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**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7866**

**Spiritwood Buried Valley 3D Geological Modelling – Part
of a Multidisciplinary Aquifer Characterization Workflow**

**C.E. Logan, M.J. Hinton, D.R. Sharpe, G.A. Oldenborger,
H.A.J. Russell, and A.J.M. Pugin**

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Abstract

A three dimensional (3D) digital geological model of the Spiritwood buried-valley aquifer complex in southwestern Manitoba is developed to support quantitative hydrogeological modelling. The model maps the bedrock surface and delineates the various hydrostratigraphic units in three-dimensions. The model is based on borehole logs, surficial geological maps, a helicopter time-domain electromagnetic (HTEM) survey covering 1062 km² as well as 63.5 line-km of high-resolution seismic reflection (HRSR) profiles. A 3360 km² model area was selected within a larger data capture area of ~12000 km². The methodologies used for preparing and interpreting various subsurface datasets to construct the geological model are presented. The 3D geological surfaces were modelled using Leapfrog[®] Hydro software. Multiple episodes of glacial erosion and sedimentation superimposed on a broad pre-glacial bedrock valley have resulted in a complex configuration of buried channels and valleys. The bedrock surface shows major erosional features: i) the broad Spiritwood buried valley, ii) deep valleys incised into shale bedrock within the broad Spiritwood buried valley, iii) narrow, steep-sided valleys both within and outside the broad buried valley, and iv) the modern Souris and Pembina river valleys. This bedrock surface detail is only possible because of the spatial continuity of the geophysical data sets and could not have been practically obtained from borehole records alone. The geological model includes 13 hydrostratigraphic units including sandstone, unfractured and fractured shale bedrock, 3 coarse sediment aquifers, 4 till units and 3 thin, near-surface units. Coarse sediment aquifers include the deep buried-valley aquifer, deep sands and gravels both within and outside the broad buried valley and inter-till aquifers at variable depths throughout the model. The model indicates potential hydraulic connections from surface recharge to the deep buried-valley aquifer and for discharge from the deep buried-valley aquifer to streams. Two digital versions of the model are provided - a 'view-only' format accessible with the freely available Leapfrog[®] Viewer and a Drawing Exchange Format (DXF) that can be imported to many 3D modelling applications.

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Introduction

As part of the Natural Resources Canada (NRCan) Groundwater Geoscience Program's inventory of nationally significant aquifers, the Geological Survey of Canada (GSC) is investigating buried-valley aquifers in the Western Canadian Sedimentary Basin. The Spiritwood buried valley in southwestern Manitoba has been selected as a study area for developing and testing geophysical survey, geological modelling and hydrogeological methods for buried-valley characterization. The integration of these multi-disciplinary components into a streamlined workflow is important not only for effective characterization of the Spiritwood buried valley but also towards developing more efficient approaches to studying buried-valley aquifer systems in glaciated terrain elsewhere in western Canada and the U.S.A. This Open File reports on the development of a 3D digital geological model of the Spiritwood buried valley in southwestern Manitoba and along the border of North Dakota. The primary aims of the model are to map the bedrock surface and to delineate the hydrostratigraphic architecture of sediments filling the Spiritwood buried valley, in particular the distribution of buried-valley and inter-till aquifers within the widespread regional till aquitards. The 3D model will support improved insight into groundwater flow dynamics and groundwater resources of the Spiritwood buried valley through development of a hydrogeological model.

The existence of prairie buried-valley aquifers has been known for well over a century (e.g. Bell, 1884; Dawson and McConnell, 1884; see Cummings et al., 2012a). The general courses of main buried channels have been mapped primarily using water well log data from northern Alberta to North Dakota (e.g. Paulson, 1983; Maathuis and Thorleison, 2000; Betcher et al., 2005). Within the study area, the location of the Spiritwood buried valley was broadly delineated using boreholes and wells by Sie and Little (1976) in Manitoba and by Randich and Kuzniar (1984b) in Towner County, North Dakota.

The Spiritwood buried valley is eroded into the shale bedrock and extends from southwestern Manitoba, through North Dakota and into northeastern South Dakota forming an approximately 500 km long branch of an estimated 20,000 km network of buried valleys that span the Western Canadian Sedimentary Basin (Figure 1). Aquifers deposited within or along this valley are commonly identified as belonging to the Spiritwood aquifer system which includes buried-valley aquifers, basal aquifers along or near the bedrock surface and inter-till aquifers.

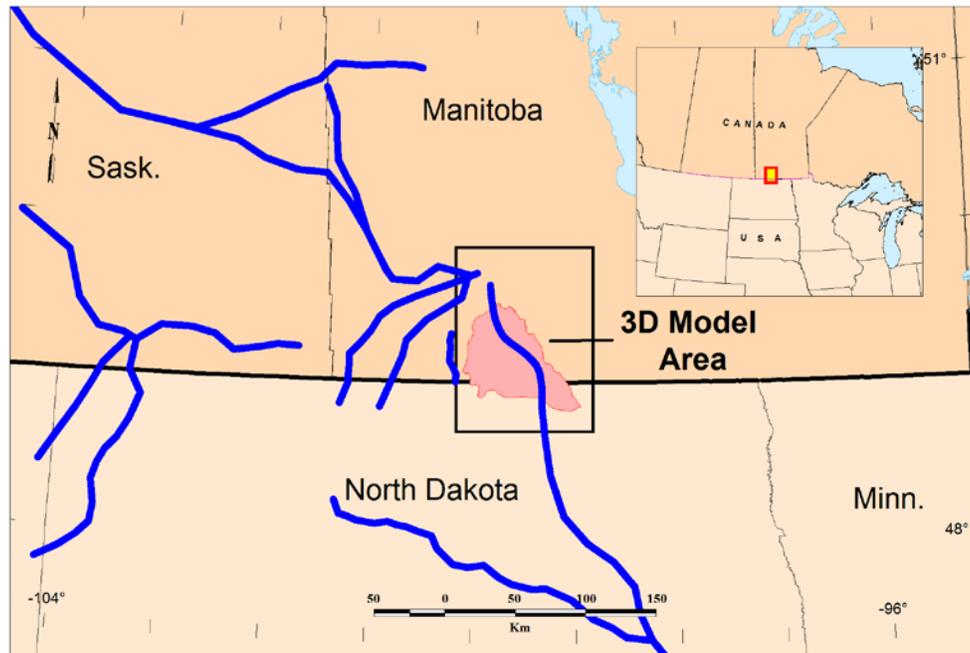


Figure 1. Spiritwood buried-valley 3D model area location (red area). The larger data capture area (black rectangle) and the approximate locations of the Spiritwood and nearby known buried-valley thalwegs are also shown (blue lines); (based on North Dakota State Water Commission, 1986; Maathuis and Thorleison, 2000; Betcher et al., 2005).

Study Area

The data capture area of ~12000 km² extends from Brandon, Manitoba to approximately 35 km south of the Canada-U.S. border. Within this area, the geological model boundary was selected to coincide with a hydrogeological model area based on watershed boundaries and piezometric surface divides. The entire data capture area was used for preliminary model development and then trimmed to the final model extent to minimize interpolation edge effects. The 3360 km² model area includes the Spiritwood buried valley between the topographic high of Turtle Mountain (approx. 700 m.a.s.l.) and the Souris-Pembina river valleys (approx. 400 m.a.s.l.). The model area includes a HTEM survey covering 1062 km² that was conducted along a portion of the main axis of the Spiritwood buried valley (Figure 2).

The study area is a sparsely populated rural agricultural landscape with some small communities. Killarney, the largest town, has a population of approximately 3400. In southwest Manitoba water usage statistics aren't available, however many rural communities and farms depend on groundwater for domestic supply (Betcher et al., 1995). The Spiritwood aquifer is among the highest yielding aquifers in North Dakota where it is primarily used for irrigation and also domestic supply (Paulson, 1983; Shaver, 1984).

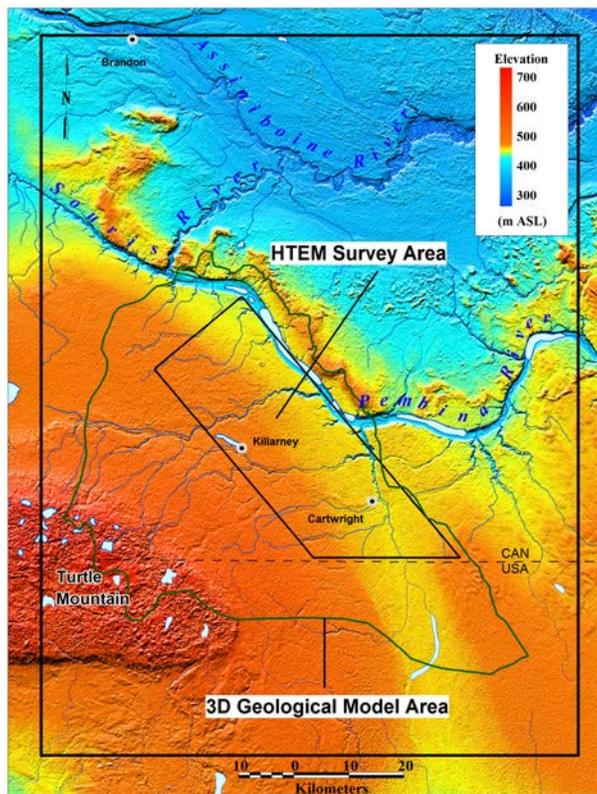


Figure 2. Extents of the 3D geological model and HTEM survey areas overlain on a Digital Elevation Model (DEM) showing hydrographic features.

Data Sources

Surficial geology maps in digital format were obtained from public provincial and state websites to provide surface control for the model. The Manitoba Geological Survey's Surficial Geology Compilation Map Series (SGCMS) (Matile and Keller, 2004a; 2004b) provided seamless coverage for the northern portion of the model area in Canada, while the North Dakota GIS Data Hub web portal provided coverage in the US portion (<http://mapservice.swc.nd.gov/>) (Clayton et al., 1980). Representing the surface expression of the 3D geology, surficial geological mapping is the most readily-accessible and observable and therefore potentially the most reliable data component of 3D modelling. Fine detail was not available in this model area because a large amount of generalization in the production of map polygons occurs with large scale mapping. Map polygons were used help guide the stratigraphic interpretation of water well logs and also to directly control the model geometry.

Over 4300 water well logs were obtained from the Manitoba Water Stewardship via NRCan's Groundwater Information Network (GIN) (http://gin.gw-info.net/service/api_ngwds:gin2/en/gin.html) - a provincial / federal government groundwater data sharing and internet-based analysis and dissemination initiative (Figure 3). To provide comparable data coverage for the portion of the model area within the United States, 551 well

logs were obtained through the North Dakota State Water Commission's comprehensive and publically-accessible website. The North Dakota well log dataset included boreholes drilled to support the development of a series of sub-parallel interpreted cross-sections (Randich and Kuzniar, 1984b). These sections run across the buried-valley aquifer and are spaced from 3 to 6 miles apart with borehole spacing at approximately 1 mile or more. Interpreted sections were also digitized and used to directly control the model. A portion of the Manitoba provincial cross-section series were similarly used to control the Turtle Mountain bedrock structure (Matile and Keller, 2012). Water well logs provide the bulk of the regional geological context for the model outside of the area of detailed geophysical surveys although it is recognized that they are subject to variable accuracy. The wash-boring technique used to economically drill most residential water wells does not always lend itself to complete and accurate reporting of sediment stratigraphy. Sediment textural observations can be obscured by the drilling fluid used to flush out cuttings. The depths from which they originate can also be difficult to determine and are often based on drilling rates, fluid loss and/or drill rig vibrations. The accuracy from log to log is variable and largely based on the skill and experience of individual drillers and the rigor used to record observations (Russell et al., 1998).

The HTEM survey was conducted to help refine the delineation of the Spiritwood buried valley and overlying aquifers. Results were presented both as maps of conductivity for 10 m thick slices between elevations of 300-450 m.a.s.l. and as a 3D set of point conductivity values developed through spatially-constrained inverse modelling of the HTEM data (Oldenborger et al., 2014; Sapia et al., 2014). These results provided a means to visualize and map electrically resistive bodies in unprecedented detail. In general, the most apparent conductivity contrast exists between shale bedrock and all unlithified sediment. The conductivity of sediment is affected by a number of factors including grain size, composition, pore water content and chemistry. Among sediment types, coarse material is generally more resistive while till and fine-grained sediment are usually more conductive particularly at the local scale where sediment types can exhibit unique conductivity signatures that are measurably distinct from one another. However, subtle changes in sediment and groundwater properties over larger distances at the regional scale can introduce enough variability in the measured conductivity to impede purely quantitative differentiation of sediment types (He et al., 2014). Through visual inspection of the 3D conductivity results, regional channel patterns (particularly in bedrock but also within sediment) can be readily observed as defined by relative changes in conductivity.

