the potential results of alternative resource management scenarios, to policy makers and to the lay public.

6. OTHER APPLICATIONS OF 3D/4D MODELLING

Collaboration among scientists who often do not have the same scientific disciplinary backgrounds, and therefore lack a common scientific language, can be made easier through the use of advanced 4D immersive visualization systems. The USGS needs to extend its individual capabilities in 3D earth science modelling and visualization to provide greater understanding and integration of coupled processes for scientific research and assessments of natural resources and hazards. It also needs to consider and potentially include the 3D/4D visualization and simulation of atmospheric and biologic processes. For example, understanding orographic processes, their effects on precipitation intensity, duration and type (rain, hail, snow), and the interplay with vegetation and ecosystem dynamics with geomorphic processes, can help explain and/or predict the impacts of ecosystem disturbances (e.g., fire, drought, floods, debris flows). Communicating such understanding can help regulators and policy makers better manage landscapes and natural resources in the face of changing land use and climate. Visualizing, understanding, and predicting the storage and flows of water, nutrients, contaminants, and sediments and their biological feedbacks can help mitigate the damages caused by natural disturbances and can also help society make better decisions on how and where to exploit natural resources, where to place infrastructure, and how to minimize human impacts on the environment.

The interrelations of temperature and topography also affect our landscapes and associated ecosystems and their evolution in time. Visualizing and predicting temperature distributions across a mountainous landscape or watershed can help us understand biologic habitats and how they may change. Stream temperatures and their variability are extremely important to the health and population distribution of fish and other aquatic species. Such temperatures and their diurnal and seasonal variability are controlled by many factors that may include slope, slope aspect, shading, groundwater baseflows, stream flow, groundwater/spring temperatures, snowmelt contributions, albedo, air temperature, relative humidity, precipitation, microbial activity, and the number of animals crossing the stream or the extent of salmon spawning. Understanding and visualizing topographic and climatic drivers can help predict the movement and intensity of fires, the spread of pests or invasive species, and/or the migration or extinction of species. USGS scientists also routinely collect high-resolution 4D snow depth change data and combine the data with climate models to estimate daily snow melt runoff as a function of solar radiation and incident angle at various elevations. Climate forecast models using 4D climate data and different global warming scenarios help understand how ecosystems and water availability might change in the future.

7. SOFTWARE NEEDS FOR 3D/4D INFORMATION FRAMEWORKS

Emerging needs for 3D/4D modeling and visualization in the USGS include fundamental capabilities to represent geologic, hydrologic, physico-chemical, and biologic information. There is also a need to integrate information across spatial and temporal scales and to better represent a wider array of natural processes, source information, and modelled information. To be most useful, 3D/4D visualization and modelling tools of the future will help:

- Display and validate raw scientific data collected in multi-dimensional, spatial frameworks and perform mathematical and statistical operations on the data, in real time;
- Represent, interpret, and possibly reconcile data and primary information collected non-synoptically;
- Display temporal changes in scientific information in an "animated" 4D framework (e.g. energy or material fluxes, disruptions in 3D structures or boundaries, or changes in the intensities of distributed characteristic properties);
- Integrate diverse types (e.g., point, line, areal, volumetric) of primary spatial information through time for any given property (e.g. porosity, permeability, physicochemical properties) or function in a 3D/4D visual environment while displaying not only the information but also the associated uncertainties and the information gaps;
- Conduct inverse, statistical, geostatistical, stochastic, or other types of modelling to create 3D/4D realizations of natural phenomena;
- Interpolate and extrapolate spatial and temporal values from observed data using a variety of methods and using interpreted and modelled information to build 3D/4D information frameworks, such as geologic mapping frameworks, that maximize the use of the knowledge available for a given issue or given spatial system;

- Maximize the ability to use the information for interpretive or predictive studies, simulations, and assessments;

- Derive and tie results and conclusions tightly to underlying databases;
- Maintain all data in non-proprietary formats for future use;
- Provide the ability for external users to add their own data and interpretations to USGS derived interpretations and data sets with full traceability, information security, and privacy controls where needed;
- Provide animations, fly-throughs, and data-discovery tools that help researchers individually or collaboratively advance their scientific understanding and communicate their results;
- Allow scientists to communicate research, monitoring, and assessment findings and their implications, to each other, decision makers, and the greater public in a simple, cost effective, and timely manner.

8. FINAL COMMENTS

With greater capabilities and freedom in displaying, understanding, and extrapolating information come greater responsibilities in tracking, understanding, and evaluating the quality and uncertainties/biases of data and other primary information and of transformations that have been applied to that information. The technology to track, determine and evaluate information gaps, sources of error, and uncertainties needs to be integrated into the 3D/4D visualization and modelling tools of the future. At the same time, the assembly of information and the potential to efficiently examine and analyze large quantities of data will help provide QA/QC checks that were not available in the past and will help better manage and understand the data and primary information that are collected.

Improvements are needed in the integration of widely diverse information. Available data and observations often represent information integrated across very different spatial and temporal scales, and often across a different number of dimensions. Connecting these different scales and providing a consistent reconciliation of the information can only occur within a comprehensive encompassing framework, i.e., usually a 3D/4D information framework. Better techniques are also needed to construct coherent conceptual models from individual observations and from simulated or reconstructed information, process models, and intermediate scale models. Iterating among data collection, interpretation, and the application of forward, inverse, and statistical modeling tools is likely to provide progress in this area.

3D/4D visualization and modelling tools have the potential to display and discover information that will help (1) advance and communicate USGS science, (2) better manage natural geologic, hydrologic and biologic resources, (3) minimize undesired impacts in using those resources, (4) mitigate some of the consequences of natural hazards, and (5) make more informed decisions in societal planning (e.g. in the wise emplacement of human infrastructure).

9. REFERENCES

Alley, W.A. 2003. Desalination of Ground Water: Earth Science Perspectives: U.S. Geological Survey Fact Sheet 075-03, 4p.

Blumberg, A.F., R.P. Signell and H.L. Jenter. 1993. Modeling Transport Processes in the Coastal Ocean: Journal of Environmental Engineering, Volume 1, pp 31-52.

Faith, J.R., C.D. Blome, M.P. Pantea, J.O. Puckeete, N. Osborn, S. Christenson, S. Pack, and T. Halihan. 2010. Three-dimensional geologic model of the Arbuckle-Simpson Aquifer, south-central Oklahoma: U.S. Geological Survey Open-File Report 2010-1123, Version 1.0, data storage CD.

Hsieh, P.A. and R.B. Winston. 2002. User's Guide To Model Viewer, A Program For Three-Dimensional Visualization of Ground-water Model Results: U.S. Geological Survey Open-File Report 02-106, 18 p. (http://pubs.usgs.gov/of/2002/ofr02-106/)

Kellogg, L.H., G.W. Bawden, T. Bernardin, M. Ballen, E. Cowgill, B. Hamann, M. Jadamec, O. Kreylos, O. Staadt and D.Y. Sumner. 2008. Interactive visualization to advance earthquake simulation: ACES Special Issue of Pure and Applied Geophysics, vol. 165, N3/4, (March/April).

Kreylos, O., G.W. Bawden, T. Bernardin, M.I. Billen, E.S. Cowgill, R.D Gold, B. Hamann, M. Jadamec, L.H. Kellogg, O.G Staadt and D.Y. Sumner. 2006. Enabling scientific workflows in virtual reality, *in*: Hong Wong, K., and Baciu, G., eds., Proceedings of ACM International Conference on Virtual Reality Continuum and its Applications (VRCIA 2006): ACM Press, New York, New York, pp. 155-162.

Larsen, L.G. and J.W. Harvey. 2010. How Vegetation and Sediment Transport Feedbacks Drive Landscape Change in the Everglades and Wetlands Worldwide: The American Naturalist, vol 176, no. 3, pp. E66-E79.

Lucas, L.V., J.R. Koseff, S.G. Monismith, J.E. Cloern and J.K. Thompson. 1999. Processes governing phytoplankton blooms in estuaries II: the role of horizontal transport: Marine Ecology Progress Series, vol. 187, pp. 17-30.

Lucas, L.V., L.R. Brown and J.K Thompson. 2009. Why are diverse relationships observed between phytoplankton biomass and transport time? Limnology and Oceanography, vol. 54, no. 1, pp. 381-390. http://www.aslo.org/lo/toc/vol_54/issue_1/0381.pdf

Molnia, B. W. and A. Post. 2010. Surges of the Bering Glacier: Geological Society of America Special Papers 2010, vol. 462, pp. 291-316.

Pantea, M.P., M.R. Hudson, V.J.S Grauch and S.A. Minor. 2011. Three-dimensional geologic model of the southeastern Española basin, Santa Fe County, New Mexico: U. S. Geological Survey Scientific Investigations Report 2011-5025, 17 p.

Phelps, G.A., R.W. Graymer, R.C. Jachens, D.A. Ponce, R.W. Simpson and C.M. Wentworth. 2008. Three-dimensional geologic map of the Hayward fault zone, San Francisco Bay region, California: U.S. Geological Survey Scientific Investigations Map 3045, 31 p.

Rodell, M., I. Velicogna and J. Famiglietti. 2009. Satellite-based estimates of groundwater depletion in India: Nature, doi:10.1038/nature08238.

Wood, T.M., R.T. Cheng, J.W. Gartner, G.R. Hoilman, M.K. Lindenberg and R.E Wellman. 2008. Modeling hydrodynamics and heat transport in Upper Klamath Lake, Oregon, and implications for water quality: U.S. Geological Survey Scientific Investigations Report 2008–5076, 48 p. [http://pubs.usgs.gov/sir/2008/5076/]

3D GEOLOGICAL MAPPING IN MANITOBA – OVERVIEW AND PRODUCTS

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1. INTRODUCTION

The Manitoba Geological Survey (MGS) has been generating 3D geological maps since early 2000 (Keller, et.al. 2009). These maps are based on data compiled over approximately a decade and data inputs include Manitoba's water well, oil well and stratigraphic drillhole databases, large lake bathymetry, Lake Winnipeg seismic survey and surface datasets such as the provincial surficial geology compilation map series. All of these datasets have been standardized in order to be utilized in a GIS environment and much of this work was completed in cooperation with the Geological Survey of Canada (GSC) either as part of the National Geoscience Mapping Program (NATMAP) or Targeted Geoscience Initiative (TGI). As a result many of these modified input datasets have become significant standalone products.

For example, the modelling methodology that the MGS employs utilizes a series of large cross-sections which represent a 5 km wide east-west transect across the Province. These cross-sections include all data available within 2.5 km from the line of the section (Figure 2). Each 3D model project uses a slightly different format for the final cross-section output, however the basic methodology is the same; the sections are created, printed and then hand interpreted. This 'final' interpretation is then captured at a 5 km east-west interval, imported as a series of 'tops' and then modelled. This methodology is being slightly modified for the southern Manitoba model (south of 55°N) in that the combined cross-section interpretations (TGI, NATMAP, SEMB, Lake Winnipeg) are being reinterpreted collectively, digitized and directly imported into our 3D modelling software as a set of vertical maps (Figure 1, 2).

These 'vertical maps' were initially thought of as a means to an end; that is, they would be measured and the unit tops would be imported and modelled. However, because of the lack of inexpensive, readily available 3D model viewing and querying software, the vertical maps were realized as a very useful product on their own. Whereas the 3D model and it's outputs are useful to a select group of clients, for example the Engineering Department at the University of Manitoba (groundwater-flow model developed from the southeast Manitoba model (Kennedy and Woodbury, 2005)), but most clients whether professional or lay, are more comfortable using an ArcGIS shape file or a jpeg image generated from one of the vertical maps. To this end, we have begun posting these vertical maps on the web, accessible by clicking a particular location on our provincial surficial map via our map server. These vertical maps have already been proven useful for educational purposes, to resolve complex aquifer issues, and have been used to define "base of groundwater protection" (the depth to which oil wells are cased) on behalf of Manitoba's Water Branch.

2. MODEL CONSTRUCTION

As discussed in Keller et al. (2009), the Manitoba Geological Survey has spent a great deal of time designing a workable infrastructure for data collection, integration and output as it relates to 3D modelling. Our cross-section methodology has allowed us to create the NATMAP southeastern Manitoba model, as well as the Lake Winnipeg model. The TGI Williston Basin model on the other hand, was modelled directly from high quality drillhole data. A modified version of the cross-section methodology is now being used to model all of Manitoba's Phanerozoic terrane south of 55°N.

During the initial stages of the modelling process, we make use of several datasets directly and indirectly related to the geological interpretation. Geological maps and reports from various geologists, including published and unpublished subsurface and surficial information they acquired, is considered. Data representing various aspects of paleogeography for the area is also included. This allows a greater understanding of both glacial retreat and glacial Lake Agassiz which both factor strongly into the interpretation. Overall, we endeavour to be sure that every piece of available information from every available source is integrated into the cross-sections.

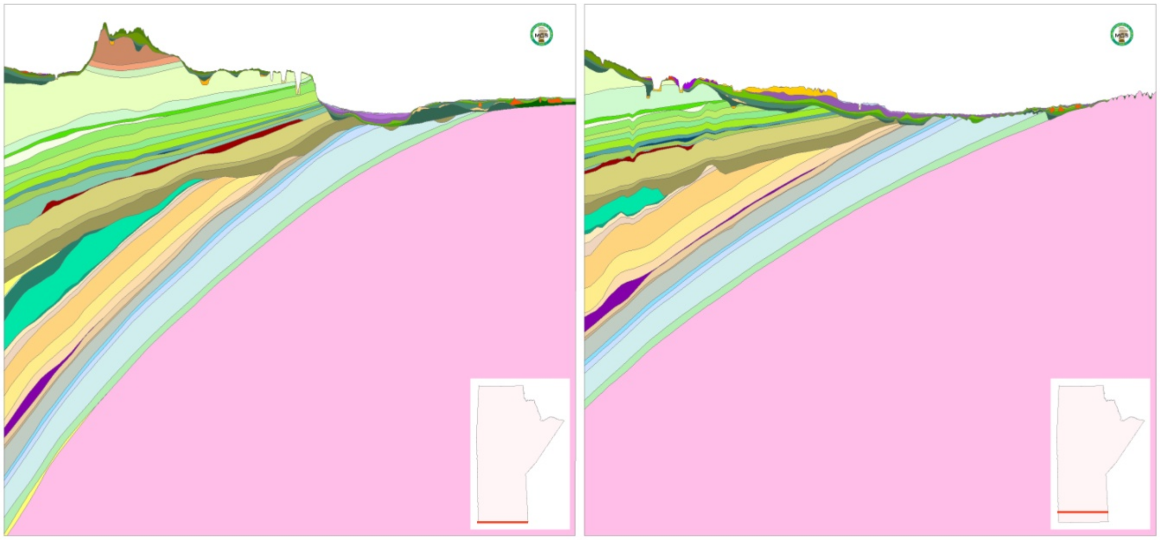
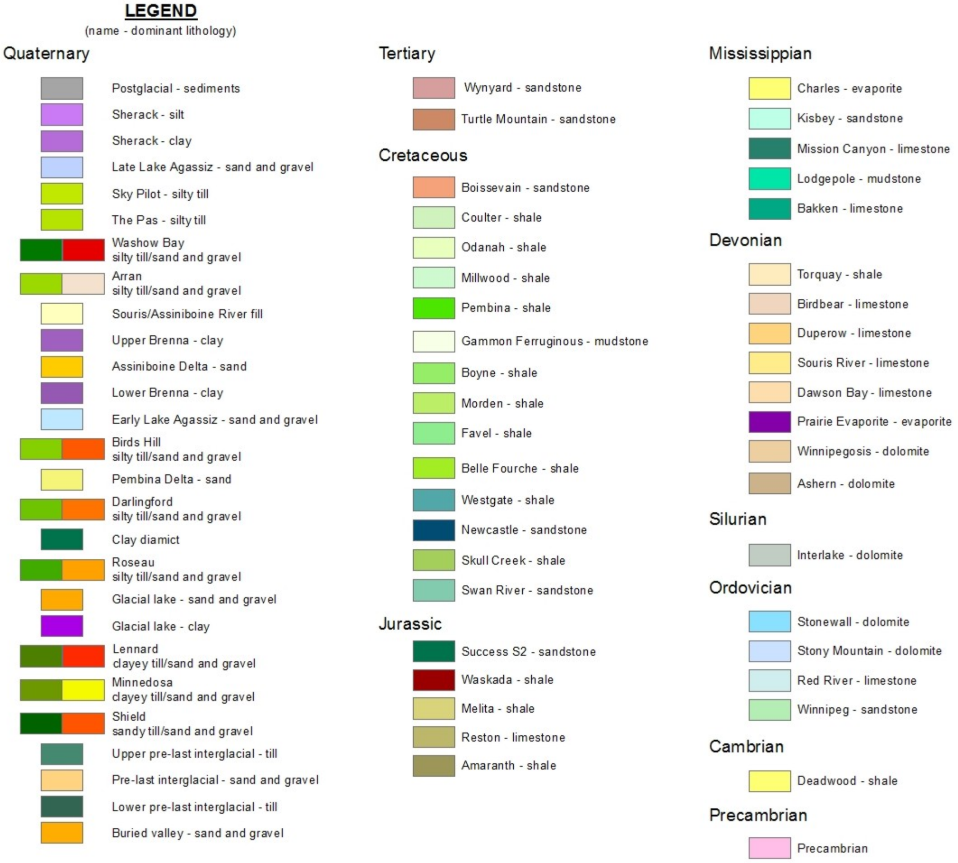


Figure 1: Transects 1, 19, are represented as vertical maps.



