GEOG_591

VANCOUVER ISLAND AQUIFER CLASSIFICATION MODEL

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PROJECT INTRODUCTION

The Vancouver Island Aquifer Classification Project (VIACP) is a geographic information system based classification model that defines aquifer regions on Vancouver Island. This project follows the work completed for the Vancouver Island Water Resources Vulnerability Mapping Project (VMP). A component of the VMP was the creation of an Upper-most Aquifer Type Classification Polygon Surface that classified the unmapped areas of Vancouver Island (approximately 80% of the island) as either fractured bedrock or surficial sand and gravel aquifers. The intent of this project was to update this classification to include the aquifer classification system devised for the Canadian Cordillera Hydrogeologic Region by M. Wei (Wei et al, 2009) and create a revised model to classify the previously unmapped areas of Vancouver Island into 12 separate aquifer types. The VIACP was developed in concert with Dr. Alan Gilchrist (Professor of Geography, Vancouver Island University).

OBJECTIVES

The objective of the VIACP classification model (hereafter referred to as "the Model") was to produce a scientifically defensible raster surface that classified all areas of Vancouver Island into twelve "upper-most" aquifer types. Upper-most refers to the first aquifer type likely to be encountered from the surface. Each type has specific criteria (see Table 1 below) and the previous data sets used during the VMP were revisited and specific data extracted to produce a set of parameters that were manipulated in ArcMap Software by ESRI to produce a raster based classification surface. The final product is a map layout and associated digital data showing the new classification. This product will be eventually submitted to VMP partners.

VANCOUVER ISLAND WATER RESOURCES VULNERABILITY MAPPING PROJECT BACKGROUND

The VMP was started in March 2006 and completed in April 2010 as an interagency project aimed at developing a GIS system that modeled groundwater vulnerability to pollution (Newton and Gilchrist, 2010). The project was directed by Dr. Alan Gilchrist from Vancouver Island University (VIU) Geography Department. Most of the work was completed by VIU faculty and graduates with input and help from many others external to VIU. The final output was groundwater vulnerability maps for Vancouver Island to supplement and extend the work completed by Natural Resources Canada in mapping the Gulf Islands.

VMP used the DRASTIC method for determining the level of threat to aquifers from ground water contamination. The DRASTIC method focuses on the major hydrogeologic parameters which affect and control ground-water movement which, in turn, influences ground water vulnerability. DRASTIC identifies seven parameters, each represented by a letter in the acronym: D – **D**epth to water, R – net **R**echarge, A – **A**quifer medium, S – **S**oil medium, T – **T**opography, I – **I**mpact of the vadose zone, and C – hydraulic **C**onductivity. All parameters are combined using an equation to determine areas of high, moderate, and low aquifer vulnerability.

The VMP utilized numerous digital and paper data sets from BC Integrated Land Management Bureau, the BC and Canadian Geological Societies, Climate BC, Ministry of the Environment, Forest Renewal BC, Natural Resources Canada and Regional Districts on Vancouver Island to create the seven DRASTIC parameters. During the development of the Model this assembled data was revisited and, at times, modified to suit the particular needs of the Model.

Canadian Cordillera Hydrogeologic Region Aquifer Classification System Background

The aquifer classification system used in the creation of the Model is taken from a system devised for the Canadian Cordillera Hydrogeologic Region by M. Wei (Wei et al, 2009). This system has four general types of aquifers:

- Unconsolidated and unconfined (Subtypes 1a-c, 2, 3 & 4a)
- