Techniques for 3D Geological and Hydrogeological Modeling. A Case Study of Conawapa Generating Station.

Sharif, S., Mann, J.D., & Smith, J.B.
KGS Acres, Winnipeg, Manitoba, Canada
Cook, G.N.
Manitoba Hydro, Winnipeg, Manitoba, Canada

ABSTRACT
As part of stage IV design studies for the proposed Manitoba Hydro Conawapa Generating Station, a 3D geology model was created. The process involved compiling all information including historical data from old file formats, and dealing with Conawapa's unique site location, geology, and groundwater conditions, as well as challenges related to amassing data collected over many years of investigations. This case study also presents the challenges related to translating the 3D geological model into its equivalent form for groundwater simulation purposes.
The 3D geological model (compiled in MVS 'Mining Visualization System' by C Tech) and hydrogeological model (compiled in FEFLOW 'Finite Element Flow' by DHI-WASY) were developed as tools to consolidate and improve the designer's ability to visualize all of the available geological and geotechnical information; and to assist with evaluating and improving confidence in the design. The tools may also provide input for use in environmental studies.

RÉSUMÉ
Dans le cadre des études de phase IV de conception pour le projet d'Hydro-Manitoba station Conawapa, un modèle géologique 3D a été créé. Le processus a impliqué la compilation toutes les informations, y compris les données historiques à partir de formats de fichiers anciens et de traiter avec l'emplacement de Conawapa site unique, la géologie, et les conditions des eaux souterraines ainsi que les défis liés aux données recueillies au cours amasser de nombreuses années d'enquêtes. Cette étude présente des cas, également, les défis liés à la traduction du modèle géologique 3D dans sa forme équivalente à des fins de simulation des eaux souterraines sont pris en compte.
Le modèle géologique 3D (compilées dans les système d'exploitation minière de visualisation 'MVS par C Tech) et le modèle hydrogéologique (compilées dans les flux d'éléments finis "FEFLOW par DHI-Wasy) ont été développées comme des outils pour consolider et améliorer la capacité du concepteur de visualiser l'ensemble des à disposition des informations géologiques et géotechniques, et pour aider à évaluer et améliorer la confiance dans la conception. Les outils peuvent aussi fournir des données pour une utilisation dans les études environnementales.

1   INTRODUCTION

Three Dimensional (3D) applications have expanded worldwide in the last few decades. Traditional (historical) technological and data handling limitations typically resulted in Two Dimensional (2D) mapping products, and analysis of geological data using cross sections. In response to geological agencies' desire to map and communicate the value of natural systems to modern society (outside of the industries of natural resource exploration and extraction), 3D methods have become prevalent (Thorleifson et. al., 2010; Berg and Leetaru, 2011). Recent transitions to 3D mapping are possible due to technology advances in digital cartography, Geographical Information Systems (GIS), data storage, analysis, and visualization tools. While not a replacement for traditional 2D methods, 3D methods can improve subsurface depictions of materials and structures, which is useful in resource and engineering projects.

Active 3D modeling practitioners include Matile and Keller (MB), Bajc and Burt (ON), Russell (Geological Survey of Canada), Berg (IL, USA), and Thorleifson (ND and MN, USA). As well, electronic geological datasets are being amassed worldwide on internet sites such as OneGeology (http://www.onegeology.org/). Common key themes with 3D geological modeling projects include the need for normalized, high quality data, a robust data handling scheme, and the capability to exchange information between proprietary software platforms. All of these challenges are typically faced in 3D modeling projects, among others.

This paper presents the 3D modeling methods, and techniques applied to create a 3D model for the site geology and hydrogeology at the proposed Manitoba Hydro Conawapa Generating Station. Data for modeling were collected from historical studies carried out between the early 1960s and 1990, in addition to data from more recent site investigation programs between 2006 and 2010. Significant understanding has been developed with respect to the regional and site engineering geology, the foundation conditions for the principal structures, and the quality and availability of construction materials. Modeling site geology was based on the accumulated knowledge collected from these investigations.