A series of nine HRSR profiles were collected by the GSC over the model area (Pullan et al., 2013; Pugin et al., 2014). The land streamer technique is a relatively fast and economical method that utilizes a series of geophones towed along roadways behind a seismic source vehicle (Pugin et al., 2009a; 2009b). The seismic results show detailed stratigraphic architecture and relationships in cross section. Additionally, they have greater vertical resolution than the HTEM survey thus allowing for better channel depth estimates.

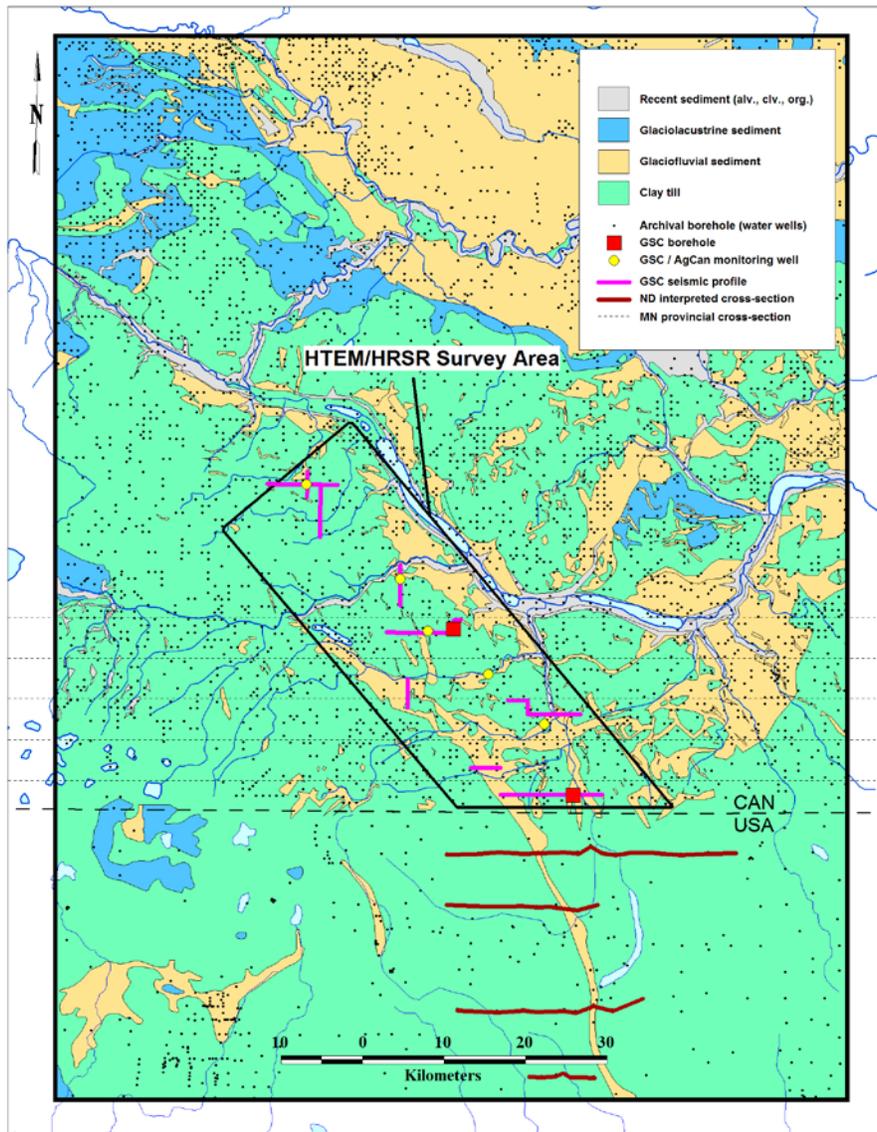


Figure 3. Model area with HTEM survey area, HRSR profile lines, North Dakota (ND) and Manitoba (MN) interpreted cross-sections and borehole coverage shown with simplified surficial geology. Geology adapted from Clayton et al. (1980) and Matile and Keller (2004a; 2004b).

Two GSC boreholes were drilled to provide control for seismic profile interpretations and to record detailed sedimentology, physical, hydraulic and geophysical properties of the sediment in this region (Crow et al., 2012b). These cored boreholes along with shallow cored monitoring wells (Hinton and Sharpe, 2014), deep provincial borehole logs and down hole geophysical logs (Crow et al., 2012a; Crow et al., 2012b) provided the most accurate benchmark for interpreting other subsurface data.

Digital elevation model (DEM) coverage for the model was 30 meter cell resolution converted to 100 meter resolution to match the planned model resolution. The DEM is publically available and was obtained from the joint National Aeronautics and Space Administration – National Geospatial-Intelligence Agency (NASA-NGA) Shuttle Radar Topography Mission (SRTM) (<http://srtm.usgs.gov/index.php>). Figure 3 shows the coverage of the main model data inputs.

Conceptual Geological Model

Valley and channel forms

A general understanding of the geologic setting of prairie buried valleys at the continental to regional scale is summarized by Cummings et al. (2012a; 2012c). These buried valleys formed as a result of two primary geological events: erosion and sediment dispersal from southwest to northeast resulting from Tertiary uplift of the Rocky Mountains and Black Hills; and multiple Quaternary glaciations. The prairie buried valleys were produced by fluvial, glacial and glaciofluvial processes that occurred in pre-glacial, proglacial and subglacial settings.

The high spatial resolution of the HTEM and HRSR results has allowed delineation of multiple channel features at various scales both within and outside the Spiritwood buried valley of southwestern Manitoba. These results have identified three distinct valley or channel types, referred to as α ('alpha'), β ('beta') and γ ('gamma') (Figure 4, Pugin et al., 2014) that reflect multiple episodes of channel erosion and sedimentation.

A broad α valley is eroded into the Odanah member of the Pierre shale and is approximately 10-20 km wide and 70 m deep (Figure 4a). The channel margin side slopes are generally less than 5% and asymmetric (Pugin et al., 2014) with gentler slopes on the western margin and steeper slopes on the east where it is bordered by a near-surface bedrock upland. Based on the large width/depth ratio and lack of gradient on the valley floor, this valley is interpreted to have been formed as a pre-glacial fluvial valley (Pugin et al., 2014). Hobbs and Bluemle (1987) indicate that a late Tertiary river, the ancestral Cannonball river, drained most of western and central North Dakota and flowed northward through Ramsey and Towner counties into Manitoba and towards Hudson Bay.

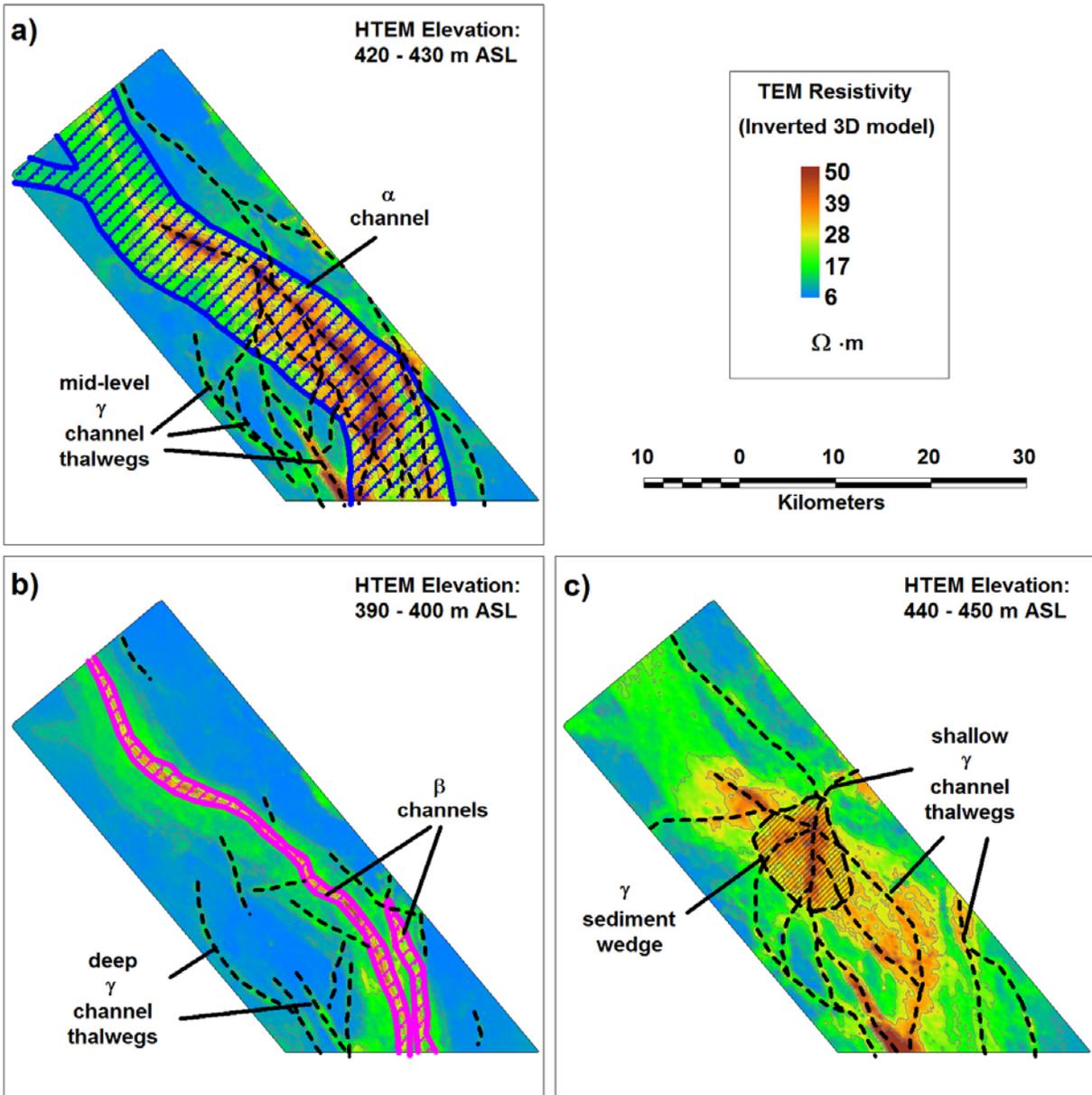


Figure 4. a) 420-430 m ASL HTEM slice showing α channel extents and mid-level γ channel thalwegs, b) 390-400 m ASL HTEM slice showing β channel extents and deep γ channel thalwegs, c) 440-450 m ASL HTEM slice showing near-surface γ channel thalwegs. Lines within the α channel show the general courses of what is believed to be a complex network of small channels. Note: Outside of the α channel, bedrock is generally shallow so here the γ channels do not change very much with depth.

Two distinct β valleys are incised within the broader α valley (Figure 4b). These β valleys are approximately 1-2 km wide and are eroded into shale bedrock to depths of approximately 100 m below ground surface or roughly 30 m deeper than the α valley. The HRSR results indicate that β valleys have flat bottoms and steep side slopes both in bedrock (30-50%) and sediments (5-20%). Whereas the western β valley is continuous through the HTEM area, the eastern β valley ends abruptly within the α valley. The orientation and gentle gradient of the western β valley is

consistent with an erosive origin of proglacial glaciofluvial drainage (Pugin et al., 2014) and similar in dimension and form to the nearby Pembina spillway (Kehew and Clayton, 1983). Hobbs and Bluemle (1987) have interpreted some of the deepest and narrowest bedrock valleys to be meltwater diversion trenches that were excavated when the northward flowing river was blocked by the advancing glacier front and was diverted southeastwards to produce the trench. The eastern β valley is stratigraphically younger than the western valley and a possible subglacial origin is considered for this valley (Pugin et al., 2014). One possible implication of a late β channel is increased vertical hydraulic connectivity as the younger β channel erodes through till that overlies the older β channel. However, the eastern valley may also be filled with less permeable material as suggested by borehole logs and ground-based TEM data (Crow et al., 2012b; Oldenborger and Brewer, 2014).

Numerous γ valleys are much more dimensionally variable than either of the α or β valleys (Figure 4a, b, c). They are generally discontinuous, narrower and steeper (30-80%) particularly where they incise bedrock, and have variable gradients (Pugin et al., 2014). They are found both within and outside the α valley. One γ valley also appears to form a fan where it crosses from bedrock terrain into the α valley (Figure 4c). These valleys are interpreted to have a subglacial origin and are found at all stratigraphic positions from bedrock to surface.

As a result of these varied and numerous episodes of channelized erosion, the topography of the bedrock surface reflects various geological processes operating at different times and scales. Consequently the Spiritwood buried valley is much more complex than a tertiary bedrock valley filled by subsequent glaciation.

Channel fill

Within the prairies, pre-glacial type buried-valley aquifers are typically found in deep bedrock valleys and may include both coarse pre-glacial fluvial and proglacial sediments (Lennox et al., 1988; Christiansen, 1992; Grasby et al., 2014). This classic model of the prairie buried-valley aquifer does not strictly apply to the Spiritwood buried valley because the depth of proglacial and subglacial erosion exceeds the depth of the pre-glacial valley. Furthermore, glacial till has been observed beneath the coarse sand and gravel fills within some buried α and β valleys such that the channel fill in these areas would not have resulted from the same event eroding the valley.

