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Using a Multiple Variogram Approach to Improve the Accuracy of
Subsurface Geological Models

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ABSTRACT

Subsurface geological models are often used to visualize and analyze the nature, geometry, and variability of geologic and hydrogeologic units in the context of groundwater resource studies. The development of three-dimensional (3D) subsurface geological models covering increasingly larger model domains has steadily increased in recent years, in step with the rapid development of computing technology and software, and the increasing need to understand and manage groundwater resources at the regional scale. The models are then used by decision makers to guide activities and policies related to source water protection, well field development, and industrial or agricultural water use. It is important to ensure that the modelling techniques and procedures are able to accurately delineate and characterize the heterogeneity of the various geological environments included within the regional model domain. The purpose of this study is to examine if 3D stratigraphic models covering complex Quaternary deposits can be improved by splitting the regional model into multiple sub-models based on the degree of variability observed between surrounding data points and informed by expert geological knowledge of the geological/depositional framework. This is demonstrated using subsurface data from the Paris Moraine area near Guelph in southern Ontario. The variogram models produced for each sub-model region were able to better characterize the data variability resulting in a more geologically realistic interpolation of the entire model domain as demonstrated by the comparison of the model output with pre-existing maps of surficial geology and bedrock topography as well as depositional models for these complex glacial environments. Importantly, comparison between model outputs reveal significant differences in the resulting subsurface stratigraphy, complexity and variability, which would in turn impact groundwater flow model predictions.

Key Words: Three-dimensional, 3D, Paris Moraine, Geologic Model, variogram, Quaternary Geology

39 INTRODUCTION

40 Many three-dimensional (3D) subsurface geological models were created for various regions in
41 Southern Ontario following the Walkerton Inquiry (O'Connor 2002) and the consequent source water
42 protection initiatives. Such models have been used in Ontario and elsewhere for a number of
43 environmental management applications including risk assessments of municipal or hazardous waste
44 and the management and protection of groundwater resources (e.g. Artimo et al. 2004; Bajc et al. 2011;
45 Thomason and Keefer 2011; Atkinson and Glombick 2015). In other cases, 3D geological models have
46 been used in the context of the delineation and remediation of contaminants, and the exploration and
47 extraction of aggregate and mineral resources (Houlding 2000; Kauffman and Martin 2008). The
48 overall aim of these models is to characterize the nature and distribution of subsurface materials, which
49 typically necessitate modelling near-surface glacial deposits, in order to constrain the modelling of the
50 groundwater flow system, contaminant migration pathways, transport rate of contaminants and risk to
51 receptors, or to optimize natural resource extraction (Wycisk et al. 2009; Babak et al. 2014; Dunkle et al.
52 2016). Accurately characterizing glacial deposits can be particularly difficult, as subsurface stratigraphy
53 in glacial settings typically have short length scales, abrupt facies transitions, and erosionally truncated
54 relationships as a result of the dynamic nature of these depositional environments and multiple and
55 spatially variable erosional and depositional events associated with repeated ice advances and retreats.

56 The scale of 3D subsurface geological models developed in the context of groundwater resource
57 management have been rapidly increasing over the past decade to cover larger model domains (Bajc and
58 Newton 2005; Logan et al. 2005; Kessler et al 2007; Arihood 2008; Gunnink et al. 2013; McLaughlin et
59 al. 2015). With increasing size, regional models (100's of km² or more) are likely to encompass a
60 variety of depositional environments resulting in multiple heterogeneous zones within a

61 stratigraphic/hydrostratigraphic model (Weissmann et al. 1999; Babak et al. 2014; Dunkle et al. 2016).
62 Modelling heterogeneity across regional study areas can lead to erroneous interpretations when models
63 are constructed using geostatistical interpolators that attempt to incorporate this variability without
64 acknowledgment of these sub-domains (de Marsily et al. 2005).

65 The most commonly applied geostatistical interpolation algorithm is ordinary kriging (Kravchenko
66 and Bullock 1999; Johnston et al. 2001; Jones et al. 2003; Kravchenko 2003; Mueller et al. 2004).
67 Ordinary kriging is a distance weighted estimation algorithm that uses a variogram to characterize the
68 variability between individual data points across a study area to optimize the weights assigned to the
69 data points during the estimation of each grid node (Issaks and Srivastava 1989; Krajewski and Gibbs
70 1996). If there is a large amount of spatial variability within the dataset, it may not be possible to fit a
71 reliable variogram, which will result in poor estimates with large associated errors (Weber and Englund
72 1994; Gringarten and Deutsch 2001). The problem with interpolating subsurface units across regional
73 models containing zones of both high and low variability (the current standard procedure), is that the
74 resulting variogram must characterize the variability within the entire model area, and as a result,
75 produces a blended estimate with unknown bias of the actual variability (Houlding 2000). This problem
76 is compounded by the fact that geostatistical interpolators are often utilized as a 'black box' tool by
77 users who do not fully understand how the predictions were calculated or if they are realistic in their
78 geologic context. Together, these factors may severely compromise the accuracy of the model outputs
79 (Goodchild and Haining 2004). Unfortunately, little attention (if any at all) is paid to variogram analysis,
80 which lies at the center of all geostatistical analysis and estimation for assessing how similar the existing
81 and interpolated data are to one another (Gringarten and Deutsch 2001; Chiles and Delfiner 2012).

82 The objective of this study is to determine if a model can be improved by splitting the regional
83 model into multiple sub-models based on the degree of variability observed between surrounding data
84 points and our understanding of the depositional environment. This modelling approach will aim to
85 incorporate the existing geologic framework ('hard' data, eg. topography, geomorphic features, geologic
86 logs) with 'soft' qualitative data (e.g. geological knowledge of specific depositional environments) to
87 define the sub-model domains, thus optimizing the measured data values as input to the geostatistical
88 model. The hypothesis is that by separating the regional model domain into sub-models based on the
89 data variability and our understanding of the geologic context, a variogram can be produced for each
90 sub-model region that is more representative of the true variability within the data for each area, thus
91 resulting in a more geologically realistic interpolation and model results for both the sub-domains and
92 entire model domain (Weissmann et al. 1999; de Marsily et al. 2005).

93 The regional model domain for this study encompasses a 165 km² area that includes a section of the
94 Paris Moraine near Guelph, Ontario (Figure 1). This was an ideal dataset to use for this study because
95 the model area contains several geological environments and has been identified by the province of
96 Ontario as an area requiring a water budget evaluation and development of a source water protection
97 policy (Ontario Ministry of the Environment 2009). Developing methods to more accurately delineate
98 the form and geometry of the subsurface sedimentary deposits as presented here can be used to help
99 quantify the impact of the Paris Moraine on groundwater recharge and flow variability as well as inform
100 our understanding of potential contaminant pathways and receptors—both important aspects of current
101 water resource management in the region (Russell et al. 2009; Ontario Ministry of the Environment
102 2009). The method developed here can also be used elsewhere, in other glaciated regions where a

103 variety of depositional environments are expected to create significant heterogeneity across a modeling
104 domain.

105 **BACKGROUND GEOLOGY**

106 The Guelph area was glaciated multiple times during the Quaternary period resulting in a
107 complex interfingering of glacial deposits overlying Paleozoic bedrock and multiple glacial landforms at
108 surface (Karrow 1963, 1968, 1987; Chapman and Putnam 1984; Barnett 1992). Drift thickness over
109 bedrock ranges from 10-15 m in the outwash and till plains and up to 40 m along the Paris Moraine.
110 The oldest glacial deposits in the region are defined as Early to Mid-Wisconsinan in age and are either
111 till (Canning Till) or stratified sediments, though these are only documented in a few places. Overlying
112 these older deposits is a relatively continuous regional basal till (Catfish Creek Till) deposited during the
113 major ice advance of the Nissouri Phase (Late Wisconsinan; Table 1) has been described by Karrow
114 (1968, 1987). The Catfish Creek Till unit is overlain by kame and outwash deposits of the subsequent
115 Erie glacial retreat phase. The Port Stanley Till is found at surface in the NW section of the study area
116 and is thought to be associated with the younger Port Bruce ice advance, whereas the Wentworth Till at
117 surface in the SE sector records an ice readvance during the overall retreat of the Erie-Ontario lobe
118 (Mackinaw Phase) (Table 1; Karrow 1987; Barnett 1992; Karrow et al. 2000). In some areas, Karrow
119 (1968, 1987) described an additional till between the Catfish Creek Till and the tills at surface, which he
120 interpreted as Port Bruce in age (Maryhill/Middle Till), although the similarities between Maryhill and
121 Port Stanley Tills in this area, and the limited stratigraphic control and radiometric data do not always
122 allow differentiation of tills at depth. Lastly, laterally discontinuous kame and outwash deposits occur at
123 surface throughout the study area and record glaciofluvial processes associated with ice retreat from the
124 region.

