Development of a GIS Water Table Visualization Tool (WTVT) for Determining Water Table Position in Heterogeneous Landscapes in the Boreal Plains Ecozone, Alberta

by

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ABSTRACT

The Boreal Plain is currently undergoing an unprecedented rate of land use change from oil and gas extraction as well as forestry. This change needs to be managed responsibly to ensure the long term sustainability of the region, both ecologically and economically. As part of this understanding the location of the water table in forested uplands is critical in predicting the potential effects of disturbance on the sustainability of water resources. Typically the water table is located using topographically based models. These models, however, were developed in regions of Canada that have very different precipitation regimes and do not experience the depth and heterogeneity of soils characteristic of the Boreal Plain, Alberta. In this research, existing eco-hydrologic information for the sub-humid Boreal Plain, Alberta has been applied to the construction of a Water Table Visualization Tool (WTVT) at the Al-Pac Catchment Experiment near Lac La Biche, Alberta. Unlike topographically based models, the WTVT incorporates landform texture, surface wetland location, and surface elevation to create a visualization of the water table. This novel application of GIS methodology involves three algorithms of water table form: one each for coarse, fine, and coarse-over-fine (COF) textured hydrologic response areas (HRAs). In addition to assessing water table elevation estimates from the WTVT, this research also examined a surficial geology texture interpretation process, and compared two different resolution wetland classifications as input for surface water location. Analysis of landform texture, which was interpreted from existing surficial geology landform mapping, indicates that the proposed interpretation process should further consider the specific localized landform development and that broad scale generalizations may be misleading. Topographic analysis of landform shape indicates that use of the two different resolution wetland classifications in the WTVT resulted in different quantities and spatial configurations of zero depth water. The higher resolution wetland classification resulted in greater total wetland area and wetlands occupying more of the concave topography within the study area. Root mean square error algorithm comparisons within individual HRAs indicated that within the coarse-textured HRA the fine algorithm performed best, within the fine-textured HRA results were unclear, and within the coarse-over-fine (COF) textured HRA the COF algorithm performed best. Manual calibration of the algorithms showed only the COF HRA had acceptable reliability with the RMSEs < RMSEu using a subset of wetland input data at both wetland classification resolutions. The validation of the COF textured HRA was within acceptability criteria. Results from both the algorithm comparisons and the calibration-validation procedure emphasized the need to deal with concave landforms discretely within the algorithms. Additionally, a water table sample design should be stratified for a larger sample distribution

over a wider range of landforms. The WTVT is able to predict the location of the water table, but further investigation of conceptual models and algorithm refinement may be warranted.

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LIST OF ABREVIATIONS

ACE	Al-Pac Catchment Experiment
Al-Pac	Alberta Pacific Forest Industries Inc
AVI	Alberta Vegetative Inventory
COF	Coarse-Over-Fine
DEM	Digital Elevation Model
EWCv1	Enhanced Wetland Classification (version 1)
EWCv2	Enhanced Wetland Classification (version 2)
GIS	Geographic Information System
GPS	Global Positioning System
HRA	Hydrologic Response Area
P	Precipitation
PET	Potential Evapotranspiration
RMSE	Root Mean Square Error
RMSEs	Root Mean Square Error systematic
RMSEu	Root Mean Square Error unsystematic
SG	Surficial Geology
WDp	Well Deep
WSh	Well Shallow
WTVT	Water Table Visualization Tool

1. INTRODUCTION

1.1. Industrial Development

The Boreal Plain overlays the Western Sedimentary basin which, due to its importance globally as an energy source, is currently undergoing large-scale exploration and development of oil and gas reserves, as well as open pit mining of oil sands. The Boreal Plain is also a major source of fibre for dimensional lumber and pulp. Forest harvest activities coupled with the oil and gas development have created an unprecedented rate of land use change. This change needs to be managed responsibly to ensure the long term sustainability of the region, both ecologically and economically.

Oil and gas developers need the ability to estimate the location of the water table to predict and mitigate the impacts of road construction and pipeline development in order to reduce operating costs and mitigate environmental impacts. According to the *2011 Reclamation Criteria for Well sites and Associated Facilities for Forested Lands* [1], the aim of reclamation under the Environmental Protection and Enhancement Act is to obtain “equivalent land capability". In order to assess whether oil and gas reclamation is achieving equivalent land capacity, reclamation professionals and regulatory agencies such as Alberta Environment need to estimate the location of the pre-disturbance water table position. This information can be used to help determine whether reclamation plans should consider surface water at local or regional scales. This information will also be important for wetland restoration and management.

In forestry, information on soil water storage and soil saturation is useful for both government agencies and forestry companies at all stages of planning and operations. Knowledge of where soil saturation occurs can be used to manage and mitigate the risk of damage to the environment, thereby reducing the chance of regulatory infractions, as well as reducing operational costs. At a cut block level, soil saturation information can be useful for harvesting operations by providing the locations of wet areas that are sensitive to skidding, and road construction. Silviculturalists can also use this information to identify areas requiring greater effort to meet reforestation objectives and to eliminate unnecessary treatments. At a regional scale, the information can be used in the development of operating area log flow scenarios and management of log inventories through the identification of summer versus winter harvest units.

1.2. Uniqueness of the Western Boreal Plain

The Boreal Forest within North America comprises approximately 2.6 million ha (Smith et al., 2007) and represents some of the last contiguous forest ecosystems of the world. Contained within the Boreal Forest is the Boreal Plains ecozone, which covers 740,632 square kilometers and has some of the highest densities of wetlands in the world. The area is abundant in wildlife, and is a continental waterfowl migration and nesting site. Due to the extensive peatland coverage, the Boreal Plains is important for maintaining carbon cycling and mitigating greenhouse gases and climatic warming. The Boreal Plains is also important globally for its oil and gas reserves as well as for its timber and fibre.

Within Alberta the Western Boreal Plains are characterized by low topographic relief and wetlands that occupy approximately 50% of the ground surface (Vitt et al., 2000). The Western Boreal Plains is unique from other areas within the Boreal Forest due to its thick glacial deposits and sub-humid climate where precipitation (rain) is slightly less than potential evapotranspiration (Woo & Winter, 1993; Devito et al., 2005). The combination of thick glacial deposits and a sub-humid climate lead to a hydrologic cycle dominated by soil water storage and evapotranspiration, creating conditions of low surface runoff (Woo et al., 2000; Devito et al., 2005; Redding & Devito, 2008; Redding, 2009; Brown et al., 2010).

Water table configurations are strongly tied to surface water and its position in the landscape. Water table configurations at both local and regional scales are influenced by the interaction of their landscape position, the geologic framework, soil texture, precipitation, and evapotranspiration (Winter, 1999, 2001). In the Boreal Plains, wetlands are expressions of this interaction, which is reflected in the diversity of wetland type and their location.

In the Boreal Plain fine-textured landforms have comparatively low vadose zone storage, infiltration and recharge capacities (Devito et al., 2005). In the forested uplands most of the available moisture from precipitation is either taken up via transpiration or captured as soil storage, which means that surface runoff occurs rarely. The interaction of evapotranspiration and soil storage has also been shown to result in water table depressions. Ferone (2001)studied the hydrology at two fine textured pond-peatland sites, each consisting of a wetland and a forested hillslope. The first site was located at a topographic high on a fine-textured moraine and the second site was located on a topographically low fine-textured clay plain. At the topographic high moraine site, water table gradients from the wetland into the forested hillslope were in excess of 0.025. The study, which spanned both dry and wet periods, reported similar water table configurations during both conditions. However, during the wet period water table mounding occurred within the peatlands, causing flow reversals towards the forested hillslopes that resulted in slightly higher water tables in the forest lands near the peatland edge (Redding & Devito, 2008). During the dry period no mounding occurred and the water table near the peatland edge was at a lower elevation with no flow reversals occurring. At the topographically low clay plain site, transects were limited to the peatlands and water tables were found consistently between the surface and a depth of 0.5 m during both dry and wet periods. During these conditions the water table remained relatively flat (<0.002 gradient) within the peat lands. Redding (2009) also studied the hydrology of fine-textured (loam) disintegration moraines forested with aspen. Under this subhumid climate, precipitation is less than potential evapotranspiration. Redding showed that water table dynamics were strongly controlled by soil texture and conductivity values. In the low conductivity, fine-textured aspen sites, relatively large water table gradients existed, creating a water table configuration that declined sharply from the wetland to beneath the forested uplands. In the fine-textured landforms in the sub humid climate of the Boreal Plains Alberta, as the distance from the wetland edge increases and the elevation of the hill slope increases, the water table generally declines, taking the shape of a subdued inversion of topography. This is in contrast to other generalizations that the water table is a subdued replica of topography (Winter, 1986; Haitjema & Mitchell-Bruker, 2005).

Boreal Plains landforms which are predominately coarse-textured will exhibit higher vadose zone storage, as well as infiltration, and recharge capacities than fine-textured landforms. These hydraulic properties lend themselves towards more regional flow systems and flatter water tables between surface water (Winter & LaBaugh, 2003; Winter et al., 2003; Haitjema & Mitchell-Bruker, 2005). At the coarse-textured subhumid outwash sites in northern Alberta, Redding (2009) noted that these properties allowed much of the snowmelt and spring rain to pass through the rooting zone soil to the water table. Water table dynamics were strongly controlled by soil texture and their corresponding hydraulic conductivities. At the high conductivity, coarse textured sites Redding noted small (flat) water table gradients between the upland crest to the wetland. Smerdon et al. (2005) investigated hydrologic controls in northern Alberta between shallow lakes on a coarse-textured outwash plain dominated by a thick layer of sand and gravels. Within the coarse-textured outwash a sub-humid climate predominated during the time of the study. At this site, water table gradients ranged from 0.005 to 0.0045 within the groundwater flow system between the lakes. Kettle depressions that when not dry were characterized by either gyttja-bottomed lakes or peatlands, depending on their intersection with the water table. Winter (1986), studying the water table configuration between lakes and beneath coarse-textured landforms (sand dunes) in the subarid climate of Nebraska, U.S.A, found water table gradients beneath the sand dunes of 0.003 to 0.002. Water tables within coarse-textured landforms are generally flat and are suggested to be of regional scale acting as linkages between the regional water table surface water expressions (Winter, 1986; Winter, 1999; Smerdon et al., 2005; Smerdon et al., 2008).

Due to the complexity of the glaciation resulting from numerous retreats and advances, a complex layering of deposits has occurred (Fenton et al., 1994). Where coarse-textured surface deposits interface with fine-textured deposits a layering of different textures is possible. All deposits however, are eventually underlain by fine-textured moraine material (Fenton, 2013). A knowledge gap exists regarding the water table behaviour in surficial deposits such as coarse-over-fine-textured.

Fine-textured deposits near the surface can be underlain by coarse textured deposits, resulting in regionally isolated perched water tables (Riddell, 2008). These perched water tables can be either seasonal or, in the case of the Boreal Plains, persistent due to the development of peat.

The objective of this research was to construct a Water Table Visualization Tool (WTVT) which estimates the location of the near surface water table in the heterogeneous landscapes in the Boreal Plains Ecozone, Alberta. Sub-objectives related to the WTVT were:

- To evaluate the reliability of input data via:
  - Comparing stratigraphy from borehole data to the Surficial Geology Interpretation process within the ACE study area.
  - Comparing water table output from the WTVT using EWCv1 vs EWCv2 as input.
- To evaluate the impact of three texture based algorithms on WTVT output.
- To calibrate and validate the WTVT.

1.3. Study Area Characteristics

1.3.1. Location

The Al-Pac Catchment Experiment (ACE) research site is 3,200 ha in size and is located 30 km north of Lac La Biche within Al-Pac's Forest Management Area (Figure 1). This area was chosen as it is representative of the subhumid climate, range of soils and surficial geology found within the western Boreal Plains.

1.3.2. Industrial Development

Clearcut-with-retention silviculture and associated road construction has occurred within the ACE study, which targeted the large stands of Aspen and Cottonwood. The retention within the cut areas took the form of small patches or individual leave trees distributed over the cut areas. Multiple years of harvest and the subsequent regeneration have resulted in cutblocks with varying age classes predominately of high density aspen. Oil and gas exploration has also occurred within the ACE area, resulting in a network of seismic lines and a number of well pads.

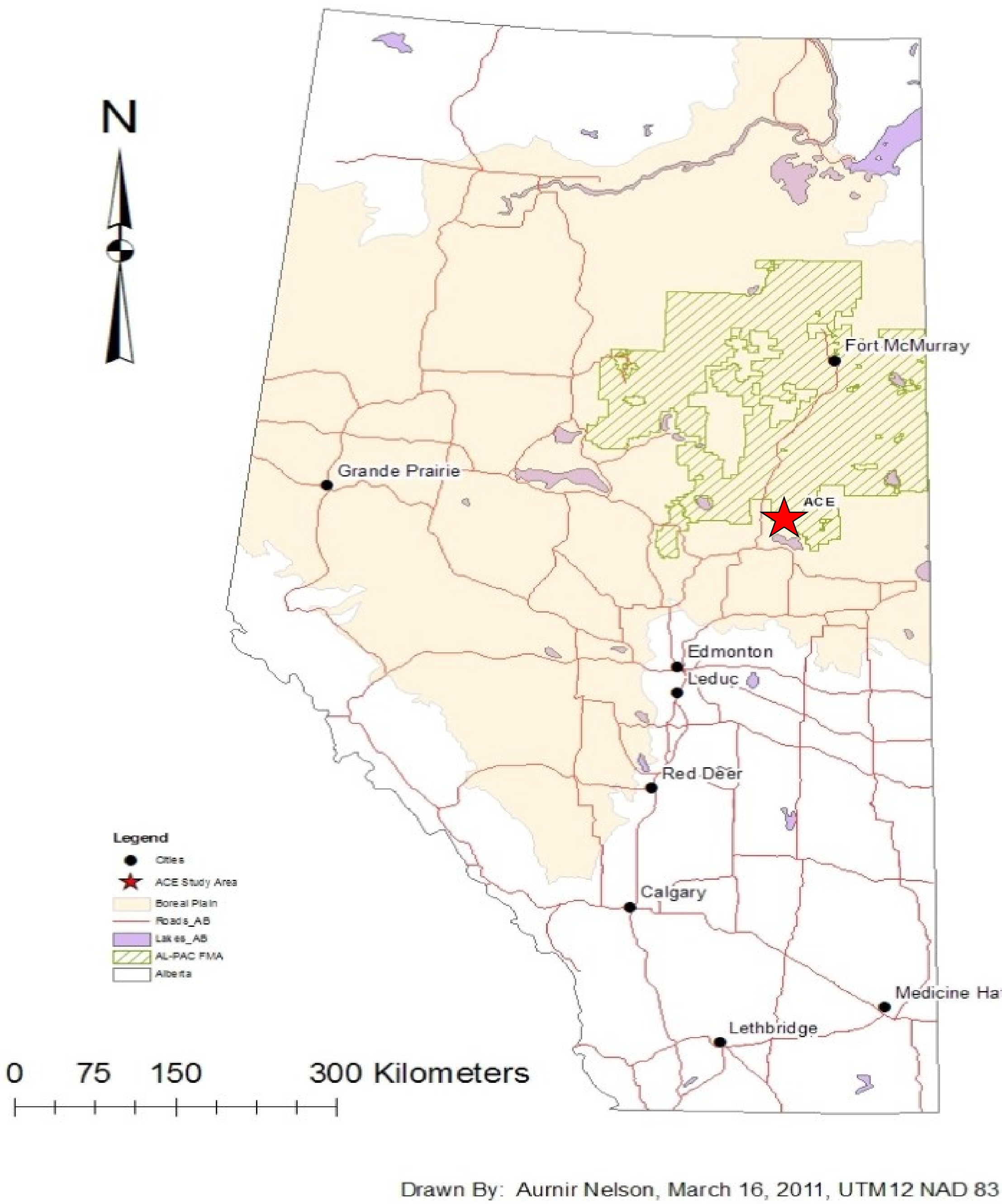

Figure 1. Location of the AL-Pac Catchment Experiment (ACE) near Lac La Biche. Also shown are Al-Pac's forest management area as well as the extent of the Boreal Plains in Alberta .

1.3.3. Water Level Monitoring Sites

Hydrogeological data are available for the ACE area from the previously established HEAD2-CRD research based at the University of Alberta. During the setup phase of the ACE study (primarily years 2005-2007), groundwater level monitoring sites were established adjacent to accessible roads, seismic lines and wetlands. Twenty eight groundwater monitoring wells were used in this thesis; approximately half of the wells were shallow (WSh) groundwater monitoring wells which ranged in depth between 0.35 to 5 m, and the other half being deep

(WDp) groundwater monitoring wells with depths of 1.4 to 13.2 m. The use of WSh and WDp nomenclature does not define a specific depth range but recognizes the relative depth of multiple wells at an individual site. In some cases a WDp at one site may be shallower that a WSh at another site. Site location information was determined from GPS waypoint locations taken at each site. Attribute database information detailing well depth, well type, and installation dates, for individual well sites was made available and were verified in the field or through reference to the field cards.

1.3.4. Climate

The ACE study site is characterized by a sub-humid climate. Interpolated climatic data were obtained from the Alberta Government Agrometeorology Application and Modelling Section (Alberta Agriculture and Rural Development, 2014) for 1974 to 2013 for the ACE area (Figure 2). Annual precipitation (P) for this period averaged 465 mm, with a low of 316 mm in 2002 and a high of 709 mm in 1996. For the same period annual potential evapotranspiration (PET) averaged 604 mm with the low of 559 mm in 1974 and the high of 649 mm in 1998. P > PET in 1975, 1996, and 1997; for all other years P < PET. Also shown are the 15 year rolling averages for P and PET (Figure 3) (Alberta Agriculture and Rural Development, 2014).

1.3.5. Surficial Geology

Quaternary-age surficial geology in the ACE area involved thicknesses between 0-126 m (Fenton et al., 1994). Shallow surficial deposits are found along the western boundary of the ACE area, with the greatest depths to 126 m along the eastern boundary. The Northern portion of the ACE area is dominated by glacial deposited moraine till while the southern portion is dominated by non-glacial surficial depositions resulting in organic, fluvial, and lacustrine sediments.