The geophysical results suggest that the western β valley is filled with relatively coarse material. The HTEM survey indicates uniformly resistive (low conductivity) sediment and the HRSR results also suggest coarse sediment facies filling, and in some sections overflowing, the valley paleosurface (Pullan et al., 2013; Pugin et al., 2014). Most of the boreholes in the study area that were completed in either β valley ($n = 12$) do show coarse sediment although a few suggest a more variable channel fill where aquifer material is sometimes interbedded with till (Figure 5). Boreholes within the deepest valleys in Towner County, North Dakota also encounter clay and till below the buried aquifer indicating that erosion and channel filling were separate geological events.

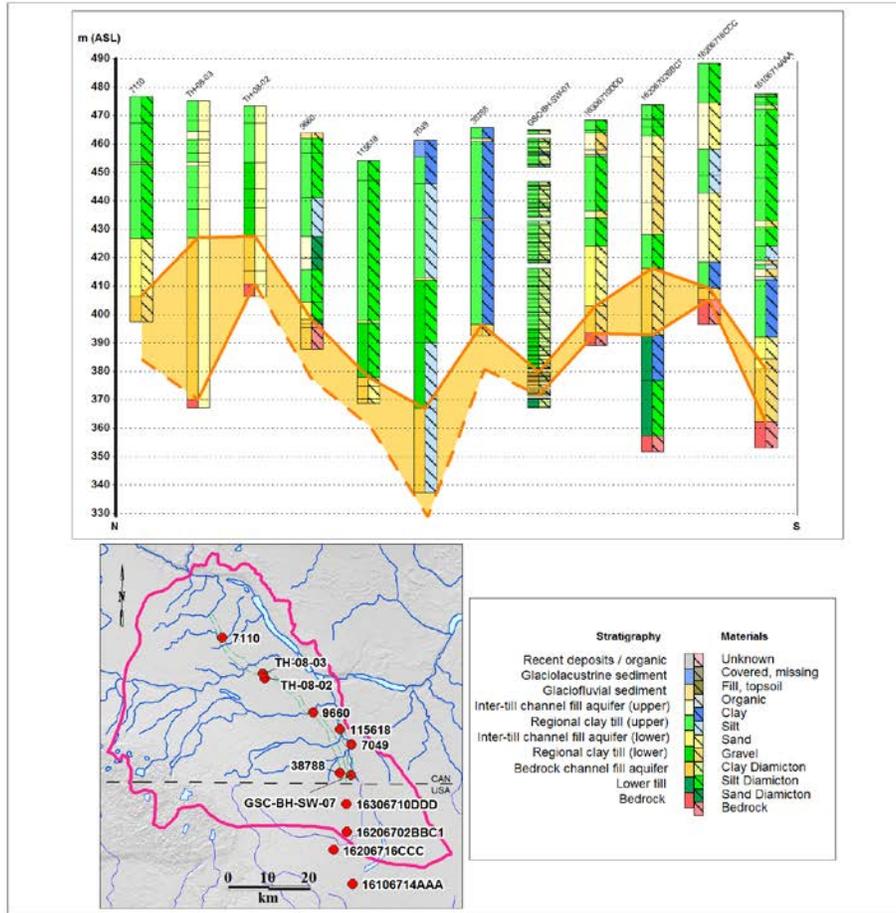


Figure 5. Borehole logs interpreted to contain intervals of β valley fill (orange shading; dashed outline indicates unknown base). Logs are plotted as they occur from north to south to correct relative elevation, but not to correct horizontal spacing – refer to inset map for actual locations. Approximate β valley location is shown on inset map (green dashed lines).

Glacial till is the main sediment type filling the α valley although sand and gravel are also encountered particularly in relation to γ and β valleys. One HRSR section shows a sand and gravel aquifer overflowing the β valley and extending laterally along the base of the α valley (Pullan et al., 2013). Although sand and gravel can, in places, be found directly on bedrock at the base of the α valley (outside the β valley), there is no suitable data to determine if any pre-glacial fluvial deposits may be present. Within the α valley, γ valleys and their more resistive fill are found at multiple elevations. This may reflect both multiple erosional events over a significant period of time and deeper erosion of late γ channels that are observed from surface to depth (Figure 4).

Interpreted as fans, the material related to the entrance of a γ valley from bedrock terrain into the α valley are the most extensive resistive sediment in the HTEM survey at shallow and intermediate depths. Numerous boreholes in these areas report sand and gravel. It would appear that a more erosive substrate or available accommodation space in the α valley allowed deposition of fan-shaped, coarse deposits (Figure 4c).

Conceptual stratigraphic model

Although the HRSR results indicate that sediment architecture can be complex, a simplified conceptual stratigraphic model has been adopted as the stratigraphic information content within the water well records is limited. From deepest to surface, the following geologic strata are recognized (Figure 6):

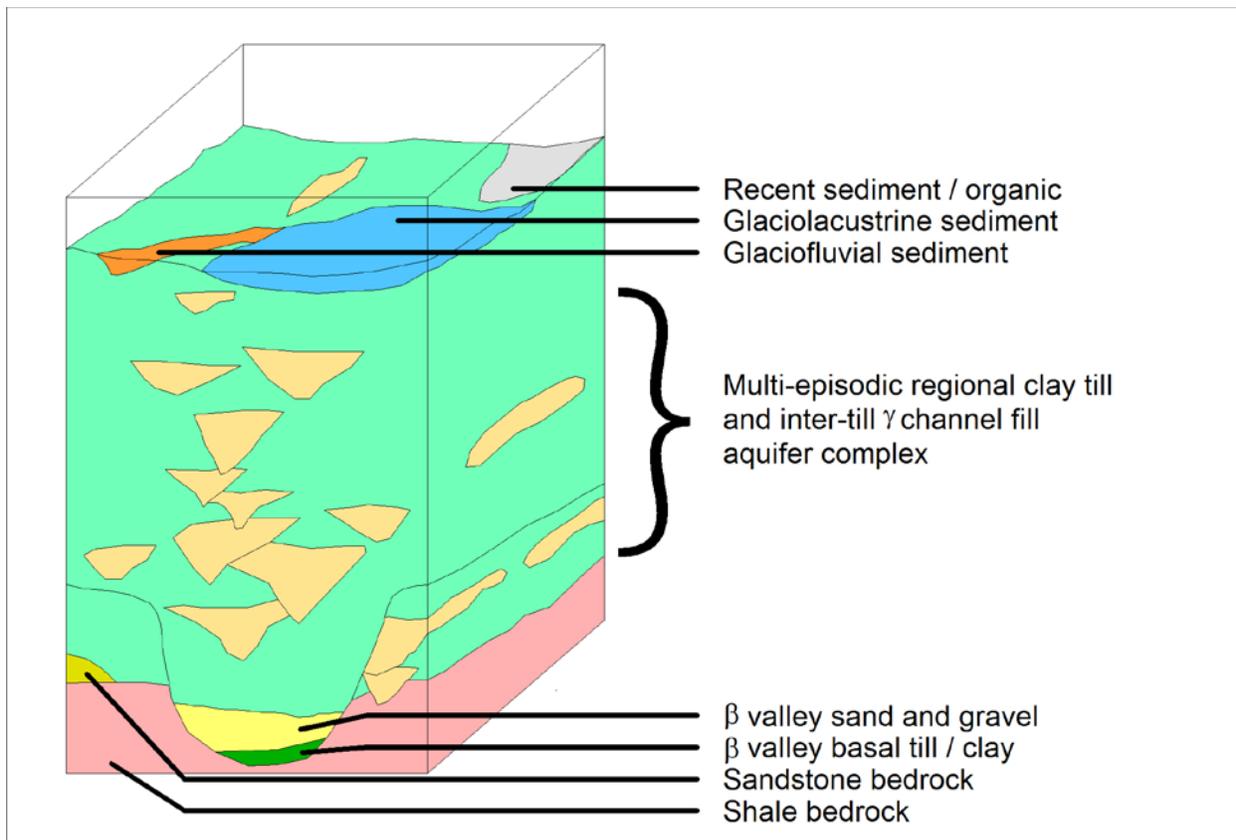


Figure 6. Simplified conceptual stratigraphic column that defines the relative positions of main strata of the 3D geological model. Layers and structures are not drawn to the correct relative scale.

- 1) Shale bedrock: In all areas except on Turtle Mountain, the uppermost bedrock unit is the Pierre Formation. The hard siliceous shale Odanah Member of the Pierre Formation underlies the entire model area whereas the soft clayey siltstone and shale of the Coulter Member lies above the Odanah beneath Turtle Mountain. The upper surface of the shale is usually jointed and fractured as a result of weathering and unloading.
- 2) Sandstone bedrock: Both the Boissevain (sandstone) and Turtle Mountain (bentonitic carbonaceous sand, silt and clay with lignite beds) Formations overlie the Pierre Formation on Turtle Mountain.

- 3) Glacial till and or glaciolacustrine clay at the base of β valleys: These local units occur primarily in North Dakota where they have been observed in a few borehole logs (Figure 5).
- 4) Coarse β valley fill: Sand and gravel within the β valleys.
- 5) Regional tills: Although several tills may be present, it is not possible to distinguish them from water well records except by elevation or relative stratigraphic position. As a result for modelling, the regional tills are pragmatically subdivided into a lower regional till unit that sits mostly on bedrock (outside the β valleys) and an upper regional till unit which includes all other tills to ground surface.
- 6) Inter-till channel sand and gravel: Several inter-till sands and gravels exist in different stratigraphic positions within the till. Many boreholes record more than one sand and gravel layer within the regional till. The thickest and most extensive inter-till sands and gravels are associated with γ valley channels or fan deposits. Deep sand and gravel of various possible origins are also sometimes encountered on bedrock or on a discontinuous basal regional till.
- 7) Upper glaciofluvial: A thin glaciofluvial sand and gravel either near or at the ground surface. This unit appears on surficial geological maps.
- 8) Upper glaciolacustrine: A thin glaciolacustrine silt or clay either near or at the ground surface. This unit appears on surficial geological maps.
- 9) Recent sediment: Mostly alluvium, colluvium and organic sediment at ground surface. This unit's extent is based primarily on surficial geology maps.

It is important to note that this list is not a chronostratigraphic description of units. The deep sediments filling the β valley (units 3 and 4 above) are likely younger than the deep regional till and some of the deeper channel sand and gravel of units 5 and 6 respectively.

Groundwater flow paths

A primary hydrogeological interest is the resource potential of the Spiritwood buried-valley aquifer. Although matrix flow through the till and the bedrock will contribute to the Spiritwood buried-valley aquifer, the low matrix permeability of these units will greatly limit groundwater fluxes. The resource potential will likely depend on more permeable hydraulic pathways. Hypothesized permeable pathways include: i) flow through "hydraulic windows" where more permeable sediments from γ channels and fans may connect to the deep buried valley, ii) flow along the bedrock contact zone either through fractured bedrock or permeable sediment on bedrock, and iii) a combination of hydraulic windows and the bedrock contact zone (Figure 7). To better understand regional groundwater flow dynamics and to test the potential significance of groundwater fluxes along these flow paths, a regional groundwater flow model is being developed based on the 3D geological model.

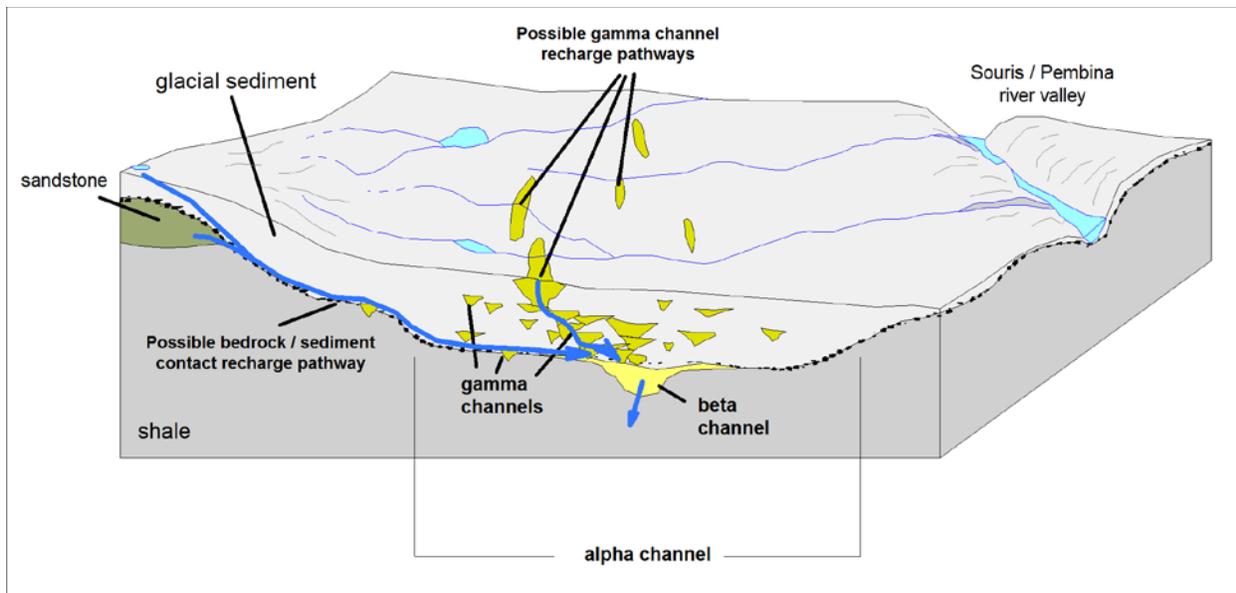


Figure 7. Block diagram illustrating hypothesized permeable flow paths to the Spiritwood buried-valley aquifer.