LEGEND
(name - dominant lithology)

Quaternary
- Postglacial - sediments
- Sherack - silt
- Sherack - clay
- Late Lake Agassiz - sand and gravel
- Sky Pilot - silty till
- The Pas - silty till
- Washow Bay silty till/sand and gravel
- Arran silty till/sand and gravel
- Souris/Assiniboine River fill
- Upper Brenna - clay
- Assiniboine Delta - sand
- Lower Brenna - clay
- Early Lake Agassiz - sand and gravel
- Birds Hill silty till/sand and gravel
- Pembina Delta - sand
- Darlingford silty till/sand and gravel
- Clay diamict
- Roseau silty till/sand and gravel
- Glacial lake - sand and gravel
- Glacial lake - clay
- Lennard clayey till/sand and gravel
- Minnedosa clayey till/sand and gravel
- Shield sandy till/sand and gravel
- Upper pre-last interglacial - till
- Pre-last interglacial - sand and gravel
- Lower pre-last interglacial - till
- Buried valley - sand and gravel

Tertiary
- Wynyard - sandstone
- Turtle Mountain - sandstone

Cretaceous
- Boissevain - sandstone
- Coulter - shale
- Odanah - shale
- Millwood - shale
- Pembina - shale
- Gammon Ferruginous - mudstone
- Boyne - shale
- Morden - shale
- Favel - shale
- Belle Fourche - shale
- Westgate - shale
- Newcastle - sandstone
- Skull Creek - shale
- Swan River - sandstone

Jurassic
- Success S2 - sandstone
- Waskada - shale
- Melita - shale
- Reston - limestone
- Amaranth - shale

Mississippian
- Charles - evaporite
- Kisbey - sandstone
- Mission Canyon - limestone
- Lodgepole - mudstone
- Bakken - limestone

Devonian
- Torquay - shale
- Birdbear - limestone
- Duperow - limestone
- Souris River - limestone
- Dawson Bay - limestone
- Prairie Evaporite - evaporite
- Winnipegosis - dolomite
- Ashern - dolomite

Silurian
- Interlake - dolomite

Ordovician
- Stonewall - dolomite
- Stony Mountain - dolomite
- Red River - limestone
- Winnipeg - sandstone

Cambrian
- Deadwood - shale

Precambrian
- Precambrian

Figure 2: 3D model vertical map legend.

The geological interpretation for the southern portion of Manitoba, south of 55°N is nearing completion. It was decided that the southwest Manitoba area should not be modelled separately as was done in previous projects, but to combine all of the previous models into one large southern MB model south of 55°N. This methodology was selected in order to resolve two issues: 1) subtle nomenclature differences from area to area and 2) TGI modelling issues resulting from rock formation edges along escarpments plotting in 3D at elevations other than the projected trend of that particular formation. To accomplish this, geological transects representing a 5 km wide east-west swath containing all available geological data for that area, along with hand-drawn rock and Quaternary (sediment) units from previously completed regions, are being combined into 134 province-wide georeferenced vertical maps. Hand drawn transects from Phase 1 (southeast Manitoba), Phase 2 (Lake Winnipeg), and Phase 3 (southwest Manitoba) were scanned, georeferenced and combined in ArcGIS with computer generated transects containing predicted stratigraphy points (PSP's) or virtual drillholes from the TGI Williston Basin project (Table 1, Figure 3). All 134 province-wide transects are currently being digitized to depict up to 41 rock formations and 35 Quaternary units (Figure 1). These complete vertical maps will then be imported into our 3D modelling software.

Table 1. Model extents (Figure 3)

Model	**Latitude Range**	**Longitude Range**	**Area**	**Units**
Southeast Manitoba	49° to 51°	-98° to -95°	45 000 sq km (17 500 sq mi)	14 bedrock units, 17 Quaternary units
Lake Winnipeg	51° to 54°	-100.3° to -95.3°	78 000 sq km (30 000 sq mi)	8 bedrock units, 24 Quaternary units
TGI Williston Basin	49° to 55.5°	-106° to -96°	494 000 sq km (190 700 sq mi)	42 bedrock units
Southwest Manitoba	49° to 55°	-101.5° to -98°	176 225 sq km (68 041 sq mi)	41 bedrock units, 35 Quaternary units (includes units from all model areas)

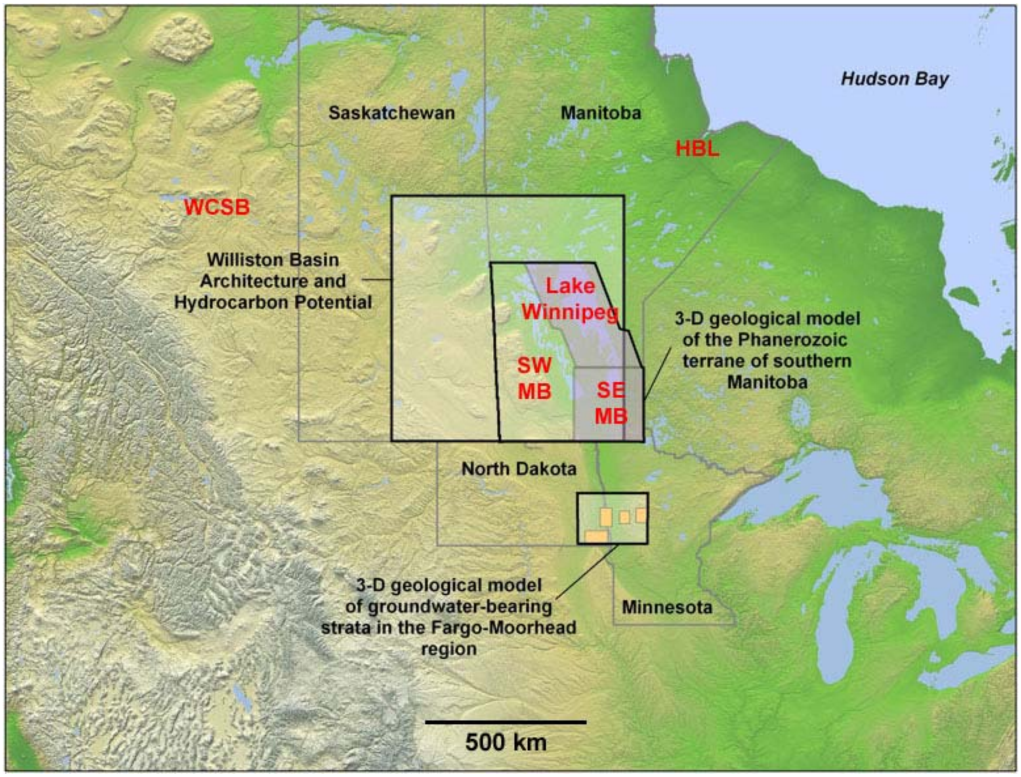


Figure 3: Index map of model areas and other 3D models in the vicinity (Fargo-Moorhead model).

3. MODEL INPUTS/PRODUCTS

It may seem unusual to mention model inputs after model construction; however, virtually every input used in the modelling process had to be modified in some manner in order to be useable, and therefore, many became significant stand alone products.

3.1 Database Standardization (GWDrill)

Although drillhole data used in the model is derived from various sources, the vast majority of drillhole information used in modelling is gleaned from the GWDrill waterwell database housed at Manitoba Conservation Water Branch (Manitoba Water Stewardship, 2007). This database of close to 100 000 holes required three significant upgrades prior to its use as an input: 1) The addition of x/y coordinates rather than township-range-section, 2) addition of an elevation or z value, 3) classification of the 75 000 unit descriptions into18 sediment types. These upgrades have made the database infinitely more valuable to clients of the Water Branch; so much so that these upgrades have been built into their version and are being maintained as such.

3.2 Digital Elevation Models and Maps

Digital elevation models (DEM) help form the backbone of the model. Without elevation, the drillhole data could not be vertically positioned and would be inadequate for modelling. Realizing our need for an accurate DEM of the province, the MGS began creating a DEM from orthophoto rectification files in the late 1990's. This DEM (DEMSM v.1), released as a web and CD product, became the survey's standard DEM until the release of the SRTM data in 2002. Understanding the educational benefit inherent in visualized DEM data, the MGS released the Shaded relief topography of Manitoba map in 2004 (Matile and Keller, 2004) which was based upon the SRTM data. An updated anaglyph version of this map was released in 2005 in association with the University of Minnesota (Morin et al. 2005).

3.3 Bathymetry and Subsurface Profiling

Large lakes such as Lake Winnipeg, Lake Manitoba, Lake Winnipegosis, Playgreen Lake and Lake of the Woods occur within the modelling area. The lake-bottom features of these large bodies of water cannot be ignored as they provide insight into the geology. In order to capture these features over 31 000 soundings on 22 Canadian Hydrographic Survey (CHS) charts were digitized and corrected relative to shorelines as depicted on NTS 1:250 000 topographic maps. Several corrections were made, including adjusting the soundings from the varying CHS low-water datum to a consistent value. The bathymetric data has subsequently been added to the SRTM DEM providing us a seamless elevation model which includes large lake bottom topography.

Bathymetry provided a valuable glimpse into the sub-lake geology; however it was seismostratigraphy which helped complete the picture. In the mid 1990's, two cruises of the Canadian Coast Guard Ship Namao recorded low and high frequency seismic data for over 1000 km of survey lines (Todd et al., 1998). The data was interpreted for Quaternary sediments and Paleozoic bedrock, and subsequently added to our knowledge base for the 3D model. In 1999, the MGS added to our knowledge of sub-lake geology by collecting several kilometres of Knudson echosounding data in areas that the original ship could not travel. This data, along with the original Namao data helped refine the location of the escarpment representing the Phanerozoic edge within Lake Winnipeg.

3.4 Surficial Geology

Accurate surficial geological mapping is an invaluable input to the 3D model as it allows a top down interpretation where there is a shortage of data. To this end, the MGS began the onerous task of creating a new digital version of the surficial geology of Manitoba which would replace the original 1:1 million mapping released in 1981 (Nielsen et al., 1981). A large part of the task had been the conversion of data from paper maps to digital vector coverage. Map legends were standardized, map polygon boundary discrepancies were corrected with the aid of the SRTM shaded relief topography and data gaps were filled using a combination of detailed soils mapping and the SRTM DEM. The final product was released in 2007 as a two-sided 1:1 million scale printed map and a DVD which included 1:250 000, 1:500 000 and 1:1 million scale maps for all of Manitoba as well as associated educational information which made the maps more usable by lay clients (Matile and Keller, 2007).

3.5 TGI Maps

A significant portion of the impending southern Manitoba 3D model utilizes modelled data from the TGI II Williston Basin Project. This project's primary objective was to develop a geological model of the Paleozoic and Mesozoic age rocks from basement to outcrop in a 494 000 sq km area in southeastern Saskatchewan and southwestern Manitoba (TGI II working group, 2009). Outputs from this project include structure (45) and isopach maps (53) as well as a 3D geological model. All of this information is available online.

3.6 Phanerozoic Geology

In addition to surficial geology, accurate Phanerozoic mapping is critical to the 3 D mapping process. In a similar fashion, Phanerozoic mapping indicates where stratigraphic units visible in drillholes should be terminated in the subsurface. The TGI Williston Basin project and subsequent mapping/modelling indicated that several changes were necessary to the existing unit edges. These changes necessitated a new map set representing the most current interpretation of the Phanerozoic rock terrane of southern Manitoba. This two map set (Paleozoic and Phanerozoic) depicting a complete sequence of 46 Phanerozoic formations for the Williston Basin area of southern Manitoba, is a valuable geoscientific and exploration tool useful to the petroleum industry, the metals industry, the industrial minerals industry as well as universities, government, industry and environmental organizations (Nicolas et al, 2010).

4. WEB CONTENT

The Manitoba Geological Survey releases the large majority of publications, data releases and maps on the web for free download. The following is a list of products associated with the MGS 3D modelling work and their associated web links:

- Manitoba Mineral Resources Division Home: http://www.manitoba.ca/iem/mrd/index.html
- *Contains links to all projects, maps and business areas under the Mineral Resources Division.*
- Surficial Geology Compilation Map Series (SGCMS): http://www.manitoba.ca/iem/mrd/geo/gis/surfgeomap.html
- *Contains a description of the mapping project, links to all maps in the series in PDF and ESRI Shapefile format (1:250 000, 1:500 000, 1:1 000 000) as well as legend descriptions and educational material.*
- Manitoba Stratigraphic Map Series: http://www.manitoba.ca/iem/mrd/geo/stratmaps/index.html
- *Contains links to the Phanerozoic geology of southern Manitoba (MAP 2010-1) two map set at a scale of 1:600 000 as well as the Williston Basin TGI II Project (98 maps).*
- Digital Elevation Model of Manitoba: http://www.manitoba.ca/iem/mrd/geo/demsm/introduction.html
- *Contains four digital elevation models (Orthophoto based as well as SRTM based) as well as several images derived from the model.*
- Three-Dimensional (3D) Geological Model of Manitoba: http://www.manitoba.ca/iem/mrd/geo/3dmodel/index.html
- *Contains video clips and data related to the southeastern Manitoba 3D model.*

5. REFERENCES

Keller, G.R., Matile, G.L.D. and L.H. Thorleifson, 2009. Progress in 3D Geological Mapping in the eastern Prairies, Three-dimensional geological mapping, workshop extended abstracts: Illinois State Geological Survey Open File Series 2009-4, 2009 Annual Meeting, Geological Society of America, Portland, Oregon, October 17, 2009, 17-23.

Kennedy, P.A. and A.D. Woodbury, 2005. Sustainability of the bedrock aquifer systems in south-central Manitoba: Implications for large-scale modeling, Canadian Water Resources Journal, 30(4), 281-296.

Manitoba Water Stewardship, 2007. GWDrill: A Data Base of Water Well Logs and Groundwater Chemistry for theProvince of Manitoba: Available through the Groundwater Management Section, Manitoba Water Stewardship, Winnipeg, Manitoba.

Matile, G.L.D. and G.R. Keller, 2004: Shaded relief topography of Manitoba; Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Geoscientific map 2004-4, 1 map. scale 1:1 000 000.

Matile, G.L.D. and G.R. Keller, 2007. Surficial geology of Manitoba: Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey, Surficial Geology Compilation Map Series, SG-MB, scale 1:1 000 000.

Morin, P., Matile, G.L.D. and G.R. Keller, 2005: 3-D topography of Manitoba; Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, Geoscientific map 2005-3, 1 colour map. Scale 1:1 000 000.

Nicolas, M.P.B., Matile, G.L.D., Keller, G.R. and J.D. Bamburak, 2010: Phanerozoic geology of southern Manitoba; Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Stratigraphic Map Series, Map 2010-1, 2 map set Sheet A: Paleozoic, Sheet B: Phanerozoic Available for free download. scale 1:600 000.

TGI II working group 2009. Williston Basin TGI: Manitoba Geological Survey and Saskatchewan Geological Survey, URL http://www.willistontgi.com [September 2009].

Thorleifson, L.H., 1996. Review of Lake Agassiz History: Sedimentology, Geomorphology and History of the central Lake Agassiz Basin: Geological Association of Canada-Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba, May 27-29, 1996, Field Trip Guidebook B2, p. 56-79.

Todd, B.J., Lewis, C.F.M., Nielsen, E., Thorleifson, L.H., Bezys, R.K., Weber, W. 1998: Lake Winnipeg: geological setting and sediment seismostratigraphy; Todd, B.J. Lewis, C.F.M. Thorleifson, L.H. Nielsen, E. Last, W.M. (ed.), Kluwer Academic, Geological Association of Canada meeting on Physical environment and history of the Lake Winnipeg basin, Winnipeg, MB, May 27-29, 1996, Journal of Paleolimnology, Paleolimnology of Lake Winnipeg, Canada, v. 19, no. 3, p. 215-244

United States Geological Survey 2002. Shuttle radar topography mission, digital elevation model, Manitoba: United States Geological Survey, URL ftp://edcsgs9.cr.usgs.gov/pub/data/srtm/, portions of files N48W88W.hgt.zip through N60W102.hgt.zip, 1.5 Mb (variable), 90 m cell, zipped hgt format [Mar 2003].

3D GEOLOGICAL MAPPING (MODELLING) IN GEOLOGICAL SURVEY ORGANISATIONS AND THE NEW BRITISH GEOLOGICAL SURVEY INITIATIVE TO BUILD A NATIONAL GEOLOGICAL MODEL OF THE UK.

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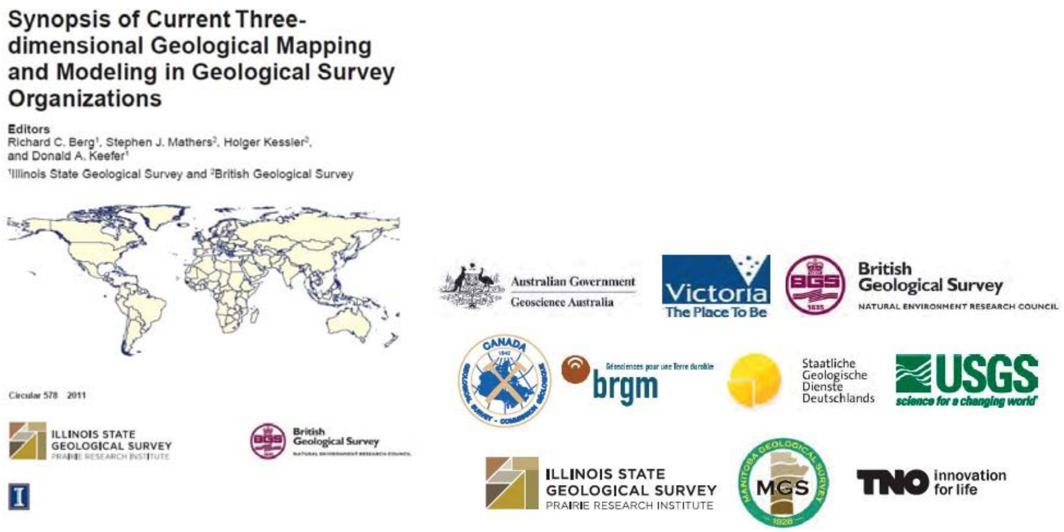
ABSTRACT

This paper summarizes the recent publication of a review of 3D Geological Mapping-Modelling in Geological Survey Organisations (GSOs) worldwide (Berg et al. 2011) and also outlines a new initiative at the British Geological Survey (BGS) to commence the construction of a multi-scaled National geological Model of the UK.

1. GEOLOGICAL MAPPING-MODELLING IN GSOS

Since 2001, six workshops on three-dimensional geologic mapping have been conducted, in association with meetings of the Geological Society of America (GSA) and the Geological Association of Canada. The 2009 workshop in Portland Oregon (Berg et al. 2009) was significant because of the unprecedented representation from the worlds' leading Geological Survey Organizations (GSOs) in 3D geologic mapping. During the workshop it became very apparent that although these GSOs share the same visions for the use of 3D geologic maps, the methodologies, software tools, underlying mapping and modelling strategies, and business models are highly varied. The decision was made to produce a report on the then state-of-the-art 3D geologic mapping-modelling in the participating GSOs and also provide advice and guidance for GSOs that are just beginning to migrate from a 2-D mapping to a 3D mapping and modelling culture. Growth of this community may eventually lead to stabilization of methods and the development and international use of geosciences data exchange standards.



Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations

Editors
Richard C. Berg[1], Stephen J. Mathers[2], Holger Kessler[2], and Donald A. Keefer[1]
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Circular 578 2011

Figure 1. Cover page and logos of contributing GSOs from Berg et al. (2011).

1.1 Key Conclusions and Recommendations

- Approaches to geologic modelling are different to suit individual GSO's needs (partly as a reflection of their customer base) and this will remain the case in the foreseeable future. Convergence or streamlining of software use might occur over time, but it is impossible to envisage a standard piece of software, as this will intrude into individual organizational policies and culture, as well as the possible capabilities of clients.

- The GSOs should be encouraged to publish geological models on the web, and make them as interactive as possible, so that differences and commonalities between geologic products from various organizations can be evaluated.
- An ultimate long-term aim of some GSOs is to provide a collective joined up model of the earth system. Geology does not stop at political boundaries and many of the emerging resource (water and mineral), environmental, and energy issues require global solutions. The authors are aware that this is an ambitious aim given the disparities between the financial resources and priorities for the various GSOs worldwide, and yet, significant advances towards collective seamless 3D models are being made at a national level in several countries, even though international cross-boundary modelling efforts are rare.
- It would be worthwhile to initiate an international dialogue on the value of standards for 3D geologic mapping and modelling. There is a need to 1) evaluate the perceived benefits of various standards, 2) prioritize the standards deduced as necessary, and 3) engage 3D geologic mapping and modelling software vendors in this dialogue. Over time, common data formats and relevant standards should emerge leading to increased interoperability and exchange, perhaps following the lead from OneGeology.

2. THE NATIONAL GEOLOGICAL MODEL OF THE UK

In order to deliver its mission to society BGS needs to lead the national effort towards managing the Geosphere which will entail:

- the construction of an accurate, multi-scalar, geospatial model of the subsurface arrangement of the rocks and sediments of the UK - the National Geological Model (NGM)
- assembly of a database of key physical and chemical properties of those defined rock-sediment volumes - National Geological Properties Database
- development of systems and workflows to combine the model and properties database to enable the parameterisation of models for use in Process modelling
- development of systems to disseminate models to enable environmental predictions, decision making and forecasting, i.e. Outcomes

Over the last 30 years BGS has developed a strong capability in 3D geological modelling using a variety of methodologies and modelling software to produce model outputs varying in resolution from national to site-specific. Currently BGS modelling concentrates on the use of two main softwares GoCAD and GSI3D. GoCAD is mainly deployed to produce models of structurally complex and heavily faulted bedrock geology drawing on datasets including geophysics, boreholes and surface geological surveying. GSI3D is mainly deployed to model superficial, artificial and simple bedrock geology to shallow depths (c.500m) through the use of expert-defined cross-sections. Together these two packages enable the survey to model almost all of Britain's geology at any resolution and evaluate all types of geoscience data in the production of these geological 3D models.

Outputs from the modelling process and many varied, they include screen grabs of models and 3D PDFs to illustrate reports, grids and tins for use in GIS systems and also the delivery of fully attributed 3D block models using our bespoke Viewer-Browser, the Sub-surface Viewer. Once constructed the Sub-surface Viewer enables the models to be queried, sliced and diced to generate synthetic borehole prognoses, specified lines of section and horizontal cuts at pre-determined elevations. Using another BGS product, Geovisionary, 3D models can be placed in a dynamic fly-through setting to demonstrate the interrelationship between terrains, surface geology and the sub-surface structure.

In 2009 BGS responded to a request to provide a national geological fence diagram of cross-sections for England and Wales (shown below) for use by the Environment Agency of England and Wales in undertaking its statutory obligations and to resolve problems at a regional-catchment scale. A fence diagram of intersecting cross-sections covering England and Wales with an average spacing of 50-70km, a minimum depth of 1km and a total section length of 5,000km was constructed. The sections were drawn digitally in GSI3D by the most experienced survey geologists with specialized knowledge of the various regions.

The bedrock geology was resolved mainly at the Group level and is based on the classification adopted on the new 1:625 000 geological map of Britain produced by BGS. The sections took account of the extensive BGS data holdings on the 3D structure of England and Wales including deep boreholes, contoured surfaces, seismic lines and regional geophysical patterns. Due to the intended resolution, it is suggested that the sections are schematic and represent broad structure and form at regional scale. More detailed subdivision of major aquifers including the Permo-Trias Sherwood Sandstone Group and the Upper Cretaceous Chalk Group were included wherever possible. They generally extended to 1 – 1.5 km in depth except where key aquifer units lie deeper. Major faults and igneous intrusions that often act as important barriers or pathways for groundwater were also depicted.

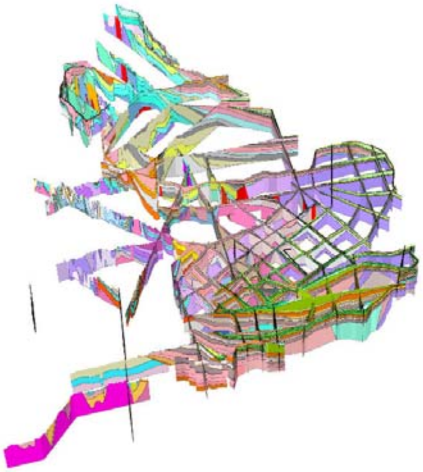

Figure 2. Fence Diagram of England and Wales 2009.

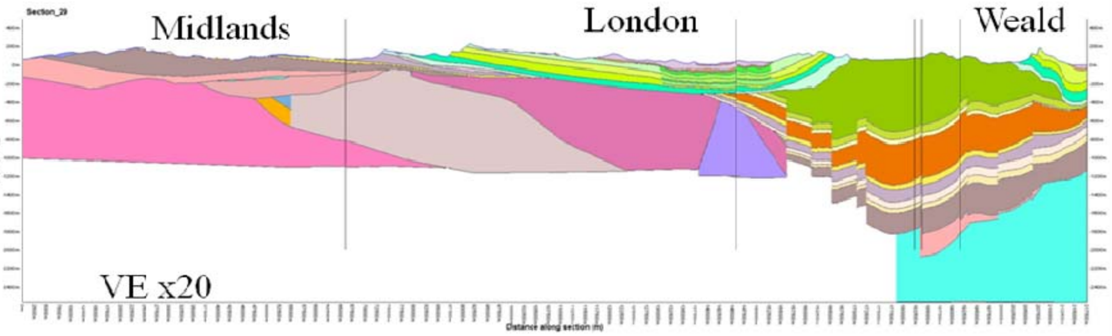

Figure 3. Detail of a single cross-section from the fence diagram. Note the extra detail within the Chalk Group aquifer (shades of green) beneath London and the extension of the section to greater depth in the Weald Basin.

Building on this fence diagram and a top-down approach, BGS has now started with the design and construction of the NGM with the following characteristics:

- geospatially correct representation of geological volumes and units attributed with overall properties
- multi-scaled construction, storage and dynamic management
- interoperable format for attribution, parameterization and analysis
- national in scope, seamless and fit for any purpose
- building on and extending existing corporate databases and dictionaries

Existing datasets for incorporation include DigMapGB at all scales and GSNI mapping (the surface layer), sub surface, offshore and survey memoirs and atlases together with contour and isopach maps -plots, existing models and surfaces, geophysical data and other published compilations. The assembly of the NGFM should be underpinned by key corporate databases and dictionaries. Other essential components that are in place are licensed Digital Terrain Models and Digital Bathymetric Models that can be merged to form an appropriate bald earth-seafloor model cap across all scales. For the first time, all these disparate sources can be unified into a common understanding.

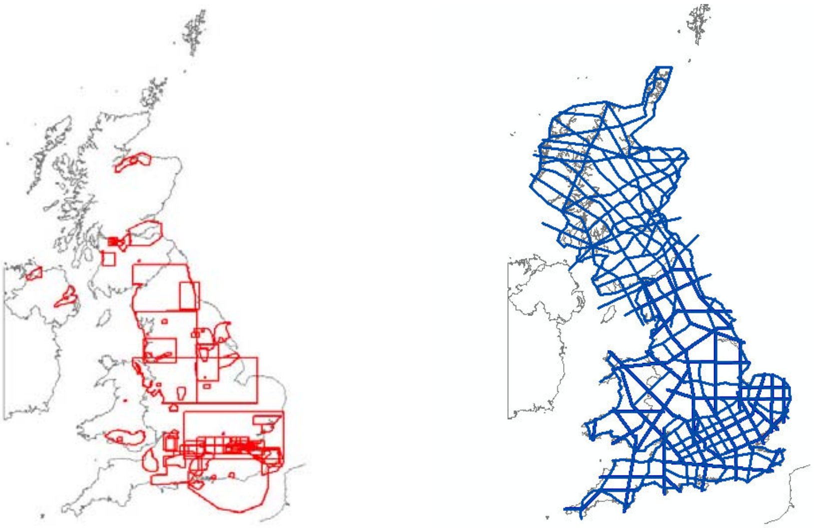

Figure 4 Existing BGS models (left) and the NGM section lines at 625K resolution (right).

3D volume models have already been calculated from the fence for each of the post Jurassic stratigraphic units in southern and eastern England, which, over the coming year will extend to the base of the Permo-Trias. All the geological units are being attributed with hydrogeological, engineering, mineral and hydrocarbon characteristics. More detailed exiting and new models will then be keyed into the framework and will be tied together across scales using nested stratigraphical classifications. The fence diagram has also been used in regional consultations for nuclear waste disposal and public understanding of science. It is also being considered with additional attribution as the basis for a risk screening tool for the assessment of potential aquifer contamination resulting from shale-gas extraction.

3. REFERENCES

Berg, R.C. H.A.J. Russell, H.A.J., and Thorleifson, L.H. 2009. Three-dimensional geological mapping: Illinois State Geological Survey, Open File Series 2009-4, 74 p. http://www.isgs.illinois.edu/research/3DWorkshop/2009/workshop.shtm

Berg, R.C. Mathers, S.J. Kessler, H., and Keefer, D. (Eds). 2011. Synopsis of Current 3D Geological Mapping and Modeling in Geological Survey Organizations. Illinois State Geological Survey Circular 578, 92pp.

INTEGRATED ENVIRONMENTAL MODELLING – THE NEW DREAM FOR GEOLOGICAL SURVEYS

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Abstract

This paper summarizes the British Geological Survey's (BGS) plans for the development of integrated environmental models to address the grand challenges that society faces. It describes a vision for an Environmental Modelling Platform (BGS 2009) that will allow integrated models to be built and describes case studies of emerging models in the United Kingdom.

1. THE CONTEXT

There is now a growing realization in the environmental and social sciences that to address the grand challenges that the world faces, a whole system approach is required. These challenges, including climate change, natural resource and energy security and environment vulnerability raise multi- and inter-disciplinary issues that require integrated understanding and analysis. Not only must we model the whole physical Earth system, bringing together climate, ecological, hydrological, hydrogeological, and geological models, to name only a few, but we must link them to socio-economic models. This may well be the only adequate way to provide the necessary framework in which decisions concerning prediction and planning can be most appropriately made.

2. VISION

The BGS vision is to provide scientists with the data, tools, techniques and support to address trans-disciplinary environmental questions impacting on human society. We plan to achieve this by being a leading member of an open community that will share data, applications and environmental models, thus enabling collaboration and achieving sustainable solutions.

3. BUILDING AN ENVIRONMENTAL MODELLING PLATFORM

Many scientific disciplines have been modelling during the past 5 to 10 years in order to better understand and analyze the processes and conditions within their areas of interest. This has led to a multitude of discipline specific models, modelling system software and workflows with greater or lesser success depending upon the quantity and sources of data and complexity within the scientific discipline concerned.

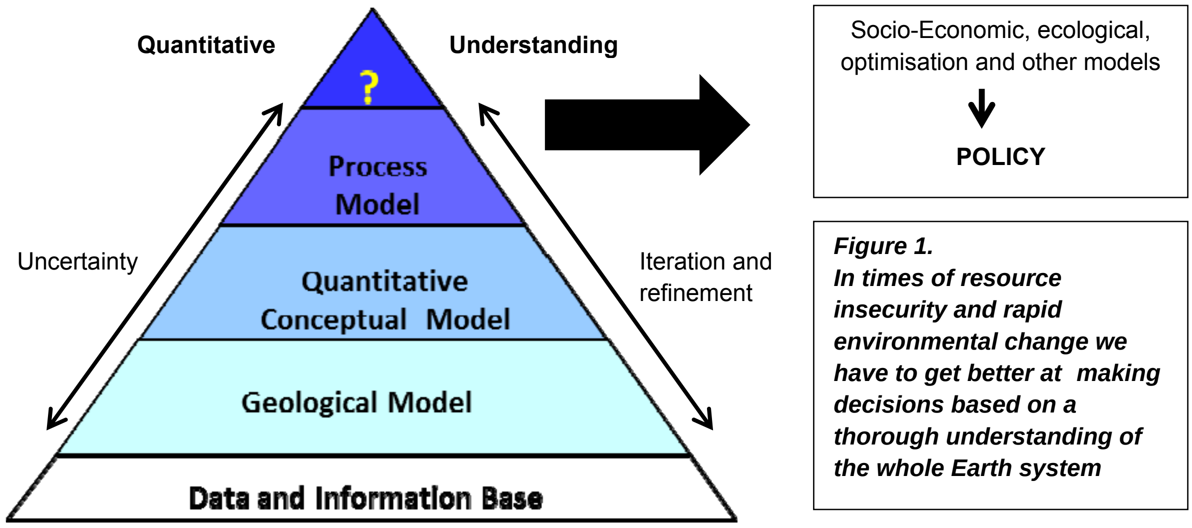


Figure 1.
In times of resource insecurity and rapid environmental change we have to get better at making decisions based on a thorough understanding of the whole Earth system

This has become most apparent within the British Geological Survey (BGS) from the wide variety of differing geoscience models generated in the past few years that need to be interlinked to fully understand the subsurface.

To this end, a scoping study was commissioned to assess the current situation and make some preliminary recommendations in order to take steps towards a more joined up and semantically harmonized future in environmental modelling. The recommendations are embodied in the DREAM Report (Giles et al 2010). The concept of the platform is summarized in Figure 1.

This Environmental Modelling Platform will be founded on the data and information that BGS holds. This will have to be made as accessible and interoperable as possible to both the academic and stakeholder decision making community. The geological models that have been built in an adhoc way over the last 5-10 years will be encompassed in a National Geological Model which will be multi-scaled, beginning with onshore United Kingdom and eventually including the offshore continental shelf. This initiative began in 2010 and has been embedded in the BGS science in recent months as the major plank of our Landscape and Geology programme. The future will be characterized by the routine delivery of 3D model products from a dynamic multiscaled 3D geological model of the UK. The deployment of this model will generate further significant requirements across the Information and Knowledge Exchange spectrum, from applications development (database, GIS, web and mobile device), data management, information product development, to the delivery of information to a growing number of public individuals and stakeholders.

Major challenges for BGS will be three-fold:

The deployment of 3D modelling in an acceptable, understandable product form, from a dynamically constructed 3D geological framework model.

The parameterisation of this framework model with physical properties and later chemical properties, with error and uncertainty bounds defined for line-work, lithostratigraphy and properties.

The use of this Environmental Modelling Platform with partners to provide the knowledge base for modelling Earth System processes at all scales is not the end. This requires linkages to climate models, surface process models, hydrological and hydraulic models and so on. However, achieving impact and value for society coupled with social, economic and financial processes and models will be necessary.

We have commenced the first of these activities and can reasonably envision the production of realistic and serviceable deliverables. Figure 2 shows an image of this progress to date.

4. INTEGRATED ENVIRONMENTAL MODELLING

The concept of Integrated Environmental Modelling (IEM) is certainly not new and a variety of initiatives have developed in the U.S. and Europe in recent years. Integrated environmental modeling (IEM) is about linking computer models simulating different processes to help understand and predict how those processes will interact in particular situations. There are currently numerous examples of global initiatives that require international science collaboration on a very large scale. For example the OneGeology project to make digital geological map data available across the internet; the Global Earthquake Model, funded by governments and the insurance industry to develop common standards and understanding of earthquake risk; the GSI3D consortium to take forward the international development of geological 3D models and a new initiative called the Global Volcano Model to develop common data, knowledge and modelling and understanding of volcanic risk. It is clear that IEM crosses all these initiatives, is a global issue and an international approach might be taken. BGS and the OpenMI Association (Gregersen et al 2007) successfully won funding to hold an international workshop to discuss IEM and ways forward globally (see Figure 3). The current BGS favoured route for model linking is to use the OpenMI standards and to promote their use in environmental modelling of the process of accreditation with the Open Geospatial Consortium.