125 The most prominent landform at surface is the Paris Moraine, a NE-SW trending topographic
126 high that cuts across the study area (Sadura et al. 2006) and records stagnation or minor readvance
127 during the Mackinaw Phase (Karrow 1968). It is defined by a core belt of hummocky topography and is
128 composed of silty sandy diamict (Wentworth Till), as well as coarse-grained outwash, kame and ablation
129 deposits. The surrounding landscape consists primarily of outwash plains on either side of the moraine,
130 as well as a drumlinized till plain with Port Stanley Till at surface on its NW side (Karrow 1968;
131 Chapman and Putnam 1984). The Paris Moraine is thought to be an important hydrogeologic feature for
132 enhanced recharge to the underlying bedrock aquifer and provides spatially distributed baseflow to
133 adjacent creeks (Blackport et al. 2009; Russell et al. 2009). The Paris Moraine is also considered to be
134 an important aggregate resource (Ontario Ministry of the Environment 2009). Delineating the 3D
135 spatial geometry of the Paris Moraine and associated deposits is important for accurately assessing its
136 economic and hydrogeologic value and potential, which in turn, can be used to inform source water
137 protection and groundwater resource management decisions.

138 **METHODS**

139 **Data Compilation**

140 A total of 1508 data points recording depth and occurrence of 7 different stratigraphic units were
141 integrated to produce this 165 km² model. 263 of these data points came from moderate to high
142 resolution geologic logs from academic studies (8), and geotechnical reports (255), whereas the
143 remaining 1245 boreholes were obtained from the Ontario Ministry of the Environment water well
144 database (Figure 1). This resulted in a data density of 9.1 data points/km² for the entire study area.
145 When using lithology data to interpolate stratigraphic models, it is best to use only (or primarily) high
146 quality and reliable data. However, in this and many other cases, the use of low quality data from more

regionally extensive databases is necessary to improve the distribution of data across the study area as there were very few high-quality data points, and many of the moderate quality data were typically very shallow (7 m or less) and clustered around local construction sites. As a result, the more regionally extensive water well database (lower quality data) was used to provide information about the subsurface lithology where high quality data were not available (MacCormack and Eyles 2010). To help reduce the number of inaccurate water well data included within the model, only data with a location accuracy of less than 100m, and elevation accuracies of approximately 3 meters or less were included. This methodology of filtering water well data has been applied in other studies forced to rely heavily on water well data (Gao et al. 2006; Puckering 2011). Removing inaccurate water well data prior to model interpolation has been done in previous studies such as Logan et al. (2006).

Lithologic and Stratigraphic Coding

The sediment description data provided for each borehole record were reduced from 108 unique descriptions to 22 textural categories. Combining similar sediment descriptions, such as (sand, fine sand, sandy, silty sand, medium sand, etc.) into categories is necessary in order to gain a better sense of the significant textural variability across a study area (MacCormack et al. 2005; Dumedah and Schuurman 2008; Dunkle et al, 2016). In this study, 22 textural categories were then grouped into assemblages representing 7 stratigraphic units: Bedrock, Undifferentiated tills, Port Stanley Till, Ablation deposits, Wentworth Till, Kame deposits, and Outwash deposits. This was done by comparing the descriptions within the boreholes to the regional stratigraphic framework and assigning stratigraphic units depending on the thickness and sequence of sediment descriptions within each borehole (Figure 2; Table 1). Bedrock was assigned to the base of boreholes that indicated bedrock or solid rock had been encountered and was drilled for at least 1m. The Undifferentiated tills unit was used where till or diamict identified in the borehole records did not fit stratigraphically or lithologically with the other till

units. Karrow (1968, 1974) suggests that finding till deposits older than the Port Stanley or Wentworth
Tills within the Paris Moraine is likely. However, the water well data typically do not contain
sufficiently detailed sediment description to accurately identify and differentiate these older till/diamict
units within the existing regional till stratigraphic framework (Table 1). The Port Stanley Till is
identified where the borehole records identified a silty sandy till, or similar description at surface or at a
relatively shallow depth below surface and in the NW sector of the study area (Table 1; Karrow 1968;
Russell 2009). Ablation deposits were identified as stratified sand and gravel typically found in a
stratigraphically similar position as the Port Stanley Till (Table 1). The Wentworth Till is a sandy to
silty till unit and is typically found in the SE sector of the study area (Table 1; Karrow 1968; Russell
2009). Above the Wentworth Till and primarily along the moraine and back slope in the SE sector are
numerous isolated and discontinuous packages of sand and gravel that have been identified as kame
deposits (Table 1; Cowan 1975; Karrow 1987). The uppermost stratigraphic unit is a more extensive
package of stratified sand and gravel identified throughout the study area as outwash deposits associated
with the stagnation and final retreat of the Laurentide Ice Sheet from this region (Table 1; Karrow 1987;
Russell et al. 2009). All borehole data were coded with picks identifying the elevation of the top contact
for each stratigraphic unit (Figure 2). If a stratigraphic unit was determined to be missing within a
borehole, the unit's top and base elevations were assigned the top elevation of the underlying horizon
resulting in a zero thickness, except if the missing unit(s) occurred at the bottom of the well, in which
case they were not recorded.

Kriging and the Use of Variography

Borehole data were interpolated using the kriging algorithm in RockWorks15 (a geological
modelling software package; www.rockware.com) to predict the vertical and horizontal distribution and
overall geometry of each stratigraphic unit. Due to the substantial differences in the spatial extent of the

193 stratigraphic units, it was necessary to produce modelled surfaces for the top and base of each unit. For
194 example, the same deposit is often laterally discontinuous so that its top surface cannot always be used
195 to define the base of the overlying outwash deposit.

196 Kriging is the most common algorithm used to interpolate geologic data (Kravchenko and Bullock
197 1999; Johnston et al., 2001; Jones et al. 2003; Kravchenko 2003; Mueller et al., 2004). This
198 geostatistical algorithm is capable of considering the spatial proximity of the observed data values (i.e.
199 depth and occurrence of the 7 stratigraphic units) as well as incorporate statistical properties of the
200 measured observations into the calculations of the predicted value (Isaaks and Srivastava 1989). This is
201 achieved by utilizing a variogram to provide additional information on the spatial autocorrelation of the
202 observed stratigraphic units with respect to the model grid nodes (Johnston 2001; Isaaks and Srivastava
203 1989). This provides an effective method of quantifying the similarity (or dissimilarity) between data
204 points with respect to distance (Cressie 1993; Logan et al. 2006, Chiles and Delfiner 2012).

205 The variogram is defined by the following equation;

206
$$\gamma_h = \frac{\sum_i^{n-h} (x_i - x_{i+h})^2}{2n}$$

207 The basic function of a variogram is to illustrate the semi-variance between two data points (X at
208 locations $\{x_i\}$ and $\{x_{i+h}\}$) over varying lag distances (h) (Houlding 2000). This equation calculates the
209 sum of the squared differences between pairs of points separated by distance. The number of points
210 used in the comparison is n , therefore $n - h$ represents the number of comparisons (Davis 2002).