1.3.6. Bedrock

Geologically the ACE study area is located within the larger western sedimentary basin and sits within the central Lea Park formation, which is primarily a clay- and silt-based mudstone

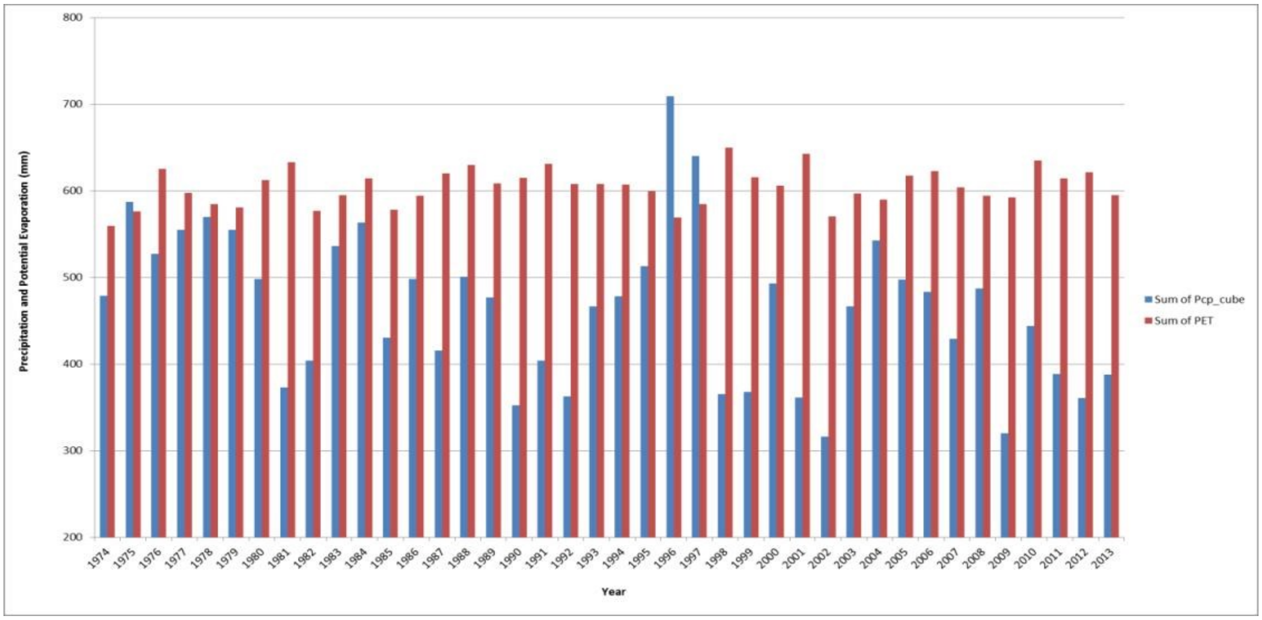

Figure 2. Average precipitation and potential evapotranspiration values (mm) for the ACE area as provided by Alberta Agriculture and Rural Development (2014).

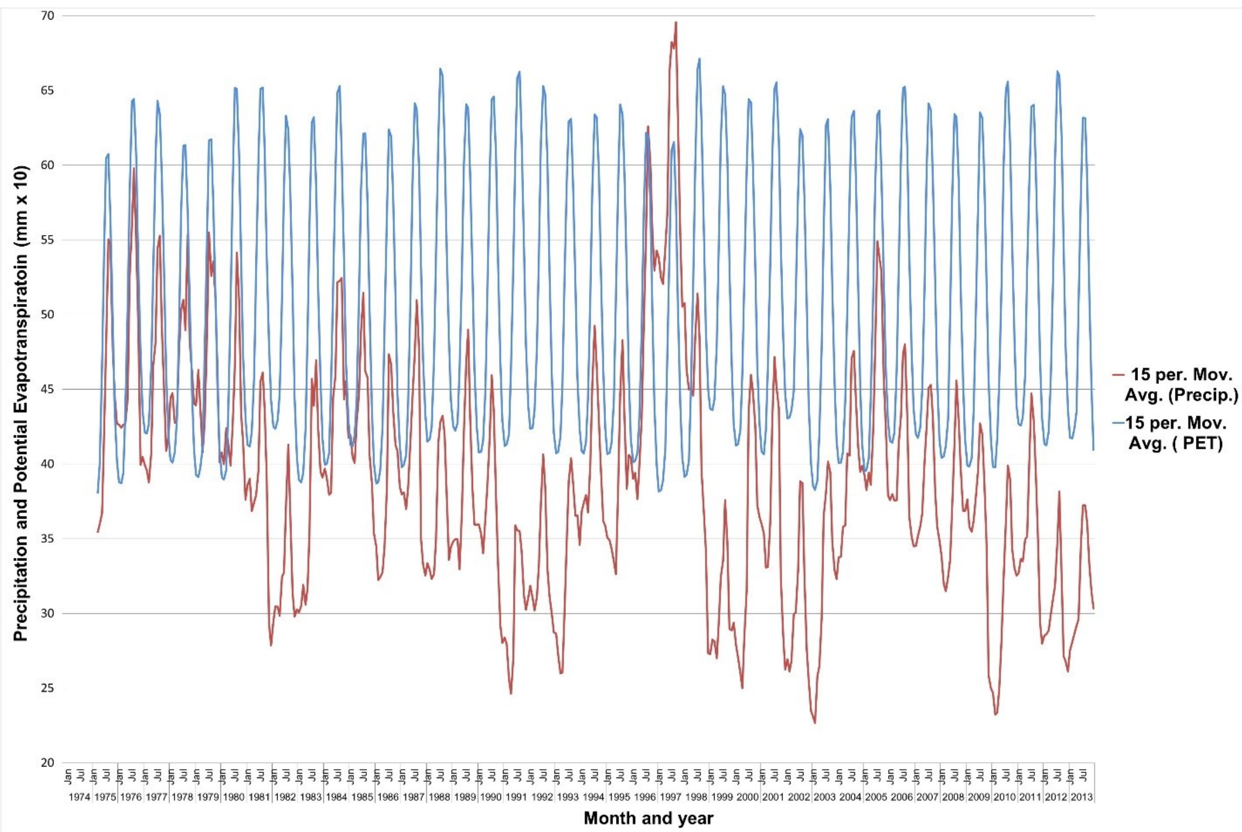

Figure 3. Five year rolling average precipitation and potential evapotranspiration values (mm) for the ACE area as provided by Alberta Agriculture and Rural Development (2014).

sedimentary rock. The regional high of the underlying bedrock occurs at 640 masl located approximately 1.2 km northwest of the midpoint of the northern ACE catchment boundary (Campbell et al., 2001). This is really a domed bedrock high with gentle slopes between 1-2%, declining in all directions towards the surrounding bedrock low. The bedrock low, like many areas in the western sedimentary basin, is actually a series of connected preglacial valleys. These preglacial valleys when viewed from above form a ring around the bedrock high with elevations that range between 390 to 480 masl and are 10-30 km distance from the high. Flow along the bedrock topography beneath the ACE area is divided, with the western half of the ACE area shedding in a southwest direction and the eastern half of the ACE area tending to shed more in an east by southeast direction. As can be expected, the regional bedrock lows coincide with many of the larger regional water features, most notably 20 km south of the ACE area in the form of Lac La Biche Lake.

1.3.7. Aspect

At a regional level the ACE study area has a southerly aspect, and a south west to south east majority at a local level although topographic variations allow for all aspects to be present in lesser amounts.

1.3.8. Vegetation

According to the Alberta Vegetative Inventory (Alberta Environment and Sustainable Resource Development, 1991) the ACE area is comprised mostly of *Populus tremuloides* leading stands (47%), followed by *Pinus banksiana* leading stands (17%), and *Picea mariana* leading (11%). *Picea glauca* leading (5%), and *Larix laricina* leading (2%) stands also are present, but in minor amounts. Non-forested land cover, such as anthropogenic land covers or non-forested wetlands, account for about 10% of the total area.

1.3.9. Topographic Catchments and Streams

The original ACE study site can be broken into five topographically defined catchments, the smallest being 26 ha and the largest 1,911 ha (Figure 4). These catchments at a regional scale occupy the upper-mid slope to the lower slope position. Two second-order low gradient streams and their associated tributaries form the major surface drainages of the ACE area. Stream A, located within catchment H1, starts from a north central position and runs Southwest draining into a clay plain wetland system and lake located 5.5 km from the catchment boundary. Stream B, located in catchment R1, drains in a north- south direction, taking waters from the central and largest portion of the ACE area. Stream B also receives water from two smaller 1st order ephemeral streams which originate in catchments R2 and H3. An ephemeral stream (Stream

C) runs from north to southeast within the eastern half of the H2 catchment. This stream in its upper reaches is essentially a connection of small wetlands, which most often contain pooled water within their local depressional areas. During the seasonal high water or wet periods connectivity occurs, producing surface flow which has caused a small channel to develop in the lower reaches of the drainage. Stream B and C drain into larger fen wetland systems located to the south of the ACE area.

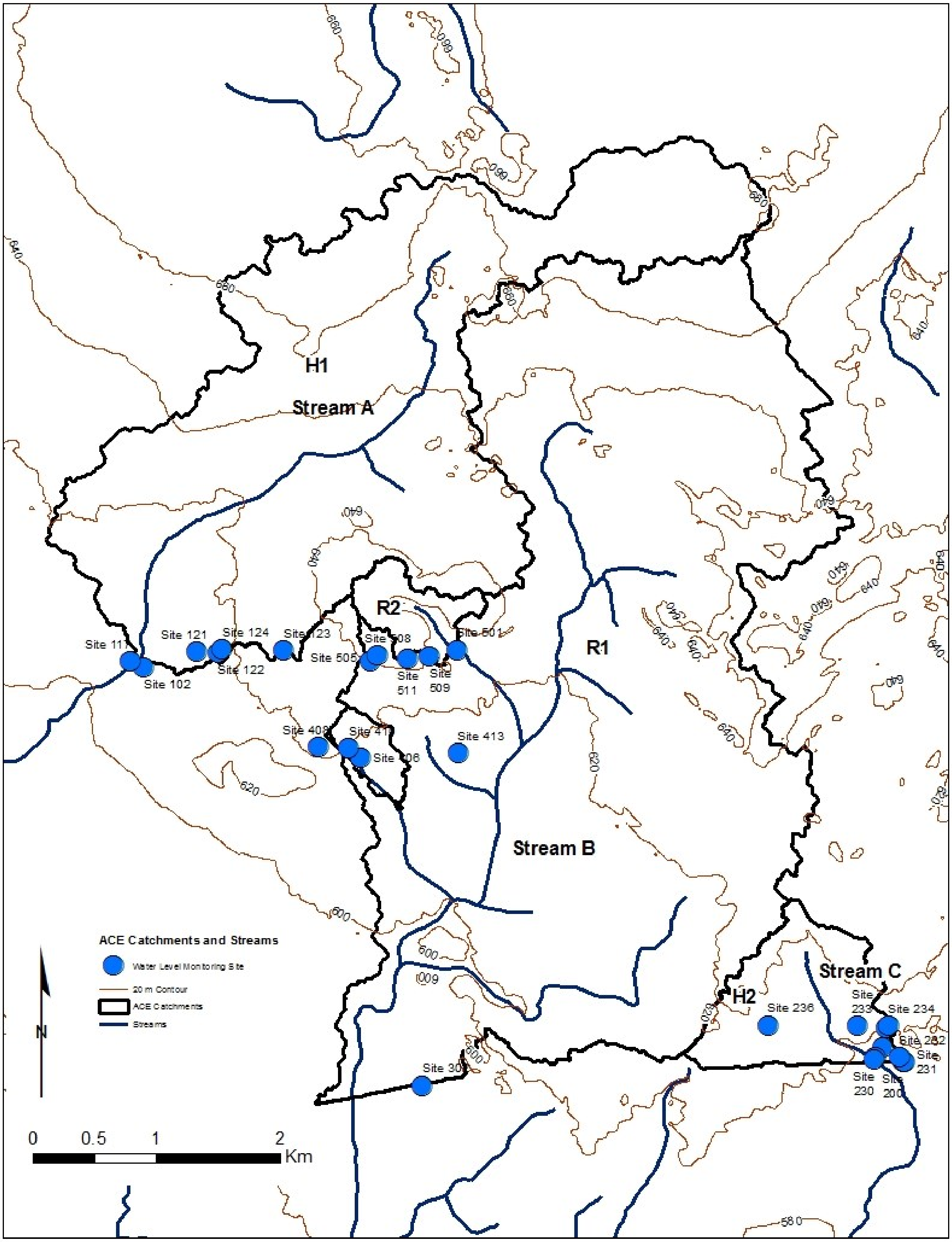

Figure 4. Hydrologic catchments, streams and water level monitoring sites in the ACE study area.

2. METHODS

2.1. Creation of Hydrologic Response Areas

2.1.1. HRA Concept

Generalizations of dominant landforms to define hydrologic response areas (HRAs) for the Boreal Plains, Alberta have been proposed by (Devito et al. (2005), Devito and Mendoza (2006), and Devito et al. (2012). The HRA concept has been proposed to describe the relationship between wetland distribution and dominant hydrologic behaviour in the sub-humid Boreal Plains, Alberta. Devito et al. (2012) defined an HRA as an area in the landscape with similar texture and characteristic water storage and transmission properties, along with characteristic responses to climate cycles.

HRAs help in understanding the variability of the landscape, and the resulting complexity regarding the location and connectivity of the water table. Three HRA types have been suggested for use within the subhumid Boreal Plains Alberta (Devito et al., 2012):

- Fine-textured – Example, moraine landform, high clay content.
- Coarse-textured – Example, Aeolian Landform, high sand content.
- Coarse-over-fine-textured (COF) – Example, Aeolian Veneer landform, Aeolian sand deposited overtop fine-textured moraine deposit.

Surficial deposits or drift that originated during or after the Quaternary period were either glacial, fluvial, lacustrine, eolian or organic in origin. The surficial deposits in the ACE area and other areas in the Great Plains are a result of numerous retreats and advances of the Laurentide glacier, which resulted in a complex layering of deposits with each deposit having a distinct sediment texture (Fenton et al., 1994; Campbell et al., 2001). During glacial times the majority of sediments deposited were primarily till and were deposited in large volumes, often to thicknesses of over 100 m. Glacio-lacustrine sediments were also common, with fine-textured deposits occurring in the distal zones and coarse-texture depositions of sand and gravels occurring in the near shore areas or lake margins. During non-glacial times, the majority of the sediments were from lacustrine origin and were the same as the glacio-lacustrine deposits having fine-textured silt and clays in the distal zones with the near shore zones being comprised mainly of coarse-textured sands and gravels. Because the location of the littoral zones also changed over time with the fluctuations of the both the glacier and lakes, a complex layering of glacial and non-glacial deposits resulted in the conditions we see today. The depth of the non-glacial surficial deposits can be as thin as a few meters to well over 100 m. In addition, other non-glacial depositions have occurred, such as eolian and alluvial, which normally resulted in large coarse-textured deposits such as sand dunes or eskers. These non-glacial deposits can only occur if a suitable soil type is available, such as a sand source from a glacial lake shore for eolian deposits (Fenton, 2013). Because of the time lags and changes in geologic processes between depositions, different layering of textures can occur; for example, coarse textured material overlaid on existing coarse or fine-textured material or fine-textured material being overlaid on top of existing fine or coarse-textured material. Where the overlying coarse-textured material is thin (< 2 m), a veneer is formed over the previously deposited material. For the landforms in the ACE area, regardless of whether the landforms are of glacial origin, or of non-glacial origin, all deposits are underlain at depth by a glacial till.

Surficial material properties have been mapped by the Alberta Geologic Survey for the ACE area (Figure 5). Genesis information for the individual landform polygon contains a unit notation which describes the genesis process (e.g., Glaciolacustrine deposit), and may contain additional information regarding the genesis such as texture, genetic and geomorphic modifications, terrain complexes, stratigraphic sequencing, and transitional associations. Creating HRA groupings involves generalizing the genesis processes and in some cases interpreting of the landforms geologic setting (Campbell et al., 2001; Fenton, 2013). The interpretation of soil genesis information to landform texture from the Alberta Geologic Survey Surficial Geology of the Wandering River Area, Alberta (NTS 83P/SE) (Campbell et al., 2001) is presented in Table A 1 Process for interpreting the Surficial Geology for the ACE study area*. The fine-textured HRAs mainly came from moraines and the off-shore lacustrine deposits. These fine-textured HRAs vary with the presence of a textural modifier that indicates a gravel or sand influence. They are grouped with the coarse-textured HRA, depending on the modifier. Most coarse-textured HRAs are a direct translation of eolian, alluvial, fluvial, and near-shore lacustrine deposits, associated with the deposition of coarse-textured materials such as sand and gravel. The textural modifiers of g (gravel) or s (sand) when present with a single Genetic class also indicate a coarse-textured HRA.

In the creation of a coarse-over-fine-textured HRA, the unit notation, along with the geologic setting, were considered in order to determine whether a coarse textured deposit has been overlaid on a fine textured deposit. If the Unit Notation indicates only a veneer exists, such as a (Ev), the adjacent landforms will give an indication whether the underlying deposit is coarse or fine-textured. If the majority of the surrounding landforms are of fine-texture, the veneer is most likely a coarse-over-fine-textured landform. The unit notation can also indicate whether the landform is part of a complex stratigraphic sequence, or transitional association.

For the purposes of this thesis any complex stratigraphic sequence or transitional association that contains both a fine-texture and coarse-texture unit notation is interpreted as a coarse-over-

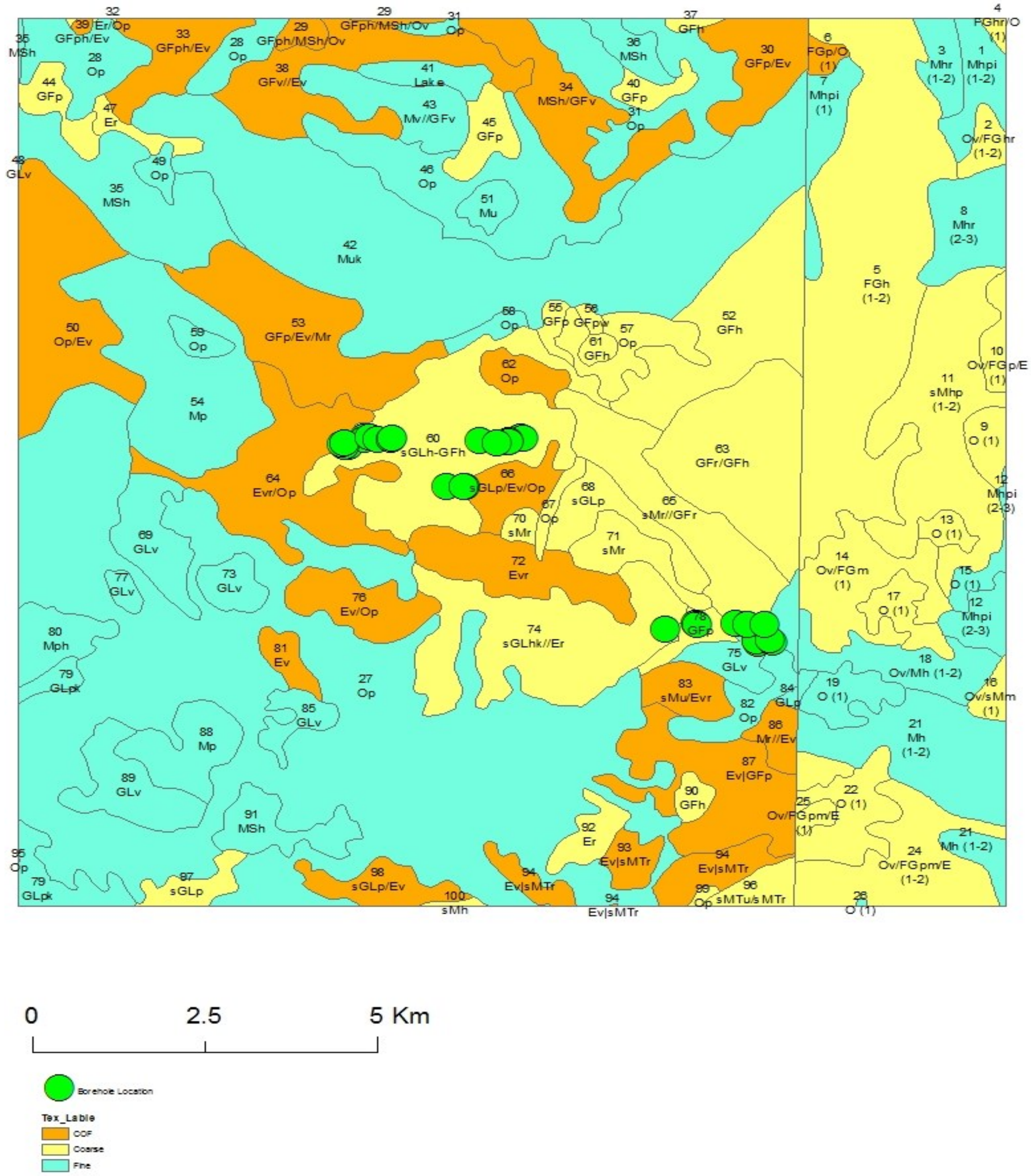

Figure 5. HRA boundaries of the ACE area following texture interpretation of the Alberta Geologic Survey Surficial Geology Mapping (Campbell et al., 2001)

fine textured landform. Organic deposits, which are indicative of either a peat forming wetland or a non-peat forming wetland, can be underlain by either a fine or coarse-textured deposit and must be considered in terms of the geologic setting. If the majority of the Organic units are surrounded by fine-texture landforms, then the organic unit can be grouped within the fine-textured HRA. Conversely, if the majority of surrounding landforms are of coarse-texture, then the underlying material of the organic deposit is most likely coarse textured, and can be grouped within the coarse-textured HRA.