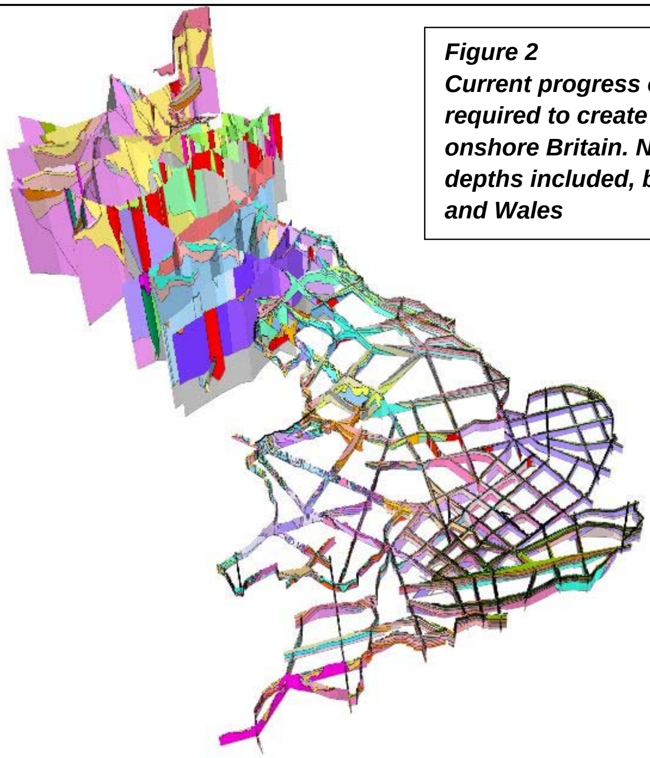
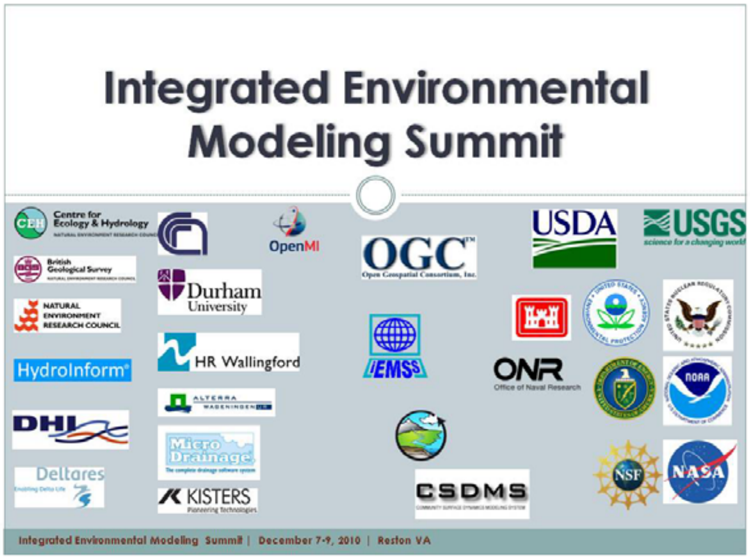


Figure 2
Current progress on developing the cross sections required to create a GSI3D framework model of onshore Britain. Note the scale differences and depths included, between Scotland and England and Wales

The second activity is more difficult, given the variability of data quality and uncertainty and the problem of incorporating geological process understanding in up and downscaling methodologies. The final challenge requires linkage to other data and modelling technologies and perhaps, more importantly, the integrated collaboration, working and modelling of disparate disciplines.



Integrated Environmental Modeling Summit

Integrated Environmental Modeling Summit | December 7-9, 2010 | Reston VA

Figure 3. The IEM summit brought together 57 scientists and managers from 10 US federal agencies and academic and non-governmental organizations, European agencies, universities, companies and International organizations. Summit participants discussed what is needed to advance the science, technology and application of integrated environmental modeling worldwide. This was funded by the UK Foreign and Commonwealth Office, BGS and the OpenMI Association.

Many fruitful opportunities for collaboration leading to projects were identified. Agreement was reached to produce a roadmap setting out how to achieve the IEM vision. The meeting offered a clear consensus that with greater collaborations, the rewards offered by integrated environmental modeling (IEM) for society and for industry would be enormous. At the highest level, the challenge was then to turn IEM from its present state, essentially something used by researchers, into an operational tool useable by anyone (IEM Summit, In Press).

The development and implementation of the roadmap was recognized to be key to the future of IEM. This is a work in progress but it will be essential to implementing projects to enhance communication, co-ordination and collaboration in integrated environmental modeling and to establish the presence of the IEM community with research organizations (the science funders like UK Natural Environment Research Council, the US National Science Foundation), national regulatory agencies, national governments, the European Commission and industry (particularly IT and Re-Insurance).

5. PROGRESS

Recent research into the importance of groundwater in flooding in Oxford has allowed for the development of the integration of groundwater levels into a GSI3D geological model (Figure 4). In addition, through Fluid Earth, the ZOOM3QD OpenMI compliant groundwater model has been linked to the HR Wallingford river model, Infoworks RS, to explore the benefits of OpenMI and IEM. Fluid Earth is an HR Wallingford initiative bringing together a community of specialists with the aim of researching and implementing integrated modeling approaches to the understanding of environmental systems (Fluid Earth, 2011).

Similar work in Morayshire in Scotland has enabled an understanding of flooding in the coastal region near Forres. Also, a new research project investigating the impacts of extreme events on the hydrological system in the Thames catchment is leading to the development of a series of distributed, partially distributed and lumped groundwater models to the a model of the River Thames, upstream of the tidal region.

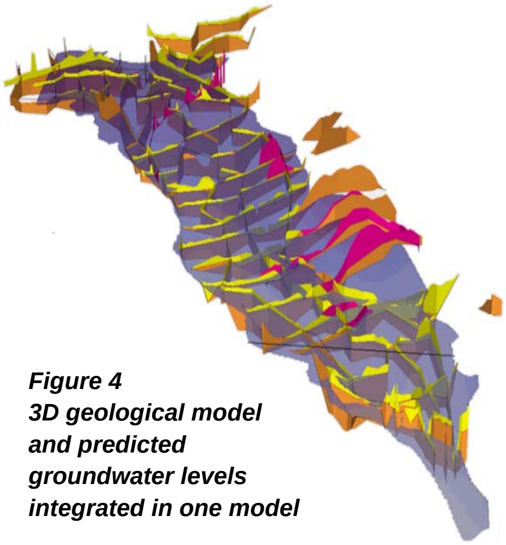


Figure 4
3D geological model and predicted groundwater levels integrated in one model

6. MAJOR CHALLENGES

The DREAM project is a vast undertaking and for BGS to have the temerity to think it can achieve this vision without international partnership, when it is but one player of many, would be foolish. Nevertheless it is at the core of our strategy for the next few years and will be the focus of our attention. The problems and difficulties we face are numerous but the prize of properly serving society is great. The DREAM report identifies a number of challenges. They include:

> selecting the most appropriate software, alignment of ontologies and semantics between disciplines, dealing with scale, heterogeneity and complex systems, taking account and understanding uncertainty, ready access to interoperable data with appropriate metadata, making use of existing model investments, having accepted appropriate international standards, easily interpreted visualization of data and model results, reduction of inherently chaotic nature of modeling multidisciplinary systems and issues to ordered repeatable processes.

Most importantly they require a major cultural change from the innately competitive nature of science research to a more collaborative endeavor between and within disciplines in addition to reaching out to the stakeholder community to a degree not often achieved to date.

7. WHAT DOES THIS MEAN FOR GEOLOGICAL SURVEY ORGANISATIONS?

Geological Surveys of the future must respond to the needs of society to provide a wider geoscience understanding. They must also allow solutions to the grand challenges mentioned earlier. They must change themselves to become increasingly relevant as they reach out to integrate with others. How many people can read a geological map, or understand the language of lithostratigraphy? People, society, decision makers all need useable relevant information. Integrated Environmental Modelling is our future not just our DREAM.

8. REFERENCES

British Geological Survey. 2009. British Geological Survey Strategy 2009-2014: Applied Geoscience for our Changing Earth. Nottingham: British Geological Survey. 28p

"Fluid Earth" Website: http://fluidearth.net/default.aspx

Giles, J.R.A., A. Hughes, H. Kessler, C. Watson, and D. Peach. 2010. Data and research for environmental applications and models (DREAM): scoping study report. British Geological Survey External Report, OR/10/020. 54p.

Gregersen, J.B., P.J.A. Gijsbers and S.J.P. Westen. 2007. Open MI: Open Modelling Interface. Journal of Hydroinformatics, 9 (3), pp175-191

IEM Summit. In Press. Workshop Report of the IEM Summit, Reston, Washington DC, USA. December 2010.

QUANTIFYING CORRELATION IN THREE-DIMENSIONAL GEOLOGIC MAPPING OF GLACIAL DRIFT

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1. INTRODUCTION

Glaciated terrain covers much of North America and other parts of the world. The depositional and erosional processes associated with glaciation produce a wide variety of sediment types and landforms. These materials have irregular geometry and represent a tremendous range of hydraulic conductivity values. The resulting complexity in the hydrogeologic framework complicates 3D mapping and the assessment of water resources or contaminant transport.

Geostatistical techniques incorporate spatial correlation to estimate the three-dimensional distribution of a material or a property of interest. Drilling data from water well installation, monitoring well installation, or exploratory boreholes provide dense material type data for vertical correlation studies, and, if of sufficient areal density, may also support lateral correlation assessment. The three-dimensional hydrogeologic correlation framework of glacial drift has not been studied significantly. Questions addressed by this study include

- Does glacial drift have a correlation structure?
- Does the glacial hydrogeologic framework differ geostatistically in different geomorphological terrain?
- Does the data quality affect the calculated geostatistical parameters?
- How do different geostatistical methods compare?

In this study, geostatistical methods are applied to nearly 300 km of drilling data derived from over 11,000 private well drilling logs (from the Minnesota Geological Survey's County Well Index, or CWI), over 200 high-quality well logs from monitoring well (MW) installation, and 9 high-quality rotosonic logs from the UMD Environmental Drilling Program (EnDriP). Analyses are focused on a 12,000 km^2 region in central Minnesota, in a setting dominated by the late-Wisconsinan Rainy, Superior, and Wadena lobes.

2. GEOSTATISTICAL METHODS

The drilling data are categorized according to the logged sediment descriptions (Table 1). In one scheme, the materials are separated according to presumed high or low permeability for use in binary indicator geostatistical and transition probability geostatistical analyses. In another, the number of categories is expanded to five on the basis of combined permeability and depositional setting information for use in a separate transition probability analysis. The two geostatistical approaches evaluated in this study were selected because they provide a means for quantifying the correlation structure of three-dimensional data.

Indicator geostatistics (e.g. Isaaks and Srivastava 1989) is a non-parametric method in which the data are partitioned into categories and assigned indicator values on the basis of a cutoff value in the case of quantitative data, or assigned based on qualitative material type. Variography is performed using the indicator values (Table 1). Indicator variograms represent the spatial structure of the data. The transition probability geostatistics (T-PROGS) process (Carle and Fogg 1996) includes calculation of transition probabilities, one- and three-dimensional Markov chain modeling of spatial structure, and conditional simulation to generate multiple realizations. This approach provides information on volumetric proportions, mean thicknesses ($\overline{L}$) and mean lens lengths, juxtapositional tendencies among the units, and directional anisotropy. Ultimately, the modeling of the subsurface sediment can serve as input to a groundwater flow model by dictating the distribution of hydraulic conductivity values (Quinn 2009).

2.1 Study Area and Data

This study considers several scales focused on a portion of central Minnesota. The regional glacial geology is assessed and related to the geostatistical analysis study area comprised of four counties (Crow Wing, Morrison, Todd, and Wadena) and the southern portion of a fifth (Cass). Together, these counties roughly form a square with an area of nearly 12,000 km² (Figure 1). The Camp Ripley training facility of the Minnesota National Guard is located in the center of the square, in northern Morrison County and contains the high-quality data.

The geology and topography of the Camp Ripley property and the surrounding counties are the result of a complex glacial depositional history involving three ice lobes that deposited drifts of various characters and colors. GIS tools were used to assign to the boreholes their geomorphological information from Mooers (1996). These assignments included lobe name and sedimentological association (till plain, supraglacial drift complex, ice contact deposit, etc.) (Figure 1). While the geomorphologic groupings relate strongly to the surficial geology and near-surface hydrogeology, they do not necessarily have much bearing on the buried materials. Still, by analyzing the borehole data of specific groups, insights may be determined on the subsurface correlation structure of different geomorphological zones. Figure 1 also serves as a key to the code numbers for data sets and their corresponding geomorphological setting and data types. Of the three key ice lobes (Rainy, Superior, Wadena), particular geomorphological zones were subdivided on the basis of geographical distribution. These subunits were delineated to provide information on the stationarity of the geomorphological units' geostatistical character (i.e., whether the local mean is constant in different locations).

Table 1. Converting from Drillers' Descriptions to Material Types

Typical Drillers' Descriptions	Material Type (Binary)	Material Type (5 Categories)
Gravel, sand & gravel, coarse sand, coarse gravel, dirty gravel, fine gravel, gravel & rocks, gravel & water, sand & rocks	High-permeability (indicator=1)	1 Outwash
Sand, dirty sand, fine to medium sand, medium sand, water sand		2 Lacustrine Sand
Silt, very fine sand, fine sand & silt		3 Lacustrine Silt
Clay, blue clay, silty clay, sticky clay	Low-permeability (indicator=0)	4 Lacustrine Clay
Till, boulders, clay gravel, clay & rocks, clay sand, clay & rock, sandy clay		5 Tills

Drilling data were assembled in the Groundwater Modeling System (GMS) as a 3D borehole stratigraphy dataset and converted to a dense set of 3D points using a custom utility. Variography was performed using tools contained in GMS, which are directly based on the GSLIB software (Deutsch and Journel 1992). T-PROGS analyses were also conducted within GMS.

3. RESULTS AND DISCUSSION

Vertical and lateral variography were performed for each of the data sets, which were divided by surficial geomorphology and by sampling technology (CWI, MWs, EnDriP). In addition, separate analyses were conducted for up to three geographically distinct areas of a particular geomorphological setting. Details on variogram search directions and the transition probability process are contained in Quinn (2009). The overall data set showed clear vertical structure in its variogram and transition probabilities; the lateral variogram indicated that the bulk of the lateral correlation was present within a separation distance of 60 m (Table 2). Vertical variograms were very well supported in all geomorphological areas, while lateral variograms varied from well supported to random scatter. The vertical correlation measurements for different data sets varied over a factor of two. The ratio of vertical to lateral range varied but had an average value of ten.

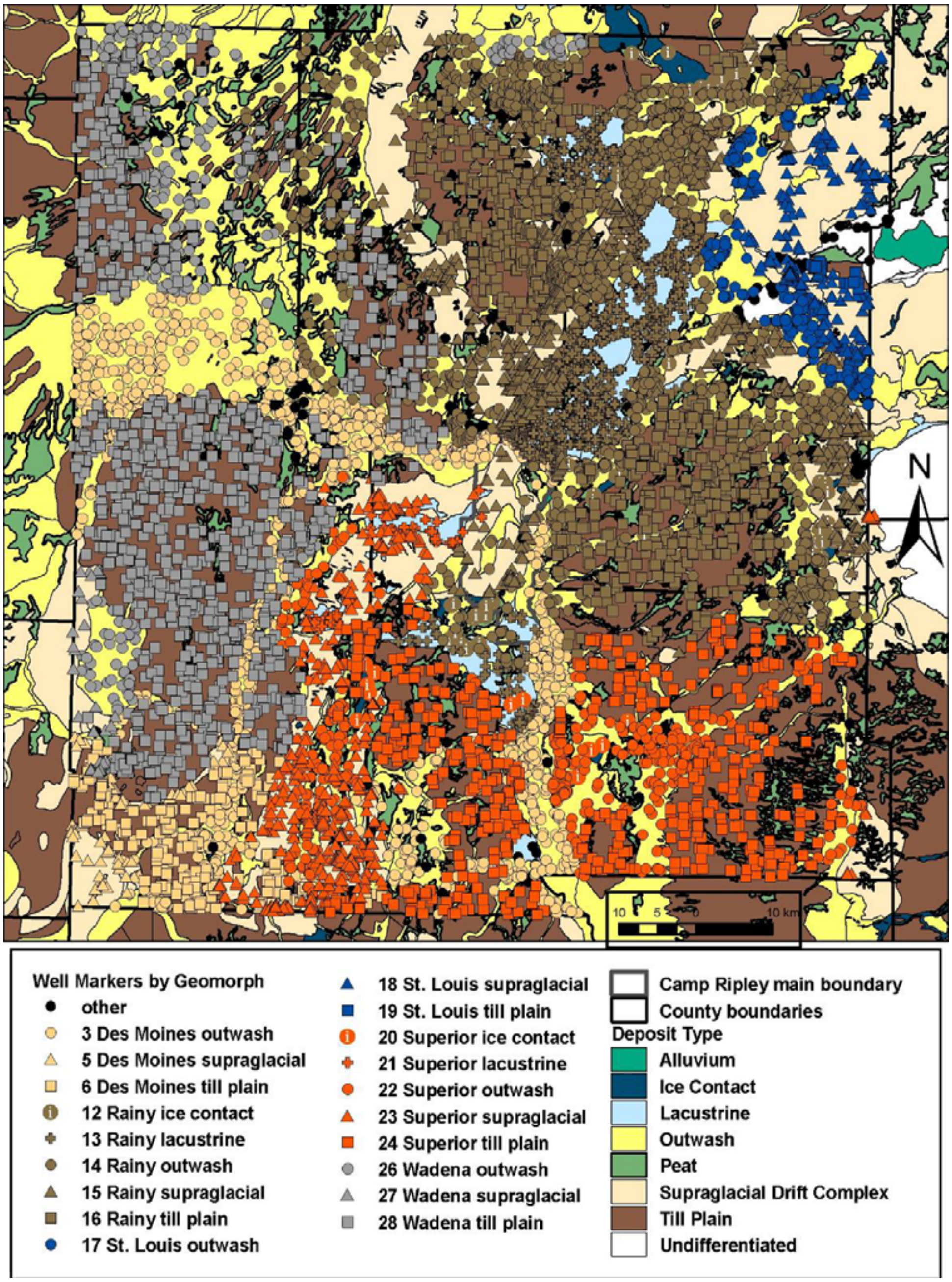

Figure 1. Well Markers According to Geomorphological Terrain

Graphed comparisons were made for variograms from geographically separate lobe and sediment groupings; examples are shown in Figure 2 for the till plain data groups and their geographic subareas. Graphed comparisons were also made for data from different drilling technologies, and for a single sediment type from different ice lobes. Details are discussed in Quinn (2009); a summary is provided in Table 2 for the vertical and lateral variogram analyses and the mean lens thicknesses from T-PROGS.