Data Preparation

Borehole Data Vetting

The location accuracy of newly acquired data was high and determined by GPS to within approximately 5 m, however archival water well datasets are often not surveyed with precision and are frequently plagued with topographical errors (Russell et al., 1998). Often such public domain data location issues can be visually identified as points plotting in areas unsuitable for human settlements (e.g. water bodies, wetlands) and, if possible, through secondary data checks with embedded address or cadastral information and/or comparing embedded elevation information if it exists with a Digital Elevation Model (DEM) (Kenny et al., 1997). It was found that the North Dakota well log dataset had no obvious gross location issues in the subset used for this model and were used without locational error vetting. Although the more numerous Manitoba well dataset also appeared to have no obvious location issues, this was perhaps due to the fact that well drillers in Manitoba are not required to provide precise well coordinates. Instead, these well logs are geographically located to the centroid of the provincial quarter-section grid cell in which they reside. As such, the level of model detail is ultimately limited by well logs spaced to, at best, a ½ mile square (~804 m) grid. Moreover, since a given well may actually be located anywhere within a grid square, an effective locational error of +/- ¼ mile (or 402 m) must be assumed on both X and Y coordinates (Figure 8). Although it effectively reduces the resolution of detail that the log data can provide, we can reasonably assume that, with a well log dataset tied to a cadastral grid, there are few if any gross location errors as a result of measurement, recording and/or typographic errors often found in similar well log databases that attempt to provide precise coordinates.

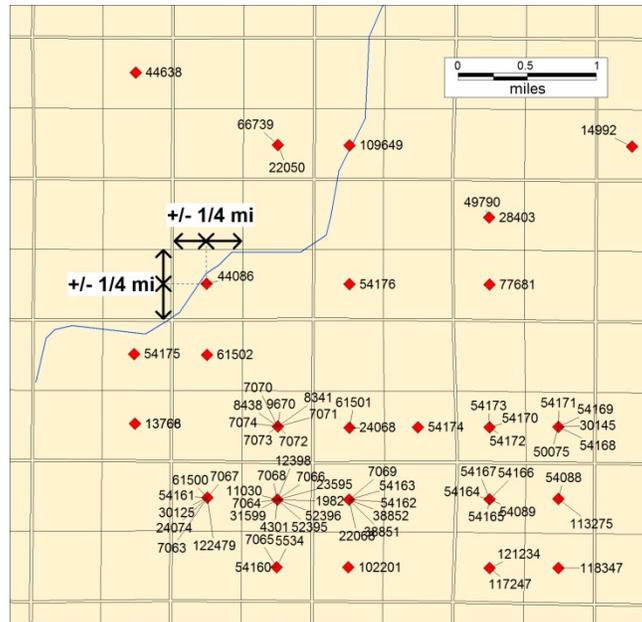


Figure 8. Illustrative example of potential spatial error introduced by provincial quarter-section water well plotting.

This method of georeferencing well log data also causes interpolation problems by creating groups of points with duplicate coordinates. To eliminate duplicate points, a single representative well was selected for each quarter-section grid in Manitoba. For each such grouping, a score was determined for each individual well based on both the total depth and the number of sediment depth range observations recorded by the well driller. The total depth is important for maximizing data coverage, and it is assumed that more numerous sediment intervals will provide both increased geological detail and more confidence in the overall care and rigor with which the well was logged.

Sediment Texture Interpretation

With both the pared-down Manitoba well log dataset and the North Dakota well logs, sediment textural descriptions recorded by the drillers had to be resolved into a sediment textural coding system (Table 1). Sediment descriptions often contain multiple textural terms with typically no quantitative estimate of the relative percentages of the described sediment that each term represents. Therefore, the relative importance of each term had to be derived from grammatical cues in the free-form description. To accomplish this efficiently for several thousand sediment descriptions, an automated data processing application was developed (e.g. Logan et al., 2006). Individual sediment textural terms were identified in the descriptions and ranked hierarchically using a system based on type of term, ordinal position in the description string, combinations of terms (e.g. 'limestone' versus 'limestone pebbles'), relative position of punctuation (e.g. commas, semicolons and parentheses), key words (e.g., 'and' or 'with') and whether terms are a noun or adjective form (e.g., 'silt' or 'silty'). Table 2 illustrates these rules through a series of

Material code	Description
99	miscellaneous; no obvious material code
11	covered, missing, previously bored
10	fill (incl topsoil, waste)
9-8	organic, topsoil
9	organic
8-9	clay, silty clay, with muck, peat, wood frags.
8-8	clay, silty clay, topsoil
8-1	clay, silty clay, with rhythmic/graded bedding
8	clay, silty clay
7-9	silt, sandy silt, clayey silt, with muck, peat, wood frags.
7-8	silt, sandy silt, clayey silt, topsoil
7-1	silt, sandy silt, clayey silt, with rhythmic/graded bedding
7	silt, sandy silt, clayey silt
6-9	sand, silty sand, with muck, peat, wood frags.
6-8	sand, silty sand, topsoil
6-1	sand, silty sand, with rhythmic/graded bedding
6	sand, silty sand
5-9	gravel, gravelly sand, with muck, peat, wood frags.
5-8	gravel, gravelly sand, topsoil
5-1	gravel, gravelly sand, with rhythmic/graded bedding
5	gravel, gravelly sand
4-9	diamicton: cl to cl/si, with muck, peat, wood frags.
4-8	diamicton: cl to cl/si, topsoil
4-2	diamicton: cl to cl/si with gr/sa/si/cl interbeds
4-1	diamicton: cl to cl/si, stoney
4	diamicton: cl to cl/si matrix
3-9	diamicton: si to sa/si with muck, peat, wood frags.
3-8	diamicton: si to sa/si, topsoil
3-3	diamicton: texture unknown
3-2	diamicton: si to sa/si with gr/sa/si/cl interbeds
3-1	diamicton: si to sa/si, stoney
3	diamicton: si to sa/si matrix
2-9	diamicton: si/sa to sa with muck, peat, wood frags.
2-2	diamicton: si/sa to sa with gr/sa/si/cl interbeds
2-1	diamicton: si/sa to sa, stoney
2	diamicton: si/sa to sa matrix
1-7	interbedded limestone/shale
1-6	sandstone
1-5	potential bedrock
1-4	dolomite
1-3	granite (poss. bedrock, prob. boulder)
1-2	shale
1-1	limestone
1	bedrock (undifferentiated)

Table 1. GSC sediment coding system.

Material Description	Principal Material	Modifier 1	Modifier 2	Modifier 3	Modifier 4	Trace	GSC Material Code	Description
HARD BLUE SHALE	bedrock	shale					1-2	shale
BROWN SANDY SILT	silt	sand					7	silt, sandy silt, clayey silt
SILT	silt						7	silt, sandy silt, clayey silt
Sandy, silty, pebbly, slightly bouldery, yellowish brown, moderately tight to tight, cohesive, oxidized (till)	till	pebbles	silt	sand			3-1	diamicton: si to sa/si, stoney
BLUE CLAY WITH GRAVEL	clay	gravel					3	diamicton: si to sa/si matrix
BROWN SILTY TILL, FEW STONES	till	silt	stones				3-1	diamicton: si to sa/si, stoney
GRAVELLY SAND	sand	gravel					5	gravel, gravelly sand
MEDIUM TO FINE GREY SAND AND SILT	fine sand	medium sand	silt				6	sand, silty sand

Table 2. Illustrative water well log material description string parsing examples.

examples. Terms parsed into principal and secondary modifiers are then systematically assigned a sediment textural code.

A small percentage of automatically interpreted material codes had to be corrected manually within the Leapfrog[®] Hydro 3D environment. As part of an iterative model development process, the data responsible for anomalous results were re-evaluated individually, compared to other nearby data and re-coded if appropriate. One common error was the misinterpretation of bedrock based on the presence of a bedrock term in the description that was likely intended to describe the composition of un lithified sediment (e.g., 'shale gravel' miscoded as 'shale')

Stratigraphic Interpretation

With all borehole data reclassified to a standard sediment coding system, the next step was to determine how best to use sediment intervals to build a 3D stratigraphic model. For this study, Leapfrog[®] Hydro geological modelling software was used to develop a 3D model of the buried-valley aquifer system. Based on the conceptual geological model, a stratigraphic column was developed to govern the 3D model and define its layers (Figure 6).

Preliminary model trials involved the use of an automated expert system to interpret and code borehole log stratigraphically (e.g. Logan et al., 2006; Janssens-Coron et al., 2009). Leapfrog[®] 3D modelling software provided a second method to interpret borehole logs that proved to be much simpler and with comparable results. Tools for filtering, splitting and grouping lithologies in a 3D environment allow an interactive, on-screen method for stratigraphic assignment of borehole logs (Velasco et al., 2013). Unlike an expert system approach, manual stratigraphic assignments are subjective and not repeatable. However, the ability to render an accurate geospatial arrangement of borehole logs in a dynamic 3D environment allows an operator and/or a geoscientist to detect trends and natural groupings of sediment intervals that would not be possible using tables of raw log data. Moreover, this technique allows boreholes to be evaluated with other 3D data sources (e.g., HTEM data, HRSR profiles and DEM-draped surface geology maps) as a reference in the 3D workspace. The complex set of expert system rules needed to match this innate human ability and the programming expertise needed to implement them are not necessary for this approach.

The material codes were altered to help simplify the manual selection of sediment log intervals. Referring to Table 3, all diamicton codes were combined into a single generic diamicton code, sand and gravel codes were combined into a single coarse aquifer material code and organic, fill and topsoil codes were also combined. Additionally, all sediment intervals directly above a bedrock interval were flagged to allow them to be more easily identified and queried for 3D analysis.

Once imported into Leapfrog[®] Hydro, the view can be manipulated to optimize view angles on the rendered borehole logs. Queries can be used to filter the display of log intervals and tools for selecting and grouping intervals are available to simplify the manual selection process. The manual stratigraphic assignment process involves splitting lithologies and re-combining them into a model stratigraphic code system. By filtering intervals and displaying horizontally, for example, upper and lower populations of a given material can be readily identified and split into appropriate stratigraphic layers. With this approach, there is no way to enforce relative stratigraphic age relationships, so the operator is responsible for ensuring that older stratigraphy is not applied to intervals physically above younger stratigraphy in the borehole log. It was decided, based on good preliminary results compared with expert system trials and the simplicity of the process, to proceed with manual stratigraphic assignments for model-building. Several iterations of model building allowed manual stratigraphic

assignments to be assessed and reassigned as necessary to produce a model consistent with the geophysical data and the conceptual understanding.

Simplified Material code	Description	Combined Material codes
99	miscellaneous; no obvious material code	"99"
11	covered, missing, previously bored	"91011" / "91011br"
10	fill (incl topsoil, waste)	
9	organic	
8	clay, silty clay	"8" / "8br"
7	silt, sandy silt, clayey silt	"7" / "7br"
6	sand, silty sand	"56" / "56br"
5	gravel, gravelly sand	
4	diamicton: cl to cl/si matrix	"234" / "234br"
3	diamicton: si to sa/si matrix	
2	diamicton: si/sa to sa matrix	
1	rock	"1"

Table 3. Combined material codes. Codes ending with ‘br’ are given to intervals that are directly above bedrock. (Note: sandstone bedrock is not differentiated at this stage)

Geophysical Data Incorporation

GSC seismic profiles are primarily oriented transverse to known buried channels in the model area and provide crucial depth and cross-sectional channel geometry information. Located to confirm and help characterize numerous linear channel trends seen in the HTEM dataset, the HRSR profiles are widely spaced throughout the model area. Although the HTEM dataset indicates the path of channels in plan view between these profiles, the channel depth and geometry shown in HRSR profiles needed to be extrapolated to more accurately model the full extents of buried channels. As the horizontal path and width of the channels are clearly defined by the HTEM dataset, this dataset was used to guide the extrusion of channel cross-section geometries identified in HRSR profiles.

The shape of channels in cross-section was approximated by selecting four representative points (Figure 9). Two define the lateral extents of the channel at its paleo-surface, and two more define the base of the channel. Typically the maximum interior and exterior inflection points of the channel form in cross-section were selected to best approximate the shape of the channel. Since the base of most seismic profile channels were either flat or ‘V’-shaped, this 4-point sampling yielded satisfactory approximations.