2.1.2. Comparison of the HRA Textures to Borehole Data Textures.

As a check on the interpretation of surficial geology landforms as HRAs, the texture of the HRAs was compared to that from the borehole data obtained during the ACE well installations. A total of 36 borehole sites were available, all of which were used in the analyses. Other sources of soil information, such as from soil probe or had auger sampling, were not included. The borehole data were derived by interpretation of the installation notes collected during the well installation process and outline the texture and color for each stratigraphic layer.

In general, each stratigraphic layer in the borehole data set was described as one of following soil textures: clay, sand, loam, or silt. In some cases organics were also given as a layer descriptor. Stratigraphic layers described as sand were considered to be of coarse-texture and layers described as clay, loam, and silt were interpreted as fine-textured. Where sand formed the majority of the sediment in the top 2 m and was underlain by fine textured sediment, the borehole was considered coarse-over-fine texture. Layers described as organic were classified as a texture of Organic.

The HRAs in the ACE area were further refined by comparing the texture of the HRA (Figure 5) to the texture from the borehole data. Where the borehole data indicated that the HRA texture interpretation was incorrect, the HRA classification was changed to reflect the borehole data prior to calibration and validation of the WTVT (Figure 6).

2.2. Water Table Visualization Tool Development (WTVT)

2.2.1. WTVT Explanation

The WTVT was developed to locate the water table specific to areas where the water pressure is equal to or greater than atmospheric pressure and to areas not confined from the effects of atmospheric pressure. In addition, the WTVT is only applicable to areas influenced by a climate where annual Potential Evapotranspiration (ET) > annual Precipitation (P) in forest lands which create conditions where soil water storage dominates the hydrologic cycle. These

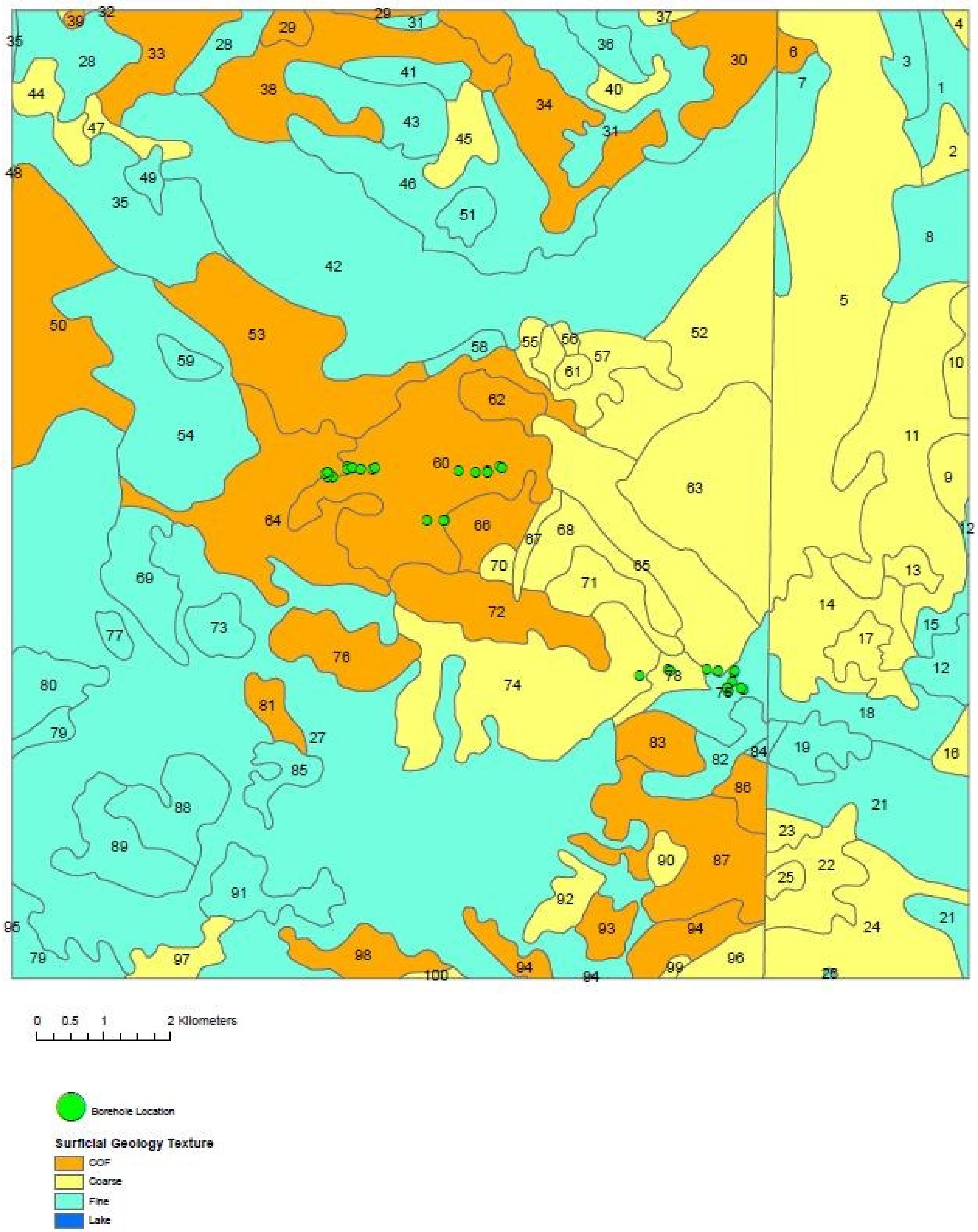

Figure 6. HRA configuration resulting from the borehole analysis.

conditions have been associated with the sub-humid climatic zone within the Boreal Plains, Alberta ((Bear, 1972); Ferone and Devito (2004); Devito et al. (2005); Price et al. (2005); Smerdon et al. (2005); Devito and Mendoza (2006); Petrone et al. (2007); Smerdon et al. (2007); Petrone et al. (2008); Redding and Devito (2008); Smerdon et al. (2008); Mwale et al. (2009); Brown et al. (2010); Devito et al. (2012)).

The WTVT is an ArcInfo Version 10.1 Geographic Information System (GIS) built in the ModelBuilder application. The WTVT as designed in ModelBuilder is a combination of geoprocessing tools that are sequenced together, feeding the output of one geoprocessing tool into another as input. The sequences form a workflow with the end result being a tool, in this case the WTVT.

In general the WTVT contains the following three submodels:

1. SG_Mask submodel that Spatially defines individual HRA boundaries,
2. SLE_Tin_Tin_to_DEM submodel which determines a reference plain elevation raster between nearest wetland surfaces as selected within the wetland data set, and,
3. The DWT_Combined submodel that calculates a depth to water table raster within each HRA.

Different versions of the WTVT have been produced in ModelBuilder to allow for specific data to be produced for the calibration and validation processes.

Prior to running the WTVT, a number of variables within ModelBuilder must be specified. With the WTVT in edit mode, the individual variables for the DEM, Surficial Geology Layer, and Wetland polygon were selected. The workspace for the resultant files must also be specified.

2.3. Data Preparation for Water Table Visualization Tool

2.3.1. Enhanced Wetland Classification EWCv1 and EWCv2

Surface water was located through the two versions of Ducks Unlimited Canada (DUC) Enhanced Wetland Classifications (EWCv1 and EWCv2), which were provided in the form of raster files for the ACE study area (Smith et al., 2007; Smith, 2011). Both versions of the EWC contain classifications of wetlands which include open water. EWCv1 (Figure 7) is the operational wetland coverage provided to DUC clients, and is created using Landsat TM imagery with a 30 m by 30 m resolution. EWCv2 (Figure 8) was produced at a higher resolution classification using composite pan sharpened SPOT data at a 10 m by 10 m resolution. Comparing the output from the WTVT using each of the EWC coverages allowed for an assessment of the impact of increased resolution. As both versions of the EWC are produced as raster files, and the WTVT requires a polygon shapefile, preparatory work outside of the

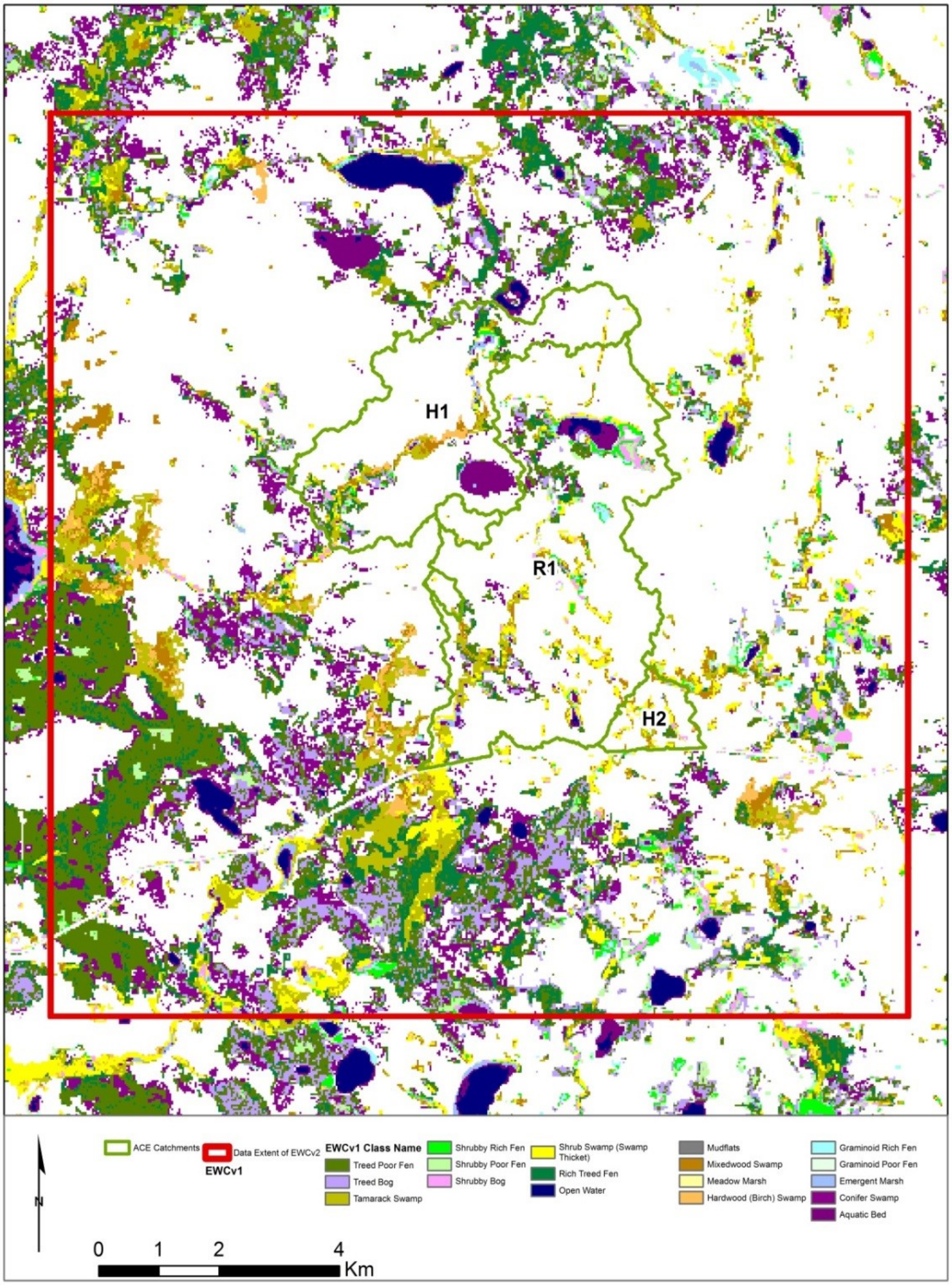

Figure 7. Enhanced Wetland Classification version 1 (EWCv1), ACE study area (Smith, 2007).

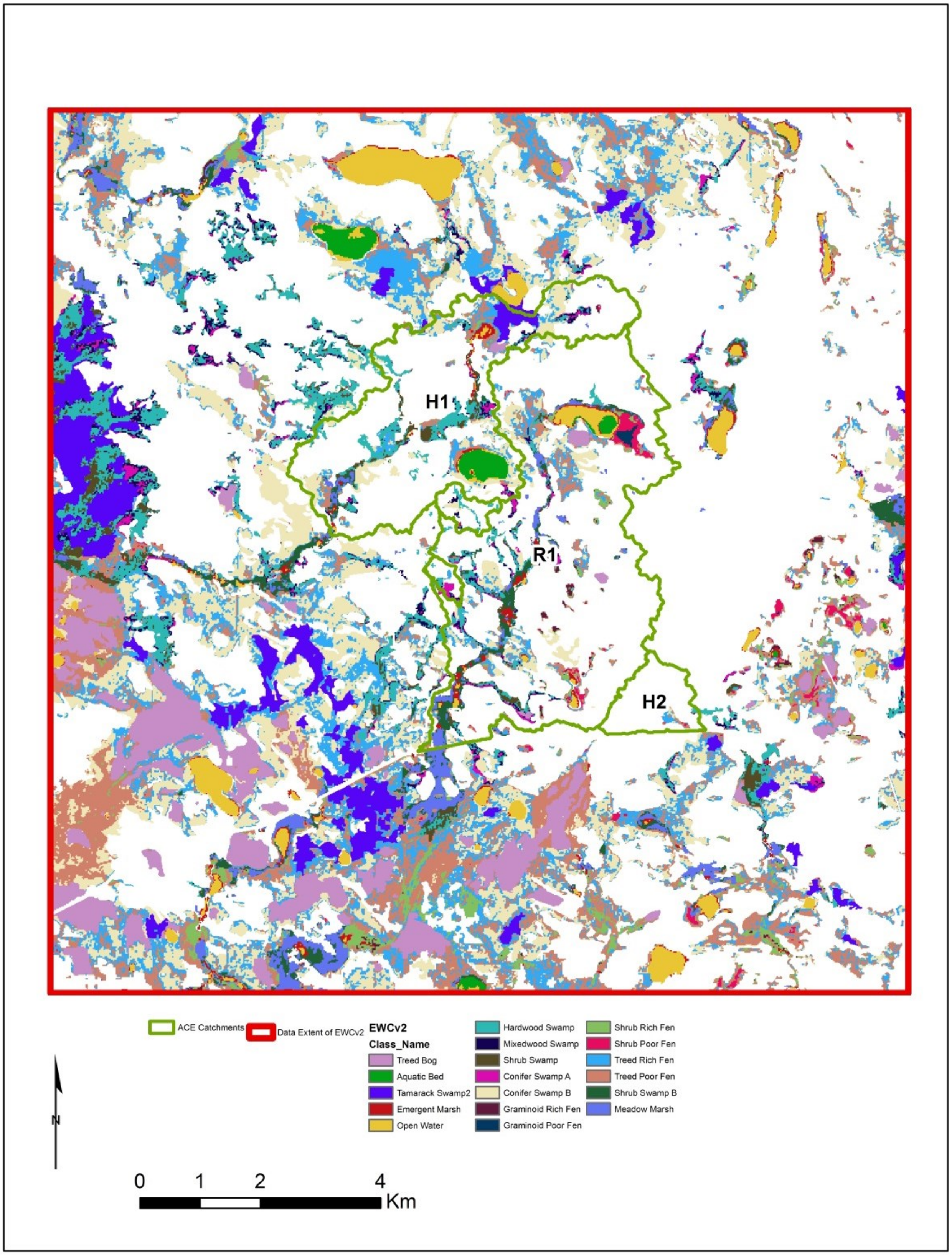

Figure 8. Enhanced Wetland Classification version 2 (EWCv2), ACE study area (Smith, 2011).

WTVT prior to using the EWC as input data was required. Because the EWC contains non-wetland classifications such as anthropogenic areas and forest cover, the preparation of the EWC data involved reprocessing the raster file so only wetlands were represented. Once a raster file of only the wetland areas was obtained, the raster was converted to a shapefile. An attribute field was added which identified the open water classifications and a Dissolve process was carried out within ArcGis which specified the added attribute field as the Dissolve_Field. The Dissolve_Field acted to identify the open water classifications and kept them as discrete polygons with the wetland complexes in which they were contained (Figure 9, Figure 10). Identification of open water is necessary for use in the calibration procedure described later. Once created, the polygon files were ready for use in the WTVT.

The geographic area of data coverage for the ACE area study was primarily determined by the extent of the EWCv2. The EWCv2, at 20,671 ha, had the smallest extent compared to the other input data, such as the surficial geology mapping, and therefore was the extent to which the data was set for this study. All data used in the model were clipped to the extent of the EWCv2.

2.3.2. Surficial Geology

As an initial step in defining the HRAs, spatial information for surficial geology was obtained free from the Alberta Geologic Survey (AGS) at http://www.ags.gov.ab.ca/surficial/index.html. For the ACE area, two separate Surficial Geology shape files were combined into a final coverage. The first was the Wandering River Area, Alberta (NTS 83P/SE) (Campbell et al., 2001)and the second was the Surficial Materials of the Athabasca Oil Sands (in situ) Area, Northeast Alberta (GIS data, polygon features) (Andriashek, 2002). For this thesis, 74 polygons in the Southeast corner of the NTS 83P surficial geology dataset and 16 adjacent polygons from the Southwest corner of the NTS 73M mapsheet were needed (Figure 5).

The two surficial geology shapefiles were clipped to the project data extent and merged into a single GIS coverage. Then the merged file was inspected for topology errors and any fragmented polygons repaired. The surficial polygon attribute data were interpreted using the surficial geology to HRA process presented in Table A 1. A text field was then added to the attribute file and was populated with the corresponding texture code of Fine, Coarse, or COF (Coarse-over-fine). The resulting interpreted surficial geology coverage is shown in Figure 5.