The Conawapa site (Figure 1) is situated on the Nelson River within the Hudson's Bay lowlands.
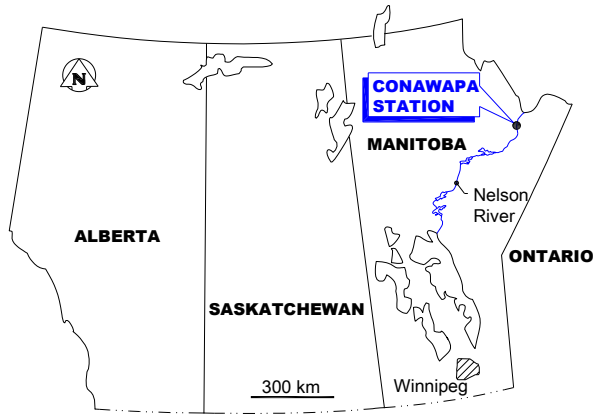
Figure 1. Location map of proposed Conawapa GS

Bedrock in the region consists of gently northeasterly dipping Ordovician aged strata (karstic limestones, dolomitic limestones and dolomites). Precambrian granodiorite gneiss bedrock is found at depth below the limestone strata. At Conawapa, the bedrock in the

southern portion of the Nelson riverbed is cut by more recent erosion that has resulted in a 30 m deep, alluvium filled trough (Figure 2).

The limestone bedrock at Conawapa is overlain by variably saturated and stratified overburden sediments, including clay, silt, sand and gravel preglacial sediments, transitional glacial/preglacial slickensided clays, glacial silty clay till (up to 60 m in thickness), interglacial intertill clays, silts, sands, and gravels, and postglacial clays, silts, sands and gravels, and discontinuous peat. Overburden strata at the site are often permafrost affected. Within the Nelson River, approximately 3 to 5 m of recent alluvium overlies the bedrock surface. The alluvium thickens to as much as 20 m in downstream areas of the river channel, and up to 30 m within the river bottom thalweg. The river alluvium is comprised of clean sand and gravel, with a thin (0.3 to 1.0 m) surficial armouring of cobbles and boulders, and is periodically underlain by zones of silty sand, silts and clays.
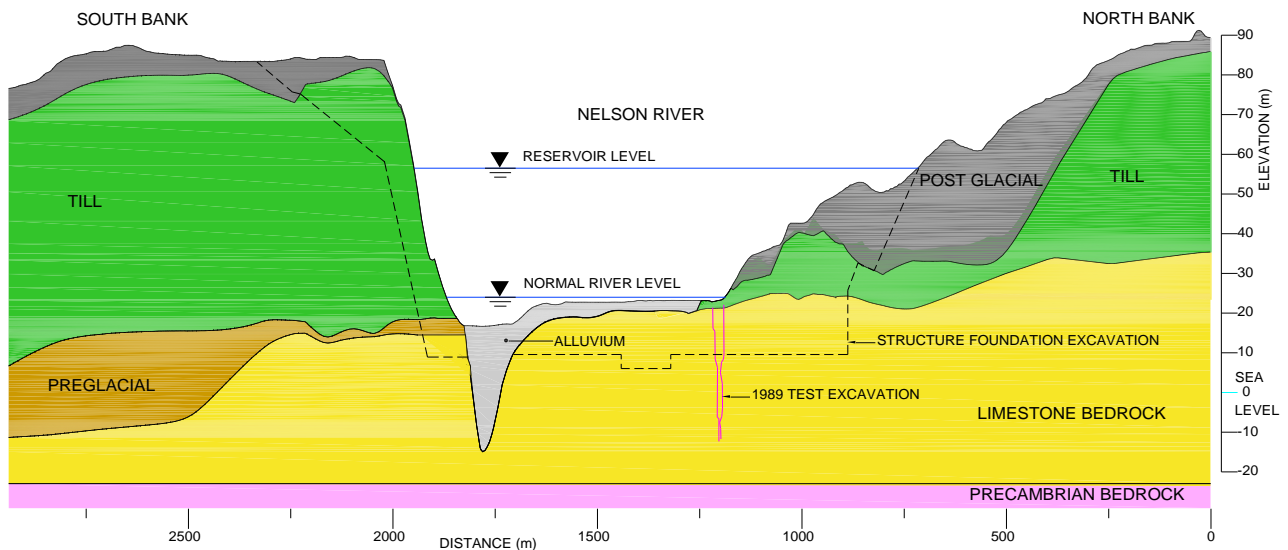

Figure 2. General stratigraphic cross section at the proposed Conawapa Generating Station, looking upstream.

2   DATA HANDLING

Data used to compile the model included historical information; in particular geological and geophysical investigation reports and composite borehole logs. Many of the older drawings were available only as hard copy, in particular the geophysical drawings from the seismic refraction investigations. Borehole logs were available in older gINT file formats, which were translated to a newer standard Microsoft Access database file format for use in the modeling studies.

The geophysical 2D profiles were digitized and translated to 3D drawings using custom computer

programs written in Visual LISP (the native built-in programming language for AutoCAD). Figure 3 shows the seismic lines in 3D compiled in one AutoCAD drawing.