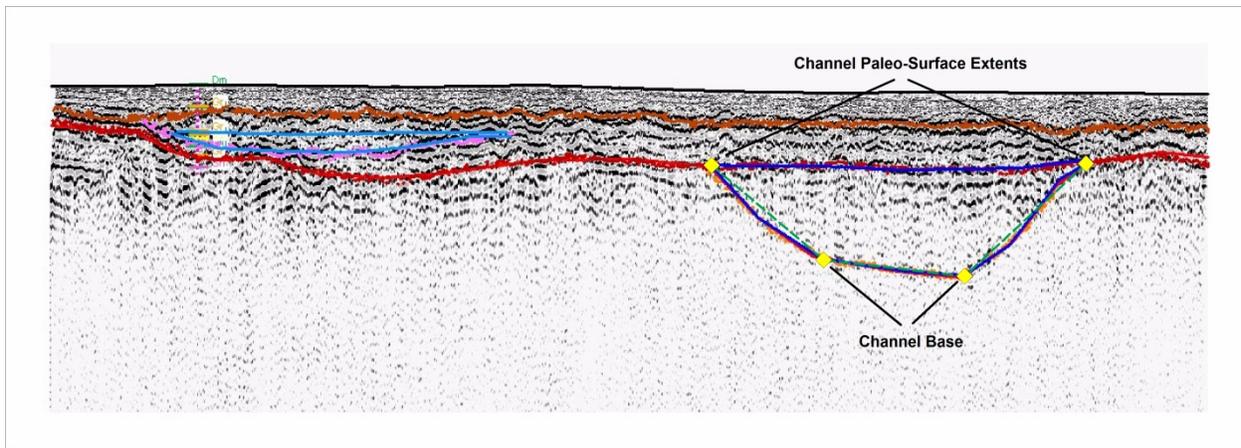


Figure 9. Four points (yellow dots) approximate a channel cross-sectional geometry on a HRSR profile.

To approximate each channel identified on HRSR profiles, four points were selected and tabulated. To extrude the channel shape, the path between each of the four corresponding points from section to section was generated in 3D space (Figure 10). The 3D path of each line is based on a constant-depth slice of the HTEM 3D model in plan view or XY plane and the seismic profiles in the depth/elevation or Z direction. Lines are converted to a series of points spaced at 50 meters. The depth of each point is determined by projecting them perpendicularly to an imaginary straight line drawn between line segment endpoints as selected from successive HRSR profiles.

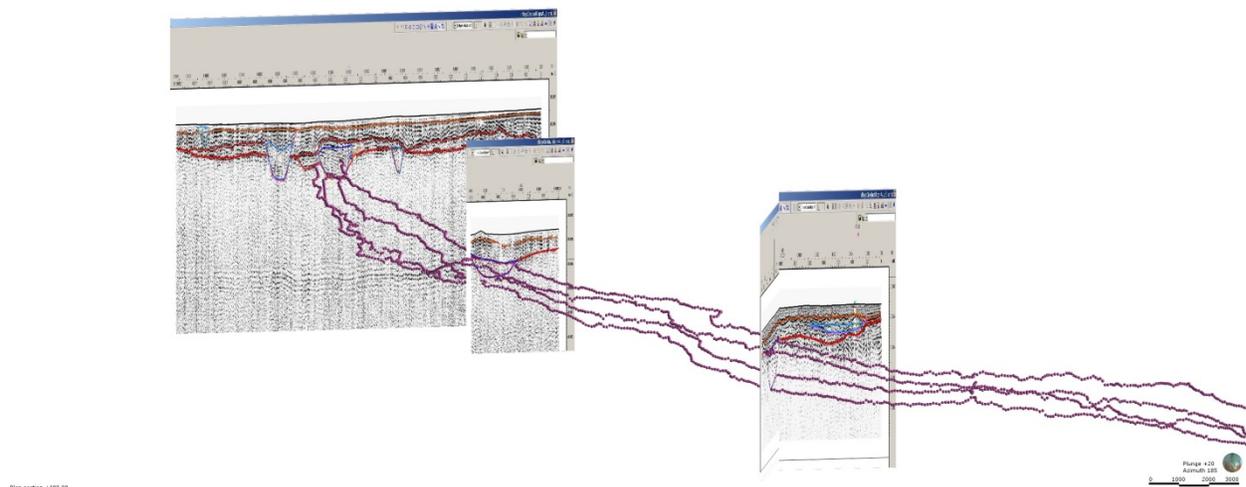


Figure 10. Channel geometry points extruded between HRSR profiles guided by HTEM data. Depth values are applied to line segment points by ranging depths projected to a straight line between start and endpoints.

In the XY plane, a series of GIS operations was undertaken to guide the line segment path along trends in HTEM conductivity data. The HTEM data, realized as a pseudo 3D model, is imported as a 3D 'cloud' of conductivity data. Additionally, the HTEM model was resampled at regular depth intervals and converted into raster depth 'slices' (Figure 4). The path of channels were apparent on these HTEM depth slices and for the sake of objectivity, repeatability, and due to the large number of line segments that were needed, an automated approach was used to digitize them. The 'Cost Distance' and 'Cost Path' tools in ESRI® ArcGIS® with Spatial Analyst® were primarily utilized to construct line segments using HRSR profile start and end points with modified HTEM depth slice grids as input

cost rasters. The end point depths were determined from HRSR data, then averaged and used to select the nearest HTEM depth slice raster grid. Using the selected HTEM grid, the average value of the seismic end point conductivities was determined. In order to convert the HTEM conductivity raster grid to a cost raster this average value was subtracted from the HTEM conductivity grid. The absolute value of this grid math result was then used to produce the final cost input grid – with a ‘cost’ at or near zero for HTEM grid cells at or near the average conductivity value. Assuming the HTEM conductivity value will stay consistent along the length of the channel feature from start to end point, the least cost path will be created along the feature from its known start to end points (Figure 11). As well as finding the path of least cost, the ‘Cost Path’ tool also attempts to find the most direct path thus serving to smooth out the channel shape by ignoring data noise and interference from vehicles, metal structures, etc. In some areas additional control points were needed to help guide the path through particularly ‘noisy’ areas, between profiles spaced widely apart and to continue channels to the boundaries of the HTEM survey area or to where they appear to terminate. The placement of these control points was determined visually with HTEM data as a reference and the depth value was estimated from nearby well logs or HRSR profiles. Line segments were then converted to a series of equally-spaced points. The depth value for each point was determined by ranging the depth values projected to an imaginary straight line in 3D space between start and end points. The depth values were subtracted from the topographic DEM to yield an elevation value that was used to help control the bedrock portion of the 3D model.

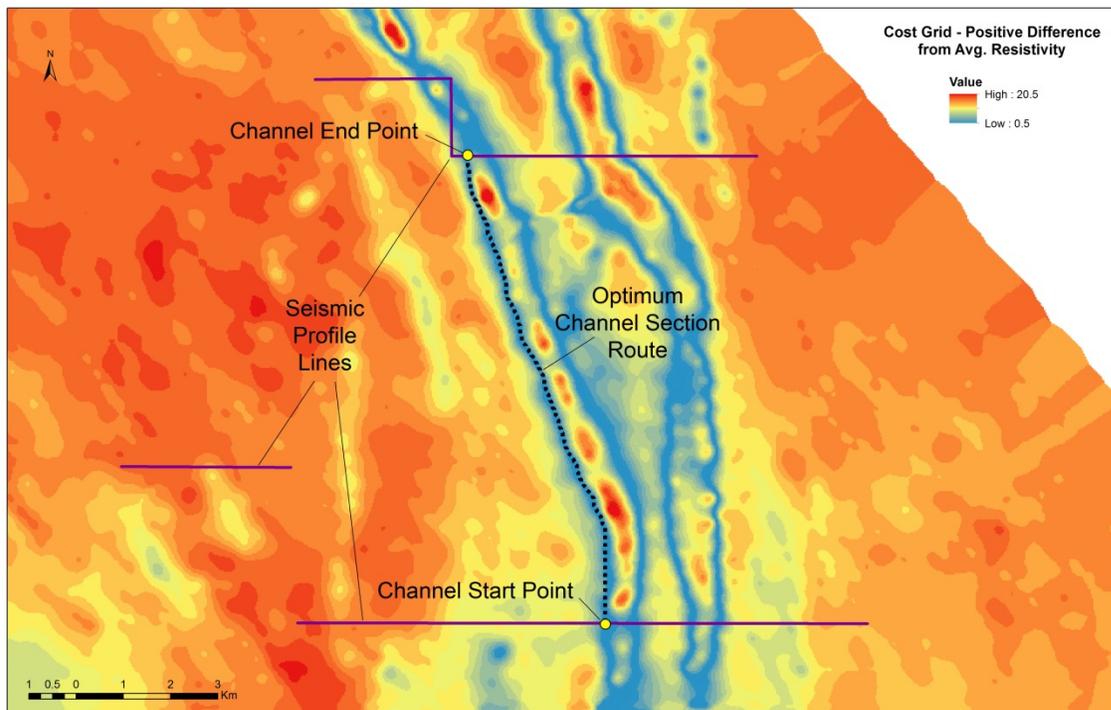


Figure 11. Top-down view of resistivity ‘cost’ grid for the channel section start and end points along seismic profile lines. Optimum section route is determined using Cost Distance and Cost Path tools.

The HRSR profile channel extrapolation workflow involves many labour-intensive steps with several intermediate maps and inputs required for each channel segment as described above. Since 147 segments had to be processed, a PythonTM script was written to cycle through the series of GIS analysis steps for each.

3D modelling

Leapfrog[®] Hydro is designed to simplify the model-building process by providing a clear workflow from 3D model extents setup, data input, stratigraphy building, editing and rendering to conversion and export to hydrogeological flow modelling formats (e.g. FEFLOW, MODFLOW). Model control data can be in the form of borehole logs, point data, polylines and raster grids. All these types of control data were used to produce the 3D model. The topographic DEM was imported and set as the model topography. This is an important component of the model as it establishes the ground surface to which the volume model is trimmed as well as providing a common surface to which borehole collars, surficial geology and other GIS mapping layers can be projected. Stratigraphic code contacts found in the boreholes dataset are scanned, tabulated and used by the software to semi-automatically build stratigraphic layers of the model. The bedrock channel points developed from HRSR profiles were used to augment the bedrock surface. The coarse distribution of well log bedrock contacts alone would not have shown complete bedrock geometry and channel forms by themselves and so would have been inadequate for accurate hydrogeological flow analysis (see Figure 12).

Model stratigraphy

A model stratigraphy has been adopted that tries to capture the key hydrostratigraphic elements of the conceptual geologic model and deals with the limitations of the stratigraphic information content within the water well records and the pragmatic requirements of geological modelling software. Because the water well records cannot distinguish between different tills nor capture all the numerous unconformities caused by erosion of bedrock valleys and channels within the till, the model stratigraphy does not attempt to honor a detailed geological stratigraphy or chronostratigraphy. Rather, it tries to represent the continuity of hydrostratigraphic units, even if these include different geological units. From deepest to surface, the following 13 hydrostratigraphic units are modelled:

- 1) Shale bedrock: Below the jointed and fractured surface of the Pierre Formation, all members are grouped together as a lower permeability shale unit.
- 2) Fractured shale bedrock: The upper surface of the shale is usually jointed and more highly fractured as a result of weathering and unloading and therefore may be more permeable than the underlying intact shale.
- 3) Sandstone bedrock: Although the Boissevain Formation sandstone is likely the more permeable of the two, both the Turtle Mountain and Boissevain Formations are likely more permeable than the Pierre Formation and so are combined here and modelled as a single low yield aquifer (Betcher et al., 1995). The Boissevain Formation is equivalent to the Fox Hills Formation in North Dakota whereas the two members of the Turtle Mountain Formation are equivalent to the Hell Creek Formation and Fort Union Group (Bamburak, 1978; Randich and Kuzniar, 1984a; Grasby et al., 2014).
- 4) β valley aquitard: This low permeability unit, consisting of glacial till or glaciolacustrine clay, occurs at the base of the β valley primarily in North Dakota where it has been observed in borehole logs.
- 5) β valley aquifer: Based on the HTEM and HRSR results and the borehole logs (Figure 5), permeable sand and gravel appears to partially fill the eastern β valley whereas it may fill the western β valley and even have extended into the broader α valley in some areas.