2.3.3. DEM – Light Distance and Ranging (LiDar)

A LiDar-based DEM was obtained through the Government of Alberta and used to interpolate the z values within each of the EWC versions. The DEM supplied was at a 1 m

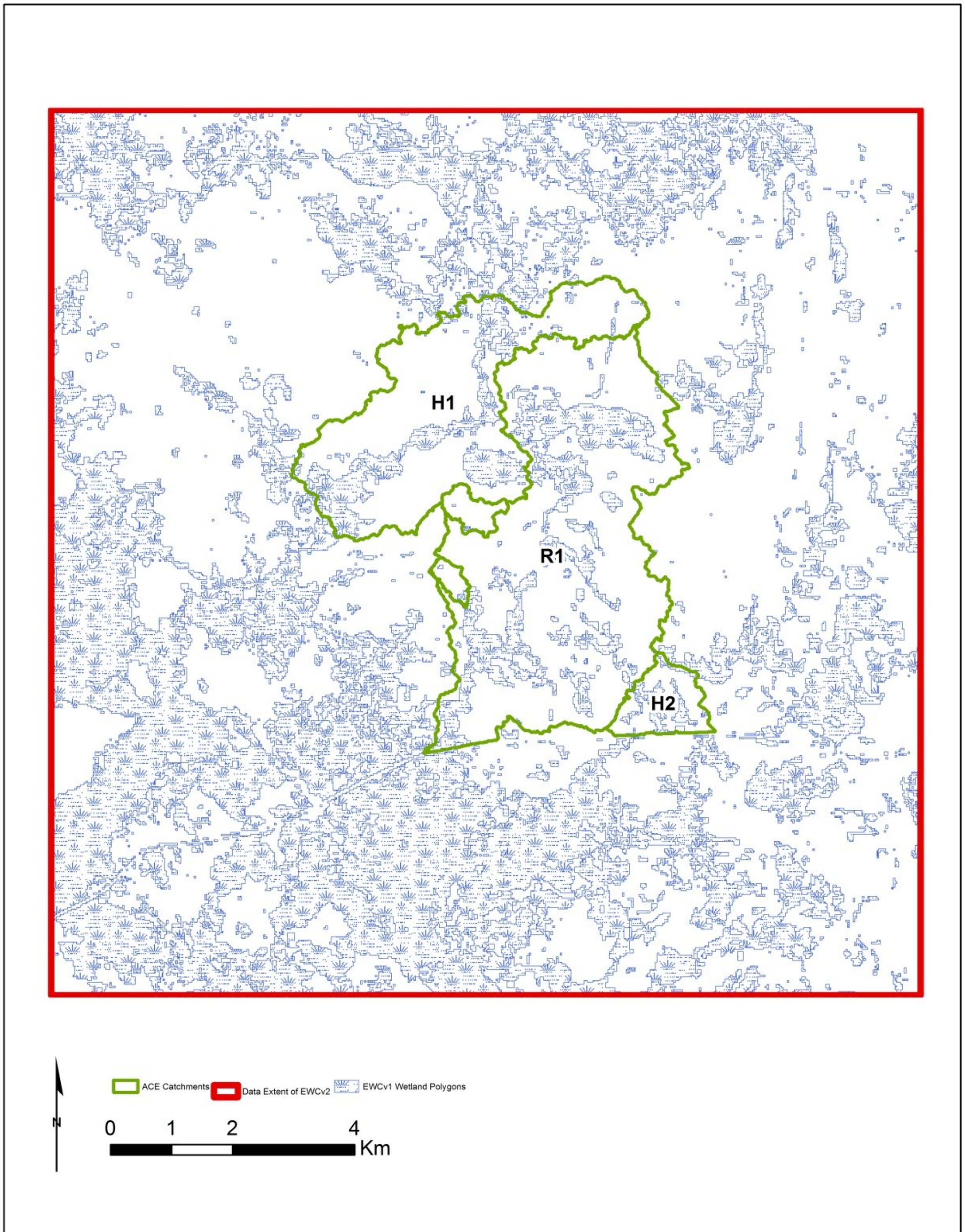

Figure 9. EWCv1 dissolved into a single polygon coverage.

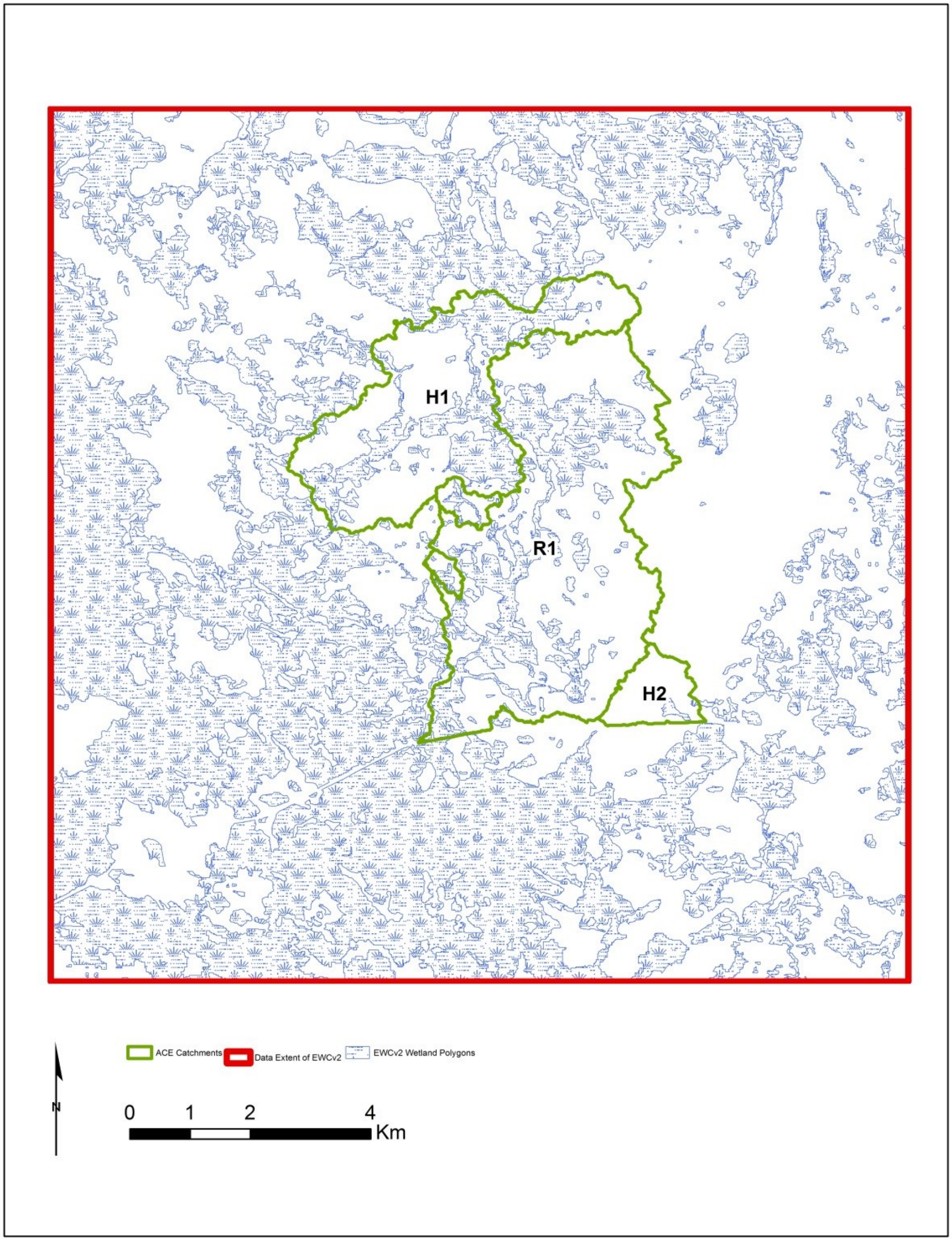

Figure 10. EWCv2 dissolved into a single polygon coverage.

resolution and for the purposes of usage within the WTVT was reprocessed at a 10 m resolution (Figure 11). The LiDar data were reprocessed to increase the speed of calculations and also to reduce fragmentation of the TIN (Triangular Irregular Networks) surfaces produced during the reference plane creation process.

2.3.4. Streams

As part of the calibration procedure, second order streams were also used as a source of surface water location. The stream data were obtained from the Alberta Vegetative Inventory (AVI) data provided by the Government of Alberta (Alberta Environment and Sustainable Resource Development, 1991). The stream coverage was prepared by selecting the streams within the project extent from the AVI stream data and classifying the streams using the Strahler Stream Order System (Strahler, 1965). Second order or greater streams were selected and buffered at 1.0 m within ARCGIS (Figure 12).

2.4. Visualization Tool Software Requirements and Process

All GIS processes described in this thesis were specific to ESRI ArcGIS 10.1 ArcInfo software ((Esri, 2012), which was desirable due to its availability, and the functionality of producing models through the built-in ModelBuilder application. Version 10.1 was also chosen as it has new capabilities for handling the large LAS files associated with the LiDar Data. To enable the advanced capabilities within ArcGIS, both the 3D Analyst and Spatial Analyst extensions were required. Additional information regarding ArcGIS 10.1 software and clarification of technical terms can be found here: http://resources.arcgis.com/en/help/ .

2.4.1. Defining the HRAs Within the WTVT

Within the WTVT, the SG_Mask submodel creates the files which represent the spatial locations of each HRA texture type. Initially, a dissolve process based on the texture code was performed on the surficial geology loader file, creating a polygon shapefile. The shapefile was converted to a raster using the Feature to Raster tool which identifies each of the individual HRAs in a raster format. A Majority Filter was then applied to this resulting raster to clean any ambiguities that have occurred along the boundaries between HRAs. Once the Majority Filter has been run, the raster is then reclassified individually three times to produce three mask rasters, one for each HRA. For each individual mask, the raster value within the HRA was set to 1 and all other values set to “nodata”. The masks were then used within the WTVT DWT_combined submodel to define the location where the calculations specific to each HRA type occur.

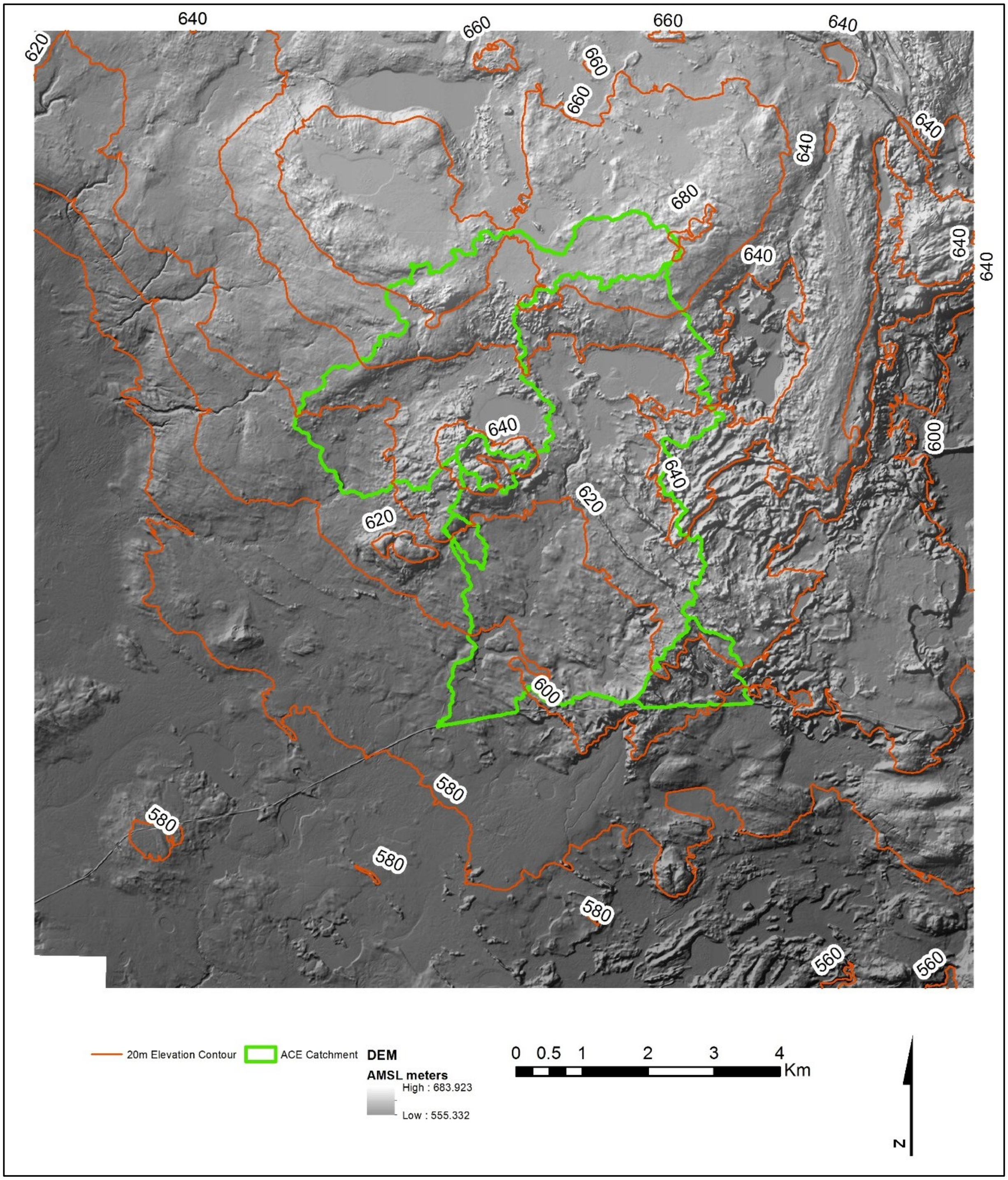

Figure 11. LiDar derived 10 m digital elevation model for the ACE area .

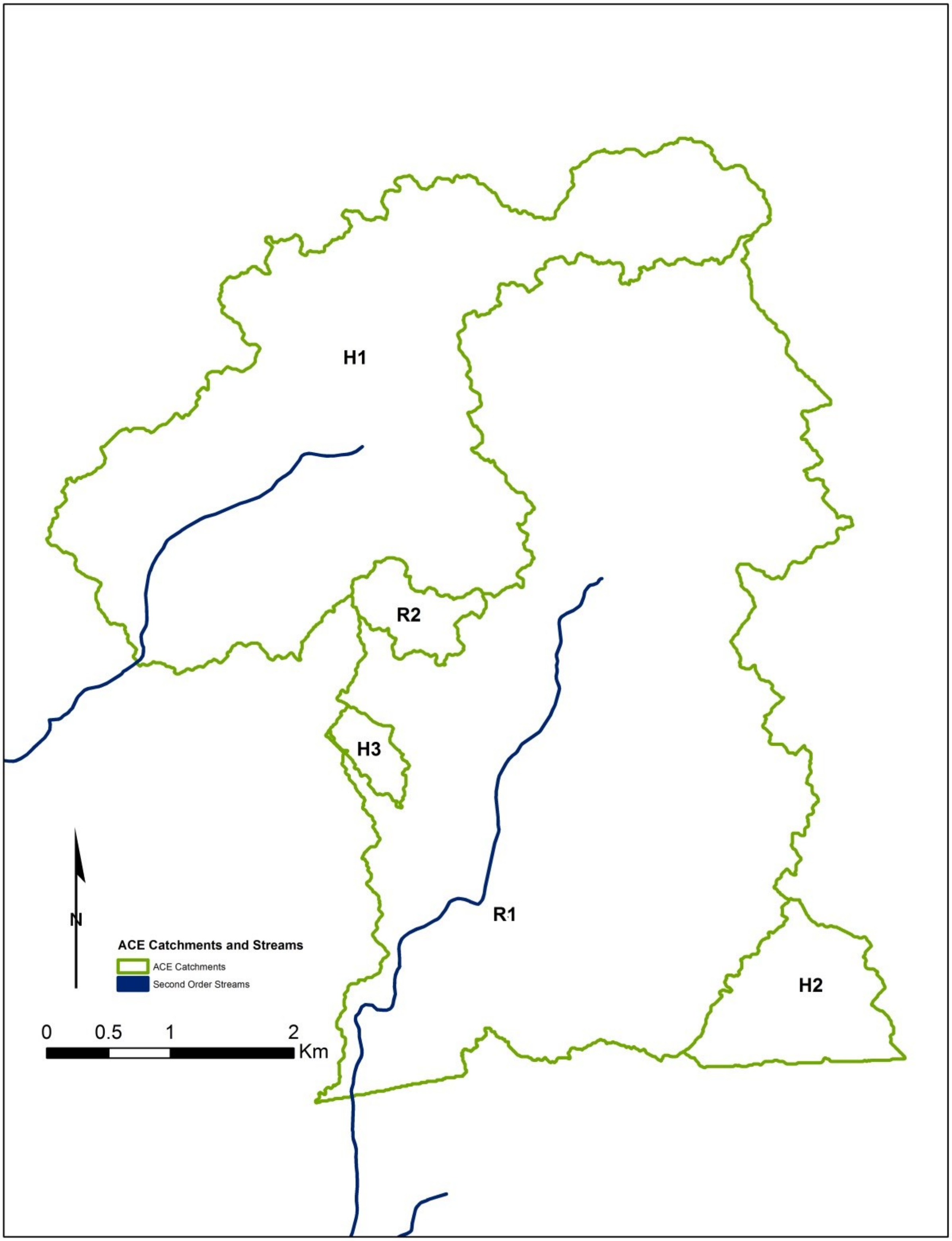

Figure 12. Second Order Streams used for input as surface water in the WTVT.

2.4.2. Creating the Reference Plane Within the Visualization Tool

A reference plane raster was created within the WTVT to represent the plane linking the nearest wetland surfaces in the wetland data set. The reference plane, which represents the shortest distance between adjacent wetlands is used as a measurement reference from which the relationship of wetland position, HRA texture, and topography can be modeled. In order to produce the reference plane, two data sets are required: the first polygon coverage of surface water and, second a Digital Elevation Model (DEM).

The reference plane was created by geoprocessing polygon coverages that represent surface water such as the Enhanced Wetland Classifications or the second order stream polygon coverage with the DEM to produce a reference plane raster. Z-values (heights) were interpolated to the surface water coverages from the DEM with the Interpolate Shape tool, creating a polygon with Z values given to the nodes around the outside perimeter of each wetland or stream polygon. The Create TIN geoprocessing tool was then used to create a TIN between the polygons, which provides a means to represent a surface through triangulation between the set of edge nodes of adjacent polygons. The Create TIN tool was used with all default values with the exception of the SF_type. The SF_type defines the role of the feature class in terms of whether the surface will cross the feature class with or without a breakline. The SF_type was specified as a hardline to instruct the TIN to have breaklines at the water surface polygon edges. The resulting TIN (Figure 13, Figure 14) was then converted to a raster using the TIN to Raster geoprocessing tool, which interpolates the cell values from the elevation at the corresponding location on the TIN.

2.4.3. Calculation of the Water Table Elevation Raster for Each HRA

The calculations for the water table elevation raster for each HRA involve data from the two other submodels. The SLE_Tin_To_DEM submodel provides the reference plane raster information and the SG_Mask submodel provides the HRA masks. A DEM variable must be defined in order for the DWT_combined submodel to run.

Within the DWT_combined submodel, individual raster calculators are set for each HRA type, each containing an algorithm specific for the HRA texture type.