211 Variogram components that provide information about the spatial autocorrelation and continuity
212 of the data (such as nugget, major range, direction of major range, sill, type of variogram model, and

213 correlation coefficient) were analyzed to assess the impact of subdividing the regional model on the
214 interpolation of each stratigraphic unit within each sub-model.

215 **Subdividing the Model**

216 Interpolating and modelling complex geological environments within a single model is often
217 very difficult, as such deposits typically include a substantial amount of natural (real) variability that
218 modeling algorithms are unable to account for (Keefer 2007; Logan et al. 2006). Conventional
219 geostatistical algorithms, such as kriging, require the assumption that the data being interpolated is
220 stationary, such that the variance and mean are the same throughout the model domain (Weissmann and
221 Fogg 1999; Davis 2002). When interpolating data across a glaciated region, it is unlikely that the
222 assumption of stationarity will remain valid considering the dynamic nature of these depositional
223 environments that result in both variable sediments at surface and a complex subsurface stratigraphy
224 (Weissmann and Fogg 1999; Babak et al. 2014). Thus, to improve the results of the regional model
225 interpolation, the study area was subdivided into regions of high and low complexity (variability) that
226 were analyzed independently. The regional model area was divided into sub-models (representing zones
227 of local stationarity) by assessing the data variability and geological complexity within the context of the
228 regional conceptual model. The Original Regional Model domain was subdivided into 3 sub-model
229 zones (Figure 1) by comparing changes in the lateral facies variability at depth in the borehole data set
230 (Figure 2) with stratigraphic and physiographic information from previous scientific publications (Table
231 1; Karrow 1968; Sadura et al. 2006; Russell et al. 2009). These publications typically include details on
232 the spatial extent of these different environments at surface as well as typical stratigraphic units
233 associated with each environment based on surficial mapping, borehole records and ground penetrating
234 radar datasets.

235 Subsurface sediments in Zone 1 are composed of a series of diamict units overlain in many areas
236 by channelized fans of outwash sand and gravel. Zone 1, which encompasses outwash and till plain
237 physiographic elements at surface was identified as a sub-model because the stratigraphic layers in this
238 region tend to be more continuous and laterally extensive in comparison to the neighbouring hummocky
239 deposits of the moraine. Zone 2 is typically very hummocky at surface with a complex internal
240 stratigraphy of Wentworth Till at surface, older till(s) at depth, as well as isolated outwash, kame, and
241 ablation deposits. Zone 2 broadly corresponds to the elongated form and geometry of the Paris Moraine
242 and will likely result in data from the stratigraphic units being correlated in a direction along the length
243 of the moraine and not in the direction of ice movement as expected for the outwash and till plain
244 sediments (Figure 1). Zone 3 encompasses the area to the southeast of the Paris Moraine. These
245 deposits are distinct from the main moraine body and modeled independently due to the highly variable
246 and complex nature of the subsurface sediments and stratigraphic units in this area. The complexity of
247 the Zone 3 deposits (Figure 1) within this region are the result of sediment reworking by gravity and
248 glaciofluvial processes and drainage water ponding between the topographic highs of the Paris Moraine
249 and nearby Galt Moraine.

250 Once the sub model domains were identified, polygon filters were created to subdivide the data
251 based on the defined sub model areas (Figure 1). The individual sub-models were interpolated using the
252 same process as the Original Regional Model. The ordinary kriging algorithm was used to interpolate
253 each model and the variogram results were analyzed to see how the nugget, distance of major range
254 (herein referred to as range), direction of range, sill, type of variogram model, and correlation coefficient
255 varied for each sub-model. A grid spacing of 100 m x 100 m in the X and Y directions respectively was
256 used for each model. This grid node spacing was chosen to ensure that our models were able to capture

the smaller-scale structures of the kame and outwash deposits, while not being too computationally intensive. This produced a total of 615,600 grid nodes covering the 165 km² study area, which offered good resolution for defining the spatial extent of each stratigraphic unit.

Re-Combining the Sub-Models

Once all the sub-models were interpolated, the upper and lower grid surfaces of each stratigraphic unit were joined together using the Grid Editor in Rockworks15. The stratigraphic units were joined with the respective stratigraphic units in neighbouring sub-model domains to form continuous layers over the entire Original Regional Model domain. There were generally sufficient data points along the common boundaries between the sub-models to permit adjacent models to be seamlessly recombined. Where stratigraphic unit grids did not align across sub-model boundaries, a local grid filter (4 grid cells x 4 grid cells) was applied to smooth the transition between the grids. Once the grid surfaces from neighboring sub-model areas were joined together, the regional model was rebuilt using the new grids for each stratigraphic unit (Figure 3).

Comparing the Model Output Results

To assess the impact that subdividing the regional model had on the model results, six variogram parameters were evaluated for the regional model and each of the sub-models: 1) Distance of range, 2) Nugget, 3) Sill, 4) Type of variogram model, 5) Direction of range, and 6) Correlation coefficient of the variogram model. By subdividing the regional model into smaller zones within which the data are more similar, it is expected that the variogram produced will be more characteristic of the data and better able to model the geological features within each submodel. This in turn should be reflected in changes in variogram parameters as discussed below. The scale of the grids used to model the regional and sub-model are the same, and the density of data for each zone are quite similar (10.8 data points/km², 7.8

279 data points/km², and 8.5 data points/km² for Zones 1, 2, and 3 respectively). Therefore the change in the
 280 size of the modelled area in and of itself, is not expected to affect the variogram parameters.

281 Root Mean Square Error (RMSE) was used to compare the model output results from the
 282 standard Original Regional Model and the proposed sub-models to the original observed/measured data
 283 points. RMSE is a good comparative statistic for assessing model output as it provides a global
 284 indication of how similar the interpolated values are to the observed/measured data point values
 285 (MacCormack et al. 2013). When analyzing the RMSE statistics, a small RMSE value indicates that the
 286 interpolated values for the output model are more similar to the observed data point values, whereas a
 287 large RMSE value suggests that the interpolated model values are less similar to the observed data
 288 points. Thus, RMSE values are used here to determine how well the model fits the observed data
 289 values, with low RMSE values indicting a high degree of model accuracy (Zimmerman et al. 1999;
 290 Davis 2002; Dille et al. 2003; Jones et al. 2003; Mueller et al. 2004).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n \left(\hat{Z}(s_i) - z(s_i) \right)^2}{n}}$$

291 Where $\hat{Z}(s_i)$ is the interpolated value at the point (s_i) , and $z(s_i)$ is the observed (true) value from the
 292 original dataset at that same location, and n is the number of points within the input dataset.

293 RESULTS AND DISCUSSION

294 The goal of this study was to investigate if by subdividing the regional model domain, based on the
 295 data variability and our understanding of the geological framework and depositional environment, the
 296 variogram produced for each sub-model would be more representative of the variability within the data
 297 for each area, thus resulting in a more geologically realistic interpolation of the entire model domain.

298 The regional 3D stratigraphic reconstructions were modelled using the same algorithm for both the
299 standard approach of modelling the entire regional domain at one time (Original Regional Model), and
300 the proposed methodology of combining sub-models of the regional domain (Subdivided Regional
301 Model); these reconstructions were then compared to one another (Figure 3). The kriging algorithm
302 used to interpolate data in each of the models is highly sensitive to the variogram model parameters
303 (Myers 1997). Therefore, the variogram parameters (distance of major range, nugget, sill, type of
304 variogram model, direction of major range, and correlation coefficient) from the Original Regional
305 Model and each of the sub-models are compared to provide additional insight into the difference in
306 model output.