- 6) Lower regional aquitard: Discontinuous basal till occurs both within and outside the α valley. Outside the β valley, it is on bedrock. Although till within or overlying the β valleys may be younger and belong to a different till unit, the lower regional aquitard is nonetheless modelled as a single, continuous unit across the β valleys where till is present in the borehole logs.
- 7) Lower regional aquifer: This permeable sand and gravel unit is based predominantly on depth rather than origin. It is typically encountered at depths greater than 30 m. Similar to the lower regional aquitard, the lower regional aquifer is also modelled as a single, continuous unit across the β valleys.
- 8) Upper regional aquitard: Although more than two regional tills may be present, this unit represents the main till aquitard that extends from the deep regional sand and gravel to near ground surface.
- 9) Inter-till aquifer: This unit represents the majority of permeable sediment above the deep regional sand and gravel unit. These are typically inter-till sands and gravels that are associated with γ valley channel or fan deposits. Many boreholes record more than one inter-till sand and gravel interval. This unit generally lies within the upper regional aquitard but extends up to surface in some areas and down to shallow bedrock in others.
- 10) Fractured upper regional till: Where the till of the upper regional aquitard extends to surface, it is usually oxidized and fractured. The enhanced permeability of this unit may be important for groundwater recharge and the development of localized shallow groundwater flow systems.
- 11) Upper glaciofluvial: A thin, permeable glaciofluvial sand and gravel unit either near or at the ground surface. This unit appears on surficial geological maps.
- 12) Upper glaciolacustrine: A thin, lower permeability glaciolacustrine silt and clay unit either near or at the ground surface. This unit appears on surficial geological maps.
- 13) Recent: Various recent units including organic deposits in wetlands, alluvial sediments and colluvium predominantly in the Pembina Valley.

Model layer type

A 3D volume model is created in Leapfrog[®] Hydro by developing a series of stratigraphic layers based on contacts within boreholes, layer surface points, lines and/or raster grids (Alcaraz et al., 2011). The type of layer selected determines how Leapfrog[®] Hydro solves ambiguous data geometries to produce an appropriate volume conforming to the geological features present. Leapfrog[®] Hydro first interpolates each stratigraphic layer surface independently using Radial Basis Functions (RBF) then rationalizes overlaps based on age relationships and type of layer. Three layer types are possible: 1) depositional, 2) erosional and 3) intrusive. With depositional layers, older layers take precedence over younger layers in areas of overlap while with erosional the opposite is true. The intrusive layer type, although generally intended for igneous bodies that intrude older stratigraphy, can also be used to depict any volume that is superimposed within or through older stratigraphy without affecting the overall geometry of the older layers (e.g. ore body). Given the lack of sufficient data support for the complex and detailed geometry of γ channel features and their fill material in this model area, simply selecting the corresponding Leapfrog[®] Hydro layer type to reflect each of the sediment types and their depositional processes did not yield a plausible volume model. For example, the β valley aquifer, although occupying an erosional bedrock channel, was set as a depositional layer type mainly because very few boreholes that were located within these narrow channels were deep enough to control the

extent of the fill. If β channel fill were modelled as an erosional layer type then the bedrock channels defined by HTEM and HRSR data would be lost.

Because the numerous inter-till aquifer deposits are generally enclosed within the upper regional aquitard, the intrusive layer type was used to simplify the model-building process. It would have been extremely difficult to render this geometric relationship from the coarse-grained intervals present in many borehole logs using either depositional or erosional layer types. Using either of these types would require that the regional till aquitard be split into several sub-units interspersed with several split sub-units of inter-till aquifer because there are often several thin layers of aquifer material in borehole logs. In addition to creating more complexity for the stratigraphic coding process, it would have added more layers to the volume model and more complexity to the hydrogeological mesh development. Using additional stratigraphy with depositional layer types would also have resulted in a geometry that favoured horizontal connection with limited vertical connectivity. Using the intrusive type layer greatly simplified the modelling process while producing a more plausibly interconnected inter-till aquifer with enough vertical connection to conform to observations and expert knowledge. In preliminary models, near-bedrock inter-till aquifer units that were modelled as an intrusive layer type often penetrated the bedrock unit yielding unrealistic scours and tunneling. To limit this effect, the near-bedrock population of inter-till aquifer log intervals were split into a lower regional aquifer unit and modelled as a depositional layer type. This corrected most bedrock scours while enhancing horizontal connectivity within this unit. Regional till aquitard log intervals directly above bedrock and below the lower regional aquifer were split into a lower regional aquitard unit to maintain a viable stratigraphic layer sequence.

Polyline edits

With a preliminary model developed from borehole stratigraphic contacts and HRSR bedrock surface points, additional control on layer geometries was introduced through iterative polyline editing. Leapfrog[®] Hydro provides this editing to help guide contact surface interpolations in portions of the model with little or no borehole coverage. The effect of polyline edits are minimized by the software if they directly contradict borehole data, so the model remains primarily data-driven. Manually drawn in 3D space, these polylines have a defined 'inside' and an 'outside' relative to layer volumes that help to shape the volume geometry. The horizontally sliced HTEM data was used to guide the placement of polyline edits in order to constrain the complex, interconnected patterns of inter-till aquifer material occupying γ channels. To help guide the polyline edits of inter-till aquifers, maps showing the horizontal gradient of electrical conductivity were calculated from HTEM data and used in concert with HTEM conductivity values as a visual reference to better determine γ channel boundaries. In this way, the inter-till aquifer volumes were revised to better conform to a more connected 3D channel network as expected through expert knowledge of glacial depositional environments in this area and HTEM results (Figure 4). Additional polylines were drawn to represent the North Dakota interpreted cross-sections unit contacts. Contacts were digitized in 3D space and added to appropriate model surfaces as polyline edits. Manitoba provincial cross-sections (Matile and Keller, 2012) were similarly used to digitize the base of the combined Turtle Mountain and Boissevain Formations.

Surface alteration zones

Additional 3D model layers were developed to allow for simulation of different hydraulic properties within the fractured upper portions of the regional till and shale bedrock units. Numerous studies have reported on the existence of fracture permeability of clayey aquitards (cited in van der Kamp, 2001) resulting in higher hydraulic conductivity near the ground surface. Similarly, fractured shale can be several orders of magnitude more permeable than unfractured shale and fracturing of siliceous shale can maintain high fracture permeability at depths in excess of 300 m (Davis, 1988). One apparent mechanism of fracturing is the result of strain due to unloading by erosion of the rock (Nichols Jr et

al., 1986). Furthermore, additional fracturing and disintegration of the shale is also possible within the weathered upper portion of the shale. Oxidation and/or weathering of the Pierre shale has been observed in outcrop in southwest Manitoba (Bamburak and Nicolas, 2013) and geotechnical boreholes in South Dakota (Nichols Jr et al., 1986). Both mechanisms may contribute to the increased presence of fractures, joints and bedding planes of the uppermost shale which appears to be extensive in the Pierre shale (Odanah member) as reported by the widespread use of the unit as a relatively low yield aquifer in southwest Manitoba (Betcher et al., 1995).

The results of oxidation and fracturing in the till and shale are sometimes reported in water well logs. Water well log descriptions were examined to determine the average thickness of these altered zones. Descriptive terms related to the colour transition from oxidized to non-oxidized materials (e.g., 'yellow' / 'brown' / 'rust' to 'blue' / 'grey') were used to establish altered till intervals, while terms that indicate fracturing (e.g., 'fractured' / 'broken' / 'cracked' / 'weathered') were used to identify altered bedrock intervals. The thickness of oxidized till intervals were tabulated from boreholes within the study area and averaged 5.0 m with a standard deviation of 4.1 m (n=84). Four cored boreholes in the study area had an average depth of oxidation within the till of 5.8 m which is consistent with the water well log database results. The top portion of the upper regional till was split into an upper oxidized zone where it was within 5 m from present ground surface. This was done to allow the simulation of near-surface groundwater recharge and flow through more permeable, weathered till.

Altered bedrock thickness averaged 1.7 m with a standard deviation of 1.4 m (n=14). An altered-to-unaltered bedrock contact surface was developed by subtracting 2 m from the initial bedrock surface. This lowered bedrock surface was then used by the modelling software to split the original bedrock volume into 2 new volumes: a lower, unweathered (but still possibly fractured) bedrock; and an upper more highly fractured bedrock zone. This configuration allows the creation of distinct hydrostratigraphic layers that can be readily incorporated into the numerical groundwater model. The resulting layers can then be modelled with different hydraulic conductivities to simulate increased groundwater flow in the uppermost fractured bedrock zone.

Surface geology maps

To provide control of modelled stratigraphic layers at ground surface, the mapped geology polygons were utilized. Leapfrog[®] Hydro allows contact surfaces to be augmented with additional elevation points to help offset areas of poor borehole data coverage. For each of the 4 stratigraphic layers mapped at ground surface, an elevation point dataset was created (Figure 3). Geology map polygons were used to 'cookie-cut' a 500 meter cell resolution version of the topographic DEM to create a clipped DEM for each mapped layer. Clipped DEMs were then exported to an ASCII point format to produce an X Y Z point dataset at 500 meter spacing that represents the portion of each layer that is exposed at ground surface. Much like the manual polyline edits, these points are regarded as secondary to borehole contacts by the Leapfrog[®] Hydro model-building process. As such, the generalized regional scale geological mapping will not overwhelm small-scale model variability if indicated by borehole log data.

Model evaluation

Several iterations of model inspection and stratigraphic code assignment checking were undertaken throughout the modelling process. Coding revisions and/or surface edits were made for each iteration until model geometries and unit interrelationships conformed adequately to expert knowledge. Leapfrog[®] Hydro's workflow process automatically re-interpolates surfaces and rebuilds the model as a result of adding new data, editing existing borehole data or editing the model itself. This greatly simplified making iterative revisions to the model.

The stratigraphic model forms the basis for hydrogeological flow analysis and is used within Leapfrog[®] Hydro to produce layer boundaries and set material types for a FEFLOW groundwater model.

Results

The most significant geological modelling result is that a suitable rendering of the bedrock surface and buried-valley aquifers would not have been possible without the geophysical survey data. The spatial continuity and stratigraphic architecture results generated by the geophysical surveys provided new information that could not have been obtained without substantially augmenting the available borehole coverage. HTEM and HRSR data have allowed the delineation of valleys and channels at a resolution that otherwise would have required thousands of additional boreholes to map. Although the water well records were sufficient to provide the general location of the α valley (Sie and Little, 1976), the existence of a deeper, nested valley was not known until it was imaged using HRSR surveys (Pullan et al., 2013). The insufficiency of borehole data alone is demonstrated in Figure 12 where the bedrock surface from archival boreholes does not include the β and γ valleys, and does not thoroughly map the α valley.

The variability of the bedrock surface topography within the HTEM survey area clearly indicates that the density of boreholes completed to bedrock would need to be very high to adequately map the surface. Therefore, the bedrock surface outside the HTEM area is not mapped in enough detail to include other possible valleys as suggested by several minor, isolated bedrock surface depth anomalies (Figure 13). Even with sub-parallel transects of boreholes drilled across the α valley in North Dakota spaced from 3 to 6 miles apart at approximately one mile or better spacing between boreholes, it was not possible to delineate continuous β valleys. Several boreholes did encounter deeper bedrock, but correlations to the β valleys in Canada were not definitive. The mapping of the bedrock surface demonstrates the extremely high cost efficiency of geophysical methods for mapping purposes compared to boreholes. However, this efficiency should not undervalue the great benefits of boreholes for identification and characterization of geological units and for the installation of monitoring wells that are used for hydraulic characterizations.

The HTEM and HRSR surveys were highly complementary. The HTEM provided excellent spatial resolution in plan view for each depth interval whereas the HRSR offered better depth control and stratigraphic architecture information. When used together as described previously, they permitted the generation of 3D geometry of the bedrock surface which was essential to this project. Ideally, the geophysical surveys would have been better supported with more cored boreholes, monitoring wells, hydraulic testing and borehole geophysics that would have permitted improved depth control, better characterization of geological, hydrogeological and geophysical properties.

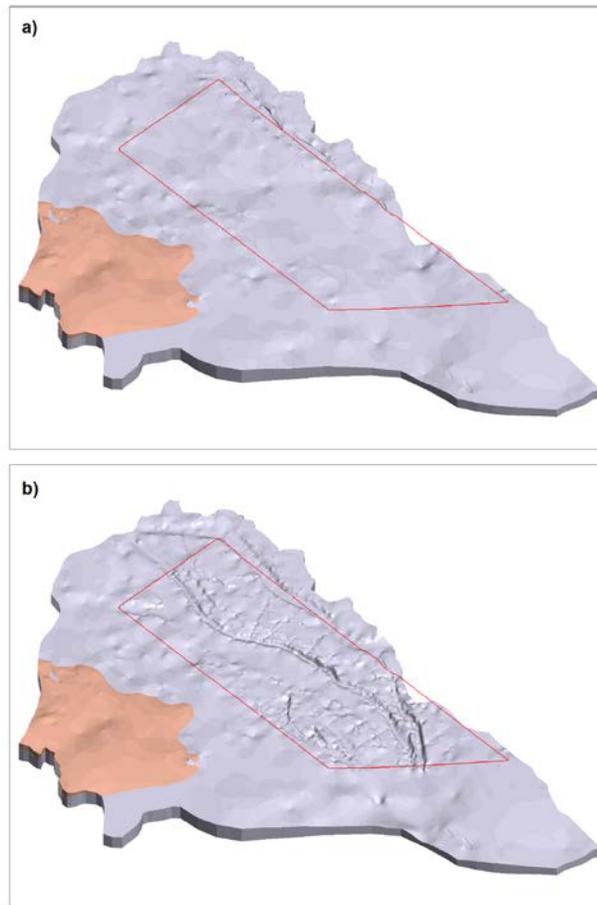


Figure 12. Comparison bedrock surfaces at 10x vertical exaggeration: a) Bedrock surface interpolated from archival borehole data alone. b) Bedrock surface with increased channel detail from addition of channel control lines derived from HTEM / HRSR data.