The DWT within the coarse-textured HRA was calculated in the Raster Calculator using the following (coarse) algorithm:

Con(("DEM" - "Coarse SLE") > 0, ("DEM" - " Coarse SLE ") * "Coarse Mask", (0 * "Coarse Mask ")

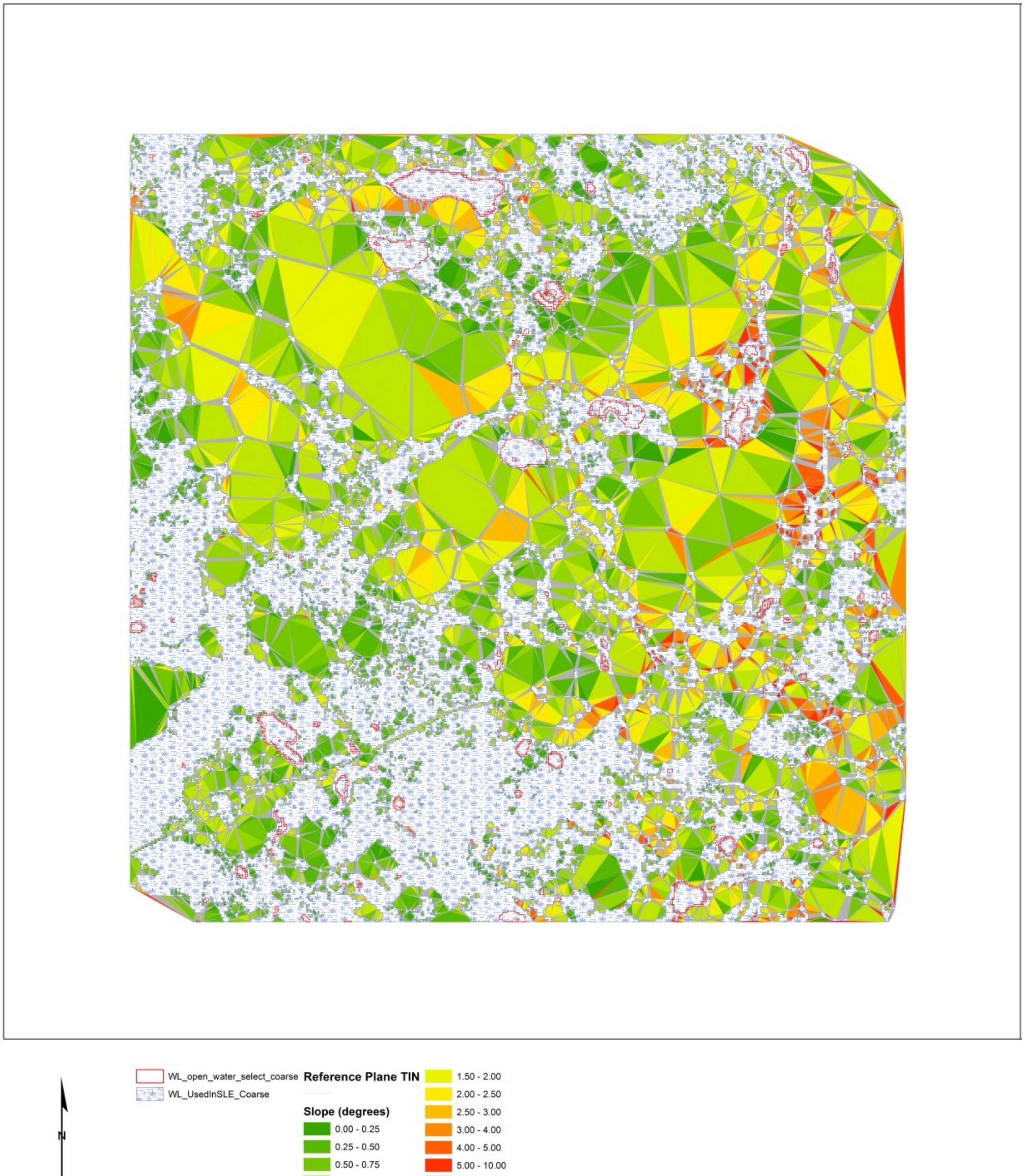

Figure 13. TIN of reference plane resulting from EWCv1.

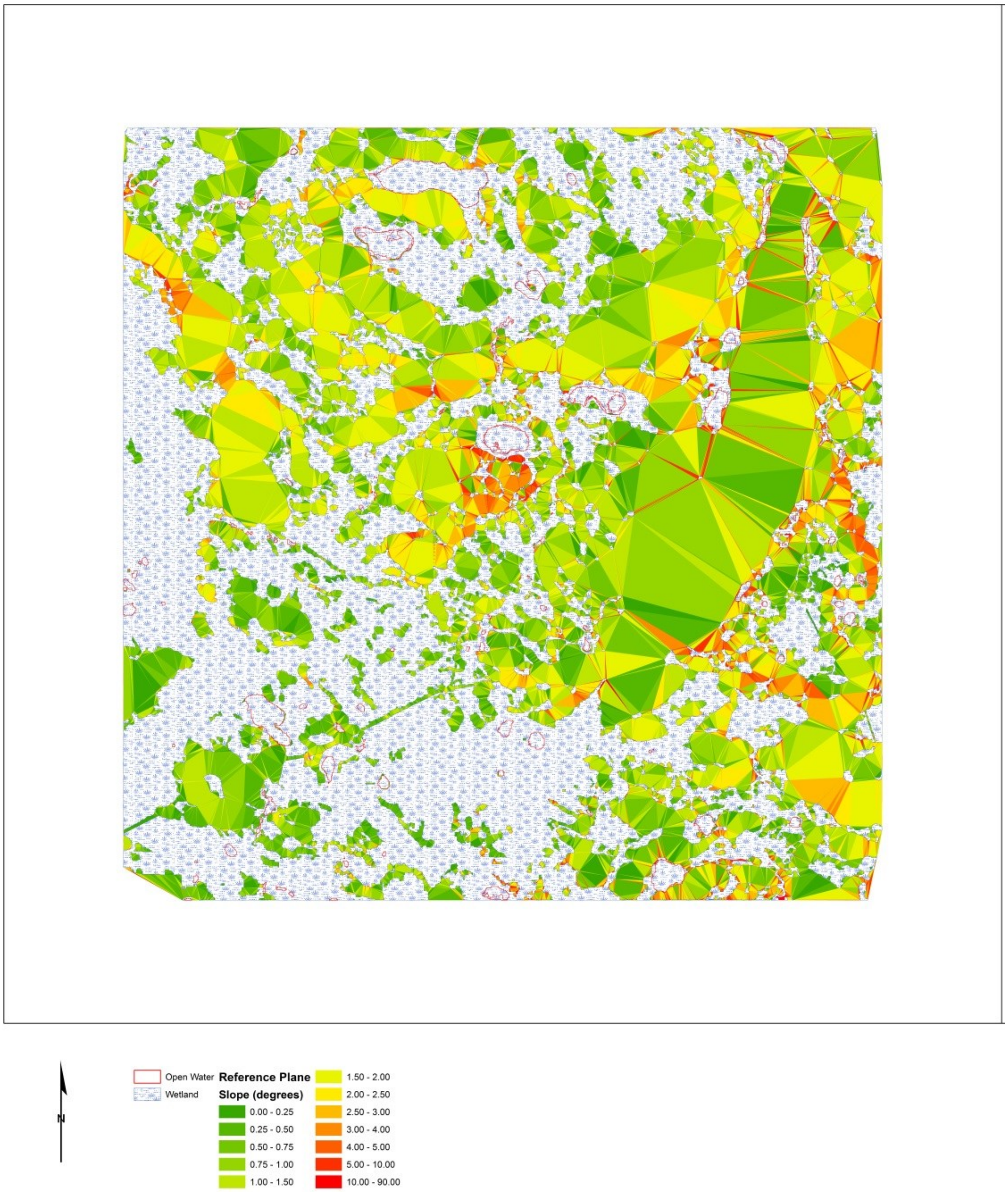

Figure 14. TIN of reference plane resulting from EWCv2.

When the reference plane is below the ground surface, such as between Wetland A and Wetland B, the expected water table is at the same elevation as the reference plane (Figure 15). When the reference plane elevation is above that of the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

The DWT within the Fine-textured HRA was calculated within the Raster Calculator using the following (fine) algorithm:

Con ("DEM" - "Fine SLE" < 0, 0 *"Fine Mask", (("DEM" -"? Fine SLE") * 2) *"Fine Mask ")

When the reference plane is below the ground surface, such as between Wetland A and Wetland B, the expected water table is at a depth that mirrors the ground surface elevation (Figure 16). When the reference plane elevation is above that of the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

The DWT within the coarse-over-fine-textured HRA was calculated with the Raster Calculator using the following (Coarse-over-fine) algorithm:

Con(("DEM" - "COF SLE")>0, Con(("DEM" - " COF SLE ")-2<0, ("DEM" - " COF SLE") * "COF Mask", 2 * " COF Mask "), 0*"COF Mask")

When the reference plane is below the ground surface, such as between Wetland A to point i and from point ii to Wetland B, the expected water table is at the same elevation as the reference plane (Figure 17). When the reference plane is below both the ground surface and the underlying fine-texture soil, such as between point i and point ii, the water table follows the elevation of the underlying fine-textured restrictive layer. When the reference plane is above the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

2.4.4. Combining Resulting Depths to Water Table Rasters.

For both EWCv1 and EWCv2 wetland spatial data the three resulting depth to water table rasters within each HRA were then combined using the Raster Calculator to create a single depth to water table coverage which spans the entire ACE area (Figure 18, Figure 19). This depth to water table coverage could then subtracted from the elevations within the DEM via the Raster Calculator to get a resulting water table elevation raster for the ACE area. .

2.5. Assessment of the Three Algorithms

In order to assess the three algorithms, the WTVT was run using the entire ACE area as a single HRA for each of the three algorithms using all wells. The resulting estimated water table elevations were compared to the observed values for these wells.

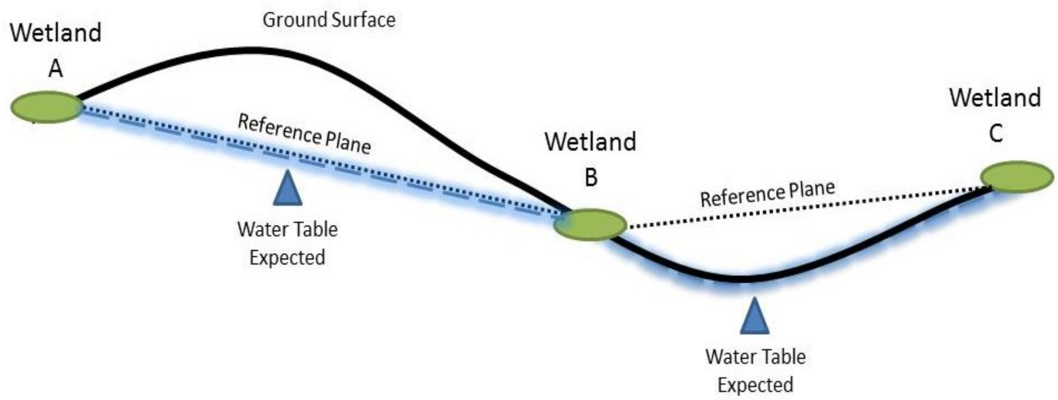

Figure 15. Conceptualization of coarse algorithm. When the reference plane is below the ground surface, such as between Wetland A and Wetland B, the expected water table is at the same elevation as the reference plane. When the reference plane elevation is above the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

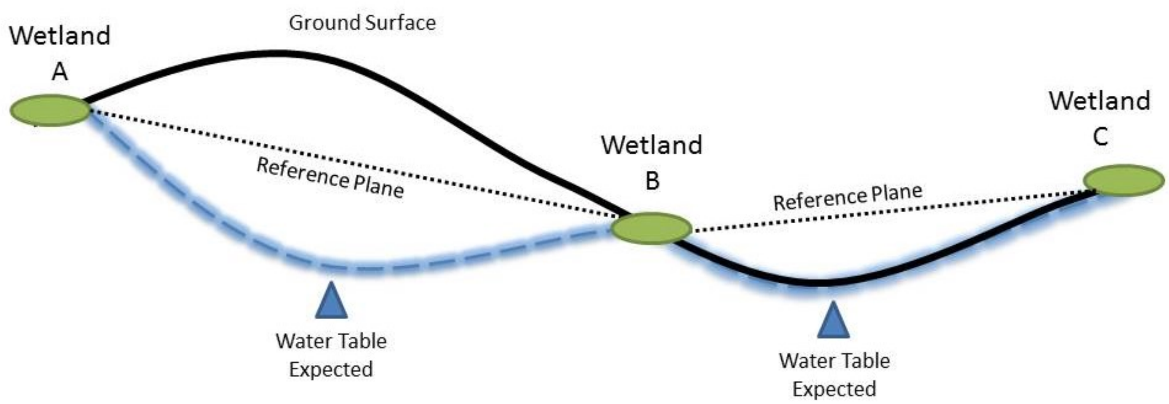

Figure 16. Conceptualization of the fine algorithm. When the reference plane is below the ground surface, such as between Wetland A and Wetland B, the expected water table is at a depth that mirrors the ground surface elevation. When the reference plane elevation is above that of the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

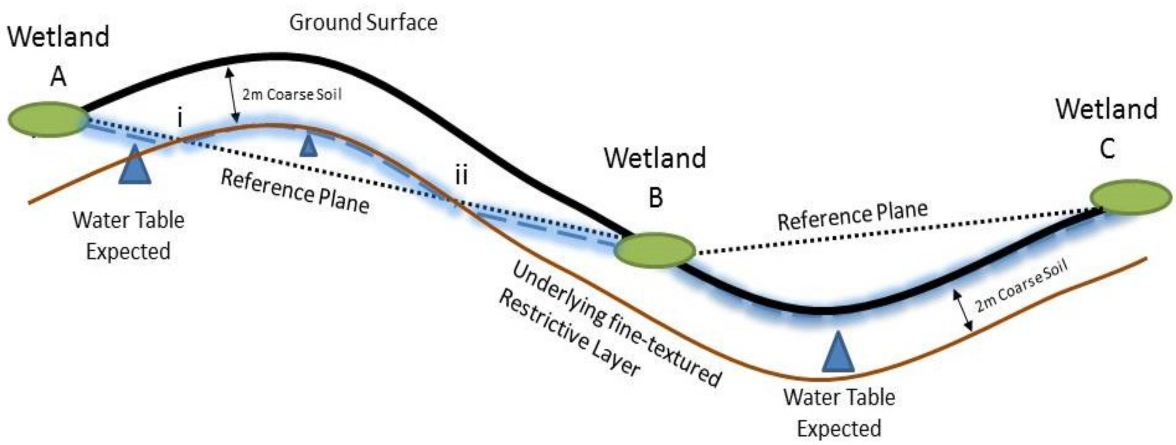

Figure 17 Conceptualization of the coarse-over-fine algorithm. When the reference plane is below the ground surface, such as between Wetland A to point i and from point ii to Wetland B, the expected water table is at the same elevation as the reference plane. When the reference plane is below both the ground surface and the underlying fine-texture soil, such as between point i and point ii, the water table follows the elevation of the underlying fine-textured restrictive layer. When the reference plane is above the ground surface, such as between Wetland B and Wetland C, the expected water table is at the elevation of the ground surface.

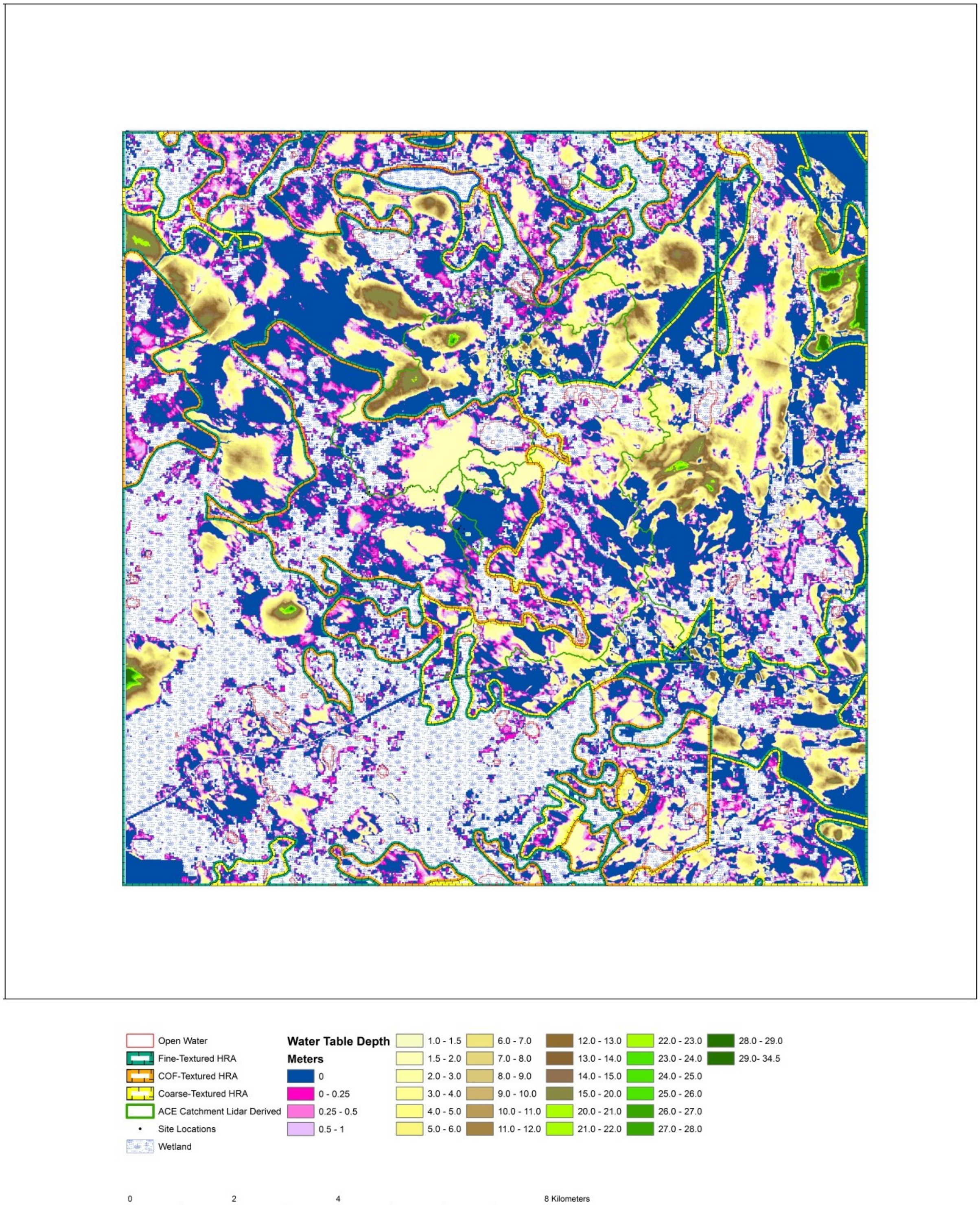

Figure 18. Water table depth map using EWCv1 All data.