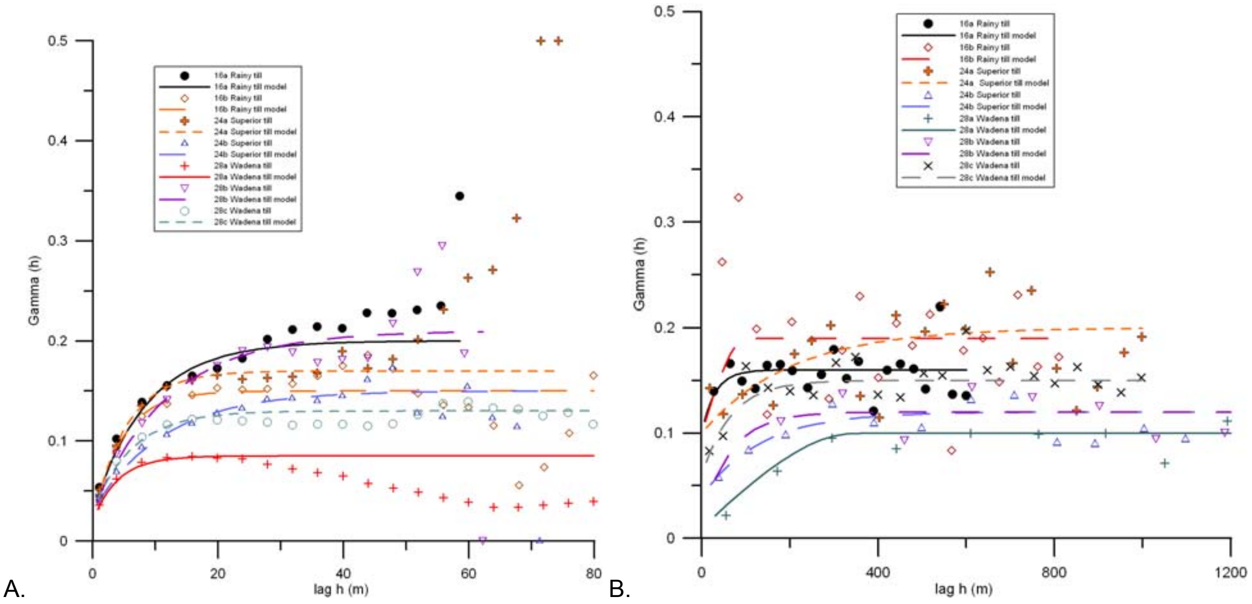

Figure 2. Vertical (a) and Lateral (b) Variogram Results for Rainy, Superior, and Wadena Till Plain Geomorphological Zone, based on Private Well Log Data

Results for the numerous geomorphological settings indicate overlapping geostatistical ranges, sills, and vertical lens thicknesses. A lack of stationarity is present, consistent with a fundamental complexity of glacial depositional and erosional processes. Correlation generally varies as much between geographically distinct zones of like geomorphology as it does between zones of different geomorphology. High-resolution data associated with monitoring well installation typically deviate from the private well data; this is attributed to site-specific geology and detailed logging of thin units.

4. CONCLUSIONS

The lateral correlation distances of drift units are small relative to the scale of 3D geologic mapping for water resources investigation; this is consistent with visual 3D inspection of the study area's drilling data. Overall results underscore the difficulty in making correlative assumptions in the 3D mapping of glaciated regions.

5. ACKNOWLEDGEMENT

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6. REFERENCES

Carle, S. F. and G. E. Fogg. 1996. Transition probability-based indicator geostatistics: Mathematical Geology, vol. 28, no. 4, p. 453-476.

Deutsch, C.V. and A.G. Journel. 1992. GSLIB Geostatistical Software Library and User's Guide: New York, Oxford University Press, 340 p.

Isaaks, E.H., and R.M. Srivastava. 1989. Applied geostatistics: New York, Oxford University Press, 561 p.

Mooers, H.D. 1996. Geomorphology of the Brainerd 1:100,000: MN Dept. of Nat, Res., Div. of Forestry, St. Paul, MN.

Quinn, J.J. 2009. Geostatistical Approaches to Characterizing the Hydrogeology of Glacial Drift [Ph.D. dissertation]: University of Minnesota, Minneapolis, 172 p

Table 2. Summary of Geostatistical Findings

Data Set*	Vertical Variogram Structure	Lateral Variogram Structure	Binary $\overline{L}$ for Low-K and High-K Materials**
All Data (CWI, MWs, EnDriP)	Clear exponential structure with range of 18 m	Nested exponential variograms with ranges of 60 m and 750 m	Low-K $\overline{L}$ 12.9 m High-K $\overline{L}$ 6.4 m
All MWs and EnDriP	Valley train sediments increase range compared to overall data set	Exponential range 120 m	Low-K $\overline{L}$ decreased compared to overall data due to drilling and sampling method
Geomorphologic subdivisions of MWs	Similar despite different landforms	Insufficient data	Different $\overline{L}$ and differences, and different from corresponding CWI results
Till plain comparisons (R/S/W)	Variety of sills and ranges. Level of variation among geographically subdivided areas is equal to that among different lobes.	Varying support	Similar $\overline{L}$, though Wadena has slightly higher Low-K $\overline{L}$
Lacustrine comparisons (R/S)	Similar ranges, but Rainy has higher sill	Lack of structure	Superior CWI has relatively large Low-K $\overline{L}$, otherwise fairly similar
Outwash comparisons (R/S/W/D)	Superior and Rainy have similar structure	Lack of structure	Fairly similar $\overline{L}$ from CWI data
Supraglacial comparisons (R/S/W)	Fairly similar ranges but different sills	Varying support	Fairly similar $\overline{L}$ from CWI data
Ice contact comparisons (R/S)	Superior range greater than Rainy's	Insufficient data	Fairly similar $\overline{L}$ from CWI data

* CWI = County Well Index (private well logs), MWs = monitoring wells, EnDriP = rotosonic logs, R = Rainy lobe, S = Superior lobe, W = Wadena lobe, D = Des Moines lobe. ** $\overline{L}$ = mean thickness.

FROM ATMOSPHERE TO BASEMENT: DEVELOPMENT OF A FRAMEWORK FOR GROUNDWATER ASSESSMENT IN CANADA

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7. INTRODUCTION

The Geological Survey of Canada (GSC) is helping map and assess the availability of groundwater resources in Canada. This effort is set within complex jurisdictions of surface water and groundwater resources in Canada where there is often no clear division between the federal and provincial governments. Responsibilities are often shared, with the federal government sharing responsibility on water issues for federal lands, territories (e.g. Nunavut), First Nation lands, boundary and transboundary waters (e.g. Great Lakes, Spiritwood aquifer), navigable waterways and where fisheries resources are concerned. Consequently, much government work completed on groundwater in Canada is done by the provinces with collaborative support from the GSC, the oldest government research institution in the country.

To advance groundwater assessment in Canada, the National Ad Hoc Committee on Groundwater proposed a framework for a national co-operative program (Rivera et al., 2003). At the same time, the groundwater program of the GSC developed a strategy to map and assess 30 key aquifers across the country (Figure 1), along with a plan to remove accessibility barriers to data discovery and retrieval (Boisvert and Broderic, 2011). The GSC is also developing a synoptic understanding of the groundwater resources in Canada by using the hydrogeological regions (Figure 1, Table 1). This paper provides an overview of the conceptual framework and methods employed to achieve these objectives. The approach is founded on a traditional basin analysis methodology (i.e., geology) with an objective of understanding the geological history of the basin to inform future work and provide a predictive framework in areas of sparse, inadequate data and hence basin knowledge. This approach is being extended from the traditional subsurface basin context to encompass the hydrological cycle and hence understanding from atmosphere to basement.

8. FRAMEWORK

An ongoing challenge in groundwater studies is the collection of datasets with adequate resolution to address issues not only at local scales but that can be interpolated to regional scales. Geologists have commonly addressed this issue through process-based conceptual models, for example the interpretation of sedimentary facies and processes to produce a depositional model of the basin (Sharpe et al., 2002). Hydrogeologists commonly require better-defined, numerical and geographically based models to support numeric groundwater flow modelling. Local and regional scale numeric geological models have been constructed for areas up to 10,000 km^2 and used for groundwater modelling (e.g. Logan et al., 2006, Rivard et al., 2008). There is an increasing demand and expectation, however that information be provided with improved resolution and at more synoptic scales. Improved national-scale data collection is making use of satellite and airborne sensors (e.g. Fernandes et al., 2007). Additionally, improved data access and standardization is being approached by development of the Groundwater Information Network (GIN) for provincial water well and monitoring datasets from distributed databases using WMS and WFS web services that adhere to the standards developed by the Open Geospatial Consortium (OGC) (e.g. Boisvert and Brodaric 2011).

8.1 Data Collection

Regional groundwater studies have traditionally relied on low-quality water well data. With increasing societal pressure on water resources, higher resolution datasets are being collected.

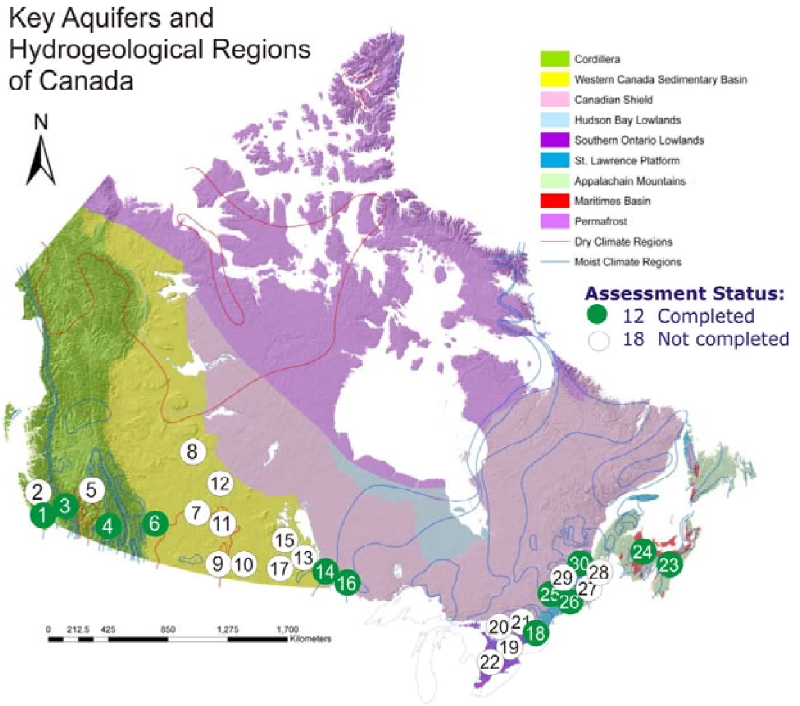

Figure 2. Hydrogeological regions of Canada with Key Candian Aquifers identified.

Table 1. Key Canadian Aquifers grouped according to hydrogeological regions. Note numbers refer to Figure 1. Letters in parenthesis refer to principal aquifer type bedrock (br), bedrock – surficial (br-s) and surficial (s).

Cordillera	**Western Canadian Sedimentary Basin**		**Southern Ontario Lowlands**	**St Lawrence Platform**	**Appalachians**
1. Gulf Islands (br) 2. Nanaimo Lowland (br-s) 3. Fraser Lowland (s) 4. Okanagan Valley (s) 5. Shushwap Highlands (br)	6. Paskapoo (br) 7. Buried Valleys (s) 8. Upper Cretaceous Sand (br) 9. Milk River (br) 10. Judith River (br) 11. Eastend – Ravenscrag (br)	12. Intertill (s) 13. Manitoba Carbonate Rock (br) 14. Manitoba Basal Clastic unit (br) 15 Odanah Shale (br) 16. Sandilands (s) 17. Assiniboine Delta (s)	18. Oak Ridges Moraine (s) 19. Grand River Basin (br-s) 20. Credit River (br-s) 21. Waterloo Moraine (s) 22. Upper Thames River (br-s)	25. Mirabel (br-s) 26. Châteauguay (br-s) 27 Richelieu (br-s) 28 Chaudière (br-s) 29. Maurice (s) 30 Portneuf (s)	23. Annapolis – Cornwallis (br-s) **Maritimes Basin** 24. Carboniferous Basin (br)

These data include a range of scales and resolutions to address specific geological, hydrogeological, hydraulic, climate and land use information such as data on aquifer heterogeneity, stratigraphy, hydrostratigraphy, recharge, flowpaths, and discharge. Geological data range from point drillhole data to reflection seismic and resistivity surveys to 3-D multi channel airborne electromagnetic surveys (Oldenburger et al., 2010). Similarly hydrogeological and hydraulic datasets range from well site hydrochemistry and water level data to stream-baseflow surveys (Hinton, 1995). To address the demand for synoptic and sustainable groundwater management scenarios there is increasing integration of remotely sensed data and derivative datasets with national coverage to calculate for example evapotranspiration (ET) and recharge using Leaf Area Indexes (Fernandez et al., 2007).

9. MODELLING

9.1 3-D geological modelling

Development of sound conceptual geological models is required to support defensible, sub-surface modelling. Subsurface investigations based on the collection of high-quality data (seismic profiles, continuous core) provide new insights into the geological structure, processes of formation, and geological history of the basin (e.g. Sharpe et al, 2002). Tested conceptual geological models guide the construction of 3-D GIS based geological models (see Russell et al 2011).

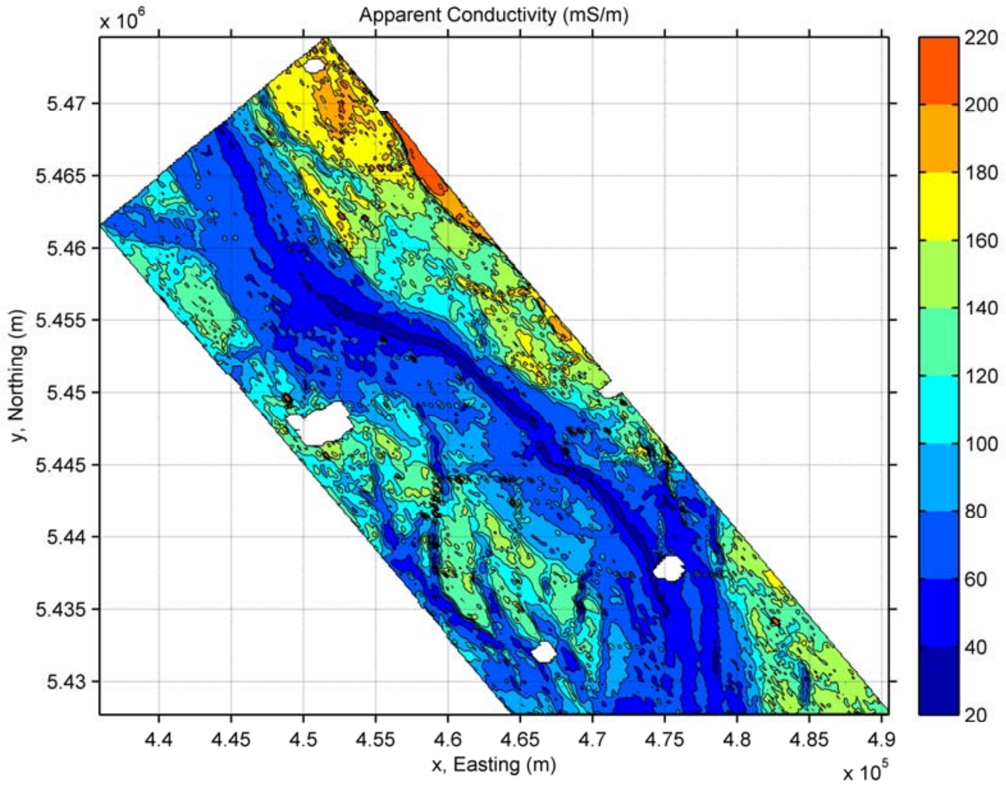

Figure 2. Total conductivity of airborne electromagnetic survey of the Spiritwood buried valley, Manitoba (from Oldenborger et al., 2010). Note the complex arrangement of bedrock hosted channels of various orientation, scale, and depth.

Geological modelling has been completed by the GSC for 6 of the key Canadian Aquifers (e.g., Logan et al 2006) and for a number of additional key aquifers by provincial agencies. Model construction is progressively driven by a hierarchal, data-classification scheme and use of high-quality data to train the interpolation of stratigraphic correlations of abundant lower-quality data. Since 2010, spatially extensive, three-dimensional geophysical datasets are providing exceptional resolution for model development (Figure 2; Oldeborger et al; 2011).

9.2 Groundwater Modelling

The Geological Survey of Canada has a history of geological mapping in 2D, 3D, and more recently in 3D geological modelling. 2D and 3D groundwater modelling at the GSC began to emerge a few years before the launching of the national groundwater program in 2003. With strong collaboration with provincial agencies and universities, the GSC has built several three-dimensional regional-scale (>1000 km^2) geological and hydrogeological models across the country (Rivera, 2007).

Numeric groundwater flow modelling has ranged from regional 3-D numeric models constructed in MODFLOW and FEFLOW (e.g. Mirabel, Chateauguay and/or Maritimes) to more specific modelling that identifies the probability of aquitard leakage and the configuration of phreatic surfaces (Desbarats et al., 2002). Modelling has also been completed at national scales for evapotranspiration and groundwater recharge using EALCO (Figure 3; Wang, 2008; Wang et al., 2011). Groundwater modelling is also being completed at much larger scales using GRACE (Huang et al., in review). With the question of groundwater sustainability and adaptation to climate change, there is an increasing interest for analysis to extend beyond the traditional steady-state groundwater modelling common to regional hydrogeology studies. The synoptic work derived from remote sensing offers enormous opportunity to better constrain elements of regional water budgets that are otherwise difficult to address but are key components of groundwater management. The coupling of groundwater models with land surface models and the use of Earth Observation (EO) data assimilation techniques provide us with more holistic and robust tools to address the physical interactions between surface water and groundwater and to assess the groundwater sustainability and vulnerability.