There is a notable geologic transition in the geologic models when crossing the border between Manitoba and North Dakota. The two well-defined β valleys and buried-valley aquifers in Manitoba merge in North Dakota. It is not clear whether this is strictly due to combining disparate data sets or whether this may be a real geological transition. Whereas the Spiritwood buried valley in Manitoba is rich in geophysical data and relatively poor in borehole data, North Dakota has much better borehole data but is geophysics poor. The incised valleys are not as easily delineated in North Dakota where borehole observations have more variable valley depths and trajectories. Conversely, the geophysical methods may not detect some of the geologic variability that is evident in the North Dakota boreholes so that buried-valley aquifer extent may be overestimated in Manitoba because β valleys are assumed to be filled with permeable sediment. It is also possible that the geologic transition is real as there is some narrowing of the α valley and convergence of a γ valley toward the transition zone near the international border.

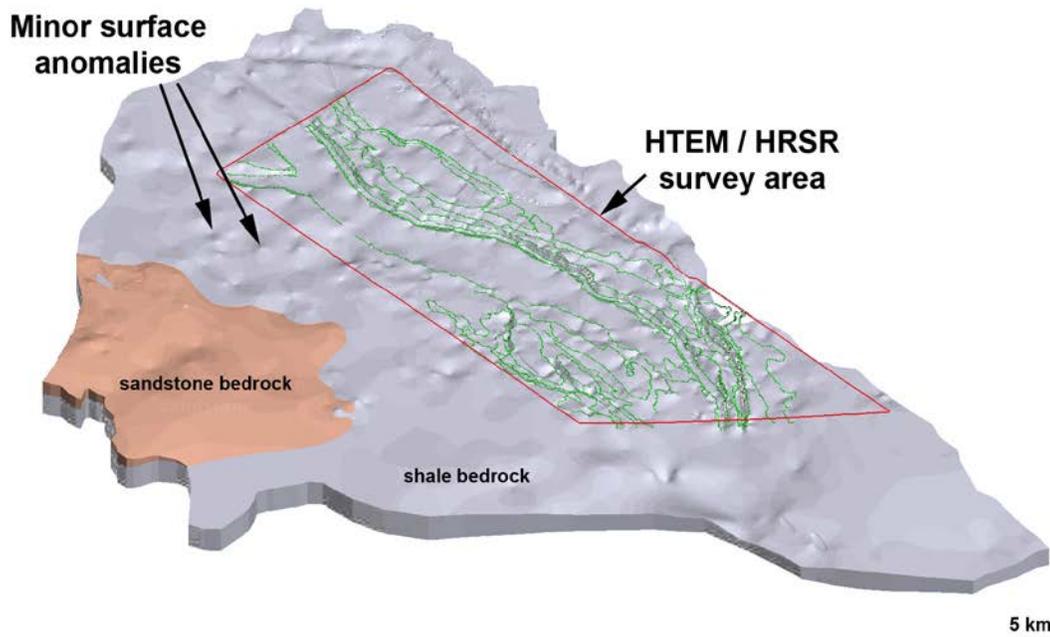


Figure 13. Bedrock surface at 10x vertical exaggeration displays minor depth anomalies outside of the HTEM survey area as controlled by borehole log contacts. Inside the survey area additional control from seismic profile extrapolated control points (green) significantly reduce surface anomalies.

Extrapolation of the β valley beyond the northwestern extent of the HTEM survey area provided valuable insight into the groundwater flow system (Figure 14). Given the depth and trajectory of the valley, the geological models indicated that the buried-valley fill would outcrop in a tributary to the Souris River valley. Satellite images and site inspections confirmed the presence of sand and gravel within the tributary valley (Figure 15). A baseflow survey by the GSC demonstrated that this area sustained discharge during a period of extended drought providing additional evidence of a hydraulic connection between the buried-valley aquifer and the ground surface. This discovery is significant to the hydrogeological conceptual model as it demonstrates that the buried valley has a natural hydraulic outlet and is not stagnant. It is also interesting to note that the sudden northward turn of the Souris River towards the Assiniboine River coincides with the intersection of the β valley in that direction (arrow A, Figure 14). Another interesting alignment occurs with the eastern β channel. Although it appears to terminate abruptly, it is in line with the modern Pembina River / Pelican Lake valley (arrow B, Figure 14). Neither of the β valleys appears to directly outcrop within Long River and Badger Creek (near B, Figure 14), however, sustained baseflow in these streams during drought and hydraulic gradients of deep monitoring wells along the buried valley indicating flow towards this area suggest that a hydraulic connection may exist between them although it is not specifically delineated in the geological model.

The geological model also shows areas where the inter-till aquifer is exposed to the surface (Figure 16). These areas are potentially significant as recharge areas as they provide permeable pathways from the surface. Field visits to several of these areas confirmed that sand and gravel were present at the surface. These outcrops could be the source of some of the glaciofluvial outwash and ice contact stratified drift mapped at surface (Elson, 1960). Some of these areas appear to be traversed and, in several cases, incised by surface drainage. If connection to inter-till or deep aquifers occurs in these areas, significant groundwater recharge may result.

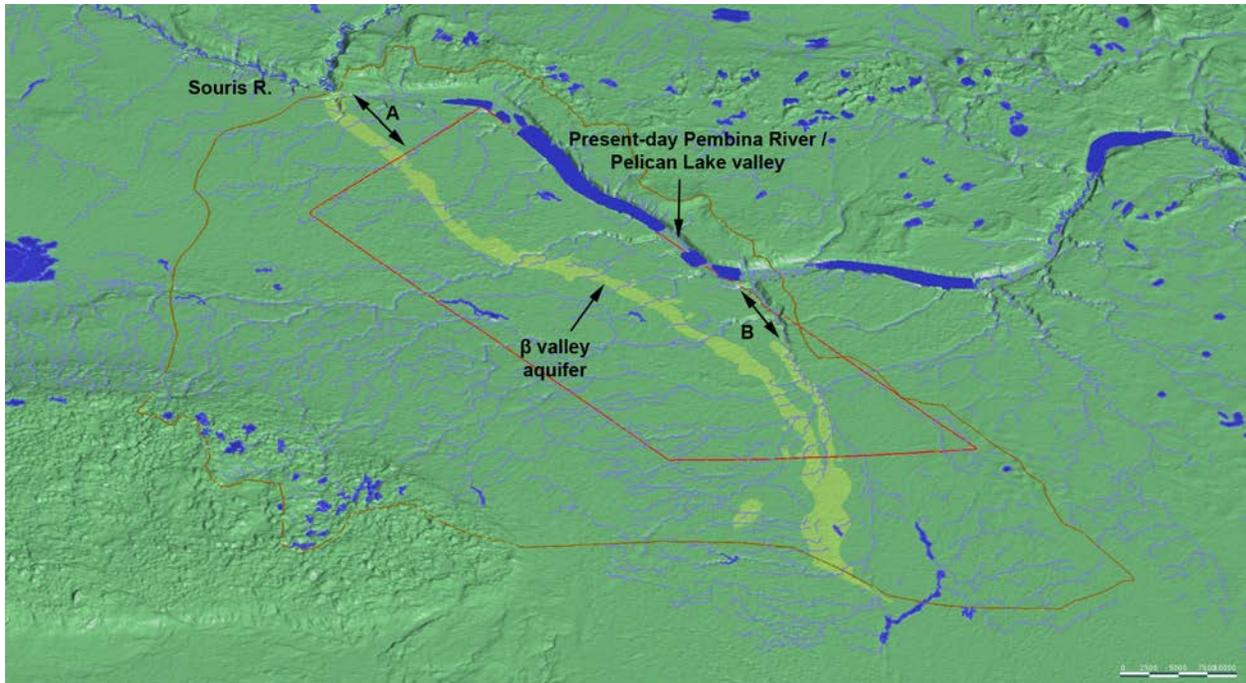


Figure 14. The modern Pembina River / Pelican Lake valley is shown with the modelled buried aquifer valley. The locations indicated with black arrows (A and B) show apparent correlations between the buried valley and surface drainage topography.

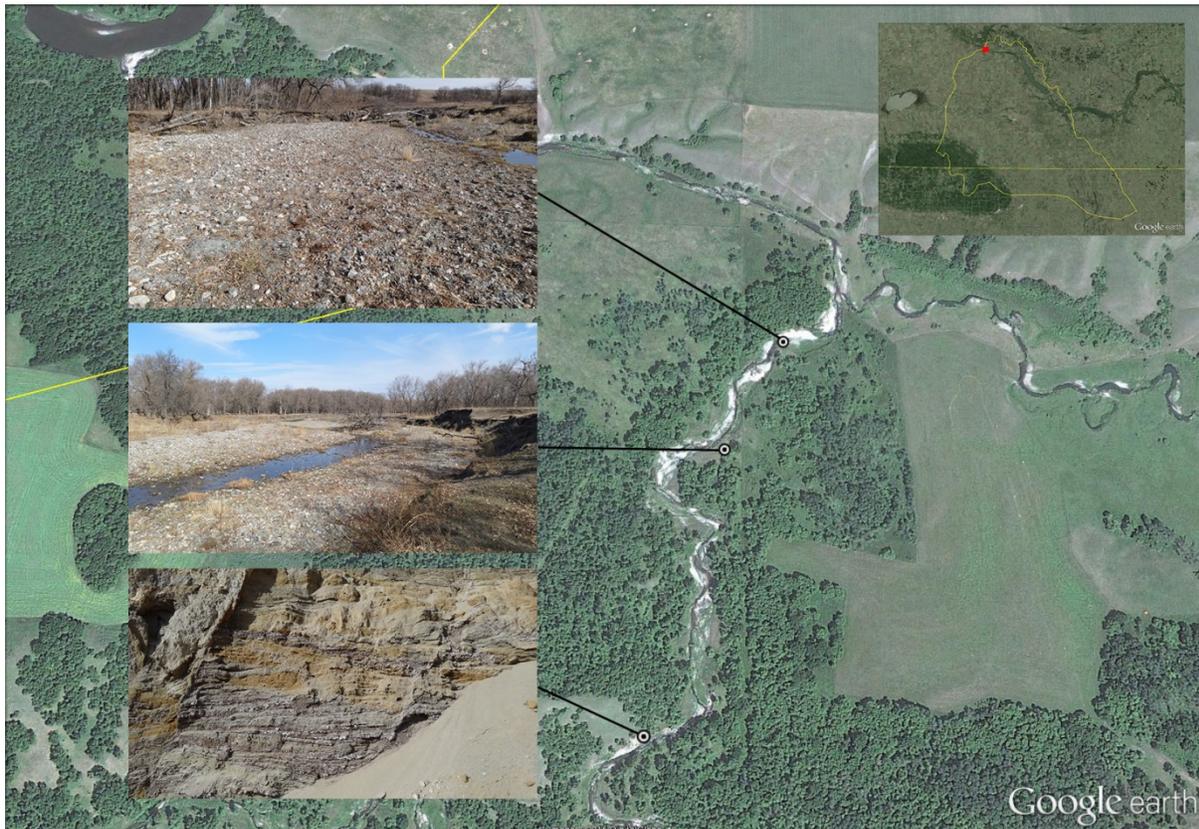


Figure 15. Field photographs of coarse-grained sediment on river bank exposures at the northwestern extent of the modelled Spiritwood buried-valley aquifer (inset). Main map: © 2015 Google; Image © 2015 Digital Globe. Inset map: © 2015 Google; Image Landsat.