307

308 **Comparing the Nature and Geometry of Stratigraphic Units**

309 Visually, there are substantial differences between the two models. The Subdivided Regional Model
310 was able to characterize additional complexity and variability both at surface (Figure 3) and at depth
311 (Figures 4, 5). The surficial outwash deposits of the Subdivided Regional Model are much less
312 extensive, and constrained to the NW and SE corner of the model domain, which is more consistent with
313 published surficial geology maps of the area (Figure 3C; Ontario Geological Survey 2003). The fence
314 diagram shows that other stratigraphic units at depth are also less extensive across the domain, resulting
315 in more complex geometry of units that pinch out or thicken in specific areas and at specific depths
316 within the domain (e.g NW and EW panels on Figure 4); this more complex geometry is thought to be
317 more geologically realistic than the simpler 'layer-cake' model of the Original Regional Model,
318 considering the sediment heterogeneity encountered in glacial deposits in general (Stephenson et al.
319 1988) and in this area in particular (Blackport et al. 2009; Russell et al. 2013; Arnaud et al. this volume).

320 The variable geometry of these units is an important consideration in the context of both local and
321 regional hydrogeological investigations where different unit geometry (with distinct lithology
322 characteristics) can affect overall recharge rates of groundwater, travel time and distribution of
323 contaminants. Improving model predictions of the form and geometry of highly heterogeneous areas
324 like this may help to identify where windows in aquitard materials exist, which may compromise the
325 integrity of the aquitard and water quality in the underlying aquifer.

326 Notably, there are also significant differences in the geometry of the sediment-bedrock interface
327 between the Original Regional Model and the Subdivided Regional Model outputs (Figure 4, 5), with
328 significantly more relief on the bedrock surface and better constrained buried bedrock valleys in the
329 Subdivided Regional Model compared to the Original Regional Model. This variable sediment bedrock
330 interface is consistent with the variable bedrock surface topography and the relatively deep and well-
331 defined buried bedrock valleys documented previously (Karrow 1968, 1987; Gao et al. 2006; Cole et al.
332 2009) and observed in recently drilled boreholes within the study area (Steelman et al. this volume).
333 Relief on the bedrock topography surface is important in both local and regional groundwater
334 applications, as it has an impact on the distribution of recharge to underlying bedrock aquifers.
335 Modeling the geometry and distribution of the glacial deposits infilling the incised bedrock valleys with
336 respect to their hydrogeologic properties allows the user to better understand groundwater migration
337 pathways and the potential for increased groundwater recharge of bedrock aquifers.

338 Although the Paris Moraine (Zone 2) in the Subdivided Regional Model is dominated by till units,
339 specific units of coarse-grained materials (outwash, kame or ablation deposits) within the moraine tend
340 to be thicker and more spatially constrained compared to that in the Original Regional Model (Figure 5).
341 This is indeed more consistent with the subsurface stratigraphy of the moraine identified as

heterogeneous and variable in regional studies based on water well records and geotechnical reports as well as more local studies based on both water well records and recovered sediment core (Blackport et al. 2009; Russell et al. 2013; Arnaud et al. this volume). Sediment composition in water well records of the Paris Moraine in the area surrounding Guelph for example suggests there is approximately 30% gravel, with relatively less sand (~10%) and mud (<10-15%) that make up the Paris Moraine subsurface stratigraphy (Russell et al. 2013). Cores recovered in the moraine together with cross section through the moraine in the Guelph area also have laterally restricted sequences of coarse grained materials adjacent (within 100's of m) to boreholes dominated by diamict (Arnaud et al. this volume). The lateral continuity of units within Zones 1 and 3 appear to have been more impacted by sub-dividing the model domain than those within the Paris Moraine. Generally, the geologic units within the Subdivided Regional Models are more laterally discontinuous, and have greater variability in unit thicknesses (Figure 5), which is also consistent with previous findings based on standard geological cross sections through the area (Blackport et al. 2009; McGill 2012; Arnaud et al. this volume), where subsurface heterogeneity, lateral discontinuity of geologic units and/or the relief on the underlying bedrock surface leads to rapid changes in unit thicknesses. For example, the basal diamict that underlies the outwash plain is not always preserved (McGill 2012), and the regional Catfish Creek Till thickens considerably from < 5m to over 25 m as it infills a topographic low in the underlying bedrock surface (Steelman et al. this volume).

Comparing Range Values

It is typically assumed that a longer range is better because it indicates that the data values were similar to one another over greater distances. However, in areas where the data are more variable over shorter distances, a variogram with a shorter range of correlation would likely produce a more realistic

365 model result. The variogram ranges for the Original Regional Model varied between 1818.9 m
366 (Outwash base grid) and 2496 m (Ablation base grid) with an average range of 2210.8 m for the entire
367 model (Table 2). The ranges for the subdivided models tended to be shorter than those of the Original
368 Regional Model (Tables 2, 3, 4, and 5). The range values in the Zone 1 sub-model varied between
369 1197.1 m for the Outwash base grid and 1712.9 m for the Undifferentiated tills top grid with an average
370 range of 1585.9 m for the entire sub-model (Table 3). The Zone 2 sub-model ranges varied between
371 1599.3 m for the Wentworth Till base grid and 2182.2 m for the Undifferentiated till base grid, with an
372 average range of 1973.8 m for the entire model (Table 4). The range values for the stratigraphic units
373 within the Zone 3 sub-model varied between 1284.9 m for the Wentworth Till base grid and 1809.9 m
374 for the Kame base grid, with an average range of 1531.4 m for all of the stratigraphic units within this
375 sub-model (Table 5).

376 Glacial ice margin advances and retreats over the study area have led to a complex interfingering
377 of glacial deposits of variable texture. Regionally, the subsurface stratigraphy has been characterized as
378 consisting of alternating diamict and stratified sediment such as sand, gravel and mud; the former
379 representing ice advances, whereas the latter records ice margin retreat and glaciofluvial and
380 glaciolacustrine processes in ice proximal to ice marginal settings. However, local studies of the
381 subsurface stratigraphy to date have demonstrated that the subsurface stratigraphy is more variable with
382 laterally discontinuous stratigraphic units (Blackport et al. 2009, Russell et al. 2013; Arnaud et al. this
383 volume). This heterogeneity is attributed to the dynamic interplay of glacial processes over time,
384 namely glaciofluvial and glacial erosion and variable preservation of previously deposited glacial
385 sediments, as well as the spatially and temporally varied distribution of glaciofluvial networks and

386 glaciolacustrine ponding that would have occurred in different places over time as the ice margin melted
387 and glaciofluvial and ice marginal processes modified the pre-existing deposits.

388 Considering the highly variable nature of the deposits described by various geological studies of
389 the Paris Moraine (Karrow 1968; Barnett 1996; Sadura et al. 2006; Russell et al. 2009; Blackport et al.
390 2009; Arnaud et al. this volume), variograms with a shorter range are probably geologically more
391 realistic, characterizing the true variability within the subsurface. By subdividing the study area prior to
392 interpolation, the average range lengths for the stratigraphic units were decreased between 11% and 31%
393 compared to the original regional model where all data were lumped rather than subdivided (Tables 2, 3,
394 4 and 5). A lower range value does not suggest that one model is necessarily better than another, but
395 rather that the variability has been constrained to the local sub-model areas, and ensuring the
396 stratigraphic variability characteristic to each sub-model zone was preserved.

397 **Comparing Nugget Values**

398 The variogram nugget represents the amount of very short range (zero distance) variability that
399 cannot be accounted for in the variogram model and is associated with unexplained errors in the data or
400 sampling procedures (Krajewski and Gibbs 1996). The nugget is often the result of sampling errors or
401 geological variability that is occurring on a smaller scale than the data point spacing and is measured in
402 units squared (Davis 2002). Although it would be ideal to have a variogram without any nugget effect,
403 this is typically uncommon in geological investigations (Krajewski and Gibbs 1996; Davis 2002). The
404 nugget for the Original Regional Model ranged from 0 to 25.3 m² for the 7 stratigraphic units, with an
405 average nugget of 14.9 m² for all units (Table 2). The Zone 1 sub-model had nugget values that ranged
406 from 0 to 15 m², with an average nugget of 6.9 m² (Table 3). The Zone 2 sub-model had nugget values
407 that ranged from 0 to 15.6 m², and an average nugget of 7.5 m² (Table 4). The Zone 3 sub-model

408 produced variograms with nuggets ranging from 0 to 9.9 m², and an average nugget of 4.7 m² (Table 5).
409 Subdividing the regional model resulted in lower nugget values for each of the sub-models as average
410 nugget values were reduced by 54%, 50%, and 68% for the Zone 1, 2, and 3 sub-models, respectively.
411 These results suggest that the variograms were able to better characterize more of the data (resulting in
412 less unexplained variability) when the subdivided models were interpolated separately. Essentially,
413 the sub-models are better at capturing smaller scale variability that is likely related to the depositional
414 conditions of each zone, thus resulting in less unexplained variability. The lower nugget values indicate
415 that by subdividing the regional model based on data variability and geologic knowledge, the amount of
416 unexplained variability within the models was reduced for each sub-model.

