Three-Dimensional Geologic Modelling for Groundwater Applications in Ontario

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Summary

The Ontario Geological Survey (OGS) has recently initiated a program of groundwater mapping under which a series of projects designed to provide geoscience information for the identification, protection and sustainable use of provincial groundwater resources have been launched. Highlights of the groundwater program to date include the development of seamless map products, 3-D modelling of bedrock aquifer units, the delineation and characterization of a buried bedrock valley network, development of a regional karst map, mapping ambient groundwater geochemistry and the focus of this abstract, regional-scale three-dimensional (3-D) modelling in thick drift.

Introduction

The May 2000 tragedy at Walkerton, Ontario, which resulted in the loss of seven lives and thousands becoming sick from drinking contaminated municipally-supplied water, focused the attention of both the public and government regulators on the importance of protecting and preserving the quality and sustainability of provincial groundwater resources. Ontario's recently enacted Clean Water Act legislates the implementation of watershed-based source water protection plans designed to protect the health of Ontarians. An important component of these plans is the development of 3-D regional groundwater flow models that are based on a sound understanding of the properties and architecture of subsurface geologic materials.

3-D Modelling in Thick Drift Areas

To assist groundwater flow modelling efforts, the OGS has undertaken a series of focused, regional scale 3-D models of thick Quaternary deposits in high priority areas of southern Ontario. Projects to date have been undertaken in: the Regional Municipality of Waterloo, the Barrie-Oro Moraine, the Brantford-Woodstock and the Orangeville-Fergus areas of southern Ontario. The goals of these projects are to reconstruct the Quaternary history of each region, produce a 3-D model of Quaternary sediments, characterize the geologic properties of potential aquifer and aquitard units, delineate possible recharge areas and areas of aquifer vulnerability and finally create a series of products that can be used by a diverse client base. As our knowledge and experience in developing 3-D models has grown, a number of modifications and advances have been made that have served to improve and streamline the development process and to improve the overall quality of the models. A few of the areas where recent advancements have been made, including data acquisition, modelling techniques and product development, will be reviewed.

Data and Data Acquisition

Water Well Information and Hydrogeologic Characterization

The OGS has typically utilized only specific bits of water well data in the development of 3-D models such as the provision of basic geologic information and, as a check, screen depths to ensure modelled aquifers coincide with where people are extracting water. Other information contained in water well records such as static water level or pumping test data has not been utilized to any great degree and depending on the nature of the model area, this is a lost opportunity. In the Barrie – Oro Moraine area of central Ontario for instance, drift thicknesses are typically in excess of 100 m and may be as much as 250 m so water wells are typically screened in overburden aquifers. Many of these wells have both screen depth and static water level information that can be displayed on the borehole trace alongside the geological materials. In many parts of the study area, and particularly where data is sparse, this information provides a useful guide for identifying which of the 11 modelled overburden aquifers the wells are screened in.

Information contained within each water well record can also provide useful data for hydrogeological characterization of the modelled formations. The presence of water well screens completed in modelled aquifer units provides verification that the unit identified is being used for water supply. Water level data for individual wells can also be plotted on model cross sections, and the interpretation of this data along with stratigraphy, can provide further insight into whether the identified aquifers are confined or unconfined. The degree to which an aquifer is confined directly affects the vulnerability of that aquifer to surface contamination, which has source water protection and human health implications. Water well records also contain pumping test data for each well, from which hydraulic conductivity and transmissivity can be estimated and applied across an aquifer.

Potential aquifers identified in our models in which water well screens are not present can represent deep, previously uninvestigated buried bedrock valley and channel infill sediments. By constructing wells in these deep systems we have been able to evaluate the relative groundwater ages and recharge cycles through sampling. Through pumping and slug tests, it has also been possible to evaluate the hydraulic properties of these potential aquifers. The investigation for new water sources is feasible only after the baseline of excellent quality 3-D modeling of the overburden sequence is complete.

By utilizing data contained in water well records that had been previously ignored or under used, valuable additional insights and robustness can be added to the 3-D models.

Expanding our Geophysical Toolkit

Geophysical surveys that are tightly constrained by high quality drilling or exposures can expand our knowledge of the subsurface relatively cheaply and easily. OGS regional-scale 3-D models have been improved by utilizing the results of a variety of geophysical surveys including shallow ground penetrating radar (GPR) surveys in coarse-textured sediments above the water table and much deeper seismic reflection surveys in saturated, fine-textured sediments. Down hole geophysics has been used in various well types to gain additional insight into subsurface conditions.

More recently, this geophysical toolkit has been expanded to include gravity survey techniques. As part of the on-going targeted Dundas Buried Bedrock Valley project in south central Ontario, drill targets were chosen following an assessment of existing records of both high and low quality drillholes coupled with the results of a regional, ground-based gravity survey used to predict the locations of multiple valley thalwegs.