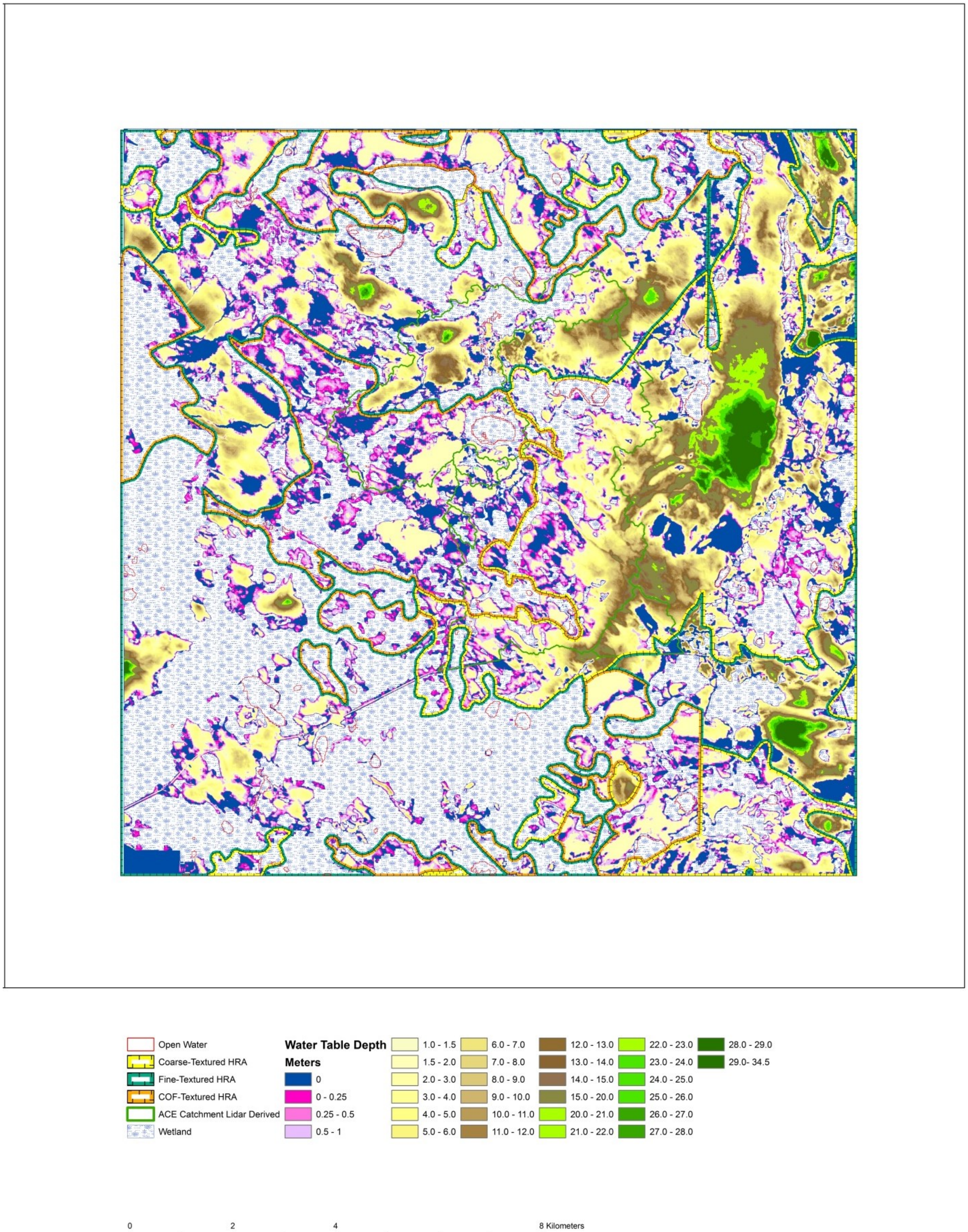

Figure 19 Water table depth map using EWCv2 All data.

Each algorithm was analyzed by extracting the center values of the WTVT output elevation raster at the locations of the calibration wells using the Extract Value to Point tool within ARCGIS. Willmont (1981, 1982) suggested the best method of evaluating model performance is the Root Mean Square Error (RMSE) of the expected compared to the observed values, in this case, water table elevations. The model which produces the lowest RMSE was considered best, and ranked highest. Reliability of the visualization output was assessed by comparing the amount of systematic error (RMSEs) to the amount of unsystematic error (RMSEu). To be considered reliable the RMSEs needed to be less than the RMSEu. Large RMSEs values, as compared to RMSEu, are indicative of greater bias within the estimates; alternatively, where the RMSEu value is large, compared to the RMSEs, the source of the error is more random (Toit et al., 1997).

2.5.1. Calibration and Validation of the Water Table Visualization Model

The reference plane and resulting water table output are strongly tied to the landscape position of the wetlands adjacent to and within an individual HRA. The changes of the predicted water table elevations to manipulations of the wetland data were carried out using model inputs derived from both the EWCv1 and EWCv2. The model was calibrated to determine what surface water data or data manipulation (EWCv1, EWCv2, or second order streams) produces the most accurate estimations of the water table elevations as compared to the observed well water levels.

Water table heights used to calibrate and validate the model were the highest water level value measured at the wells between 2005 and 2010. Using the maximum water table height would provide the most likely estimates of the maximum area of surface saturation. The high water observed values were selected following a thorough review of the high water values for each of the individual wells. For quality control, each measurement was cross referenced to the field notes. The chosen value was compared to the total well depth and to the other existing measurements for that well. Measured high water depth values were removed from the sample pool when:

1) the total depth of the measurement was greater than the total depth of the well, or

2) they were suspect due to a large unexplainable discrepancy when compared to the seasonal high water pattern for the particular well.

2.5.2. Selection of Wells for Calibration and Validation

A total of 29 groundwater monitoring wells within the ACE area were used in a random selection process; 27 of the wells were used with the EWCv1 WTVT analysis, and 26 of the wells were used with the EWCv2 WTVT analysis. For Calibration and Validation approximately 50% were randomly selected for each procedure. Only well installation locations were used as measure points for the analysis. Where more than one well existed at an individual well site cluster (i.e., shallow well and deep well), the deeper well was chosen to avoid pseudo replication within the sample population.

2.5.3. Manipulations of Wetland and Stream Input Data

Seven data sets were used with each EWC version in the configuration of the WTVT. The data sets were created through the manipulation and filtering of the EWCv1 and EWCv2 wetland data. The data manipulations and filtering used on both the EWCv1 and EWCv2 data sets were as follows:

1) All - entire intact data set,
2) Expand and contract by five 10 m pixels,
3) Wetland complexes > 10 ha,
4) Wetland complexes > 20 ha,
5) Open Water All – all open water classified wetlands,
6) Open water > 5 ha, and
7) Open water > 50 ha.

The Expand and contract by five 10m pixels EWC coverages were created from the EWC original shapefile. These coverages were created through a process of reducing and then expanding each individual wetland complex to eliminate appendages, such as peripheral drainages that connect to a larger wetland body. The appendages, depending on the local terrain, could be at a significant elevation difference from the main wetland complex body and therefore could significantly affect the location of the reference plane. The wetland coverage was prepared for the contraction and expansion process by taking the original wetland shapefile and then converting the dissolved polygons to a 10 m raster coverage. Trials were conducted to determine a suitable number of pixels by which to reduce the edge of each wetland to eliminate the appendages. Through a process of trial and error five pixels or 50 m was chosen. This number of pixels eliminated the appendage during the contraction but restored the larger main wetland body to a shape close to its original location. The reduction and expansion was conducted using the Shrink tool specified at five cells. The resultant output was then geoprocessed with the Expansion tool specified at five cells. This process of shrinking and expanding effectively eliminated the appendages while maintaining the main wetland complex body shape. The resultant raster was then converted back to a polygon shapefile and used as input in the WTVT. Two input coverages to improve the accuracy of estimates using wetland complexes filtered to minimum area criteria were also investigated. A Dissolve geoprocessing in ARCGIS created wetland complex input files limited to 20 ha and 10 ha minimum wetland complex areas. The size of the complex was determined by implementing a Dissolve on the intact input wetland coverage which also calculates an updated area for the resulting polygons. The updated area allowed for a minimum area selection to be applied and a coverage with complexes greater than 10 ha and another with complexes greater than 20 ha to be exported for use as input for the WTVT.

Three individual coverages using Open water polygons identified within the EWC were also created for use as input files. Open Water All was created by selecting all open water within the EWC All polygon shapefile and exporting it as a coverage. EWC All version was then used with an attribute selection process for minimum area criteria of five ha for Open Water > 5 ha, and then again at minimum size criteria 50 ha to create the Open Water > 50 ha. The three Open Water input files were then used within the WTVT to examine their effect on the WTVT output.

Another type of data based on second order streams was created as a source of wetlands for the WTVT analysis was also created. This data set was created by extracting the 2nd order stream polyline data from the Alberta Vegetative Inventory data set and applying a buffer at 0.5 m to create a polygon. The resultant buffer file was then used as the polygon shapefile as input in the WTVT.

2.5.4. Calibration Procedure

Each individual WTVT output derived from the wetland and stream input data described in section 2.5.3 was then ranked by RMSE to allow for comparisons of EWCv1, EWCv2 and the 2nd order stream WTVT output. The WTVT estimates were obtained by extracting the center values of the WTVT output elevation raster at the calibration well location using the Extract Value to Point tool within ARCGIS. The RMSE was then calculated and used to rank different WTVT output. The smallest RMSE value was ranked 1st or best and the largest last or worst. Only the top three ranked results for EWCv1 and EWCv2 are presented in the results. Where these comparison techniques produced the same RMSE values, the data set with the least manipulation (closest to intact "All" data set) was ranked higher. Reliability of output was considered acceptable where RMSEs < RMSEu.

2.5.5. Validation Procedure

The WTVT was then run using the best data configuration for both EWCv1 and EWCV2 data as determined in the calibration procedure. The run was validated by extracting the center values of the WTVT output elevation raster at the locations of the validation wells that were reserved for this purpose. ArcGIS was then used to determine the value at the center of the raster using the Extract Value to Point tool within ARCGIS at the location of the validation well. In order to help gauge the performance of the WTVT the RMSE, RMSEs, and RMSEu values were calculated and reported.

2.6. Gradient Analysis

The spatial relationship of the water levels at each of the individual well sites to the wetland configuration (EWCv1 input and EWCv2 WTVT input files) was examined by determining the gradients from the observed groundwater locations to the surface water expressions used in the WTVT input. This relationship was further analysed in ARCGIS using the Near 3D tool. The Near 3D tool (Esri, 2012) considers the three-dimensional distance and angle of an input feature (well point water level) to the nearest feature (individual wetland) that belongs to an input feature class (EWC wetland data set). The expected and observed well water table locations at the well sites and both the intact ("All") versions of EWCv1 and EWCv2 were used as inputs for the Near 3D tool. Output of distance and vertical angle from the expected and observed water table locations to the closest point of the nearest wetland was calculated. For gradients, the Near 3D vertical angle are calculated as follows: horizontal is given as zero, straight up is 90, straight down is -90, up at 10 degrees above horizontal is 10 (Esri, 2012).

The distribution of gradients of the expected water table elevations produced using EWCv1 and EWCv2 were also analysed. The area analysed encompassed the bounding data extent of the WTVT input data. To do this a 100 m sample point grid was created within ARCGIS. To avoid any edge effect caused by being close to the spatial edge of the data, the grid points within 1050 m from the edge were removed. Two point data sets were then created for both EWCv1 and EWCv2 data sets which contain the sample points that were outside of the wetland polygons. This amounted to 10,285 samples for EWCv1 and 9,057 samples for EWCv2. Both sample grids then had the corresponding WTVT data output expected elevations interpolated to each sample point. Near 3D measurements were made between the corresponding sample points data set to the closest EWCv1 and EWCv2 wetland. The distribution of the vertical angles were grouped to slope gradient classes of < 0.005, 0.005 to 0.025, and >0.025 and where negative >-0.005, -0.005 to -0.025, and <-0.025.

2.7. Land Form Shape Analysis

Quantitative analysis of the surface topography was conducted using SAGA GIS software (Böhner & Conrad, 2002). The general curvature was analysed using the Zevenbergen and Thorne (1987) method in the Slope, Aspect, and Curvature geoprocessing tool set. This general curvature method produces a raster that divides the topography into convex and concave topography classes (Figure 20) The convex topography class is assigned positive values and the concave topography class is assigned negative values. This raster file was then further adjusted in ARCGIS using the Reclass tool to isolate the concave locations and convert them into polygons. The concave polygon areas were then spatially compared to the areas of WTVT output with zero water table distance from the ground surface (water table at ground surface) as well as EWC wetland location.

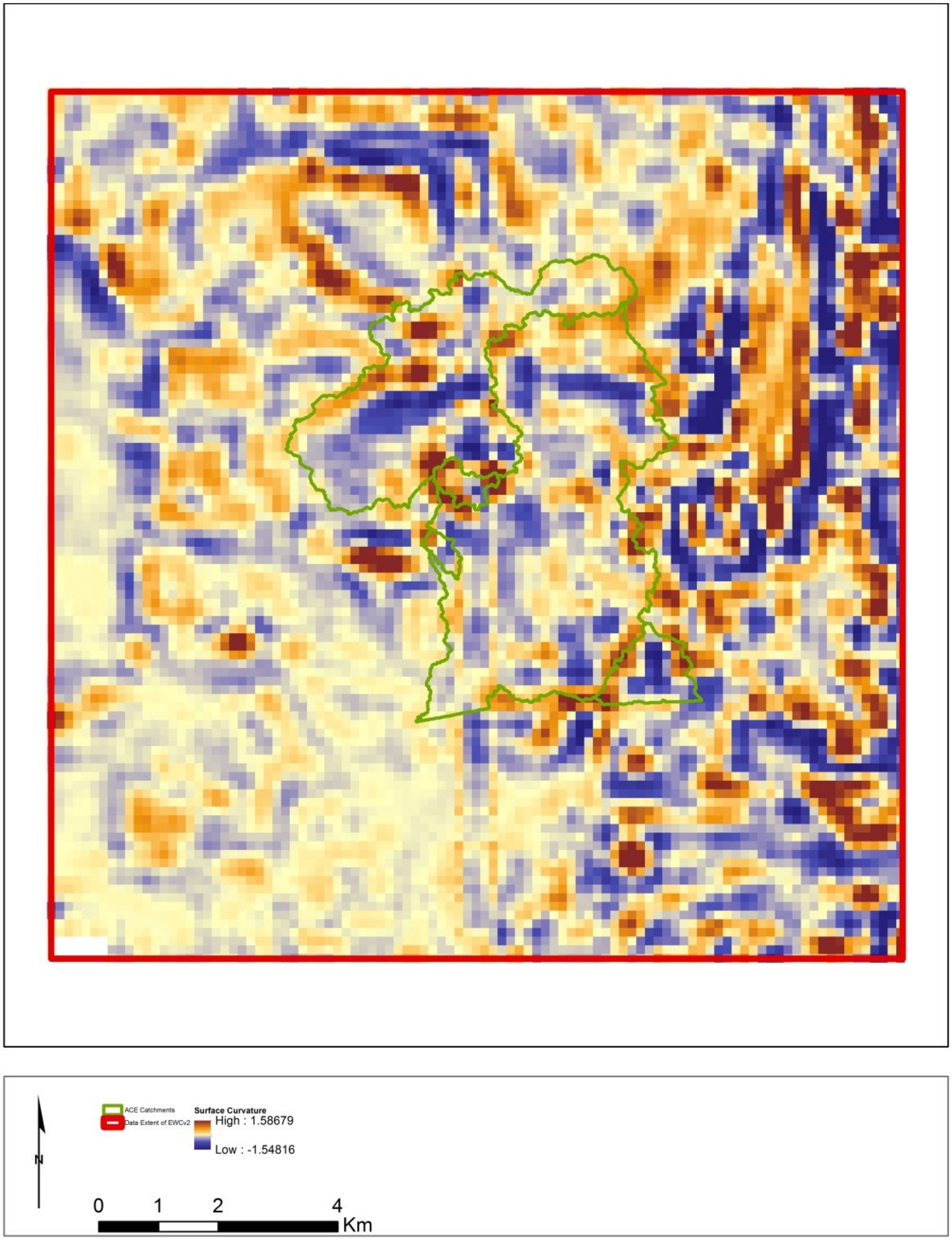

Figure 20. Surface curvature of the ACE study area.

3. RESULTS AND DISCUSSION

3.1. Borehole data and HRA Comparisons.

3.1.1. HRA Texture

Of the 37 boreholes 45.9% were located within polygon 60 (Table 1)(Campbell et al., 2001; Andriashek, 2002), a nearshore latoral sGLh-GFh (sand glaciolacustrine hummocky transitional to glaciofluvial hummocky) landform. Within this polygon, 12 of the 17 boreholes from sites 100, 102, 116, 121, 122, 123, 124, 408, 508, 509, 510, and 511 were COF-texture, and the other five were fine-textured soil from sites 105, 113, 410, 500, and 501. The borehole stratigraphy indicates a prevalence of coarse deposits < 2 m thick over top fine-textured deposits. Shallow boreholes which were established by the author (unpublished data) also indicated sand deposits < 2m thick overtop fine-texture soil within this unit. The interpretation of original coarse-textured SG (Figure 5) was based on the sand modifier as well as the glacial lacustrine and glacial fluvial development. The broad scale interpretation of this type of soil genesis as a coarse-textured deposit may be misleading, causing incorrect assumptions of higher probability for regional scale water table connectivity as well as higher likelihoods of wetland perching (Winter, 2001). Refining the interpretation methodology for coarse-textured deposits to estimate the depth of underlying fine-textured deposit more accurately may be necessary. The final SG interpretation used in the WTVT was changed to COF-texture based on these results.

Nine boreholes were established in the upper western edge of distal GLv (distal glacial lacustrian veneer) polygon 75 (Campbell et al., 2001; Andriashek, 2002). Five boreholes were of COF-texture, at sites 201, 204, 205, 231, and 234. Three boreholes from sites 213, 214, and 230 were comprised of coarse-grained sands. Only a single borehole located at site 232 was fine-textured. All boreholes were located near the edge of the SG polygon and neighbor a COF-textured polygon. Due to this proximity, glacial process overlap is likely (Fenton et al., 1994; Fenton, 2013). No changes were made to the original fine-texture interpretation.

Five boreholes were drilled along the eastern edge of Evr/Op (eolian veneer ridged) in polygon 64 (Campbell et al., 2001) at sites 103, 104, 117, 118, and 120 all, of which were COF-textured. The original SG COF-texture classification agreed with the borehole data.

Two boreholes, established near the eastern boundary of littoral sGLhk//Er (littoral sand glacial lacustrine hummocky collapse) polygon 74 (Campbell et al., 2001) at sites 238 and 337, were COF-textured. It is difficult to determine, from such a small number of boreholes, whether the original SG texture interpretation of coarse may be incorrect or if this sequence is indicative of perching. This polygon is adjacent to the northern edge of a large regional-scale organic deposit which developed from a distal lacustrine deposit, which is underlain by fine and COF-

Table 1. Summary of surficial geology polygons (SG) (Campbell et al., 2001) containing boreholes.

Reference Map Polygon Number (Borehole Count n=36)	SG* Polygon Lable	SG classification using system	Borehole Texture (number of boreholes with texture)	SG* Classification Used within the WTVT
65(1)	sMr//GFr	Coarse	Fine(1)	Coarse
74(2)	sGLhk//Er	Coarse	COF(2)	Coarse
78(2)	GFp	Coarse	Coarse(2)	Coarse
60(17)	sGLh-GFh	Coarse	Fine(5), COF(12),	COF
64(4)	Evr/Op	COF	COF(4)	COF
66(1)	sGLp/Ev/Op	COF	COF(1)	COF
75(9)	GLv	Fine	Coarse(3), COF(5), Fine(1)	Fine

*SG = Surficial Geology

textured soil (Unpublished data). Because of this proximity, the likelihood of underlying near-surface fine-texture deposits is greatly increased in the neighboring SG polygons, especially those that are glaciolacustrine in development.

Two boreholes drilled within GFp (glacial fluvial plain) polygon 78(Campbell et al., 2001), at sites 212, and 236 were coarse-textured. The borehole data support the SG interpretation as coarse-textured and may provide some additional credence to adjacent polygon 74 being interpreted as coarse-textured.

Polygon 65, originally classified as a sMr//GFr (complex of at least 60% sand morrain ridged and no more than 15% glacial fluvial ridged) landform, contained a single borehole of fine-texture at site 233 (Campbell et al., 2001). This texture does not agree with the SG interpretation of coarse-textured and may indicate a near surface fine-textured deposit. Other samples (Author's unpublished data) within this polygon also support the categorization of near surface fine and COF-texture deposits, perhaps indicating perching in a coarse-textured landform or the development of a larger COF polygon. Due to the small number of samples and clustering of the samples, the original SG texture interpretation was not changed.