Other tools created in-house were used extensively to parse and analyse the original borehole log database and alter the database structure to a query-ready format. For example, some of the key geological information required for model inputs was often saved within a long text-based "description" database field. Most of these programs were written in Visual Basic (VB) and Visual Basic for Applications (VBA). All data translation was also manually verified against the original logs, where possible.
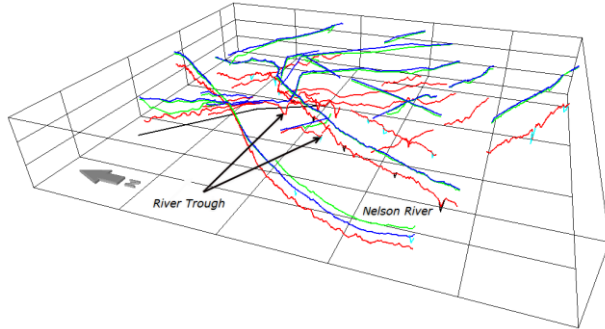
Figure 3. Seismic refraction profiles, translated from 2D drawings to 3D lines. Scale grid 1 km x 1 km x 25 m

Coordinates were converted to Universal Transverse Mercator (UTM) North American Datum of 1983 (NAD83) coordinate system for all project data. ESRI GIS software was used as the main software to handle any coordinate translation, and borehole location verification. Figure 4 shows a 3D representation of borehole locations at the site.

Computer applications were also created to handle translation of data between the geology modeling, groundwater simulation, AutoCAD, and AutoCAD Civil 3D applications.
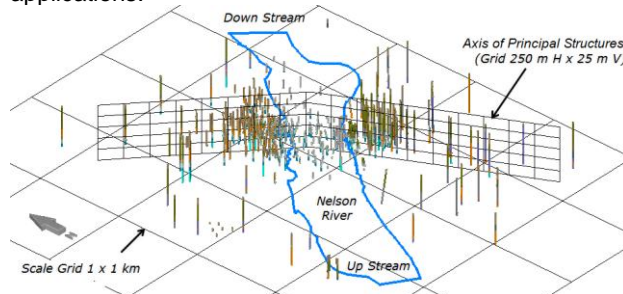

Figure 4. Sample visualization of the borehole logs.

3   COMPILING THE 3D GEOLOGICAL MODEL

Different geological modeling software packages were reviewed. Selection criteria were based on features, flexibility, expandability, documentation, support services, cost, and ability to exchange data with engineering design applications. Mining Visualization System (MVS), developed by C Tech Inc., (www.ctech.com) was used to create the site 3D geology model. MVS is a module-based software program where the user connects customizable "tools" or "modules" to perform a series of computational, translational, or visualization tasks (Figure 5). This type of flexibility in the software allows for fully customizable modeling of complex natural systems.

MVS also has semi-automated built-in tools to create 3D geological models, with limited user-application of a site conceptual geological model. These approaches were used at the early stages in the modeling study as a screening tool to identify areas where additional work was required to generate a representative model.
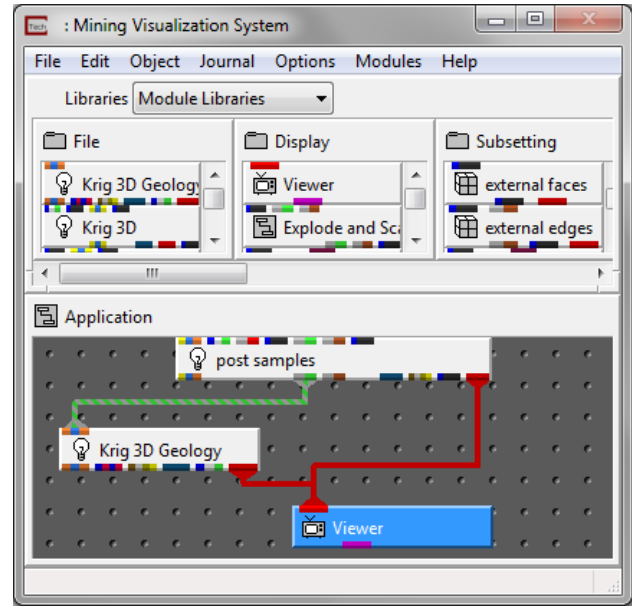

Figure 5. MVS interface showing a sample application

FEFLOW was used to simulate groundwater behaviour for the site in 3D. FEFLOW is a professional software package for modeling fluid flow and transport of dissolved constituents and/or heat transport processes in the subsurface. It is developed by DHI-WASY GmbH (www.feflow.info). The following subsections discuss some of the issues and challenges addressed in the Conawapa modeling process.