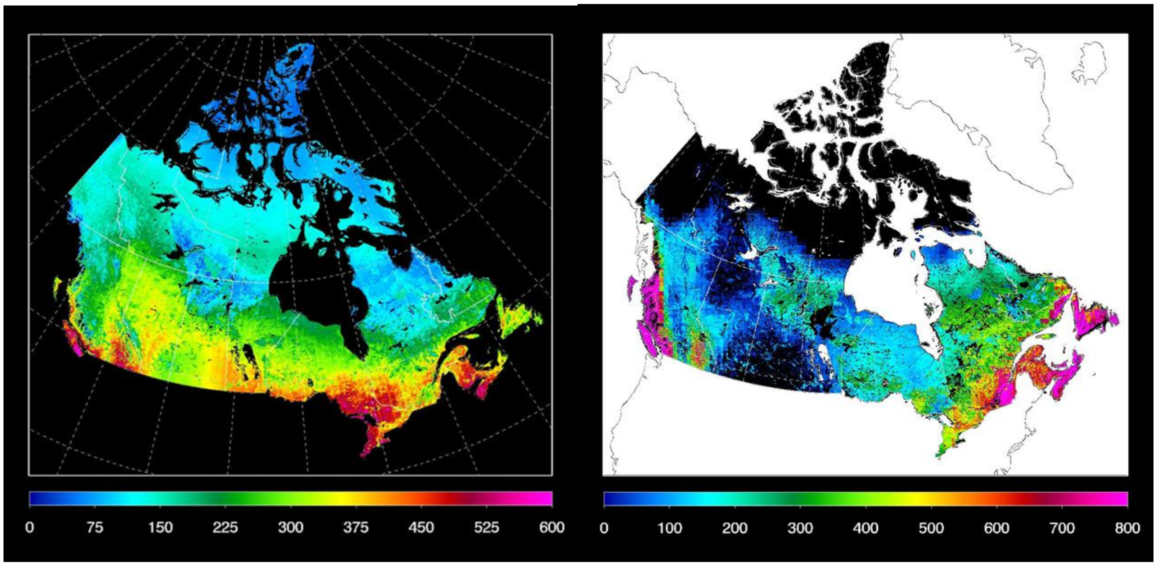

Figure 3. Land surface evapotranspiration (left) and groundwater recharge (right) over Canada's landmass in mm of water per year. The maps show the annual total value (30-year average of 1979-2008) simulated by the EALCO model at 30-minute time step. The simulation was based on multi-source, national scale EO data for Canada, including climate, soil/surficial material, vegetation, and terrain topography.

10. SUMMARY

The evolving government responsibility for water resources in Canada provides a complex arena for groundwater studies by the GSC. Work on developing a national framework for groundwater management (Rivera et al., 2003) and sustainable development of groundwater has provided a collaborative environment between provincial and federal agencies working on groundwater. In response to this environment the GSC has been developing a national framework for groundwater assessments with integrated approaches using remote sensing, state-of-the-art geophysics, 3D geological models and 3D numerical hydrogeological models (Rivera, 2008). These activities are being further focused on methods development, particularly integration of geophysical data into groundwater studies, whether satellite-derived data, airborne geophysical data or ground- based data (seismic). Integration of these datasets into a basin analysis scheme is contributing to increased understanding of groundwater resources within 3-D modelling environments from regional to national scales.

11. REFERENCES

Boisvert, E., and Brodaric, B. (2011). Groundwater Markup Language (GWML)—Enabling Groundwater Data Interoperability in Spatial Data Infrastructures. Journal of Hydroinformatics, doi: 10.2166/hydro.2011.072.

Desbarats, A.J., C.E. Logan, M.J. Hinton, and D.R. Sharpe, 2002, On the kriging of water table elevations using collateral information from a digital elevation model: Journal of Hydrology, v 255, no. 1–4, p. 25–38.

Fernandes, R., Korolevych, V., and Wang, S. 2007, Trends in land evapotranspiration over Canada for the period 1960–2000 based on in situ climate observations and a land surface model: Journal of Hydrometeorology, v. 8, p. 1016–1030.

Hinton, M. J., 1995. Measuring stream discharge to infer the spatial distribution of groundwater discharge. Proceedings of the Watershed Management Symposium, Canada Centre for Inland Waters, Burlington, Ont., December 6-8, 1995. Canadian Water Resources Association, Cambridge, Ont., p. 27-32.

Huang, J., Halpenny, W., van der Wal, C. Klatt, T. S. James, and A. Rivera, in review. Detectability of groundwater storage change within the Great Lakes Water Basin using GRACE. Submitted to Journal of Geophysical Research.

Logan, C., Russell, H.A.J. Sharpe, D.R., and Kenny, F.M. 2006, The Role of GIS and expert knowledge in 3-D modelling, Oak Ridges Moraine, southern Ontario, in J. Harris, ed., GIS for the Earth Sciences, Chapter 23: Geological Association of Canada, Special Publication 44, p. 519–542.

Oldenborger, G., Pugin, A. J. M., Hinton, M.J., Pullan, S.E., Russell, H.A.J., and Sharpe, D.R. 2010, Airborne time-domain electromagnetic data for mapping and characterization of the Spiritwood Valley aquifer, Manitoba, Canada: Geological Survey of Canada, Current Research, no. 2010–11, 16 p.

Pugin, A.J.M., Pullan, S.E., and Hunter, J.A. 2009, Multicomponent high-resolution seismic reflection profiling: The Leading Edge, v. 28, no. 10, p. 1248–1261.

Rivard, C., Michaud, Y., Lefebvre, R., Deblonde, C., and Rivera, A. 2008. Characterization of a regional aquifer system in the Maritimes Basin, Eastern Canada; Water Resources Management, 22, 1649-1675.

Rivera, A., A. Crowe, A. Kohut, D. Rudolph, C. Baker, D. Pupek, N. Shaheen, M. Lewis, and K. Parks, 2003, Canadian framework for collaboration on groundwater: Geological Survey of Canada, Contribution Series, 55 p. http://ess.nrcan.gc.ca/gm-es/reports/pdf/canadian_framework_collaobration_gw_e.pdf

Rivera, A., 2007. Groundwater modelling: from Geology to Hydrogeology. *Geological Society of America,* Annual Meeting, Denver CO, USA, Minnesota Geological Survey, Open File 07-4: 51-57.

Rivera, A., 2008. Groundwater Sustainable Development in Canada – Emerging Issues. Canadian National Committee International Year of Planet Earth CNC-IYPE. GEOSCIENCE CANADA. Vol. 35, no. 2, 2008; pages 73-87.

Russell, H. A .J, E Boisvert, E., C Logan, C., S J Paradis, D.J., M Ross, M. and D R Sharpe D.R. 2011 Chapter 7, Geological Survey of Canada: Three-dimensional Geological Mapping for Groundwater Applications; In Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organization, edited by R Berg, S.J Mathers, H Kessler, and D. A Keefer, 31-41. Champaign, Illinois: Illinois State Geological Survey, Circular 578, 2011. www.isgs.illinois.edu.

Sharpe, D.R., M.J. Hinton, H.A.J. Russell, and A.J. Desbarats, 2002, The need for basin analysis in regional hydrogeological studies: Oak Ridges Moraine, southern Ontario: Geoscience Canada, v. 29, no. 1, p. 3–20.

Sharpe, D.R., H.A.J. Russell, S.E. Grasby, and P.R.J. Wozniak, 2008, Hydrogeological regions of Canada: Data release: Geological Survey of Canada, Open File 5893, 20 p.

Thorleifson, L.H., R.C. Berg, and H.A.J. Russell, 2010, Geological mapping goes 3-D in response to societal needs: GSA Today, v. 20, no. 8, p. 27–29.

Wang, S., 2008, Simulation of evapotranspiration and its response to plant water and CO2 transfer dynamics. Journal of Hydrometeorology, 9: 426-443, DOI: 10.1175/2007JHM918.1.

Wang, S., Y. Yang, and X. Geng, 2011, How much water is available for groundwater recharge over the Canadian landmass? GeoHydro2011 Conference, Quebec City, Canada, August 28-31, 2011.

GEOMODELLING AT TNO – GEOLOGICAL SURVEY OF THE NETHERLANDS

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1. INTRODUCTION

The Geological Survey of the Netherlands defines digital geological models as predictions of both geometry and properties of the subsurface. In contrast to singular observations in boreholes and the projected information of traditional maps, models provide continuous representations of the subsurface built with all of the geological expertise available. The models are quantitative and user oriented, meaning they are applicable for non-geologists in their own area of expertise. They are also stochastic in nature, which implies that we are able to quantify model uncertainty.

The Geological Survey of the Netherlands systematically produces 3D models of the upper 500 meters of the Netherlands. To date, we have built and maintained two different types of nation-wide models: (1) layer-based models, in which the subsurface is represented as a series of tops and bases of geological or hydrogeological units and (2) voxel models, in which the subsurface is subdivided in a regular grid of voxels of, for instance, 100m by 100m by 0.5 m. Layer-based models include the geological framework model DGM (Digital Geological Model) and the geohydrological model REGIS-II (Regional Geohydrological Information System). The layer-based models are well-established: REGIS-II, for instance, is widely used by regional authorities and water supply companies in their groundwater modelling studies. In contrast, the voxel models GeoTOP and NL3D are relatively new: NL3D was recently completed and GeoTOP is currently available for about 35 % of the country. The first applications of the voxel models include long-term forecasts of land subsidence and risk maps used in the deepening of waterways.

Our models are disseminated via the DINO-portal (www.dinoloket.nl) in a number of ways, including an online map viewer with the option to create vertical cross-sections through the models, and a series of downloadable GIS products. A new addition to the portal is the freely downloadable Subsurface Viewer based on GSI3D, allowing users to download and visualize the layer-based models on their desktop computers. Together with Hans-Georg Sobisch we are currently extending the Subsurface Viewer's capabilities to voxel models. Another new development is an iPhone/iPad App showing synthetic boreholes through the models at the user's current location.

This extended abstract explores the four main models, with an emphasis on the GeoTOP voxel model, discusses the way in which we disseminate them and gives some examples of applications.

2. LAYER-BASED MODELS: DGM AND REGIS-II

Modern digital mapping of the Dutch subsurface started in 1999 with the development of the so-called Digital Geological Model (DGM; Gunnink et al., in prep.). DGM, constructed using a set of some 16,500 consistently interpreted boreholes, is a 3D stacked-layer lithostratigraphical model of the entire onshore part of the Netherlands up to a depth of 500 meters. It consists of a series of raster layers, where each lithostratigraphical unit is represented by rasters for top, bottom and thickness of the unit. Raster layers are stored in the raster format of ESRI (ArcGIS). The lithostratigraphical units are at formation level; the complex fluvio-deltaic Holocene deposits are represented by one layer only. Part of the model is shown in Figure 1.

A second important step in digital mapping was the development of the Regional Geohydrological Information System (REGIS-II; Vernes and Van Doorn, 2005). The model uses the same dataset of some 16,500 boreholes as used in DGM. REGIS-II further subdivides the lithostratigraphical units of DGM into aquifers and aquitards. In addition, representative values of hydrological parameters (e.g., conductivity and effective porosity) are calculated and assigned to the model, making it suitable for groundwater modelling on a regional scale. Similar to DGM, REGIS-II models the Holocene deposits as a single confining layer. Both DGM and REGIS-II are downloadable from TNO's

website (www.dinoloket.nl) and are widely used by regional authorities and water supply companies in groundwater modeling studies.

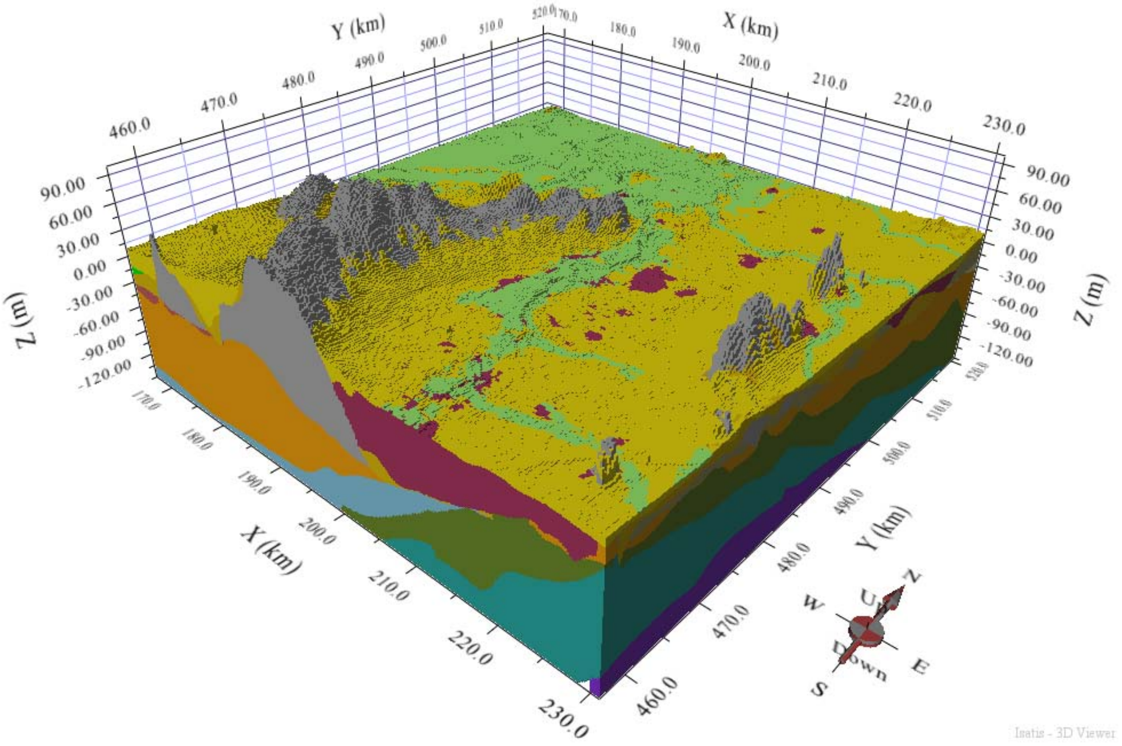

Figure 1. 3D view of a part of DGM showing ice-pushed ridges (grey) and part of the IJssel River valley in the central part of the Netherlands. Pleistocene fluvial sediments (red and orange) and aeolian cover sands (yellow) are visible in between the ice-pushed ridges. The course of the River IJssel, a branch of the Rhine, and several small tributaries are indicated in light green. Tertiary marine formations (blue, olive green and purple) are dipping below the Pleistocene deposits.

2.1 Voxel models: GeoTOP and NL3D

GeoTOP is the last generation of Dutch subsurface models at TNO - Geological Survey of the Netherlands. GeoTOP schematises the shallow subsurface in millions of voxels of 100m by 100m by 0.5 m up to a depth of 30 – 50 meters, which is the main zone of current Dutch subsurface activity (Stafleu et al., 2009, in prep.). The model provides estimates of lithostratigraphy and lithology (including grain-size classes), as well as physical and chemical parameters, such as hydraulic conductivity and chemical element concentrations. The model provides a base for answering subsurface related questions about, amongst others, groundwater management and infrastructural issues. Modelling is carried out per province using all available digital borehole descriptions, components of the DGM model and a context of geological maps created during the last few decades (e.g. 1:50.000 map sheets and channel belt mapping (Berendsen and Stouthamer, 2001)). An important component of the GeoTOP model workflow is that all database boreholes are stratigraphically interpreted using automated procedures. These procedures deliver a set of uniformly and objectively interpreted boreholes that are used in the subsequent modelling stages.

The Holocene deposits are modelled in high detail using a framework of lithostratigraphical units (up to the Bed level) and lithofacies units such as sandy channel belt deposits. Figure 2 shows the channel belt system of the Holocene deposits with grid cells filled with lithology and sand-grain size classes, providing more insights into the internal build-up of the channel belts and the occurrence of grain size trends in both vertical and horizontal (downstream) directions.

TNO is currently extending the model towards other parts of the Netherlands. Meanwhile, a low resolution voxel model called NL3D was constructed to serve users in areas that lack GeoTOP coverage. NL3D models lithology and sand-grain size classes within each of the geological formations defined by the framework model DGM in some 37 million voxels, each measuring 250 meters by 250 meters in horizontal directions and 1 meter in the vertical direction.

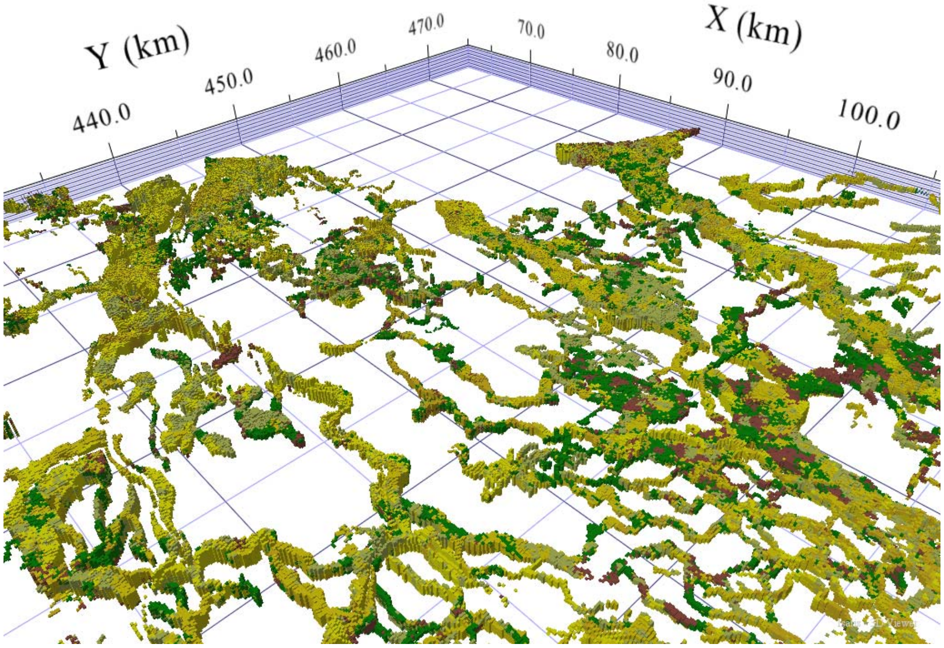

Figure 2. Channel belts of Rhine and Meuse in the GeoTOP voxel model of the western part of the Netherlands, looking towards the North Sea. Yellow colors indicate sand in three different grain-size classes, green colors are clays and brown peat.

3. DISSEMINATION OF RESULTS

Our models are disseminated via the DINO-portal (www.dinoloket.nl) in a number of ways, including an online map viewer with the option to create vertical cross-sections through the models, and a series of downloadable GIS products. A new addition to the portal is the freely downloadable Subsurface Viewer based on GSI3D, allowing users to download and visualize the layer-based models DGM and REGIS-II on their desktop computers. Users can download the models as 1:50,000 map sheets (each measuring 20 km by 25 km; Figure 3).

Together with Hans-Georg Sobisch we are currently extending the Subsurface Viewer's capabilities to voxel models. This new viewer allows the user to query the voxel data by defining selections on attribute values. As an example, the user might want to see the voxels containing peat with a probability higher than 80%.

4. APPLICATIONS AND NEW GEOLOGICAL INSIGHTS

The first practical applications of the voxel models include, amongst others:

- Long-term (up to 200 years) forecasts of land subsidence in the western part of the country, based on the detailed spatial distribution of soft sediments (clay and peat).