417 **Comparing Sill Values**

418 The sill represents the amount of variability observed between the data points at the variogram
419 range. Theoretically, if the distance between the sample points is zero, the value at each data point will
420 be compared with itself and therefore the variance would also be zero. As the distance between points
421 get slightly larger, so too would the difference in values. At some distance, the points are so far apart
422 that they are no longer spatially related. At this point, the variance (gamma), which is measured in units
423 squared, between successive data points no longer increases and it is referred to as the sill. If the sill is
424 reached at a low gamma value, this indicates that there tends to be less variability between data point
425 values. In contrast, if the sill is reached at a high gamma value, then there is generally more variability
426 between data point values. Statistically, it is better to have a variogram with a low sill value, which
427 indicates that there is lower variability between the data points even up to the distance at which the
428 points are no longer statistically similar to one another (Krajewski and Gibbs 1996). However,
429 geologically, a low or high sill value allows the level of variability within the stratigraphic dataset to be

430 established, which in turn provides information on the subsurface variability within each of the sub
431 model zones.

432 The Original Regional Model variogram produce d sills ranging from 36.4 – 144.2 m², with an
433 average sill of 103.5 m² (Table 2). The Zone 1 sub-model variograms produced sills ranging from 10.6
434 – 90.2 m², and an average sill of 57.2 m² (Table 3). The Zone 2 variogram sill values ranged from 20.6
435 – 98.8 m², with an average sill of 66.7 m² (Table 4). The Zone 3 sub-model variogram sill values ranged
436 from 19.2 – 83.1 m², with an average sill value of 45.2 m² (Table 5). The sub-model variograms had
437 lower average sill values than the Original Regional Model (103.5 m²; Table 2). A lower sill value does
438 not suggest that one model is better than another, but rather that there is less variability within the data
439 used to model the variogram. The results of this study indicate that there is less variability between the
440 data points within the sub-model variograms than in the Original Regional Model variogram
441 representing the entire model domain. The lower sill values are consistent with our current
442 understanding of the local geology: Zone 1 and Zone 3 are characterized by the drumlinized till plain
443 and outwash plain, and have relatively consistent subsurface stratigraphy dominated by till and stratified
444 sediments respectively, whereas the slightly larger sill value observed for Zone 2 is representative of the
445 more heterogeneous deposits of the Paris Moraine (Arnaud et al. this volume). By subdividing the
446 regional model into sub-models of similar data variability, the respective variograms were able to better
447 characterize the site variability and are more likely to produce a more realistic representation of the
448 volumes for each geologic unit.

449 **Correlation Coefficients**

450 The correlation coefficient is used to assess how well the variogram model matches the data,
451 which provides some information on the predictive capabilities of the interpolation parameters. The

correlation coefficient is a measure between -1 and +1, indicating that there is a perfect negative correlation (-1), no correlation (0), or a perfect positive correlation (+1) between the data points and the variogram model. A correlation coefficient close to 1 indicates that the variogram was able to accurately define the spatial relationship of the data points and that there is a good fit between the observed data points and the variogram model that will be used to predict the grid surfaces; both of which are extremely important in order to achieve an accurate interpolation result. The correlation coefficient is therefore a useful statistic to help analyze how well the variogram model is able to match the observed data, which provides some information on the predictive capabilities of the interpolation parameters. In this study, we are interpolating the elevation of specific stratigraphic units, therefore the correlation coefficient was used to assess how well the variogram model was able to predict the elevation of the stratigraphic units at observed (borehole) locations.

The Original Regional Model produced correlation coefficients between 0.89 and 0.99, with an average of 0.96 for all grids (Table 2). The Zone 1 sub-model produced variogram models with better correlation coefficients ranging from 0.98 – 1.0, with an average of 0.98 (Table 3). The Zone 2 sub-model correlation coefficients ranged between 0.97 and 1.0, with an average of 0.99 (Table 4). The Zone 3 sub-model values ranged between 0.88 and 0.99, with an average of 0.95 (Table 5). The Zone 1 and 2 sub-models both performed better than the Original Regional Model, whereas the Zone 3 sub-model performed equally as well as the Original Regional Model.

It is apparent that there is higher variability amongst the data of the Zone 3 sub-model due to the lower average correlation coefficient. This may be due to the complex depositional conditions that would have existed in this area during ice retreat and that include slumping of sediments along the Paris Moraine back slope as the buttressing ice retreated from the area, as well as glaciofluvial reworking and

ponding that would have occurred as the ice retreated to the position of the Galt Moraine to the SE. In addition, some of the lower correlation coefficients observed in Zone 3 may be related to the difficulty of identifying those units at depth (e.g. Port Stanley and Undifferentiated tills; Table 5). This may be due to several factors including: i) the possibility that these lower tills were partially eroded and therefore more randomly distributed, ii) the predominance of low quality data point in Zone 3, which makes it difficult to distinguish between the various tills at depth, and iii) the relatively sparse coverage of data points within portions of Zone 3.

It is likely that the lower correlation coefficient observed within the Zone 3 sub-model is causing the lower correlation coefficient observed within the Original Regional Model, as both the Zone 1 and 2 sub-models produced variograms with better (higher) correlation coefficients (0.99 and 0.98 respectively; Tables 3 and 4) than the Original Regional Model (0.96; Table 2). Therefore, by subdividing the regional model into sub-model areas, it was possible to limit the amount of influence between the regions of increased variability observed within the Zone 3 sub-model, and the less variable model areas of Zones 1 and 2. Developing a geologic model that more realistically characterizes the stratigraphy and subsurface heterogeneity will ultimately provide a more robust framework for assigning hydrogeologic parameters in groundwater flow models used in regional resource management or contaminated site remediation applications (de Marsily et al. 2005).

Optimal Variogram Model

For the variogram to be used in the interpolation process, a variogram model must be fit to the data to provide a prediction of the unknown values at specific locations. The Variogram model is essentially a generalized mathematical equation that provides the best fit to the observed data (Isaaks and Srivastava 1989; Gringarten and Deutsch 2001; Chiles and Delfiner 2012). There are a variety of

496 variogram models (ie. spherical, exponential, linear, gaussian, nugget, hole-effect, and drift) that can be
497 applied to data depending on how quickly the data variability increases as the distance between data
498 points increases. Many software packages will automatically assign a spherical model when fitting a
499 variogram unless otherwise specified. For this study, variograms were fit using each type of variogram
500 model to determine which variogram model produced the best fit with the observed data points, had a
501 high correlation coefficient, and corresponded with our understanding of the spatial variability for each
502 specific stratigraphic unit (Gringarten and Deutsch 2001). A complete list of variogram models and
503 their implications to model output can be found in Isaaks and Srivastava (1989), Krajewski and Gibbs
504 (1996), Gringarten and Deutsch (2001), and Johnson (2001).