3.1   Model Grid

The data structure used by FEFLOW to represent a 3D groundwater model is based on a Triangulated Irregular Network (TIN) mesh, which covers the model space in the X-Y domain. The mesh is extruded in the Z direction in multiple layers, with each layer continuous throughout the model domain. The number of 3D prism elements in all layers is equal, which is the same as the number of the 2D elements in the base mesh. The model requires a minimum thickness to be assigned to elements where a geological unit is pinched out (typically 0.1 m or less).

By default, MVS uses eight node hexadron elements to build its model. This is changed by using an external TIN mesh to create a model of six node prism elements similar to FEFLOW.

The TIN mesh (Figure 6) was chosen for the final model generation for the following reasons:
1-   Flexibility in mesh design. Nodes can be added at any location as needed, such as at borehole locations.
2-   Size of the mesh elements can vary significantly which allows using larger elements at areas of sparse data and where less detail is required, hence reducing the computational time for model generation
3-   Allows for better representation of irregular shapes and steep slopes within the model domain.

Like many engineering and technical computer applications, both MVS and FEFLOW allow to import and export most of its input data and output files in readable

text based formats (also known as ASCII "American Standard Code for Information Interchange"). This feature allows programmers to expand software usage by writing external applications to generate input files, and analyse or edit output files. Both software documentations include brief descriptions for most of their text file formats.

Design of the base mesh was carried out inside an AutoCAD application. The mesh points were located based on detailed modeling requirements and borehole locations, and expansion of node spacing in data sparse, or less critical modeling areas was completed programmatically using in-house Visual-LISP programs.

Additional mesh nodes were added at areas of steep topographic or surface changes, such as at the south river

bank and the deep bedrock river trough. The mesh nodes were exported to an ESRI GIS application to add elevation values from the LiDAR model. The LiDAR was comprised of topography and river bathymetry data. The new set of 3D points were used to create a 3D topography surface using AutoCAD Civil 3D and exported in LandXML file format (LandXML is a standard file format for sharing civil engineering and survey data).

A Visual Basic application was designed to translate from Land XML to the native input file format used by MVS (.EFF file format). This EFF file was used as the base mesh for the geology model. The next step in model generation involved determination of the geological hierarchy, and strata to be represented within the model.
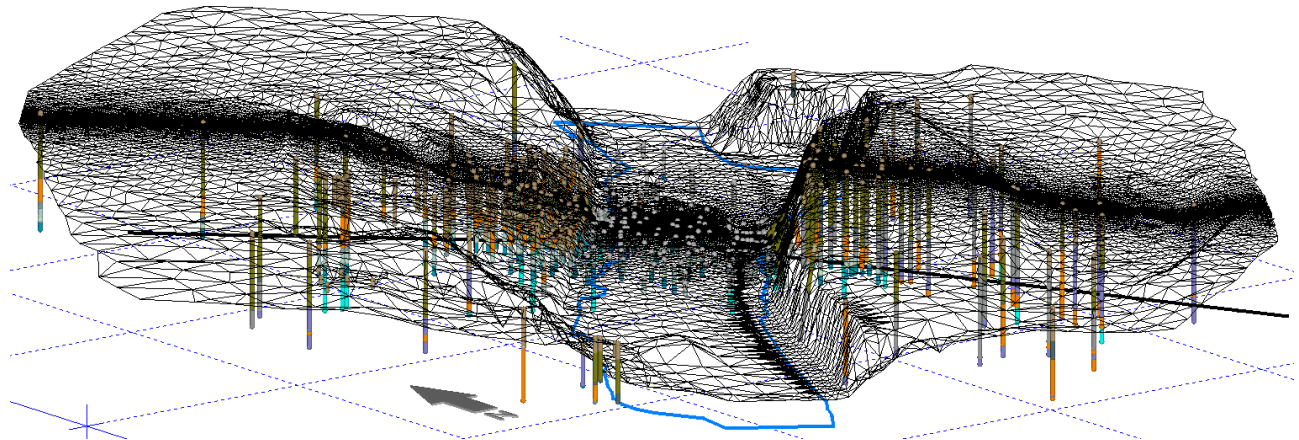

Figure 6. TIN mesh used for the final Conawapa geology model. Scale grid is 1x1 km.

3.2   Interpolation/Extrapolation Methods

Geology does not always follow statistical rules; however statistical algorithms (i.e. kriging) to interpolate existing available geological data were used. The MVS "Krig_2D" module was used to individually interpolate data for each geological unit. Krig_2D allows for using an external grid and provides several different interpolation algorithms. Tests carried out to compare these algorithms showed that the statistical "Kriging" algorithm provided the best results compared to other mathematical algorithms (mainly Inverse Distance Weighting "IDW" set with different control and search parameters). Similar findings were reported by MacCormack et. al.(2011).