- The construction of risk maps used in the deepening of a river north of Utrecht, based on the architecture and sediment composition of channel belts.
- Risk and cost assessment in the construction of a new subway in the city of Rotterdam, with an additional local voxel model based on additional borehole descriptions.
- Search for areas with favourable conditions for ground source heat pumps (closed loops that are capable of heating and cooling of private homes).
- Study of salt water penetration problems in aquifers in Zeeland.

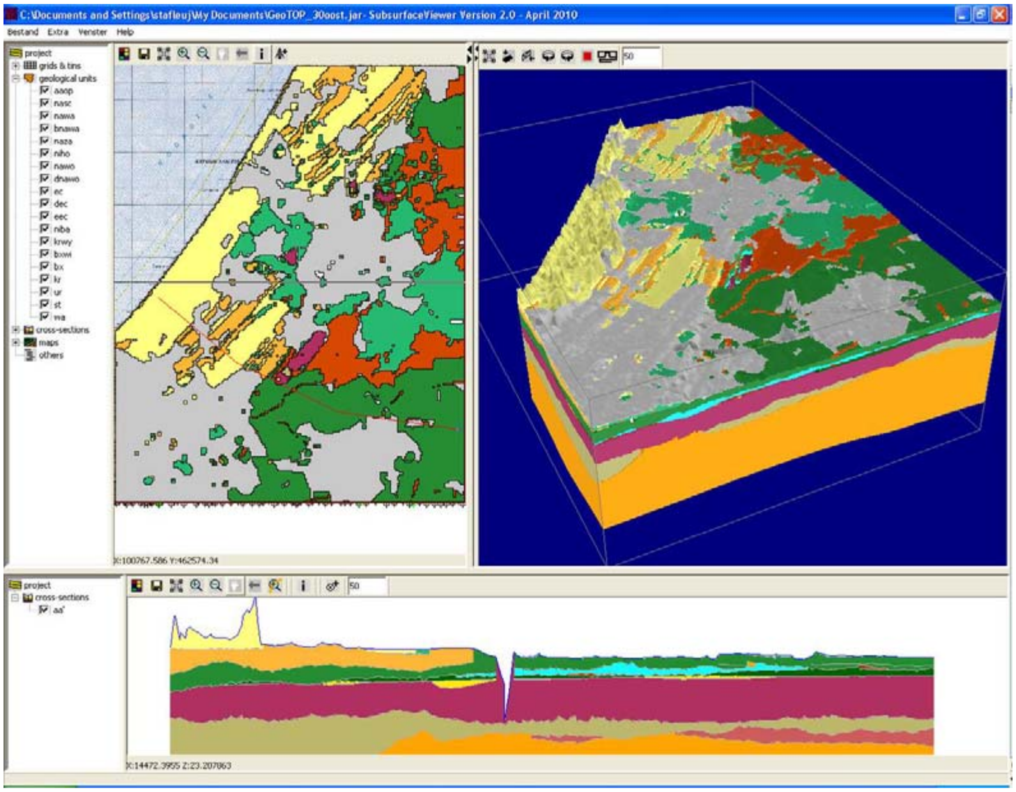

Figure 3. Screenshot of the Subsurface Viewer with the layer-based model DGM showing geological formations in the area around The Hague and Leiden (20 by 25 km). The viewer contains a map view (top left), 3D view (top right) and a vertical cross-section (bottom).

Besides serving as a source of subsurface information for the applied geosciences, the voxel models also give new insights in the geological evolution of the Netherlands throughout the Quaternary. The combination of large amounts of borehole data and the use of powerful new visualisation software reveals new geological patterns that were not known from earlier, traditional geological studies. A striking example is the discovery of the infill of a large incised palaeo valley of the Rhine River in the NL3D model.

5. REFERENCES

Berendsen, H.J.A., and E. Stouthamer. 2001. Palaeogeographic development of the Rhine-Meuse delta, The Netherlands, Van Gorcum, Assen, 268 p.

Gunnink, J.L., D. Maljers, S.F. van Gessel, A. Menkovic and H.J. Hummelman (in prep.). A 3D geological raster model of the Netherlands.

Stafleu, J., F.S. Busschers, D. Maljers & J.L. Gunnink (2009); Three-dimensional property modeling of a complex fluvio-deltaic environment: Rhine-Meuse Delta, The Netherlands. In: Berg, R.C., Russell, H.A.J. & Thorleifson, L.H. (eds.): Workshop Extended Abstracts of the 2009 Annual Meeting, Geological Society of America, October 17 2009, Portland, Oregon, USA, p.47-50.

Stafleu, J., D. Maljers, J.L. Gunnink, F.S. Busschers & A. Menkovic (in prep.). 3D modeling of the shallow subsurface of Zeeland, the Netherlands. Submitted to Netherlands Journal of the Geosciences.

Vernes, R.W. and Van Doorn, Th. H. M., 2005. Van Gidslaag naar Hydrogeologische Eenheid – Toelichting op de totstandkoming van de dataset REGIS II. Netherlands Institute of Applied Geosciences TNO, Report 05-038-B, 105 pp.

3D GROUNDWATER MAPPING IN DENMARK BASED ON CALIBRATED HIGH-RESOLUTION AIRBORNE GEOPHYSICAL DATA.

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1. THE DANISH HYDROGEOLOGICAL SETTING

Denmark occupies a total area of some 43,000 km^2. Most of the country consists of Quaternary deposits overlying Cretaceous chalk, limestone, and Tertiary sand and clay. The topography is low-lying, reaching a maximum of 172 m above sea level. The combination of low topography and widespread, consolidated, and unconsolidated aquifers ensures a plentiful and easily accessible water resource. Groundwater recharge averages 100 mm per year, but can vary in the range of 50–350 mm. Currently, approx. 800 10^{-6} m^3 of water is abstracted annually. Household consumption by the 5.35 million inhabitants amounts to approx. 250 10^{-6} m^3 per year. Of this amount, 99.9 % derives from groundwater. **Groundwater quality in Denmark is generally good, which obviates the need for complex and expensive water purification**. Moreover, the Danish water supply is decentralized, which renders expensive, lengthy pipelines serviced by large, central water plants unnecessary. The drinking water is not chlorinated and is of bottle water quality at the tap. Altogether, there are around 2,900 public water supplies. Two thirds of the water abstracted for the national water supply derives from 200 municipal waterworks and one third from private cooperative waterworks.

1.1 The background for the mapping program

Contamination from urban development and agricultural sources increasingly threatens the groundwater resource. In 1995, growing problems with water quality in Denmark due to urban development and contamination from agricultural sources led the Minister for the Environment to approve a 10-point plan to improve groundwater protection. One of the major initiatives was to ban the use of pesticides that can contaminate the groundwater. Another was that the regional authorities should draw up new water-resource protection plans. By the end of 1997, the regional authorities had classified the country into three types of groundwater-abstraction areas: particularly valuable, valuable, and less-valuable water abstraction areas (Figure 1; Thomsen et al. 2004).

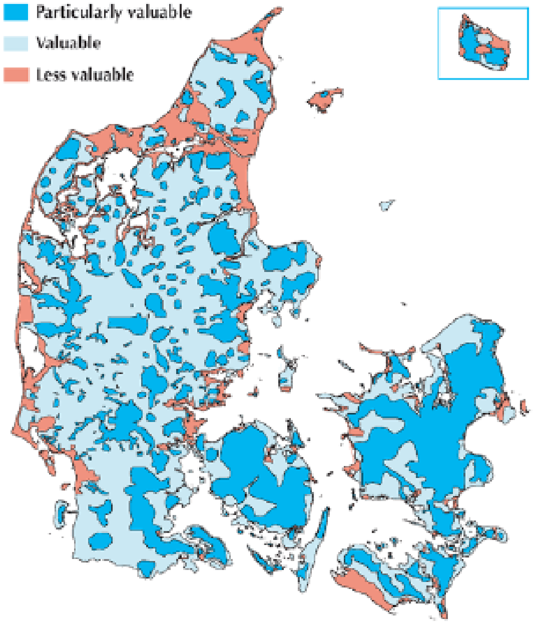

Figure 1 Groundwater classification map showing subdivision of Denmark into particularly valuable, valuable, and less-valuable groundwater-abstraction areas in 2001.

This classification is based on an evaluation of the size and quality of all groundwater resources in the country. In July 1998, the Danish Parliament adopted an ambitious plan to significantly intensify hydrogeological investigation to facilitate protection of the groundwater resource in order to meet future water-supply challenges. Parliament decided that, in addition to being responsible for water-resource planning, the regional authorities should also be responsible for ensuring spatially dense mapping and hydrological modelling of the water resources as a basis for establishing site-specific groundwater protection zones.

The mapping and planning work is to be carried out over a 15-year period and encompasses all parts of Denmark classified as particularly valuable water-abstraction areas. Together, these areas cover almost 17,800 km^2 or 41 % of the total area of the country. Water consumers finance the mapping program by paying 0.04 € per m^3 of consumed water, i.e. about € 4 per family per year. For one m^3 the consumer pays 6 € and that covers drinking water, treatment of vast water, green tax, and vat. The cost of the mapping program is less than 1 %. At the end of the program in 2015, the total cost is estimated to be about 250,000,000 € with a significant part spent on geophysical mapping. The cost of the mapping program is, on average, € 7,500 per km^2 which encompasses geophysical profiling every 250 m, survey drilling every 4 km^2, water sampling, and hydrological modelling.

1.2 Site-specific ground water protection

The objective of the groundwater mapping project is to acquire a well-described picture of the aquifers with respect to their localization, distribution, extension, interconnection, etc., and to obtain maps detailing groundwater vulnerability. These maps will be used to establish site-specific groundwater protection zones to prevent groundwater contamination from urban development and agricultural sources.

The rationale for setting up site-specific groundwater protection zones is that some areas are more vulnerable to groundwater contamination than others. The goal is thus to subdivide a given area according to the different potential of the various sub-areas as regards specific purposes and uses.

The Danish site-specific groundwater protection strategy is based on three steps:

1. Spatially dense hydrogeological mapping based on “old” data supplemented with new geophysical surveys, survey drilling, water sampling, hydrological modelling, etc., aimed at facilitating the establishment of site-specific protection zones. Vulnerability is interpreted in relation to the local hydrological and chemical conditions.

2. Mapping and assessment of all past, present, and possible future sources of contamination—both point sources and diffuse sources.

3. Preparation and evaluation of an action plan stipulating politically determined regulations for future land use within the site-specific groundwater protection zones. The action plan has to be evaluated through a public planning process with a high degree of transparency and public participation. Moreover, it must include a timetable for implementation and a description of who is responsible for its implementation. The protection zones and guidelines will be used to prevent groundwater contamination from urban development and agricultural activities and for planning the remediation of contaminated sites.

This three-step protection strategy is based on previous experience with groundwater protection in Denmark and abroad. In Denmark, the new site-specific protection zones shall encompass the whole recharge area, with particular emphasis on protection of the capture zones. The protection zones will be established on the basis of model calculations of groundwater flow and calculations of the degradation of the contamination from point sources and diffuse sources, taking into account knowledge of the local geochemical conditions. The new type of protection zone ensures that the protection is now also directed at contamination from diffuse sources such as agricultural use of fertilizer and pesticides, which can cause extensive loading from large areas. According to the Danish guidelines, the establishment of protection zones of this type imposes demanding requirements as to mapping of the water resources, because the restrictions associated with the zones have to be set at property level.

2. THE MAPPING PROGRAM

Traditional geological maps are not sufficiently detailed and precise to enable delineation of the new protection zones.

At the national level, borehole data are the most important source of information about the condition of groundwater and aquifers. The national archive of borehole data at the Geological Survey of Denmark and Greenland contains information dating back to 1926 and has hitherto been the primary source of geological and hydrological information about aquifers. At the country level, there are more than 240,000 boreholes, corresponding to an average of approx. 6 boreholes per km^2. This data density, however, allows for only a very general description of the complex geological composition of Danish aquifers because most boreholes are too shallow to contribute to deeper aquifer delineation.

Spatially dense geophysical mapping in and around the city of Aarhus during the period 1994–1997 has revealed that traditional mapping based solely on borehole data can be improved considerably and may be used for establishing site-specific groundwater protection zones. The proposal of the national mapping program is based on the experience from this mapping.

In recent years, new geophysical mapping methods have been developed through a collaborative effort by regional authorities, the University of Aarhus, GEUS and the Public Utilities of Aarhus. These geophysical methods are very important tools for carrying out the spatially dense mapping needed to determine the extent, vulnerability, and water quality of Danish aquifers in 3D as the basis for delineating protection zones. In the mapping program, 10 % of the budget has been allocated to development of mapping methods, data interpretation, and to establishing databases for mapping data and mapping results. It has been acknowledged politically that the mapping methods could be improved in the mapping process.

2.1 Aquifer Delineation

In Denmark, the aquifers of interest are found within the upper 250 m of the subsurface. Aquifers in Denmark often occur in buried valleys eroded into the Tertiary clay substratum and they are usually interconnected to some degree. The buried valleys are often unrecognizable in the terrain. It is important to delineate the regional structures and their interconnectivity in order to be able to assess potential areas for water abstraction, to quantify regional resources, and to identify aquifers that are vulnerable due to the nature of their overlying soil layers. As the buried valleys are sometimes 200–300 m deep and often 1 km wide, they are difficult to delineate using boreholes, even in areas with a high borehole density.

2.2 Geophysical methods used in the hydrogeological mapping

The most important geophysical methods are electrical and electromagnetic methods, which are combined with reflection seismic profiling and borehole logging at selected localities. The most commonly used geophysical method in the groundwater mapping program is the airborne transient electromagnetic method, SkyTEM (Sørensen & Auken 2004),which is one of the new methods that has been developed to improve and optimize groundwater mapping. The SkyTEM method is used for mapping up to a maximum depth of 250–300 m. Numerous buried valleys have been mapped in Denmark by means of the TEM method, in particular in the central parts of the country where highly impermeable and low-resistive Palaeogene clay layers form the lower boundaries of the aquifers and where the valleys are easily detected. At the end of 2010, TEM and SkyTEM data cover an area of about one quarter of the area of Denmark.

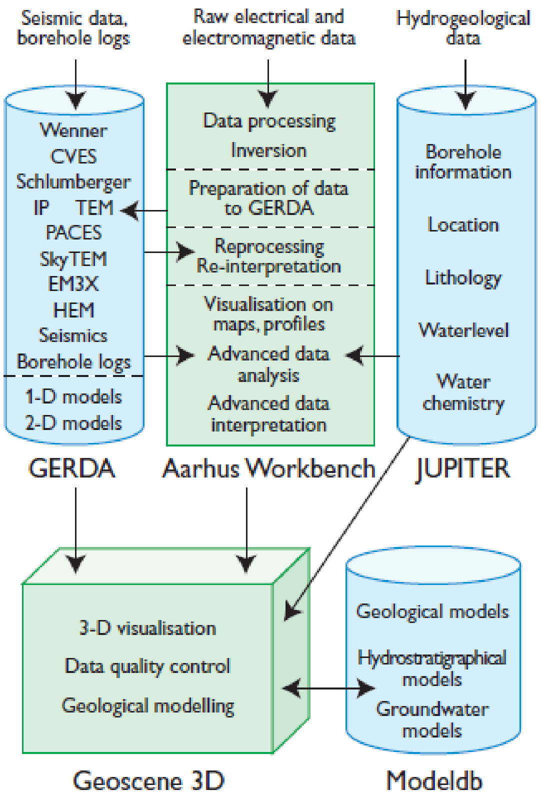

Figure 2 The arrows show the flow of data between the geophysical database GERDA, the borehole database Jupiter, the Aarhus Workbench program package, the Geoscene 3D visualisation and modeling tool and the geological model database Modeldb.

2.3 Data administration

The Groundwater Mapping Program is split up into many smaller areas to ease the administrative handling and to be able to meet priority criteria (Møller et al. 2009). Careful and standardized treatment of data is required to ensure that the resulting ‘patchwork’ is of high and uniform quality and has no visible seams. Therefore, standards and guidelines are worked out for geophysical data acquisitioning, calibration of instruments (Validation of the SkyTEM system, 2010), data processing, interpretation, and geological modelling.