At site 409 a single borehole of COF-textured soil was recorded within littoral polygon 66 (Campbell et al., 2001) and classified as an sGLp/Ev/Op landform (littoral complex of at least 60% sand glacial lacustrial plane, not more than 40% eolian veneer and not more than 15% organic plane). No changes to the original SG texture interpretation were made as the borehole data support the COF-texture.

Only in one instance (polygon 60) was the original surficial texture interpretation changed due to borehole information. There is evidence, however, to suggest that the COF-textured HRAs are more prevalent, and in which water table behaviour and ecohydrology are not greatly understood or described (Riddell, 2008). If true, this may indicate a larger abundance of related wetland features such as treed swamps. The final HRA configuration used in the WTVT analysis runs is shown in Table 1.

3.2. Algorithm Analysis

3.2.1. All Well Sites - Single HRA

For the EWCv1 data set the algorithms ranked COF > C > F, in descending order of performance based on RMSE values (Table 2). The RMSE for the coarse algorithm was within 0.2 m of that of the COF algorithm. The average absolute difference, total absolute distance, and standard deviation of the COF algorithm are lower, illustrating the effect of the 2 m maximum depth enforced by the COF algorithm. In all cases the unsystematic error was greater than the systematic error (RMSEu > RMSEs); hence, an acceptable level of model performance was achieved.

For the EWCv2 data set the algorithms ranked F > C > COF, in descending order of performance based on RMSE values (Table 2). RMSE for the coarse algorithm was within 0.3 m of that of the fine algorithm. The fine algorithm total difference and standard deviation were also slightly less than those for the coarse algorithm. The greater depth of the predicted water table below the reference line with the fine algorithm improved results. Model performance was also acceptable (RMSEu > RMSEs). EWCv2 observed slopes had absolute mean values greater than 0.025, the range of values associated with fine-textured soils.

The RMSE values for the EWCv2 data set were lower than those for the EWCv1 data set, except for COF EWCv2; perhaps due to the improved accuracy within the EWCv2 wetland mapping, which greatly reduced the amount of predicted zero depth water tables (Table 3). The mean and range of both observed and expected slopes were larger in EWCv2 than in EWCv1. The slope from the well water level to nearest wetland edge is dependent on the distance and elevation difference between these features. The higher resolution EWCv2 resulted in greater minimum and maximum slopes. At the same time EWCv2 had lower minimum and greater maximum distances than did EWCv1. With the assumed greater accuracy of the EWCv2 wetland location, in certain cases there may be a coincidental increase in the range of slopes. The difference between the EWCv1 and EWCv2 reported slopes may also be the result

Table 2. Algorithm comparison of depth of water (m), using all well sites in a single HRA (EWCv1 n = 27, EWCv2 n = 26).

	EWCv1 Coarse Algorithm	EWCv1 Fine Algorithm	EWCv1 COF Algorithm	EWCv2 Coarse Algorithm	EWCv2 Fine Algorithm	EWCv2 COF Algorithm
ABS Difference Average	1.6	2.1	1.4	1.3	1.3	1.8
Stan. Dev.	2.2	2.8	2.1	1.8	1.4	3.2
Total ABS Diff.	43.9	56.2	38.4	34.1	33.8	46.0
RMSE	2.7	3.5	2.5	2.2	1.9	3.7
RMSEs	1.0	1.2	1.1	0.5	0.6	0.4
RMSEu	2.2	3.3	2.3	2.2	1.8	3.7

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

Table 3. Area summaries for concave topography analysis. All units are in ha.

Area Summaries	EWCv1	EWCv2
Study Area Data Extent	20,671	20,671
Total concave area*	14,215	14,215
Total wetland area	7,180	8,929
Total area water table depth.= 0*	10,001	8,909
Total area in concave topography where water table depth = 0.	8,055	7,713
Total wetland area within concave topography.	6,155	7,890
Total wetland area in concave topography where water table depth = 0	3,705	6,024
Total area in concave topography outside of wetland where water table depth = 0.	4,350	1,689
*includes EWC wetland area and non-wetland areas		

of differences in inclusion and exclusion of well sample points due to the differing wetland locations.

Differences in results were also influenced by landform shape with the majority (68.8%) of the topography being concave (Table 3). The total area in concave topography where water table depth = 0 was 56.7% of the total concave area for EWCv1 and 54.3% for EWCv2. The total wetland area in EWCv2 is 24.4% greater than that in EWCv1, while the total area outside of wetland with the water table = 0 is 10.9% lower. The differences in wetland edges affect the elevations used in determination of the reference plane location and the water table elevation.

3.2.2. Coarse HRA

For the EWCv1 data set the algorithms ranked F > C = COF, in descending order of performance based on RMSE values (Table 4). In all cases, the unsystematic error was greater than the systematic error (RMSEu > RMSEs), indicating an acceptable level of model performance was achieved. Limited numbers of wells exist (n=4) within this stratum and all RMSE values are within 0.2 of each other. These similar results are due mainly to the reference line being above the ground surface in concave topography. Additional sample locations with a broader distribution might produce more conclusive results. Additionally, EWCv1 contains wetlands near sample locations which are not part of EWCv2 and were field confirmed to be non-existent (Author unpublished data). These wetlands cause the reference line to be nearer the surface. In such cases where perched water tables are potentially included in sample locations, misleading lower RMSE values would result. The lower resolution and implied reduced accuracy in wetland identification with EWCv1 may also result in higher than actual wetland water table elevations.

For the EWCv2 data set the algorithms ranked F > C > COF, in descending order of performance based on RMSE values (Table 4). For each algorithm, the RMSEu > RMSEs, indicating acceptable model performance. The fine algorithm had total differences of expected to observed distances that were half those found using the coarse algorithm. A methodology that would adjust the reference line to the actual regional water table elevation might improve accuracy of predictions using the coarse algorithm. A subset of the wetland input data with a reference plane more representative of the regional water table elevation may also improve results. All wetlands above this line could then be assumed to be perched. Alternatively, wetland perching could be approached with probability mapping based on slopes. The accuracy of any methodology would be dependent upon delineating the HRA accurately, choosing representative wetlands, and having accurate wetland boundary locations. Further augmentation of input data with other regional level information such as forest cover could also improve results (Pike et al., 2010).

The RMSE values for the EWCv2 data set were lower than for the EWCv1 data set, except for COF EWCv2. This was influenced by total wetland spacing in EWCv2 being greater than in EWCv1. Also reducing the amount of concave topography within the non-wetland areas resulted in lower zero depth (water at surface) area (Table 3).

Table 4 Algorithm comparison of depth of water (m), using well sites within the Coarse HRA. (EWCv1 n = 4, EWCv2 n = 4).

	EWCv1 Coarse Algorithm	EWCv1 Fine Algorithm	EWCv1 COF Algorithm	EWCv2 Coarse Algorithm	EWCv2 Fine Algorithm	EWCv2 COF Algorithm
ABS Difference Average	3.9	3.8	3.9	3.8	1.8	6.9
Stan. Dev.	4.0	3.9	4.0	3.0	0.9	5.7
Total ABS Diff.	15.7	15.2	15.7	15.1	7.0	27.5
RMSE	5.6	5.4	5.6	4.8	2.0	8.9
RMSEs	3.9	3.7	3.9	2.8	0.9	5.7
RMSEu	4.0	4.0	4.0	4.0	1.7	6.9

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

3.2.3. Fine HRA

For both the EWCv1 and EWCv2 data sets, all algorithms within each set were ranked equally (Table 5). In all cases, the unsystematic error was less than the systematic error (RMSEu < RMSEs), indicating an unacceptable level of model performance. The equal rank of all algorithms within each set was due to the concave nature of the landscape in the location of the wells. All fine textured wells were in close proximity to each other. A larger sample number over a wider variety of fine-textured landforms may increase the accuracy of the results.

In all cases the RMSE values for the EWCv2 data set were lower than those for the EWCv1 data set; differences, however, were < 0.1 m, indicating that little advantage in using one data set over the other. Results are likely influenced by the limited distribution of sample locations and the concave shape of the topography.

Table 5 Algorithm comparison of depth of water (m),, using well sites within the fine HRA (EWCv1 n = 7, EWCv2 n = 8).

	EWCv1 Coarse Algorithm	EWCv1 Fine Algorithm	EWCv1 COF Algorithm	EWCv2 Coarse Algorithm	EWCv2 Fine Algorithm	EWCv2 COF Algorithm
ABS Difference Average	0.9	0.9	0.9	0.8	0.8	0.8
Stan. Dev.	0.8	0.8	0.8	0.8	0.8	0.8
Total ABS Diff.	6.2	6.2	6.2	6.1	6.0	6.1
RMSE	1.2	1.2	1.2	1.1	1.1	1.1
RMSEs	0.9	0.9	0.9	0.9	0.8	0.9
RMSEu	0.7	0.7	0.7	0.7	0.7	0.7

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

3.2.4. COF HRA

For the EWCv1 data set, the algorithms ranked COF > C > F, in descending order of performance based on RMSE values (Table 6). As the unsystematic error was greater than the systematic error (RMSEu > RMSEs), an acceptable level of model performance was achieved. The total absolute difference for the COF was 5.4 m less than that for the coarse algorithm. This difference is associated with the 2 m maximum water table depth criterion within the COF algorithm.

For the EWCv2 data set the algorithms ranked C > COF > F, in descending order of performance based on RMSE values (Table 6). Model performance was also acceptable (RMSEu > RMSEs). The COF algorithm RMSE was 0.1 m greater than the coarse algorithm RMSE. The COF algorithm total absolute distance was 0.6 m less than that for the coarse algorithm. With the EWCv2 data set the reference line was kept primarily within 2 m of the surface depth.

The RMSE values for the EWCv2 data set were lower compared to those for the EWCv1 data set, except for the Fine algorithm in EWCv2 (Table 6), perhaps due to a more accurate identification of wetlands in EWCv2. The effect of greater wetland spacing in both EWC results is illustrated by the comparatively higher RMSE value of the fine algorithms as compared to the other two. The lower fine algorithm RMSE occurred in the EWCv2 data set, coincident with shorter distances (Table 6).

Table 6. Algorithm comparison of depth of water (m),, using well sites within the coarse-over-fine HRA (EWCv1 n = 16, EWCv2 n = 14).

	EWCv1 Coarse Algorithm	EWCv1 Fine Algorithm	EWCv1 COF Algorithm	EWCv2 Coarse Algorithm	EWCv2 Fine Algorithm	EWCv2 COF Algorithm
ABS Difference Average	1.4	2.2	1.0	0.9	1.5	0.9
Stan. Dev.	1.5	2.8	1.1	1.0	1.7	1.0
Total ABS Diff.	21.9	34.8	16.5	12.9	20.7	12.3
RMSE	2.1	3.6	1.5	1.3	2.3	1.4
RMSEs	0.2	1.1	0.5	0.4	0.7	0.7
RMSEu	2.1	3.4	1.4	1.3	2.2	1.2

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

3.3. Calibration Results

3.3.1. Coarse HRA

For both the EWCv1 and EWCv2 data sets using the total absolute difference (Table 7) the "All" data set produced water table elevations that were closest to observed elevations. However, the low number of sample points (n=2) make the statistics unreliable (Willmont, 1981, 1982).

3.3.2. Fine HRA

For the EWCv1 data (well sits n=3) set every data configuration had the same ranking based on the RMSE values (Table 8). RMSEu < RMSEs, indicating model performance was unacceptable.

For the EWCv2 data set (well sites n=4), all data configurations had similar RMSE values except Open Water > 50 ha, which was larger (Table 8). The highest ranked was the EWCv2 All data as it was the most intact. In all cases RMSEu < RMSE, indicating model performance was unacceptable.

The highest ranked EWCv2 data configurations had an RMSE value that was 0.1 m less than the best value for the EWCv1 data configuration. The concave form of the landscape and the clustering of all sample points resulted in similar results for all of the data configurations.

Table 7. Coarse-HRA calibration of depth of water (m), (EWCv1 n = 2, EWCv2 n = 2).

	EWCv1 All	EWCv1 Complex >10 ha	EWCv1 Complex >20 ha	EWCv2 All	EWCv2 Open water > 5 ha	EWCv2 Open water All
ABS Difference Average	0.3	0.4	0.4	3.6	5.0	5.0
Stan. Dev.	0.2	0.1	0.1	3.6	4.7	4.7
Total ABS Diff.	0.6	0.7	0.7	7.2	9.9	10.0

Table 8. Fine-HRA calibration of depth of water (m), (EWCv1 n = 3, EWCv2 n = 4).

	All EWCv1 configurations	All EWCv2 configurations exept EWCv2 Open Water > 50 ha
ABS Difference Average	0.6	0.5
Stan. Dev.	0.4	0.5
Total ABS Diff.	1.8	1.8
RMSE	0.7	0.6
RMSEs	0.6	0.5
RMSEu	0.4	0.3

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

3.3.3. COF HRA

For the EWCv1 data set, the top 3 data configurations with acceptable model performance ranked “Complex > 10 ha” > “Expand and Contract 5 Pixels” = “complex > 20 ha”, in descending order of performance (Table 9). All top three RMSE values were within 0.1 m of each other, indicating that some amount of wetland data manipulation that eliminates the smaller wetlands within the COF HRA improves results. It is unclear, however, if this change to the input data is merely removing wetlands that do not exist in the field. If this is the case, the actual water table may be deeper, producing lower predicted values and greater absolute differences.

For the EWCv2 data set, the data configurations with acceptable model performance ranked “Complex > 10 ha”= “Open water all” = “open Water > 5 ha”, with the same level of performance (Table 9). Similar to the result for EWCv1, eliminating smaller wetlands improved results. Within the COF HRA, wetlands and the adjacent forest lands often have small

Table 9. Coarse-over-fine HRA calibration of depth of water (m), (EWCv1 n = 6, EWCv2 n = 6).

	EWCv1 Complex > 10 ha	EWCv1 Expand and Contract 5 pixels	EWCv1 Complex > 20 ha	EWCv2 Complex > 20 ha	EWCv2 Open Water All	EWCv2 Open Water > 5 ha
ABS Difference Average	0.9	1.2	1.1	1.1	1.2	1.2
Stan. Dev.	1.0	0.9	1.0	1.0	0.9	0.9
Total ABS Diff.	5.5	7.4	6.7	6.7	7.4	7.4
RMSE	1.4	1.5	1.5	1.5	1.5	1.5
RMSEs	0.9	1.0	0.7	0.7	1.0	0.6
RMSEu	1.0	1.2	1.3	1.3	1.2	1.4

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

differences in elevation and distances between wetlands are short, contributing to smaller standard deviations (Table 9). These data manipulations most likely increased the distance between wetlands and lowered the reference elevation of the reference plane. In this situation the observed water table is close to the 2 m maximum depth constraint within the COF algorithm and may predispose the COF algorithm to higher accuracy as compared to the other algorithms.

3.4. Validation Results

3.4.1. COF HRA

For EWCv1 data set, calibration of each of the HRAs resulted in only the COF HRA having acceptable model performance (RMSEu>RMSEs). Within the COF calibration procedure EWCv1 Complex > 10 ha was ranked first based on acceptable model performance and minimal RMSE values. Validation also resulted in acceptable performance (RMSEu>RMSEs)(Table 10). The average difference and standard deviation of the average difference are likely low enough to allow predicated water table elevations to be of use to land managers (Rex & Dubé, 2006; Pike et al., 2010), especially where the location of near surface water levels need to be understood.

Within EWCv2 data set, the COF HRA was the only HRA that had acceptable performance (RMSEu>RMSEs). The EWCv2 Complex > 20 ha ranked highest with acceptable performance levels (RMSEu>RMSEs) in the COF HRA. Similar to the validation results of EWCv1 the average difference and its corresponding standard deviation may be low enough to be of use in determining near surface water locations (Table 10).

The EWCv1 results showed a slightly lower average difference when compared to EWCv2 results but also had a slightly higher standard deviation of average difference. These small differences between data sets could be assigned to the slight differences of inclusion and exclusion of well sites resulting from wetland and sample site overlap. From these results it is not clear whether the higher resolution EWCv2 data set provided any advantage over EWCv1 in predicting the water table elevation.

Table 10. Coarse–over-fine HRA validation of depth of water (m), (EWCv1 n = 10, EWCv2 n = 8).

	EWCv1 Complex > 10 ha	EWCv2 Complex > 20 ha
ABS Difference Average	1.4	1.5
Stan. Dev.	0.5	0.4
Total ABS Diff.	13.6	12.1
RMSE	1.4	1.6
RMSEs	0.6	0.6
RMSEu	1.3	1.4

ABS Difference Average = absolute difference between predicted and observed,
Stan. Dev. = standard deviation of ABS Difference Average,
Total ABS Diff. = sum of differences between predicted and observed,
RMSE = Root Mean Square Error,
RMSEs = systematic error associated with RMSE, and
RMSEu = unsystematic error associated with RMSE.

3.5. Water Table Slopes

3.5.1. Slopes of All HRA Well Sites to Nearest Wetland

The calculated slopes from the observed samples using EWCv1 data ranged from flat to greater than 0.07 (Table 11). Expected slopes were within the range for coarse-textured soils. Predicted values were also within ranges anticipated for coarse-textured and fine-textured soil.

Observed slopes in the EWCv2 data set had mean absolute values greater than 0.025, with the range of values falling within the range associated with both coarse-textured and fine-textured soils.

The mean and range of both observed and expected slopes were larger in EWCv2 than in EWCv1. The slope from the observed water level to nearest wetland edge is dependent on the distance and elevation difference between these features. A tightly clustered spatial distribution of the samples could skew the slope data.

3.5.2. Slopes of Coarse HRA Well Sites to Nearest Wetland

Absolute expected and observed slopes within the EWCv1 and EWCv2 were greater than 0.005 (Table 12). A wider range of expected slope values occurred within the EWCv2 data set, and distances between wetlands within EWCv2 were up to 102.8 m greater than in EWCv1. The greater range of distances in EWCv2 may be associated with better delineation of wetland boundaries within the EWCv2 data set.

3.5.3. Slopes of Fine HRA Well Sites to Nearest Wetland

Observed slopes were > the 0.005 threshold (Table 13). Expected slopes within EWCv1 had a slightly larger range than observed. EWCv2 observed positive mean slopes were above 0.025 and minimum slopes were below 0.005, while the EWCv2 expected mean slopes were above 0.025 but minimum slopes were seen below 0.005. The greater range of slopes in EWCv2 coincides with mean, minimum, and maximum distances that are more than half the distances found using EWCv1 data. The greater maximum observed and expected slopes in EWCv2 are partly due to the shorter distances to wetland edge and the assumption of the water table being at surface within the wetland polygon.

3.5.4. Slopes of COF HRA Well Sites to Nearest Wetland

Expected and observed slope values for both EWCv1 and EWCv2 were within the threshold expected for coarse-textured soils Mean slopes for EWCv2 were smaller than those for EWCv1 for both expected and observed results. Minimum distances for EWCv2 were 5.2 times less than the EWCv1 minima while maximum distances for EWCv2 were 22.9 m less than the EWCv2 maxima (Table 14).