3.3   Geological Hierarchy

Historical studies for the proposed Conawapa site include a large amount of excellent 2D work related to geology, stratigraphy, and site characterization. When this work was combined with the updating of the electronic gINT database, it was directly used as input to define the conceptual model for the site on a borehole-by-borehole basis, and using judgment to define the model input data.

Early phases of modeling site geology used a simplified set of units. Till strata were combined into one, and later divided into three units based on detailed field logging (i.e. upper till sheet "till1", intertill, and lower till

sheet "till2"). Similarly, with detailed logging information and available 2D cross section interpretations, preglacial deposits were divided in later modeling phases into five units (a till/preglacial transitional unit, and 2 fine, 2 coarse grained units).

Other overburden units included; postglacial deposits (PGD), and gravel over till (GOT). The complete list of final site stratigraphy included, in top to bottom order, Alluvium, PGD, GOT, tills (three units), preglacial deposits (five units) followed by carbonate bedrock (seven units). The model includes 19 geological units in total.

3.4   Handling Differences in Geological Units between North and South Bank

There is a lack of continuity of some of the geological strata between upstream and downstream areas, as well as between the north and south banks. As a result, most geological units are not continuous in all areas of the model domain.   Bedrock Unit 8, for example, has not been mapped on the south bank. Interpolating the distribution of this unit using north bank bedrock contact elevation data can, however, project some thickness of Unit 8 in areas of the south bank, where exploration borehole data indicates that bedrock Unit 8 is not present. Model compilation techniques, combined with good judgement, were critical in producing a representative geological model for the project.

One possible option to mitigate this issue was to introduce additional control points to data files to apply zero thickness in extensive areas where particular geological units are not present. This solution, incorrectly, affects interpolation results elsewhere within the model, particularly where data is sparse. As an alternative, the thickness data associated with discontinuous geological units (such as bedrock Unit 8) was constrained to minimum (zero) thickness using the "Field Math" and "Area Cut" modules inside MVS. Using this method, the limits of the geological strata on the north bank were defined within an area based on available borehole data and the overall conceptual understanding of site geology. Inside these limits, the model was allowed to interpolate the occurrence of the strata based on the available data. Outside the defined limits, minimum (i.e. zero) thickness is applied. The same technique was used on other strata on a case-by-case basis, as required.

3.5 Modeling Thin Geological Units

Interpolation (kriging) of elevation values for thin geological units present at Conawapa (e.g. postglacial gravel over till zones, inter till zones, transitional till/preglacial sediments, and underlying preglacial sediments) often created a non-representative model. Large thicknesses of these typically thin strata would be projected into areas of sparse borehole data. To control these modeling anomalies, these thin units were created by kriging thickness values instead of top or bottom geological contact elevation values. The elevation values for strata interpolated by thickness were computed by either subtracting thickness from base surface of the unit above, or adding the interpolated thickness to the top surface of the unit below. Control surfaces of well defined geological contacts (such as the topography, base of till, and bedrock surface) were also used to constrain the interpolation of these thin geological units. The kriged results had to "fit between" defined control surfaces. Sections 4 and 5 discuss modeling methods in detail.

3.6 South Abutment - Deep River Bedrock Trough

While the significant number of boreholes in the river area helped to understand the shape of the deep bedrock trough located close to the south abutment, these boreholes alone were not enough to create a more extensive bedrock surface shape in this area. Data from seismic refraction investigations throughout the Conawapa site provided secondary level information for the shape of the river bed, as well as for the top of bedrock. A list of 3D points was extracted from these lines and added to the data files, and was used to fine-tune the shape of river bed and top of bedrock. These lines were sometimes adjusted to match any nearby borehole logs, if warranted.

Due to the steep side slopes of this erosional feature, kriging elevation values of geological contacts tends to average available values, creating a non-representative surface. To fix this and in order to extend the shape of the feature through the larger model domain; additional bedrock points were included in the data file before kriging. These included points created by linearly interpolating between the bottom of the trough and points created by linearly interpolating between top edges of the trough. The surface created from this process was used in the final modeling procedure to cut all units that are eroded by the river. By this method, the pre-erosion interpolation of the bedrock strata was modeled, followed by "cutting in" of the overlying alluvium shape, defined by the cutting surface, which included the bedrock trough feature. In this way, rules of superposition were maintained, and unit thicknesses at erosional contacts were preserved, rather than "thinning" and "draping" over underlying stratigraphic surfaces. Such techniques have been applied successfully by others in the past (e.g. Burt and Bajc, 2007).