505 The Exponential variogram model most often provided the best fit for the stratigraphic unit
506 datasets in this study. Exponential variogram models typically provide the best fit for datasets where the
507 variance increases quickly at short-distances and then gradually tapers off for data points that are further
508 apart (Gringarten and Deutsch 2001). This seems appropriate considering many stratigraphic units in
509 this study area are quite variable at short distances, however because these units are often dispersed
510 throughout the study area, the data tends to fit best with models with positive correlations that persist
511 below the sill for large horizontal distances, and often do not reach the expected sill variance. All of the
512 grid surfaces for the Original Regional Model were modelled using an Exponential variogram either
513 with or without a nugget (Table 2). Only three surfaces in the Zone 1 and 2 sub-models (outwash
514 deposit top in zones 1 and 2 and base in zone 1) were modelled with a Gaussian variogram model both
515 with and without a nugget (Tables 3 and 4). Gaussian variogram models typically provide the best fit
516 for datasets whose variance initially increases gradually, then begins to increase more rapidly as the
517 distance between points increases, which is likely considering the outwash deposits have a patchy

distribution at the surface (Figure 3C; Krajewski and Gibbs 1996). The only other grid that used a variogram model other than Exponential was the Ablation base grid in the Zone 3 sub-model, which used a spherical model (Table 5). Spherical variogram models are characteristic of datasets where variance initially increases linearly with increasing distance up to a well-defined sill, and are also typically used for modelling properties with higher levels of short-range variability (Krajewski and Gibbs 1996). In general, there was very little change in variogram type between the Original Regional Model and the individual sub-models, and therefore, subdividing the regional model domain for this study area was minimally impacted by the type of variogram selected.

Variation in the Direction of Longest Variogram Range

In order to determine the direction for which the variogram range is the longest and produces the greatest correlation over the greatest distance, variograms were evaluated in multiple directions to test the data for anisotropy. The direction of longest variogram range provides a sense of the direction in which sediment types are most consistent from one data point to the next. This parameter may change when the regional model is subdivided, if dominant processes change from one area of the regional model to the next. The direction of longest variogram range is also expected to be more closely aligned for the top and base of geological units in a sub-model zone, as that zone will have been subjected to specific depositional conditions and be associated with specific geological features that are directionally more consistent, compared to the wide range of depositional conditions and anisotropy captured in a regional model. Lower correlation between the top and base of thicker or more extensive units is expected where the basal contact and the overlying sediment result from different processes (e.g. glaciolacustrine sediments blanketing an irregular topography associated with the underlying depositional regime).

The results from the anisotropic variograms revealed that the direction of longest range changed for some stratigraphic units when the regional model was subdivided into sub-models based on data variability and geological context. For example, the top and bottom grid surfaces of the Kame deposit for the Original Regional Model produced the longest ranges at N 135 and N 141 respectively. When the variograms were produced for the subdivided models, the top and bottom grid surfaces of the Kame deposits for the Zone 2 sub-model produced the longest ranges at N 7 and N 9 respectively, which represents a 130 degree shift (Table 2 and 4). Kames can have a wide variety of ranges considering that they are deposits that represent the internal drainage that was occurring on and within the ice (Benn and Evans, 2010). The change in the direction of longest range between the Original Regional Model and the Zone 2 sub-model highlights the variation of the kame deposits between the sub-model zones while maintaining consistency within each sub-model zone.

The consistency of the range direction did indeed increase for 2 of the 3 sub-model regions when the Regional Model domain was subdivided. The direction of longest range within the Original Regional model varied between N 3.9 – N 169 (degrees from North; Figure 6A; Table 2) for the seven stratigraphic units. The direction of greatest correlation range for the sub-models were much more consistent within the Zone 1 and 2 sub-models. The major axis for stratigraphic units within Zone 1 ranged from N 121 to N 149, which is a difference of only 28 degrees, and coincides with the orientation of drumlins, the direction of ice flow and melt-water run-off in this study area (Karrow 1968, 1987; Barnett 1992; Figure 6B; Table 3). There was also much greater consistency between the top and base grids for each stratigraphic unit within Zone 2 (average difference of only 12.6 degrees; Figure 6C; Table 4). Although the range direction for the Zone 2 sub-model stratigraphic units varied between N 7 and N 176 (a 169 degree difference), the rose diagram for the Zone 2 sub-model (Figure 6C) shows that

the direction of longest range for the majority of stratigraphic units were aligned in the direction of ice movement and meltwater runoff to the NW. In contrast, the kame deposits and uppermost outwash deposits of Zone 2 were aligned nearly N-S (Figure 6C, Table 4), which in some places is aligned with the front edge of the Paris Moraine (Figure 1) and explains the 169 degree difference in range directions for the different stratigraphic units of Zone 2. It is perhaps not surprising that kames are not consistent with the rest of the data considering their deposition is related to glacial hydrology controlled by localized ice configuration and drainage networks. In contrast, the Zone 3 sub-model showed considerable variation in the direction of the unit variogram long axis. The directions ranged from N 8.6 to N 177, which is a difference of 168.4 degrees (Figure 6D; Table 5). This is consistent with the palaeoenvironmental model for this area that suggests initial deposition and deformation by ice in the SE-NW direction, further deposition by debris flows as the ice retreated and support of the moraine sediment was removed, and lastly glaciofluvial and glaciolacustrine reworking of sediments along the back slope of the Paris Moraine in the NE-SW direction as water drained between the Paris Moraine and the adjacent Galt Moraine. The difference in direction between the top and base grid surfaces for each unit was also significantly lower with an average difference of 54.4 degrees (Figure 6D; Table 5).

Visually, the 3D stratigraphic models of the Original Regional Model and the Subdivided Regional Model appear quite different from one another (Figures 3, 4, 5). The most substantial difference is in the Outwash deposit, which appears much less extensive in the Subdivided Model, and is limited to two broad swaths; one in Zone 1 and one in the SE corner of the study area in Zone 3 (Figure 3). Zone 2 of the subdivided model is characterized by more extensive tracts of Wentworth Till, kames and minor outwash (Figure 3B), which are consistent with the distribution of Wentworth Till and gravel identified in the surficial geology map (Figure 3C). The variation in the range direction between the top

584 and bottom of the Outwash stratigraphic unit in the Original Regional Model was 40 degrees (Figure
585 6A; Table 2). However, when the Outwash unit was interpolated in the sub-model sections, the
586 variation between the top and bottom grids was a maximum of 20 degrees (Tables 2, 3, 4 and 5). The
587 reduced variation in range likely occurred because there was greater correlation between the direction of
588 longest range between the top and bottom grids of the stratigraphic units, which resulted in a more
589 localized and streamlined model representation of the Outwash deposits (Figure 3). In contrast, the
590 deposits within Zone 3 had much more directional variability than those of Zone 2 or 1 (Figure 6D). It
591 is likely that the greater directional variability of the stratigraphic units within Zone 3 significantly
592 affected the Original Regional Model variograms, resulting in more directional variation and greater
593 inconsistencies between top and bottom of each unit, therefore biasing the form and geometry of the
594 Outwash unit. By subdividing the regional model, it was possible to produce variograms that better
595 characterize the individual stratigraphic units within each zone, thus revealing the different degrees of
596 variability associated with each zone, reflective of depositional environments and spatial data.

597 In geological terms, the subdivided model variograms were able to capture the variability in flow
598 direction associated with each zone and thus better infer the resulting distribution of the Outwash
599 stratigraphic unit in those different meltwater drainage networks. In Zone 1, the direction of longest
600 variogram range is consistent with meltwater flow directions away from the ice margin and the Paris
601 Moraine and influenced by the NW-SE drumlin orientations of the pre-existing till plain. In Zone 2, the
602 direction of longest variogram range for the top and base of the outwash deposit varies by 20 degrees,
603 consistent with the likely more variable drainage patterns influenced by the chaotic hummocky
604 topography of the moraine. Lastly in zone 3, the direction of longest variogram shifts to a NNW-SSE
605 direction, which is perhaps capturing some of the predominant NW-SE drainage as well as some

606 deflection of that flow towards the south as meltwater was routed between the Paris and adjacent Galt
607 moraines.