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Table 11. Near 3D slope analysis, all well site locations (EWCv1 n=27, and EWCv2 n=26). (Units are m/m)

	EWCv1 Obs. Pos Slope	EWCv1 Obs Neg Slope	EWCv1 Obs Dist (m)	EWCv1 Exp Pos Slope	EWCv1 Exp Neg Slope	EWCv2 Obs Pos Slope	EWCv2 Obs Neg Slope	EWCv2 Obs Dist (m)	EWCv2 Exp Pos Slope	EWCv2 Exp Neg Slope
Mean	0.0346	-0.0095	109.355	0.0709	-0.0095	0.0513	-0.0264	75.357	0.0794	-0.0178
S.Dev.	0.0223	0.0056	87.433	0.0811	0.0063	0.0958	0.0179	87.299	0.1149	0.0148
Min	0.0022	-0.0183	2.978	0.0026	-0.0181	0.0045	-0.0581	2.932	0.0015	-0.0454
Max	0.0755	0.0000	368.736	0.3222	-0.0001	0.4032	-0.0028	370.948	0.4148	-0.0001

Obs. = Observed   Exp = Expected
Pos = Positive   Neg = Negative
Dist = Distance   S.Dev = Standard Deviation of Mean
Min = Minimum   Max = Maximum

Table 12. Near 3D slope analysis, within the coarse-textured HRA (EWCv1 n=4, and EWCv2 n=4). (Units are m/m)

	EWCv1 Obs. Pos Slope	EWCv1 Obs Neg Slope	EWCv1 Obs Dist (m)	EWCv1 Exp Pos Slope	EWCv1 Exp Neg Slope	EWCv2 Obs Pos Slope	EWCv2 Obs Neg Slope	EWCv2 Obs Dist (m)	EWCv2 Exp Pos Slope	EWCv2 Exp Neg Slope
Mean	0.0192	-0.0108	84.4351	0.2169	-0.0091	0.0619	-0.0268	174.8854	0.0049	-0.0137
S.Dev.	0.0011	0.0021	83.3901	0.1489	0.0026	#N/A	0.0193	150.6644	0.0025	0.0041
Min	0.0184	-0.0122	33.8726	0.1116	-0.0109	0.0619	-0.0486	12.7489	0.0032	-0.0166
Max	0.0199	-0.0093	208.1079	0.3222	-0.0072	0.0619	-0.0120	370.9480	0.0067	-0.0108

Obs. = Observed   Exp = Expected
Pos = Positive   Neg = Negative
Dist = Distance   S.Dev = Standard Deviation of Mean
Min = Minimum   Max = Maximum

Table 13. Near 3D slope analysis, within the fine-textured HRA (EWCv1 n=7, and EWCv2 n=8). (Units are m/m)

	EWCv1 Obs. Pos Slope	EWCv1 Obs Neg Slope	EWCv1 Obs Dist (m)	EWCv1 Exp Pos Slope	EWCv1 Exp Neg Slope	EWCv2 Obs Pos Slope	EWCv2 Obs Neg Slope	EWCv2 Obs Dist (m)	EWCv2 Exp Pos Slope	EWCv2 Exp Neg Slope
Mean	0.0192	-0.0108	84.4351	0.2169	-0.0091	0.0619	-0.0268	174.8854	0.0049	-0.0137
S.Dev.	0.0011	0.0021	83.3901	0.1489	0.0026	#N/A	0.0193	150.6644	0.0025	0.0041
Min	0.0184	-0.0122	33.8726	0.1116	-0.0109	0.0619	-0.0486	12.7489	0.0032	-0.0166
Max	0.0199	-0.0093	208.1079	0.3222	-0.0072	0.0619	-0.0120	370.9480	0.0067	-0.0108

Obs. = Observed
Pos = Positive
Dist = Distance
Min = Minimum
Exp = Expected
Neg = Negative
S.Dev = Standard Deviation of Mean
Max = Maximum

Table 14. Near 3D slope analysis, within the COF-textured HRA (EWCv1 n=16, and EWCv2 n=14). (Units are m/m)

	EWCv1 Obs. Pos Slope	EWCv1 Obs Neg Slope	EWCv1 Obs Dist (m)	EWCv1 Exp Pos Slope	EWCv1 Exp Neg Slope	EWCv2 Obs Pos Slope	EWCv2 Obs Neg Slope	EWCv2 Obs Dist (m)	EWCv2 Exp Pos Slope	EWCv2 Exp Neg Slope
Mean	0.0365	-0.0084	134.5444	0.0644	-0.0120	0.0259	-0.0313	74.4384	0.0596	-0.0243
S.Dev.	0.0239	0.0093	98.4336	0.0603	0.0082	0.0127	0.0205	66.4285	0.0786	0.0161
Min	0.0022	-0.0183	2.9782	0.0026	-0.0181	0.0047	-0.0581	3.8742	0.0017	-0.0454
Max	0.0755	0.0000	368.7355	0.2282	-0.0001	0.0459	-0.0028	232.3276	0.2680	-0.0062

Obs. = Observed
Pos = Positive
Dist = Distance
Min = Minimum
Exp = Expected
Neg = Negative
S.Dev = Standard Deviation of Mean
Max = Maximum

4. WTVT LIMITATIONS, POSSIBLE IMPROVEMENTS AND FURTHER WORK

4.1. Does the WTVT Work?

The WTVT does work. Three conceptual models of WT position (C, F, COF) were created, and their associated algorithms were executed within the WTVT, producing a water table visualization for the study area. This was the first time such a technique has been executed, and it shows advantage over strictly topographic driven models. The WTVT produced water table elevations that were not limited to simply the flow accumulation areas and depressions. The WTVT also has some limitations; some are related to input data, some to data interpretation and some to limitations in the algorithms used.

4.2. Surficial Geology Mapping and Interpretation of Texture to HRA

The current limitations of the interpretation process are illustrated by the borehole comparisons, e.g., the SG mapping is surface mapping and does not show how deep deposits are, and individual landform soils may not be homogeneous. Overcoming these limitations lie both in improvements to the interpretation process as well as improved SG mapping itself.

The initial interpretation of the SG mapping was done by manually looking at each polygon and appraising its geologic setting as well as its genesis. Due to limited borehole data only seven SG polygon textures could be compared. Borehole data sets currently available through the Alberta Geologic Survey (AGS) could be used to check additional polygon texture interpretations.

The AGS is also currently producing updated SG mapping which incorporates LiDAR with computer based genesis classifications. This results in a higher resolution landform classification and also provides additional attributes to the traditional SG mapping. It should be noted these data sets are already available for select areas within Alberta but were not used in this thesis. Their use could be explored in future work.

Defining the HRAs to address more site specific yet widespread conditions should be explored as a future avenue to improve the WTVT. Further research is needed to better understand the behaviour of the water table within the concave areas which occupied the majority of the study area. The three conceptual models (F, C, and COF) could then be improved on this basis. Higher resolution DEMs, which are able to define the shape of landscape more accurately, may prove useful in exploring the role of surface topography in HRAs.

When viewed at larger scales than that of the SG mapping, an HRA will often contain areas that are not homogeneous. This was evident during ground truthing of individual HRA. It may be possible to overlay other kinds of information on a HRA to identify areas of surface moisture heterogeneity. Edatopic moisture values from the Alberta Vegetation Inventory is one potential source, as is LiDAR based soil moisture indices. Additionally, this type of information may prove useful in identifying perched water tables.

4.3. WTVT in ARCGIS

4.3.1. HRAs

Creation of the HRAs was tedious and laborious, dealing with topology issues and combining the discrete data sets which were separated by map sheet. Additionally, the SG mapping attribute data are currently primarily used for cartographic labeling and theming. As such, preparing large extents of data for use within the WTVT would be quite time consuming. Therefore, a texture interpretation algorithm to enable rapid reclassification of the SG polygon should also be developed. Prior to this, however, an algorithm to restructure the attribute data to make it usable for interpretation is necessary. This includes developing automated topology rules to deal with issues such as overlap and incomplete polygons. Once automated these could be incorporated into the WTVT. Some manual co-ordination of the differing SG attributes, which vary depending on the data set, will likely still be required.

4.3.2. Algorithms

The WTVT was able to compute algorithms which matched the three conceptual models used in this study. However, as mentioned above, additional HRAs, or changes to existing algorithms, may be required to address the wider range of hydrologic conditions both in the study area, as well as across the Boreal Plain. Other important conditions to be considered are: salt wetlands, river edges, river deltas, road rights-of-ways, bedrock near the surface, bedrock consisting of mudstone, harvested areas, and reclaimed areas. All of these may have their own district hydrologic response given the same climatic input.

The algorithms were based on relationships between precipitation and evapotranspiration for each HRA. Algorithms could be further refined to reflect more complex relationships resulting from varying chemical, mechanical, kinetic, or thermal conditions (Tóth, 1999).

More detailed adjustment of algorithms could also be derived from inputs from AVI forest types. For example, in the coarse-textured HRA allowing the predicted water table to mound under pine dominated landscapes might improve accuracy. Likewise, spruce growth patterns within a coarse-textured HRA might also signal saturated surface conditions, such as from wetland perching, or surface drainage connectivity.

Algorithms such as the fine algorithm are tied to the topographic pattern of the surface. Although changes in topography might influence the shape of the underlying water table, a linear relationship likely does not exist. This relationship is likely more subtle and a refined algorithm could provide a more realistic predicted water table.

4.3.3. Elevations

The LiDAR data used in this study had a 1 m resolution and a $\pm$ 0.03 m vertical error, and was used to define relative elevations of forested lands and wetlands. Additional error was likely added by reprocessing the 1 m DEM to a 10 m DEM. The DEM was reprocessed to keep computational times for the WTVT relatively fast. With the 10 m DEM water table, estimates could be produced for the entire 20,671 ha study area in approximately 5 min. Processing times would have been up to 10 times longer using the 1 m DEM.

The water wells were located on the x, y plane with a $\pm$ 6 m horizontal error. This horizontal error may impact which LiDAR elevation location was used in the determination of the well elevation. These sources of error may have slightly increased or decreased the actual error at each well site.

Errors associated with the well elevations could be diminished by using other technologies, such ground surveying with a referential GPS, or with more traditional survey equipment, tied into a provincial monument. Relative elevations could be affected by other sources of error such as ground swelling due to changing moisture contents and temperature. None of these sources of error were accounted for in the analysis.

4.3.4. Surface Water and the Creation of the Reference Plane

The current underlying assumption that water is at the surface in all identified wetlands might significantly affect the creation of the reference plane in the WTVT. Although the reference plane concept proved useful, there are instances where improvements could be explored which would change the elevation of the reference plane and may result in substantial differences in the predicted water table elevation. For instance, wetland type may be a useful variable in determining whether surface water is actually present in a particular wetland over a complete climatic cycle.

Peat storage, which is indicative of saturated conditions, would influence the likelihood of persistent near surface water and may help in identifying the difference between perched and regionally connected water tables. For example, if certain wetlands in a coarse HRA are regionally connected, peat development is more likely to occur. The remaining non-peat forming wetlands are more likely to be perched. If true, the use of the peat forming wetlands should be used to draw the reference plane. This would result in a deeper connected water table, which at the same time would distinguish all wetlands above the plane as perched.

Climate change is expected to increase mean annual temperatures in southern Canada by as much as 4.20°C (Foote & Krogman, 2006). In Alberta, between 1900 and 1998, the warming has occurred mostly in winter with a reported increase of over 2°C in average mean temperature (Zhang et al., 2000); this has resulted in increasing snow-free periods which may reduce soil moisture storage. The amount of yearly precipitation in Canada has increased by 18% over a 113 year period (1900 to 2012). Areas within Alberta, however, have not experienced the same increase in precipitation and decreasing precipitation has been observed in the spring (Vincent et al., 2015). This decrease, synchronized with the spring vegetative leaf out, would further reduce soil moisture. Over-all climate change may lead to drier conditions with more frequent and severe droughts (Foote & Krogman, 2006). If this is the case the general relationships between precipitation and evapotranspiration characteristic of the study regions would not be maintained.

Damming of streams by *Castor canadensis* (beaver) has been associated with increased wetland extent and alluvial groundwater recharge (Westbrook et al., 2006). Beaver activity could increase levels of groundwater in the adjacent forested uplands, resulting in higher observed water levels within the forested uplands (Polvi & Wohl, 2011). Beaver removal of vegetation could affect local evapotranspiration-precipitation balances, allowing for increases in soil moisture. It is likely that observed water levels would rise within a HRA following the establishment of beaver dams within it. This would fit better with the assumption within the WTVT of the water table in wetlands being at the wetland surface, increasing the accuracy of the reference plane position.

Surface water locations from the remotely sensed EWCv1 data set were determined at coarser data resolutions than EWCv2, but EWCv2 required considerably more supervised image classification. The extra effort expended for the EWCv2 data set appeared to result in better precision of wetland edge identification and may increase the accuracy of wetland elevations. This difference in EWCv2 yielded better results from the WTVT. Future research could address the differences in the wetland classification and precision between the two techniques.

Wetland configuration and topography are important when predicting the position of the water table. Concave topography was associated with the majority of identified wetlands. EWCv2 limited the amount concave topography in the forested area and minimized the amount of zero depth water tables. Further investigations into the role of topography and wetland landscape position should be made in the Boreal Plains, Alberta.

The ability to estimate the water table location in the Boreal Plains, Alberta is critical to managing the environmental impact of industrial activities, such as road construction and pipeline development. Environmentally sensitive wet areas usually have higher development, maintenance, operating, and reclamation costs. Understanding how to manage these areas would likely result in lower operating cost. The WTVT can supply valuable information for road planning and construction by indicating where activities are more likely to interact with the near surface water table. For example, road construction that intercepts the water table within coarse-over-fine texture configurations has been observed to increase ditch flow in both winter and summer, leading to higher maintenance costs and increased environmental damage. Both Oil and gas, and forestry development plans could use the information from the WTVT in planning access routes that would limit the interaction with the water table. This would ultimately lessen the impact of industrial development on wetlands and wetland connectivity by avoiding interruption of the near surface water table flow paths. Seasonal operability of forestry operations for individual landforms can be determined from the WTVT. This is a consideration for determining longer term harvest plans and log delivery schedules. Forestry practitioners could also use the WTVT output for planning silvicultural activity for both site preparation and planting. Further investigation into these benefits is warranted.

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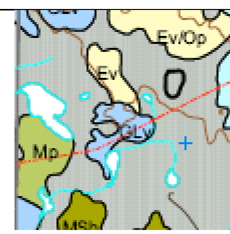
APPENDIX

Table A 1 Process for interpreting the Surficial Geology for the ACE study area*.

Interpret the texture from the polygon unit notation and the polygons geologic setting using the following steps: Step 1. Ascertain the general texture of the Genetic Class for each component in an individual unit as outlined in Section 1 – Genetic Class. Step 2. If a textural modifier is present and is specified in Section 2 – Textural Modifiers, assign appropriate texture to the component, unless; a. The unit is a Complex, in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 4 –Complexes; or b. The unit is a stratigraphic sequence in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 5 – Stratigraphic Sequence; or c. The unit is part of a transitional association in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 6 – transitional association; Step 3. If a textural modifier is not specified and a geomorphic modifier is present and is specified in Section 3 Geomorphic Modifiers, assign appropriate texture to the unit, unless; a. The unit is a Complex, in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 4 –Complexes; or b. The unit is a stratigraphic sequence in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 5 – Stratigraphic Sequence; or c. The unit is part of a transitional association in which case the individual component texture will have to be used in comparison to other components within the polygon as specified in Section 6 – Transitional Association.

Section 1 – Genetic class interpretation	Texture Examples:
The textures of individual units with an absence of genetic and geomorphic modifiers are as listed below:	
C, F, L – need to use vegetation to classify texture.	TBD – individual polygon locations and vegetation need to be assessed.
E - coarse texture as these deposits are usually fine sand .	E = coarse
GL – fine texture if offshore (distal) deposit as a large proportion of these units are made up of silt and clay. Use map color key.	GL (offshore) = fine
GL - coarse texture if nearshore (littoral) resulting from shoreline deposits of sand and gravels on glacial lakes. Use map color key.	GL (nearshore) = coarse
GF or FG - coarse texture resulting from glacial meltwater streams such as sand and gravels.	GF or FG = coarse
FGI - coarse texture due to large coarse sediments deposited by glacial meltwater streams	FGI = coarse
M – fine texture due to unsorted mixture of clay, silt and sand.	M = fine
MS – fine texture due to unsorted mixture of till	MS = fine
MT – fine texture formed from till deposits more compressed than other M types.	MT = fine
MF – fine texture till deposited parallel to local ice flow direction.	MF = fine
FP – coarse textured pre glaciation sand and gravel deposits.	FP = coarse texture
RT – coarse textured unconsolidated fluvial gravels	RT = coarse texture
R – bedrock terrain features with will produce surface flow, unless, The bed rock is sedimentary which could indicate larger storage capacities. Determination of bedrock type must be completed.	R = impermeable
RK – coarse texture	RK = coarse texture
Special Case - Genetic Class = O O designated units should be interpreted once surrounding landforms have been interpreted. O = assumed underlying fine texture; unless, The majority of O unit is surrounded by a coarse textured terrain class then O is given a coarse texture.	O = fine  OF (surrounded by coarse) = coarse

Section 2 –Textural Modifiers	Texture Examples:
The following textural modifiers if present will be used to define the texture of the particular terrain class and are interpreted as follows: g, s - will be given a coarse texture $, c texture modifier indicate a fine texture When more than one textural modifier is presented for an individual terrain class the textural modifier to the right as listed will indicate the texture. For the purpose of interpretation other texture modifiers can be ignored.	sGF = coarse sGL (littoral) = coarse  sMr = coarse $LGL = fine $sGLp = coarse
Section 3. Interpretation of Geomorphic Modifiers	Texture Examples:
Only geomorphic modifiers of v are considered important and are classified as flows. If the Genetic class is a “v” modifier the polygon will be of coarse-over-fine texture. For the purpose of interpretation other Geomorphic modifiers can be ignored	 Ev = Coarse-over-fine

Section 4. Complexes	Texture examples:
Components of O (organic) are ignored and the following classifications are used: Fine, if all the terrain classes are of fine texture, or Coarse, if all the terrain classes are of coarse texture, or Veneer-type, if there is a combination of coarse with either fine or coarse-over-fine units. Complexes of terrain classes with the first class having greater than 60% and a 15% minor component designated by a // will be characterized by the texture from first terrain class only.	Op/MShb/$GLv = fine sMp/FGpm/E = coarse Ov/FGm/sMp = veneer-type MSu//GFv = fine
Section 5. Stratigraphic sequence	
Superimposing of materials of different origin or texture are shown by a | symbol dividing terrain classes. Stratigraphic sequence will be interpreted as follows: Fine texture if all terrain classes are of fine texture, or coarse if all terrain classes are coarse texture, or coarse-over-fine-texture if both fine and coarse textured terrain classes are present or if one of the terrain classes is COF, unless, one of the terrain classes is rock (R), then the texture class will be impermeable.	| = stratigraphic sequence MShd|Md = fine Er|sGLph = coarse FGv | Mp = Veneer-type Mvr | R = impermeable
Section 6. Transitional Association.	
Where two or more units are juxtaposed due to related origin, temporal sequence or not being geomorphically distinct the texture class will be assessed as being: fine, if all terrain classes are fine texture, or a combination of fine and veneer-type. coarse, if all terrain classes are coarse texture, or coarse-over-fine, if the terrain class is an association of fine and coarse textured classes.	OB-OF = fine GFx-GFp = coarse sGLv-GFv/MSh = Veneer-type
*see Campbell et al. (2001) for a detailed explanation of unit notation components referred to in this table.	