3.7 Compatibility between Geology and Groundwater Simulation Models

The goal for the 3D geology model was not limited only to geological visualization purposes (Mann et. al., 2008), but was also envisioned as a design tool. Computer applications, written in Visual Basic, were designed to translate the models between MVS and FEFLOW. Compatibility between both models was achieved by assigning material properties to each FEFLOW model element (prism) from its spatially equivalent element in MVS, even though the mesh design between the two models was not exactly alike. Techniques such as this have been documented in the literature (e.g. Smirnoff et. al., 2011).

4 EVOLUTION OF THE 3D GEOLOGY MODEL PROCESS

The Conawapa modeling process evolved in four major phases:
1- Using MVS built-in capability to create the model directly. "Krig_3D_geology" and "map_geology" modules were used to create the site geology in one step. This phase was essential to examine the integrity of the data and visualize different geological units. It was used, also, to ensure that the geological hierarchy was properly defined. Many control points were incorporated to refine some details (bedrock river trough area for example).
2- Using a custom, externally defined mesh, a much better model representation was created. The model was compiled one geological unit at a time, starting from the topography, working downward to the base of the upper till sheet. The base of the lower till sheet was not identified in many shallow borehole logs; hence, it was not reliable to build other geological units beneath it. As a result, geological units between the top of the bedrock and bottom of the lower till sheet were created from the bedrock surface, moving upward. The "top to bottom" and "bottom to top" models created two potential surfaces for the bottom of the lower till sheet. An MVS application was designed to find the differences between these two surfaces. Both surfaces were matched in subsequent

model iterations, incorporating additional control points into the lower till sheet data.

Each unit was created by kriging either the elevation or the thickness data for the borehole log. In the case of thickness kriging; elevation was calculated either by subtracting thickness from upper unit or adding thickness to lower unit, depending on which unit was created first. Top-bottom and bottom-top iterations were applied whenever necessary, to optimize the model and minimize clashes between adjacent geological surfaces. This model technique was suitable for direct translation to other applications especially to groundwater simulation applications. Localized steep geometrical changes in some areas of the model, however, created draping surfaces and pinch outs, which caused numerical instabilities in groundwater modeling FEFLOW applications.

3- Since direct geology model translation to groundwater simulation software (i.e. using identical slice surface geometries) was not highly stable within the groundwater modeling environment, a third approach was taken to construct geology and groundwater models separately, with mesh and slice designs optimized within each model. The model for groundwater simulation was created using many mesh slices with much less elevation variance. As well, some geological strata were lumped into hydrostratigraphic units within the groundwater model. Hydraulic conductivity values were assigned to each element of the groundwater model by acquiring the material type for the element centroid from the MVS model. An MVS application, as well as a stand-alone computer application was written (in Visual Basic) to handle acquiring and assigning material types from MVS to FEFLOW (Figure 7). This process assured maximum compatibility between both models in terms of geology and stratigraphy, but allowed use of independent mesh and layer/slice designs.
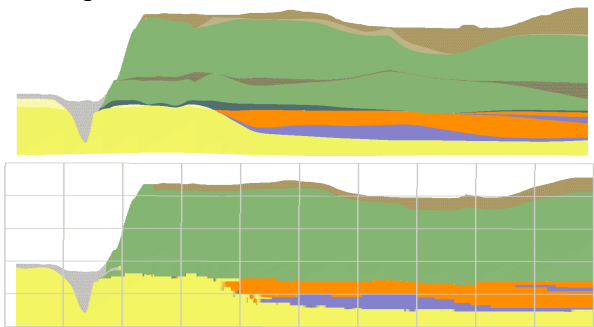

Figure 7. Profile along main axis on the south bank in geological model (MVS, top) vs. hydrogeological model (FEFLOW, bottom). Scale grid is 250 m H x 25 m V

4- In the final modeling process, some geological surfaces (well-defined bottoms or tops of geological units) were identified as "control surfaces". These included; topography, bottom of alluvium, bottom of the upper tills, and top of bedrock. Visualization of the final model is shown in Figure 8. The final modeling workflow was simplified to exclude the sequencing of