608 **RMSE Results**

609 Root mean square error results have been used in many studies as an effective method of
610 assessing the accuracy (i.e. how closely the model matches the observed points) of interpolated results
611 (Zimmerman et al. 1999; Davis 2002; Dille et al. 2003; Mueller et al. 2004). RMSE results were used in
612 this study to compare the model accuracy of the regional model interpolated using all the available data
613 (Original Regional Model) and the regional model produced by subdividing and interpolating sub-
614 models based on data complexity/variability (Subdivided Regional Model; Figure 3). The Subdivided
615 Regional Model produced a lower RMSE value (0.57) than the Original Regional Model (0.86).
616 Therefore, subdividing the regional model domain into sub-models produced a more accurate spatial
617 interpolation of the regional data.

618 Ideally, only data from high quality and reliable data sources would have been used. However, as is
619 often the case in regional geological models, it was necessary to include variable quality data from
620 regional databases due the size of the regional model domain, and the fact that the available moderate
621 quality data were often clustered and did not penetrate very deep in the subsurface. It is likely that as
622 additional high quality data becomes available for the model domain, the performance of the subdivided
623 model variograms will improve further, thus having an even greater impact on the 3D stratigraphic
624 model accuracy and an improved basis for informing hydrogeologic parameter variability. Stochastic
625 modelling approaches could also be applied within sub-model zones to visualize and assess multiple
626 model realizations and capture the variability in the model predictions (Kearsey et al. 2015). The next
627 step is to integrate this improved representation of the geologic spatial variability with hydrologic

parameters to assess the effects on flow system conditions where water balance and hydraulic head distributions from field and model outputs can be evaluated. This improved delineation of the subsurface deposits within the Paris Moraine will in turn be useful for the management of groundwater resources as source water protection policies are implemented in coming years.

CONCLUSIONS

The objective of this study was to determine if subsurface geological model accuracy could be improved by splitting the regional model into multiple sub-models based on the degree of variability observed between surrounding data points and our knowledge of the geological/depositional framework from previous studies. The hypothesis is that by separating the regional model domain into sub-models based on the data variability and our understanding of the geological context, a variogram can be produced for each sub-model region that is more representative of variability within each area, thus resulting in a more geostatistically appropriate and geologically realistic (cf. Karrow 1968) model interpolation for the entire study area that can be used to better inform aggregate and groundwater resource characterization studies (Weissmann et al. 1999; de Marsily et al. 2005).

The results showed that by interpolating the regional stratigraphic units within sub-models based on the spatial variability within the data, the kriging algorithm was able to produce a more representative variogram of the data. The Zone 1 and 2 sub-models produced variograms with lower ranges, more consistent major axis directions, higher correlation coefficients, and lower sill and nugget values. This is to be expected considering the stratigraphic units in Zones 1 and 2 are typically elongate and laterally continuous deposits in the SE-NW direction for the outwash and drumlinized till plain deposits (Zone 1),

649 recording the dominant meltwater and ice flow directions, and in the NE-SW direction along the Paris
650 Moraine (Zone 2). Thus, the variogram models for these sub-models were more constrained and able to
651 better characterize the observation data than when the data for the entire model domain was considered
652 as a whole. The Zone 3 sub-models produced variograms with the shortest ranges, lots of variability in
653 the major axis direction, and produced lower correlation coefficients. The Zone 3 sub-model data were
654 evidently more difficult for the variogram to characterize, suggesting that this area contains the most
655 variable and complex stratigraphy within the model domain. This variability is attributed to sediment
656 reworking by gravity and glaciofluvial processes, and drainage water ponding between the topographic
657 highs of the Paris Moraine and nearby Galt Moraine. Zone 3 likely requires additional high resolution
658 field data to help characterize this complexity or further subdivision to improve variogram parameters
659 and model outputs.

660 The results of this study reveal that when all of the data were modelled together as one large regional
661 model, the resulting variograms produced blended estimates of the variogram parameters. However,
662 when the Zone 3 sub-model data were modelled independently of the Zone 1 and 2 sub-models, the
663 variograms were better able to capture the subsurface characteristics of each zone. The increased
664 variability within Zone 3 attributed to the complex sediment reworking and variable glaciofluvial,
665 glaciolacustrine and ice marginal processes associated with ice margin retreat to the adjacent Galt
666 moraine was confined to Zone 3 and did not impact the sub-models of the neighbouring zones.
667 Conversely, the data characteristics of the more laterally extensive and directionally consistent
668 stratigraphic units within the outwash and till plain of Zone 1 as well as the elongate form and geometry
669 of the stratigraphic units within the Paris moraine (Zone 2) sub-models were confined to those areas and
670 did not reduce the variability observed within the Zone 3 sub-model area.

671 The proposed sub-model approach produces a more geologically realistic model of the study area
672 when compared with the regional model approach as evidenced by comparing the model results against
673 the regional surficial geology map (Ontario Geological Survey 2003) and previous subsurface studies in
674 this area (Karrow 1968, 1987; Blackport 2009; Arnaud et al. this volume). In the sub-model outputs,
675 various stratigraphic units, are laterally more constrained and their bounding surfaces, including that of
676 the underlying bedrock, exhibit more significant relief. This is consistent with subsurface observations
677 in the study area where tills are laterally discontinuous, stratified sediments are found in close proximity
678 to diamict within the moraine and the underlying bedrock surface is dissected by various well-defined
679 buried bedrock valleys. The sub-model results are also more consistent with what is generally known of
680 sediment landform associations in terrestrial glaciated landsystems, namely the relative lateral continuity
681 of facies in till and outwash plains and the relative variability of facies found in ice marginal or ice
682 contact sediments (Stephenson et al. 1988; Benn and Evans 2010). The integration of sub-models
683 provides a means to highlight the heterogeneity across the regional domain and avoids blending areas of
684 differing variability together, resulting in a more realistic characterization of the nature, geometry and
685 extent of geological and hydrogeological units within this complex depositional environment. This is
686 turn can improve the geological framework used in various groundwater flow modelling efforts, both in
687 site specific contaminant transport investigations or in regional susceptibility or groundwater supply
688 studies carried out in previously glaciated regions like Southern Ontario.

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Table 1: Generalized Stratigraphy as Described by Previous Studies in this Region

Karrow 1968	Karrow 1987-NW sector	Karrow 1987-SE sector
Wentworth Till	Kame/ outwash	Kame/ outwash
ablation deposits	Port Stanley	Wentworth Till
	Kame/outwash/Maryhill	Kame/outwash/Maryhill
Middle till	Till	Till
Catfish Creek Till	Catfish Creek Till	Catfish Creek Till
Canning Till or older	Canning Till or older	Canning Till or older
Bedrock	Bedrock	Bedrock

*Note: A major unconformity surface exists between the Silurian bedrock and overlying Quaternary deposits

Table 2: Variogram parameters for the Original Regional Model

Unit	Direction	Range (m)	Sill (m ²)	Nugget (m ²)	Type	Cor. Coef.
Outwash Deposit top	169	2000.3	36.4	0	Exponential No nugget	0.98
Outwash Deposit base	129	1818.9	70.7	10.9	Exponential w/ nugget	0.97
Kame Deposit top	141	2121.5	91.8	14.5	Exponential w/ nugget	0.94
Kame Deposit base	135	2109.5	95.4	15.1	Exponential w/ nugget	0.95
Wentworth Till top	3.9	2253.5	65.6	0	Exponential No nugget	0.99
Wentworth Till base	125	1957.1	78.2	12.3	Exponential w/ nugget	0.97
Ablation top	138	2448.1	124.1	20.1	Exponential w/ nugget	0.93
Ablation base	148	2496	130.1	22.2	Exponential w/ nugget	0.89
Port Stanley top	9.5	2344.7	138.7	25.3	Exponential w/ nugget	0.94
Port Stanley base	161	2343.3	137.3	23.5	Exponential w/ nugget	0.97
Undifferentiated Till top	160	2357	139.3	23.9	Exponential w/ nugget	0.98
Undifferentiated Till base	162	2380.9	144.2	25.2	Exponential w/ nugget	0.99
Bedrock top	126	2109.2	93.5	0	Linear No nugget	0.98
Average	123.65	2210.77	103.48	14.85		0.96