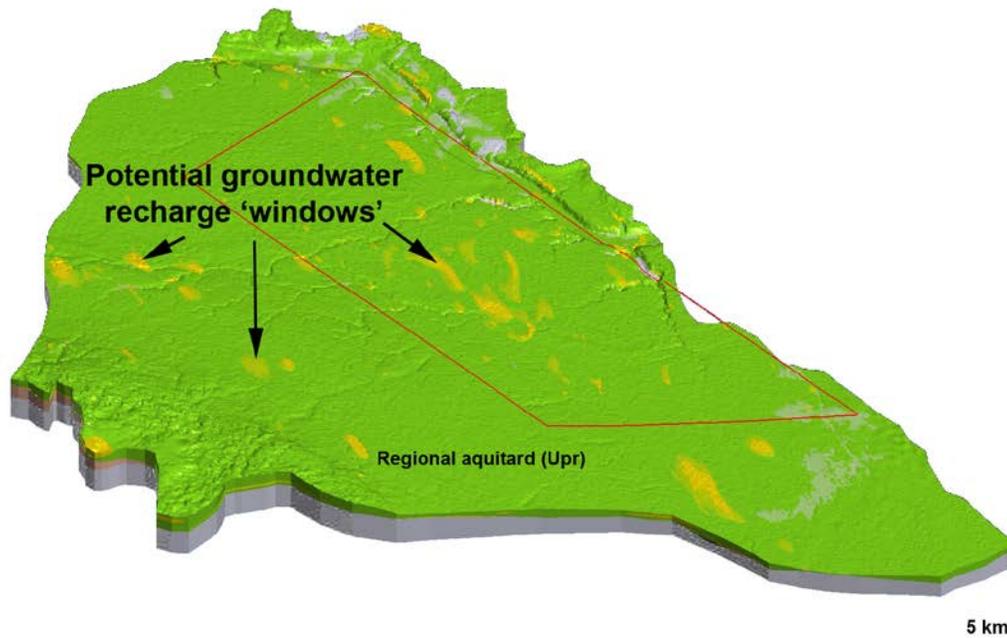


Figure 16. Surface exposures of inter-till aquifer may provide recharge pathways to deeper channel aquifers. Semi-transparent portions show additional exposure potential via the near-surface altered till zone.

Although the β valley aquifer appears to be well constrained and largely confined to the incised channels (Figure 17), this is largely due to way the top of the unit was defined at the top of the western β valley. Where overbank deposits exist, these are included within the lower regional aquifer unit. The direct contact of the lower regional aquifer unit and the β valley aquifer in some areas provide a broader lateral hydraulic connection to the deep β valley aquifer. In North Dakota, interpreted cross-sections guide the β valley aquifer to broaden into an apparent outwash plain type geometry (Figure 17). This appears to be the result of the difficulty in delineating a distinct β bedrock valley from the borehole logs. Consequently, the β valley walls are gentler and the merged β valley is wider in North Dakota.

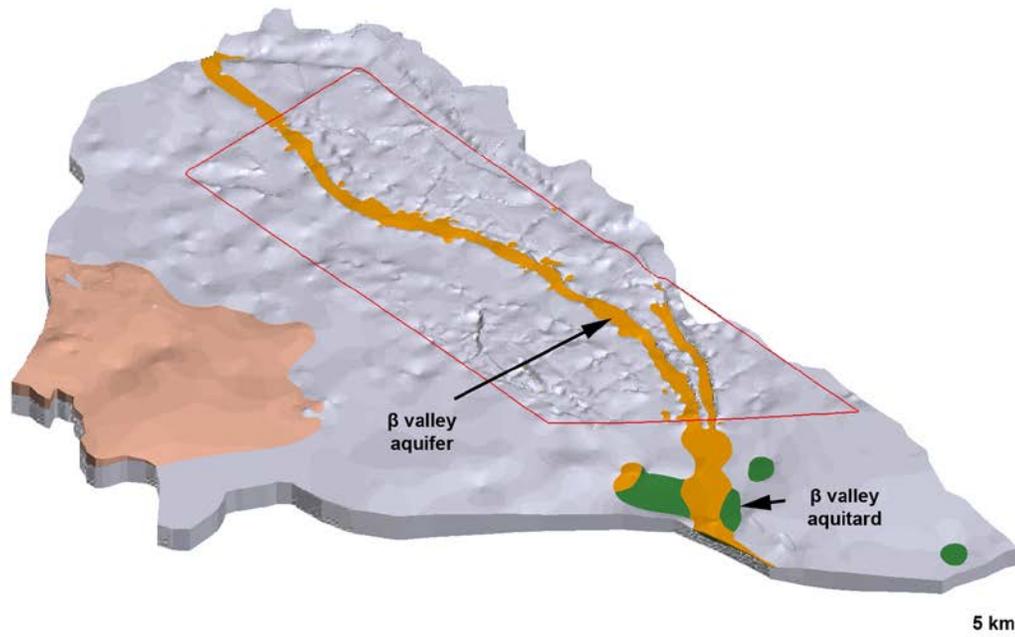


Figure 17. β valley aquifer showing possible outwash feature at the southern extent.

The use of Leapfrog[®] Hydro for geological modelling had both positive and negative features. The ability to display, select and query all the data and the geological models in 3D allowed for effective interpretation of the results. Easy model updating allowed for the creation of several different versions of the model as features were tested and corrections implemented. Given the modelling software's tendency to correlate depositional layer contacts horizontally, data coverage gaps may have resulted in some overly horizontally-connected model layers particularly outside the HTEM survey area (Figure 18). This is an issue with the lower regional aquitard and aquifer layers that were modelled as depositional units to prevent excessive bedrock tunneling effects. Limited control on the interpolation of contact surfaces was sometimes problematic at the regional scale. Accurate rendering of model layer geometries and features can only be achieved with borehole log data alone if the data density is high enough to support the level of detail that needs to be depicted. At regional scales, the cost of such data coverage would be prohibitive. The use of control lines, an intrusive layer type for the inter-till aquifer and manual stratigraphic coding helped to alleviate this problem within the HTEM survey area.

The inter-till aquifer geometry, even with a similar sparse data coverage, appears to form more discreet geometries that are more realistic and in line with HTEM data. This is due to the use of the intrusive layer type in Leapfrog[®] Hydro to better approximate the complex geometry of a multi-episodic, anastomosing channel network within a regional till aquitard (Figure 19).

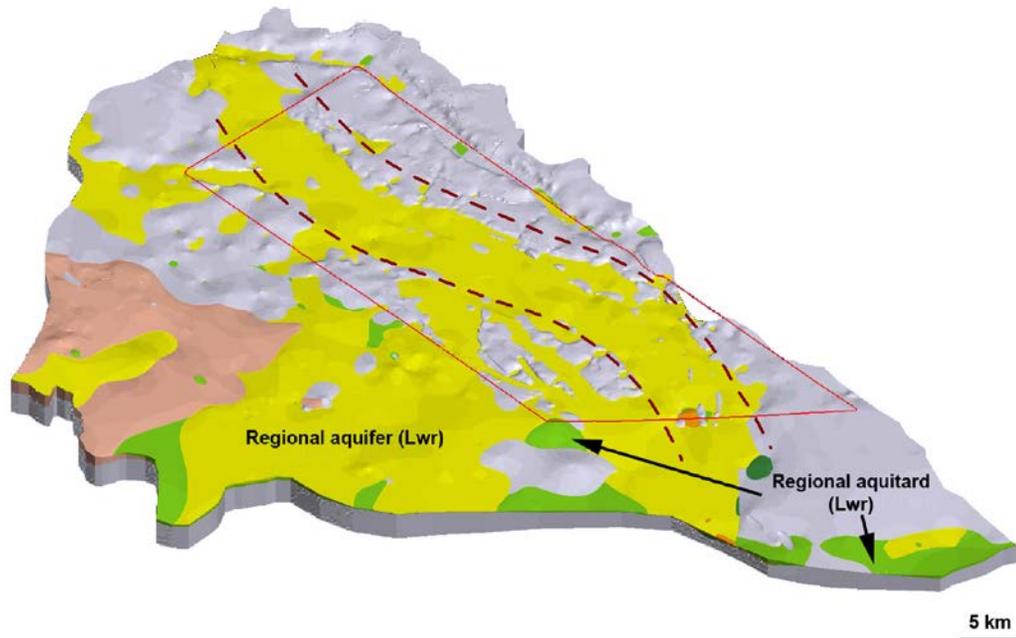


Figure 18. Interpolation of lower regional aquifer primarily from log data with recorded coarse-grained material above bedrock. Sparse data coverage, with little or no intervening data to prevent it, results in excessive horizontal connection. Lower regional aquifer includes β valley aquifer overbank sediment within the α channel (dashed outline).

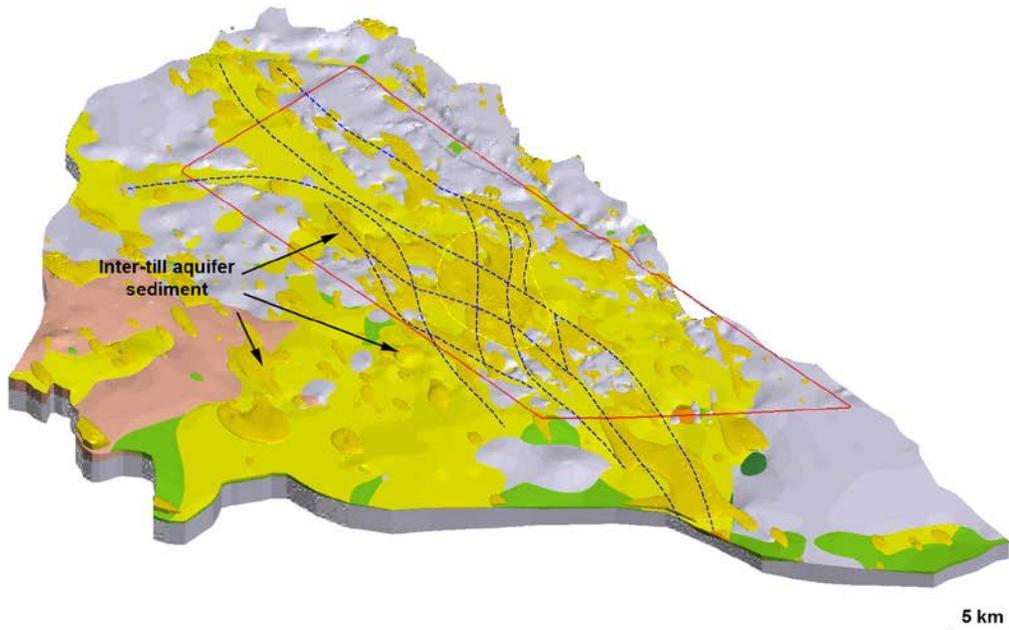


Figure 19. Inter-till aquifer (orange) showing possible channel trends (dashed lines). Thicker, broad geometry (yellow oval) corresponds with shallow, fan-like feature seen in AEM data (Figure 4c). The lower regional aquifer is shown in yellow.

Summary

A 3-D hydrostratigraphic model has been constructed for the Spiritwood buried valley in Southern Manitoba. The model integrates a diverse suite of archival, legacy, and new geophysical and geological data. New HTEM and HRSR data in particular have provided a much improved depiction of the complex arrangement of buried valleys than would not have been possible using only borehole log data in this regional-scale model. In the absence of this data, and relying upon water well records and geological mapping alone, very little of the current bedrock and sediment-hosted valley geometries would have been defined. Nevertheless, considerable effort was required to convert the conductivity model to a 3D geological model. The extrapolation of HRSR profiles guided by HTEM data to better define incised bedrock channels was a key element of the model development process. Similarly, the interpretations of inter-till channel and fan aquifers made possible from the geophysical data advanced the conceptual understanding of the geological setting and assisted in the delineation and hydrostratigraphic assignment of units. The hydrogeological implications of the shape, inter-relationships and connectivity of inter-till aquifers will greatly influence the study of groundwater flow dynamics based on this model.

Leapfrog[®] Hydro modelling software provided a useful platform and workflow to manage and interpret borehole log data and combine with other 3D data components to produce a reasonable geological model. Iterative model checking, editing and reconstruction cycles are simplified by the software's ability to automatically integrate added data and edits and reprocess revised models. Considerable work to manually select and properly code well log intervals was required as well as significant processing power and time was needed to develop model iterations. With a lack of borehole data coverage compared with the level of detail needed to support hydrogeological modelling, the effectiveness of Leapfrog[®] Hydro to render suitable model layers based on borehole log contacts is limited at regional scales. Excessive horizontal connection when using a depositional layer type is a result. With the support of 3D model editing tools, more realistic geometries were possible within the HTEM / HRSR survey area as supported by this data. The hydrostratigraphic model developed in Leapfrog[®] Hydro is being used to build a numerical groundwater flow model in FEFLOW in order to understand regional groundwater flow and assess the potential significance of increased hydraulic connectivity from surface to deep buried valley aquifers.

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Appendix: 3D Geological Model

Accompanying this publication is a version of the 3D model converted into Leapfrog[®] Viewer format. Coded layers are as follows: 100 – Shale bedrock; 100_A – Fractured shale bedrock; 101 – Sandstone bedrock; 200 – β valley aquitard; 300 – β valley aquifer; 401 – Lower regional aquitard; 501 – Lower regional aquifer; 402 – Upper regional aquitard; 402_A – Fractured upper regional till; 502 – Inter-till aquifer; 700 – Glaciofluvial sediment; 800 – Glaciolacustrine sediment; 900 – Recent. The current installation file (as of publication date) for the freely-accessible viewing software is provided as a convenience, however it is advised that the most current version be obtained from Aranz Geo Ltd. and used if possible. The current web-based installation file location is:

<http://www.leapfrog3d.com/products/Leapfrog-Viewer>