geological surface interpolations and clash resolution using "bottom to top" modeling. Independently kriged geological units were inserted between appropriate control surfaces, honouring borehole data, and rules of superposition. As well, key bedrock units were created first, and contact data for eroded river areas were removed from the data set for primary interpolation. The resulting bedrock surfaces did not include the deep bedrock river trough (erosion). Each surface was then cut using the bottom of alluvium surface (i.e. one of the key control units). The detailed report (a portion of which is shown in Figure 9) of the final workflow is considered an important result of the study.
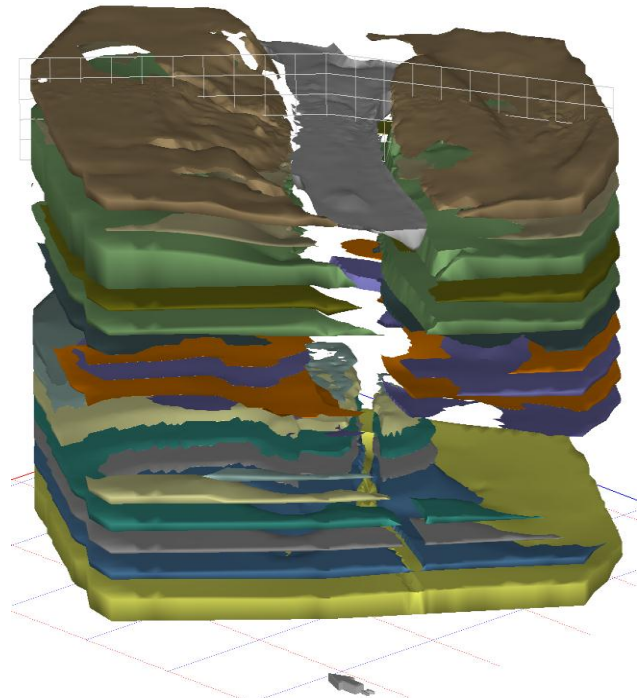

Figure 8. Final MVS geology model (exploded) for Conawapa, looking downstream. Basal scale grid 1 x 1 km. Grid along axis of principal structures is 250 m H by 25 m V.
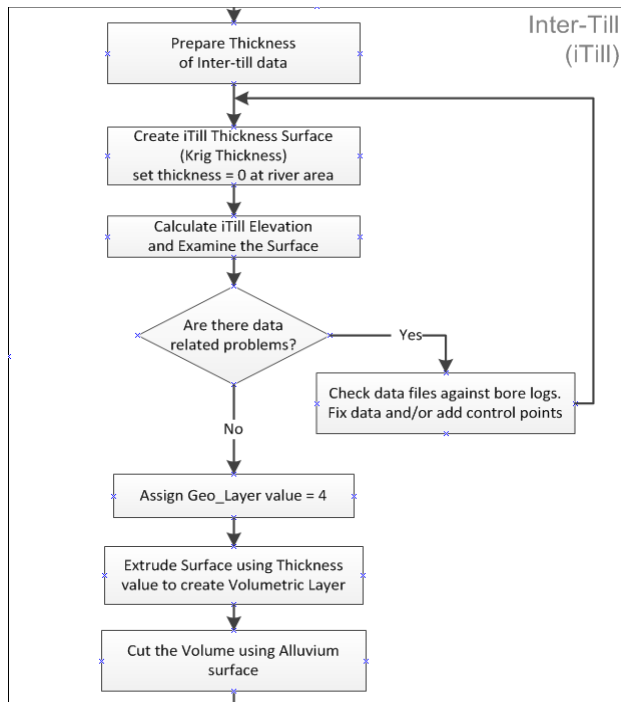
Figure 9. Portion of the illustrated step-by-step report for the geology modeling procedure used for the Conawapa site.

5   FINAL MODEL WORKFLOW

The following summarises the steps taken to create the final Conawapa site geology model:

1- Design and create a mesh to be used for the model.
2- Create the topography surface by projecting mesh nodes on the DEM.
3- Create the river trough surface (the erosional "cut" surface, or bottom of Alluvium) to be used to cut the underlying, volumetric bedrock layers. The trough surface (as well as all other surfaces) will use the same grid from step 1 above. For areas outside the river zone, the cut surface elevation is shifted above ground surface to ensure that it will not create any clashes in those areas.
4- Create other "control" surfaces; which in this case include the top of bedrock and bottom of upper till units. These units are considered as control surfaces because they are well-defined and easy to interpret from borehole logs, typically contain more data picks than other strata and/or the modeller may have a better understanding of the elevation of contacts and the spatial distribution of these strata.
5- Create the remaining bottom of unit surfaces separately from top to bottom. This is done by kriging either elevation values from borehole picks or unit thickness values. In all cases, extra control points may be added as needed. For example, control points can be zero thickness values added in areas where geological interpretation reports indicate that the unit does not exist. The choice between kriging geological contact elevations versus unit thickness values relies mostly on the variance of data. As a rule of thumb, thin geological units can be modeled more accurately by kriging thickness values whereas units with more data "picks" and higher variance in thickness and elevation of contacts could not be modeled easily by kriging thickness values. In these cases, kriging elevation values produce more defendable results. Each surface is compared with the control surface below, in order to resolve surface clashes. Similarly, preglacial units are checked against top of bedrock.