Table 3: Variogram parameters for the Zone 1 sub-model

Unit	Direction	Range (m)	Sill (m ²)	Nugget (m ²)	Type	Cor. Coef.
Outwash Deposit top	125	1329.8	10.6	1.4	Gaussian w/ nugget	1
Outwash Deposit base	132	1197.1	74.8	0	Gaussian No nugget	0.98
Kame Deposit top	149	1634.5	88.3	14.7	Exponential w/ nugget	0.98
Kame Deposit base	148	1639.6	90.2	15	Exponential w/ nugget	0.98
Wentworth Till top	154	1535.4	25.2	4.2	Exponential w/ nugget	0.99
Wentworth Till base	122	1506.2	35.6	5.3	Exponential w/ nugget	0.98
Ablation top	145	1694.6	106.5	17.6	Exponential w/ nugget	0.98
Ablation base	142	1688.1	108.3	17.7	Exponential w/ nugget	0.98
Port Stanley top	145	1701	107.7	16.8	Exponential w/ nugget	0.98
Port Stanley base	144	1702	101.8	16.6	Exponential w/ nugget	0.98
Undifferentiated Till top	144	1712.9	103.2	17	Exponential w/ nugget	0.98
Undifferentiated Till base	149	1687.3	100.5	16.4	Exponential w/ nugget	0.98
Bedrock top	121	1588	43.4	6.4	Exponential w/ nugget	0.99
Average	140.00	1585.88	76.62	11.47		0.98

Table 4: Variogram parameters for the Zone 2 sub-model

Unit	Direction	Range (m)	Sill (m2)	Nugget (m2)	Type	Cor. Coef.
Outwash Deposit top	156	1837.1	20.6	0	Gaussian No nugget	0.99
Outwash Deposit base	176	2010.7	34.8	0	Exponential No nugget	0.98
Kame Deposit top	7	2085.3	47.6	0	Exponential No nugget	0.99
Kame Deposit base	9	2102.7	53.7	0	Exponential No nugget	0.99
Wentworth Till top	163	1692.7	28	0	Exponential No nugget	0.97
Wentworth Till base	120	1599.3	60.7	9.2	Exponential w/ nugget	0.99
Abblation top	120	1952.8	86.8	9.1	Exponential w/ nugget	0.99
Abblation base	126	1951.7	85.8	10.5	Exponential w/ nugget	1
Port Stanley top	121	2028.3	83.5	12.1	Exponential w/ nugget	1
Port Stanley base	123	2033.6	84	12.3	Exponential w/ nugget	1
Undifferentiated Till top	126	2142	88.3	13.2	Exponential w/ nugget	1
Undifferentiated Till base	123	2182.2	98.8	15.6	Exponential w/ nugget	0.99
Bedrock top	123	2040.4	94.9	15.2	Exponential w/ nugget	0.99
Average	114.85	1973.75	66.73	7.48		0.99

Table 5: Variogram parameters for the Zone 3 sub-model

Unit	Direction	Range (m)	Sill (m2)	Nugget (m2)	Type	Cor. Coef.
Outwash Deposit top	146	1410.8	19.2	2.6	Exponential w/ nugget	0.99
Outwash Deposit base	156	1522.4	39.3	6.4	Exponential w/ nugget	0.98
Kame Deposit top	8.6	1809.4	54.5	0	Exponential No nugget	0.99
Kame Deposit base	177	1809.9	83.1	0	Exponential No nugget	0.98
Wentworth Till top	39	1772.1	60.1	0	Exponential No nugget	0.99
Wentworth Till base	116	1284.9	35.9	6.6	Exponential w/ nugget	0.96
Abblation top	98	1390.8	43.6	9.9	Exponential w/ nugget	0.95
Abblation base	121	1504.4	41.5	0	Spherical No nugget	0.94
Port Stanley top	124	1553.6	40.8	6.4	Exponential w/ nugget	0.93
Port Stanley base	83	1417.1	36.1	7.6	Exponential w/ nugget	0.9
Undifferentiated Till top	95	1415.6	35.3	7.2	Exponential w/ nugget	0.88
Undifferentiated Till base	102	1501.2	46.1	6.4	Exponential w/ nugget	0.94
Bedrock top	107	1515.7	52.4	7.8	Exponential w/ nugget	0.97
Averages	105.58	1531.38	45.22	4.68		0.95

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712 **Figure 1.** Map of the Regional Model Domain, data point locations and locations of cross sections (A-
713 A¹, B-B¹, and C-C¹). There are 1245 lower quality data points (red dots) from the water well database,
714 263 moderate quality data points (yellow dots) from more reliable sources such as cored boreholes and
715 geotechnical reports and 6 high quality data points (green dots) from related research of the co-authors.
716 The three sub-model regions are delineated with white lines and identified as Zone 1, Zone 2, and Zone
717 3. Note that Zone 2 broadly coincides with the Paris Moraine. Coordinates are in UTM zone 17N,
718 Datum: NAD83.

719 **Figure 2.** Three-dimensional borehole representation of the data distribution and regional stratigraphy.
720 The vertical exaggeration of this model is 20x.

721 **Figure 3.** Three-dimensional geological models of A) the Original Regional Model for which all the
722 data was interpolated, and B) the Subdivided Regional Model for which the 3 sub-models were
723 interpolated independently and then recombined. Models have a vertical exaggeration of 10x. C)
724 Surficial geology map of the study area for comparison with model outputs, note the improved
725 correlation between the surficial geology map and the Subdivided Regional Model. Note that orange
726 and yellow in A) and B) represent the sand and gravel (undifferentiated) of the outwash and kame
727 stratigraphic units, whereas orange and yellow in C) represent gravel and sand respectively. Map in C)
728 created using ESRI ArcMap 10.1 and data from Ontario Geological Survey (2003); white lines represent
729 the sub-model boundaries defined in Figure 1; black hatched lines represent the location of the cross-
730 sections in Figure 4.

Figure 4. Fence diagram through A) the Original Regional Model, and B) the Subdivided Regional Model. Both fence diagrams have a vertical exaggeration of 20x.

Figure 5. Cross sections through the model domain highlighting the difference in output based on a single (original model) versus a multiple (subdivided model) variogram. See Figure 1 for location of transects. Cross section distances: A-A¹=18.5 km; B-B¹= 12.5 km; C-C¹= 11.1 km. All cross sections have a vertical exaggeration of 20x.

Figure 6. Rose diagrams indicating the direction of longest variogram range correlation from Tables 2-5, with red line representing the average: A) the Original Model, B) Zone 1 sub-model, C) Zone 2 sub-model, and D) Zone 3 sub-model.

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Table 5: Variogram Parameters for the Zone 3 Sub-model.

Map of the Regional Model Domain, data point locations and locations of cross sections (A-A1, B-B1, and C-C1). There are 1245 lower quality data points (red dots) from the water well database, 263 moderate quality data points (yellow dots) from more reliable sources such as cored boreholes and geotechnical reports and 6 high quality data points (green dots) from related research of the co-authors. The three sub-model regions are delineated with white lines and identified as Zone 1, Zone 2, and Zone 3. Note that Zone 2 broadly coincides with the Paris Moraine. Coordinates are in UTM zone 17N, Datum: NAD83.

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Figure 2, MacCormack et al., PDF

Three-dimensional geological models of A) the Original Regional Model for which all the data was interpolated, and B) the Subdivided Regional Model for which the 3 sub-models were interpolated independently and then recombined. Models have a vertical exaggeration of 10x. C) Surficial geology map of the study area for comparison with model outputs, note the improved correlation between the surficial geology map and the Subdivided Regional Model. Note that orange and yellow in A) and B) represent the sand and gravel (undifferentiated) of the outwash and kame stratigraphic units, whereas orange and yellow in C) represent gravel and sand respectively. Map in C) created using ESRI ArcMap 10.1 and data from Ontario Geological Survey (2003); white lines represent the sub-model boundaries defined in Figure 1; black hatched lines represent the location of the cross-sections in Figure 4.

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Figure 5 MacCormack et al. PDF

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