All electric, electromagnetic and seismic data measured during the past 20 years have been reported to a national database called GERDA (GEophysical Relation DAtabase), (GERDA; http://gerda.geus.dk). GERDA is hosted by GEUS. GERDA contains measured data as well as a geophysical interpretation of these data. GEUS also hosts another database, Jupiter, for borehole data (Jupiter; http://jupiter.geus.dk). Jupiter contains information on geological and lithological descriptions, groundwater level, and water quality observations. Both the Jupiter and GERDA databases have web-based graphical user interfaces where any user can search for and download data free of charge. Geophysical data are handled from data processing to geological interpretation in an integrated system formed by the GERDA and the Jupiter databases and by two software packages the Aarhus Workbench and the Geoscene3D in combination with a geological model database hosted at GEUS (Figure 2; Møller et al. 2009). The Aarhus Workbench (Hydro Geophysics Group 2007b) has modules for handling, processing, inverting, interpreting, and visualizing electrical and electromagnetic data, all combined on a common GIS platform and a common database. The different maps are entered into the 3D visualization and modelling tool GeoScene3D. (I-GIS, http://www.i-gis.dk)

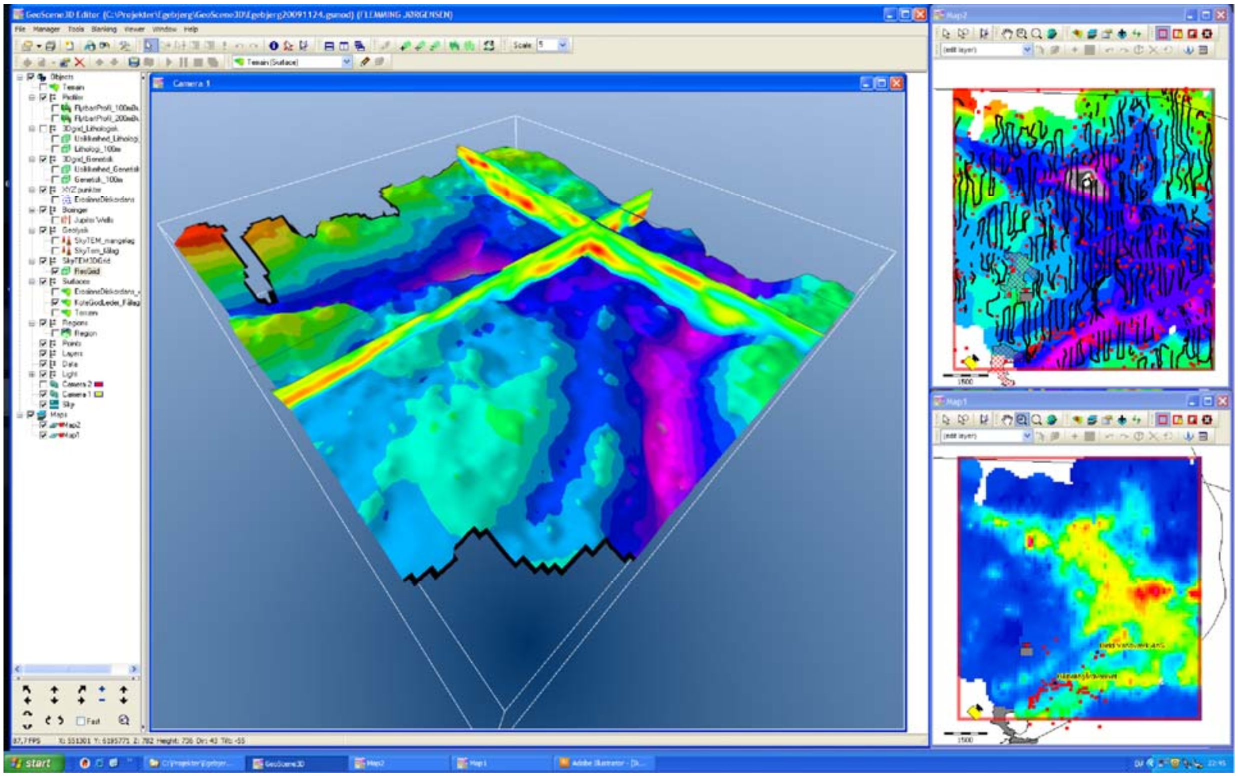

__Figure 3. 3D visualisation: Deep conducting layer and vertical slices through 3D resistivity volume.__

The mapping results are integrated into local 3D hydrogeological models in Geoscene 3D and these models are now being used by the local utilities and water administration at all levels. GEUS is working on a program to establish a national 3D database that can be a source for updating and for the future use of 3D geology/hydrogeology in the local administration. 3D visualization is extensively used to illustrate the mapping results to the public because the creation of site-specific protection zones must obtain public approval (Figure 3).

The Danish strategy to protect the groundwater resource presented here shows that dense mapping with newly developed geophysical measurement methods deployed in large contiguous areas plays a key role in the ongoing hydrogeological mapping.

3. REFERENCES

HydroGeophysics Group 2007a: Guide to processing and inversion of SkyTEM data. Version 1.2. Århus: Department of Earth Sciences, University of Aarhus, http://www.hgg.geo.au.dk/rapporter/guide_skytem_proc_inv.pdf.

Møller, I, Søndergaard, V.H. and Jørgensen, J. 2009: Geophysical methods and data administration in Danish groundwater mapping ROSA, Geological Survey of Denmark and Greenland Bulletin 17, 41–44. Available at: www.geus.dk/publications/bull

Møller, I., Søndergaard, V.H., Jørgensen, F., Auken, E. & Christiansen, A.V.: Integrated management and utilization of hydrogeophysical data on a national scale. Near Surface Geophysics. 2009, 647-659

Sørensen, K.I. & Auken E. 2004: SkyTEM – A new high-resolution helicopter transient electromagnetic system. Exploration Geophysics 35, 191–199.

Thomsen, R., Søndergaard, V.H & Sørensen, K.I. 2004: Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. Hydrogeology Journal **12**, 550–562.

Validation of the SkyTEM system at the extended TEM test site, 2010, http://geofysiksamarbejdet.au.dk/en/publications/new/reports/

GEOLOGIC FRAMEWORK MODELLING FOR GROUNDWATER APPLICATIONS IN NORTHEAST ILLINOIS

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1. INTRODUCTION

Growth in the Chicago Metropolitan area has prompted an active awareness of long-term water resources and goals. The Illinois State Geological Survey (ISGS) has been a primary scientific resource for local and regional decision-makers in the area (CMAP, 2010). Many communities in northeast Illinois have yet to fully address the long-term water resource potential of unconsolidated glacial sediments. McHenry County has responded with an aggressive implementation of a water resource action plan coupled with scientific investigations including 3D geologic mapping of glacial deposits and associated groundwater flow modelling.

With the rapid development of software packages that readily incorporate geospatial data, workflows for building 3D geologic models are certainly non-unique. The ISGS is developing a multi-tool iterative approach to building geologic framework models (GFMs) as tools for water resource assessments and as the basis for groundwater flow modelling studies (Keefer, 2011). Our iterative approach to model construction includes an intensive phase of data acquisition and quality control followed by 3D visualization, analyses, and interpretation. Subsequent data acquisition (mostly field data) is often aimed at better understanding geologic uncertainties at local scales or testing previous geologic interpretations. Further incorporation of those data into multiple 3D visualization packages (ArcGIS and Geovisionary) allows for rapid analyses and interpretation. Final stages of developing the GFM incorporate section-based modelling (GSI3D), which allows for rapid integration and interpretation of a variety of datasets.

1.1 Geologic Setting

The surficial geology of McHenry County has been developed almost completely as a function of pre-Wisconsin and Wisconsin Episode glaciations (Figure 1), which specifically include ice marginal/subglacial and proglacial deposits (moraines/till and outwash, respectively). The morphology of the landscape includes some of the most prominent preserved moraines and outwash fans in the Midwest. The sediments include at least 2 sequences of pre-Wisconsin Episode deposits and 3 Wisconsin Episode deposits, which cumulatively range in thickness between 3 and 150 meters thick. These deposits generally lie atop a regionally extensive fractured carbonate bedrock unit. However, that unit is sometimes fully incised by steep bedrock valleys, which may have as much as 100 meters of relief. These bedrock valleys are largely filled with sequences of pre-Wisconsin Episode proglacial outwash and lacustrine deposits.

Three major aquifer systems in the Quaternary deposits are utilized in McHenry County and have been the focus of this study and previous studies (Curry et al., 1997). These deposits include a lowermost sand/gravel unit most often in contact with fractured carbonate bedrock. This unit is likely associated with Pre-Wisconsin Episode glaciations and interglacial periods of erosion. A second aquifer system is associated with the first advance of the Wisconsin Episode glaciation in McHenry County, but also often includes proglacial deposits of the Pre-Wisconsin Episode retreat. These two deposits are often unconformably separated by a preserved paleosol. Lastly, an extensive surficial aquifer includes late stage outwash deposits of the last Wisconsin Episode glacial retreat and other modern alluvial deposits. In McHenry County, there are several major glacial meltwater discharge paths that were likely reoccupied by multiple glacial events. Thus, in these areas all three major aquifers are often interconnected.

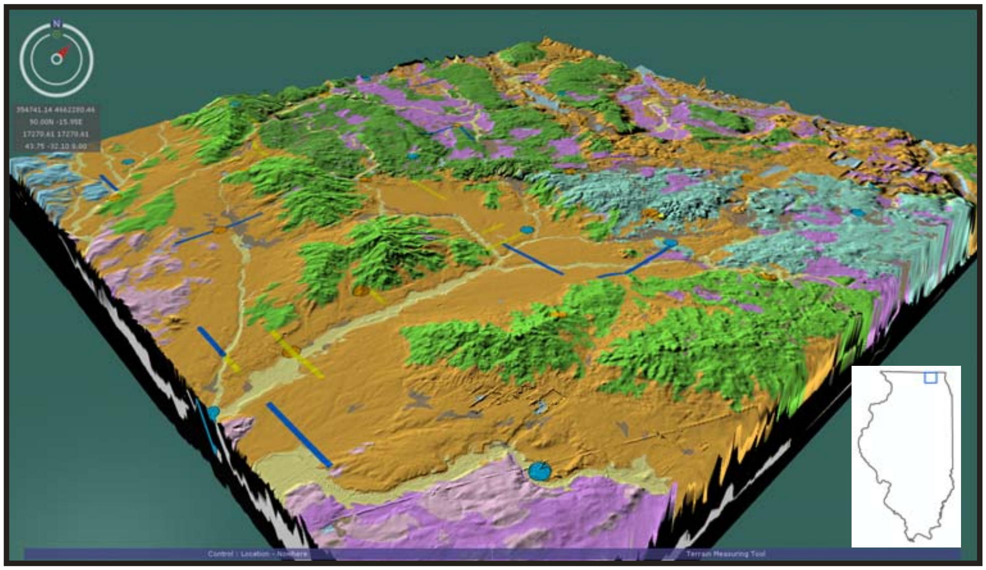

Figure 1. Perspective view from southwest of the topography and surficial geology of McHenry County. Shades of green and purple indicate fine-grained deposits such as till or lake sediments, while shades of orange and yellow indicate glacial outwash and modern alluvium.

2. DATA ACQUISITION, QUALITY CONTROL, AND ANALYSES

In two field seasons, ISGS and McHenry County collected 30 continuous lithologic cores to bedrock (17 wireline-mud rotary, 14 rotosonic), which included downhole geophysical logs at each location (gamma ray and electrical resistivity). These cores are in addition to 25 others collected from previous studies in the County in the past two decades (Curry et al., 1997, NIPC). The ISGS also collected approximately 90 km of 2D geophysical profiles (seismic (51 km) and resistivity (39 km)). These field data have been the key datasets for regional and local geologic interpretation in the County.

Another primary data source that is often abundant in McHenry County is the historical water well record dataset. The quality of water well records is a common concern when using these data for geologic interpretation, and various approaches are used by geologists to assess the value of those records. The ISGS has incorporated a two-fold approach to address the quality of those records, which includes lithologic standardization and location verification. 3D visualization of well record data requires lithologic standardization of the seemingly infinite number of unique lithologic descriptions. Thus, in McHenry County, approximately 95% of the formation descriptions from well records have been generalized into 17 descriptive lithologies. Variability is lost in any standardization scheme, and certainly various levels of detail can be retained depending on the scheme, but any level of generalization is valuable when trying to interpret bulk water well record datasets. In addition to lithologic standardization, errors associated with data point locations are important to address. In McHenry County, the locations of approximately 53% of the ~22,000 well records have been verified to the best location available (e.g. street address). Although expensive and time consuming, well-location correction has been one of the most worthwhile efforts to address data quality, because it has been a critical means to reduce the inherent variability in water well record dataset (e.g. elevation errors associated with mislocated data).

The ISGS has also been using a suite of software packages to develop a workflow aimed at 3D geologic mapping from raw data to a final product. Key to this workflow is the ability to visualize and interpret geologic data in the 3D environment, which at this point, has been achieved using custom tools in ArcGIS (Figure 2a). These tools simply integrate the built-in toolsets in ArcGIS, but they allow for rapid 3D visualization of attributes associated with the data (e.g. lithology, color, stratigraphy, downhole geophysical logs, combinations of attributes). Furthermore, these tools allow for “on the fly” geologic interpretation in the 3D environment such as water-well record “picks” and interpolation of geologic contacts. In McHenry County, using these tools, more than 11,000 stratigraphic interpretations have been made in the water-well records since the start of the project (2008). However, as versatile and efficient as these tools are, inherent limitations within ArcGIS constrain their application to 3D geologic mapping. For example, the efficiency and stability of ArcGIS are dependent upon the RAM capabilities of the workstation. Detailed land surface models (e.g. LIDAR), large borehole datasets and other 3D visual datasets (cross sections, downhole geophysics) can significantly limit processing efficiency. Therefore, a second software package, Geovisionary, has been used as a supplemental 3D visualization tool. Geovisionary is capable of displaying high resolution datasets (e.g. LiDAR, aerial photography) in full resolution in a 3D visualization environment along with other subsurface geologic data (well records, geophysical profiles) (Figure 2b). For example, these visualization capabilities have allowed for the highest resolution of geomorphic relationships to soil types/geology than ever before in McHenry County (e.g. lithologic facies within glacial outwash fans). However, the ability to build and record geologic interpretations in Geovisionary is limited to strictly digitization at land surface. Furthermore, subsurface digitizing functions in both ArcGIS and Geovisionary are extremely limited or absent.

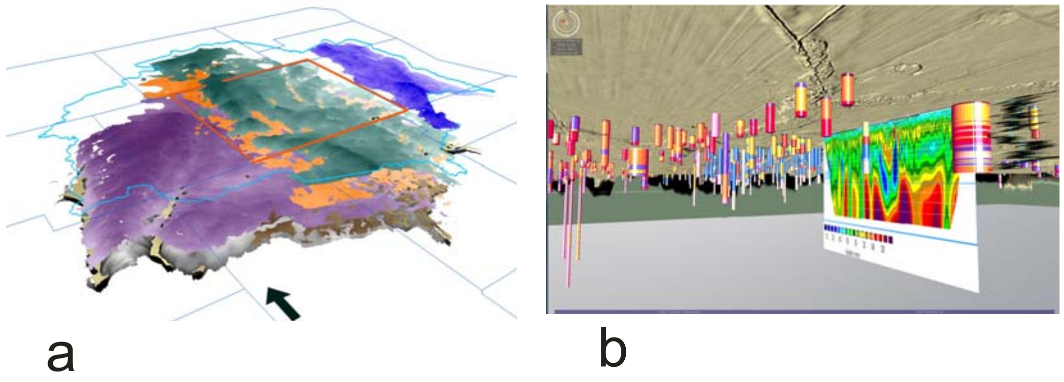

Figure 2. (a) Perspective view from southwest of selected surfaces from 3D geologic map of McHenry County (county boundary shown in red) as viewed in ArcGIS. (b) Visualization of subsurface data in Geovisionary.

Building a 3D GFM based on interpolation of individual 2D surfaces is often painstakingly tedious and may often underrepresent the sedimentological nature of the geologic contacts (e.g. erosional scour relationships). Thus, GSI3-D is also being incorporated into the workflow as a final model-building tool and client-user interface. GSI3-D is a 3D geologic mapping software package developed by Insight, GmbH and the British Geological Survey that constructs 3D maps from cross sections and allows for versatile digitization in a stratigraphic context. Borehole interpretations and interpolated surfaces that are iteratively generated from ArcGIS® and Geovisionary can be viewed in GSI^{3D}® and incorporated into interpretations, and the cross section-based approach allows the geologist to further incorporate sedimentological relationships between stratrigraphic units (e.g. erosional, depositional, etc). In McHenry County, 16 key cross sections, which incorporate the highest quality data drilling and geophysical data, were used as an initial framework for the 3D model (Figure 3). Many additional sections have been included to further delineate geologic complexities at both county and local scales.

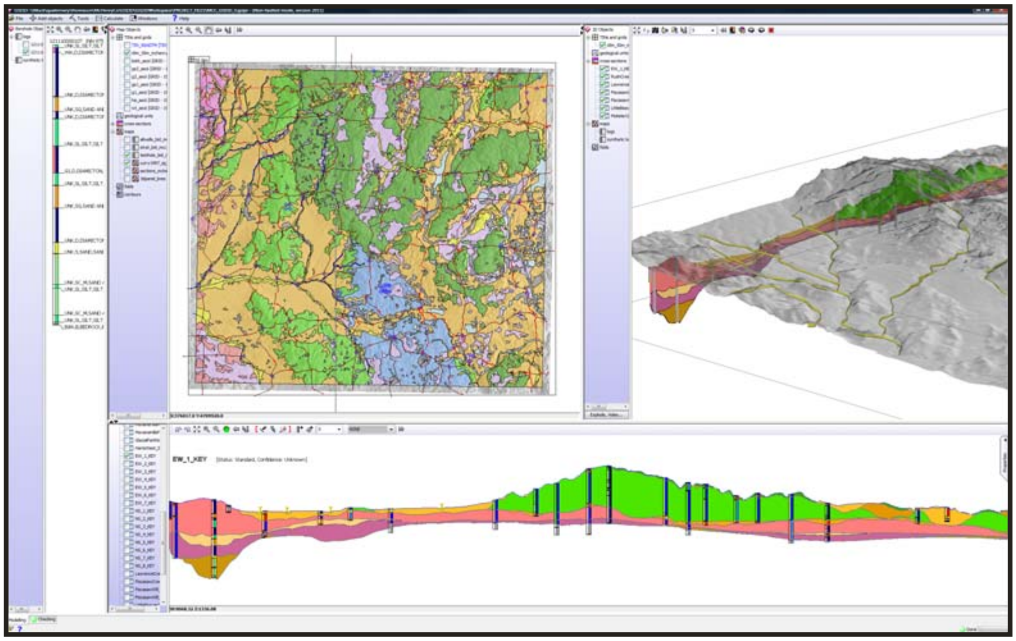

Figure 3. View from GSI^{3D}® showing selected data and interpretations in McHenry County.

3. SUMMARY

The ability to make geologic interpretations while immersed in a 3D visual environment has been a driving motive to developing an iterative approach to geologic framework modelling. Efficient visualization of the available data (borehole, geophysics, maps, cross sections) facilitates the discovery of 3D relationships through 3D perception. These visualization capabilities have been essential to developing a comprehensive GFM in McHenry County, IL. Still, given the limitations in allowable file size, mapping functionality or visualization capability of individual software applications, a multi-tool workflow has allowed for efficient geologic model construction while incorporating some of the highest resolution data available. Testing this workflow with other projects and applications will most certainly provide feedback to help improve efficiency, provide insight into further software development, or even exploration of other software packages.

4. REFERENCES

Chicago Metropolitan Agency for Planning, 2010. Water 2050, Northeastern Illinois Regional Water Supply/Demand Plan, March 2010, 186 pp.

Curry, B.B., R.C. Berg, and R.C. Vaiden, 1997, Geologic Mapping for Environmental Planning, Illinois State Geological Survey Circular 559, 92 pp.

Keefer, D.A., 2011. Chapter 10: Illinois State Geological Survey: A Modular Approach for 3-D Mapping that Addresses Economic Development Issues. In R.C. Berg, S.J. Mathers, H. Kessler, D.A. Keefer (Eds), Synopsis of Current Three-dimensional Geological Mapping and Modeling in Geological Survey Organizations. Illinois State Geological Survey Circular 578, Champaign, Illinois, pp.53-59.