6- Each surface is extruded, using thickness data, to create a volumetric model of the unit. These units will have a pre-erosion shape at the river area. Subsequently, geological units are "cut" using the bottom of alluvium control surface to create the representative erosional shape and truncation of strata along the river channel.
7- Merge all volumetric units into one file. Each node within each unit will contain data representing the geological unit number, bottom elevation, thickness and the cut surface data.

The model is set to show cells that are not cut and have thickness value more than 10 cm.   The geology model is saved as a single file that is manipulated and used for different design and visualization purposes.

Figures 10 - 12 illustrate some examples of how the model was used to show the site after excavation, and visualization of the geological units along proposed grout curtain alignments.
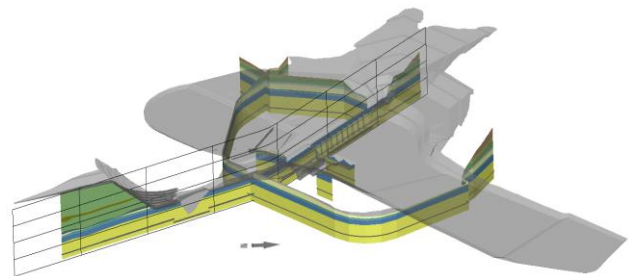

Figure 10. Excavation surface (grey) with geology units mapped on proposed grout curtain alignments. Scale grid along axis is 250m H x 25 m V
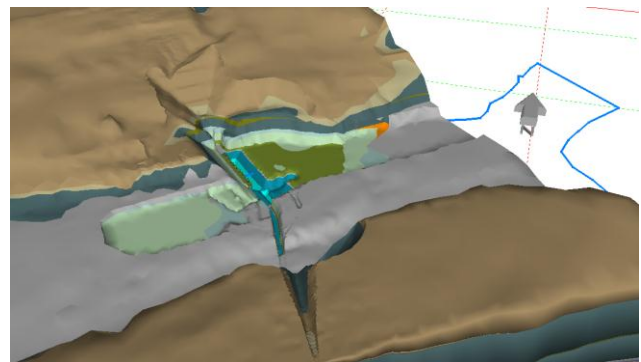

Figure 11. Site geology shown within proposed excavation for Principal Structures.
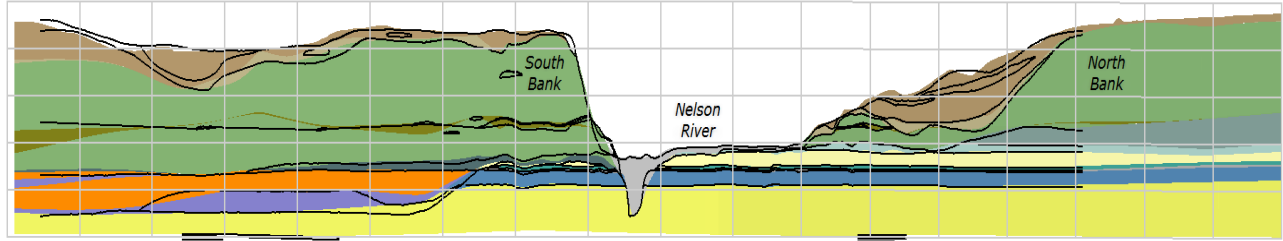
Figure 12. Comparison between historical 2D cross section data (black lines) and MVS geology profile (solid colors) along axis of main structures (looking upstream). Grid scale is 250 m H x 25 m V.

6   CONCLUSIONS

There is no simplified or generic procedure for creating a geological model for a site. The modeller should, in all cases, review all available geological reports and traditional 2D data to gain an understanding of the site geology, and develop a conceptual model for the site. The engineers' or geologists' interpretation of the site in composite borehole logs and in 2D mapping and cross section generation are key elements in creating a 3D model.

Although having normalized and well-distributed soil investigation and borehole data is important to build improved and more representative geological models (especially in 3D), understanding site geology and creating a robust conceptual model plays a bigger role in this process to produce an accurate end product.

The final Conawapa model was considered a representative interpretation and presentation of the site geology. Site complexity did not allow addressing all model construction details in one modeling phase. Breaking down the process, where each phase addressed a specific technical issue (without affecting previously compiled data sets), aided in creating a representative model.

Since there is no standard or generic procedure nor "off the shelf" translation tools for handling data and generating 3D geological models, writing custom computer programs can accelerate data and model property exchange between different computer applications. This allows use of the model in engineering design and analysis applications.

Documenting modeling procedures is a vital step in building know-how that helps in optimizing future geology modeling tasks.

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