Modelling

Integrating Variable Quality Data

The OGS modelling process is based on a series of 3-D points (referred to as ‘picks’) identifying the upper surface of a given stratum that are manually digitized onto each borehole trace. A particular trace may have any number of picks depending upon the number of strata that can be identified. Additional ‘off-trace’ picks can be added adjacent to or below the borehole traces in order to refine the geometry of the modelled surfaces. The upper surface elevation of each stratum is estimated by extending a user-defined search radius around both real borehole collars and a series of 'virtual' borehole collars created on a regular grid. For each real or virtual borehole, the elevation of the stratum is estimated from all of the picks within the search radius. If less than three picks are found within the search radius, the stratum is considered to be absent and no elevation is assigned.

Recent changes to the interpolation process used by the OGS address the problem of integrating data of varying quality. Under the original mapping system, each pick carried the same weight, or significance, regardless of user confidence in the reliability of the source data. This method worked reasonably well although, on occasion, some of the highest quality data was not honoured. In the new system, each pick is attributed with a quality of either high, medium or low based on confidence in the data source. For example, continuously cored boreholes and exposures are considered high-quality sources, most geotechnical records are medium quality sources and mud rotary monitoring wells, questionable logs and water-well records are considered low-quality data sources. A minimum of 1 high-quality, 2 medium-quality or 3 medium- or low-quality picks are required within the given search radius to assign an elevation to a given surface. These changes result in a surface that both preferentially honours high-quality data and may be more continuous where the data distribution is sparse.

Modelling Thick Valley Fills

Scripted rules within the 3-D modelling software (Datamine Studio®) used by the OGS ensure the stratigraphic integrity of the model is maintained where individual strata are absent whether due to non-deposition or erosion, but do not fully address problems resulting from large and rapid changes in elevation. For instance, in areas where large tunnel valleys have cut through older glacial strata and the valleys subsequently partially filled by younger sediments, the modelled surfaces of the older upland sediments are pushed down below the elevations of the younger channel-fill sediments. However, the sides of the valleys end up draped in thick wedges of older sediments and a series of ridges cover the valley bottoms. The cells near the valley sides have elevations estimated from both the uplands and the valley bottoms, which may be as much as 150 m lower. Recent modifications to the customizable interface within the Datamine Studio® application allow the surface elevations of the 'upland' and 'valley' strata to be modelled separately. A 3-D clipping surface is used to carve the valleys out of the upland strata and trim the excess away from the valley strata. Finally, the 2 sets of strata are merged into a single model. This process reduces or eliminates the instances of wedges and ridges along the valleys.

Creating Really Useful Products

The OGS is committed to creating products that can be used by a wide range of client groups ranging from geologists and hydrogeologists to public policy makers. A key part of the process is communicating with clients to find out how they are using both our primary data and the derived models and reports as well as being open to suggestions for improving the way we deliver geoscience information. These improvements might be as simple as adding a two colour aquifer / aquitard classification column to graphic borehole logs or might involve developing new product lines.

Groundwater Resource Studies summarizing the geology and the properties of the modelled hydrostratigraphic units as well as companion digital data sets including grid files of modelled surfaces and abridged versions of the subsurface databases used for the construction of the 3-D surfaces are key program deliverables designed for geoscience specialists.

Other products are geared to a more diverse client group. A cross-section viewer and a .kmz file that portrays transparent overlays of structural contours, isopachs and aquifer recharge/susceptibility maps as well as borehole locations and lithologic information in a webbased (Google™ Earth) environment allows for enhanced user interaction with the spatial data. The cross section viewer enables clients to create stratigraphic cross sections anywhere within the model boundaries by simply clicking on two endpoints. The cross sections can be coloured according to aquifer / aquitard class, individual hydrostratigraphic units or packages of units. Saved cross sections can be viewed in Google™ Earth in conjunction with the map overlays.

How Good Is This Model?

An ongoing challenge for 3-D modellers is to address the questions of reliability and uncertainty within a model while at the same time not undermining client confidence in the overall product. The OGS has adopted a simple visually-based solution. A series of maps have been produced that show the location of picks used to interpolate each model surface. The picks are shown as dots that have been colour-coded according to the reliability of the source data and off-trace picks used to refine the model surface are shown by an X. The maps show the user exactly how many borings intersect each modelled unit, provide an estimate of the reliability of the source data and give an indication of whether the borings are spread out across the study area or are concentrated in one place. The dot maps are presented beside the isopach map or structural contour map for each strata within the body of the report.

Conclusions

Since the inception of the groundwater program, the OGS has striven to increase the general understanding and knowledge of the subsurface environment while developing products for stakeholders that model the distribution of aquifers and aquitards. The OGS and partner agencies are actively engaged in the search for 'new' groundwater resources that will enable sustainable development and allow for healthy community growth. The broader benefits of this work include: 1) inputs to land-use management plans; 2) providing direction on protection issues; 3) assessing the accuracy of models; 4) providing information for assessing and resolving public heath issues; 5) assisting with the development of science-based policy; and 6) informing the general public.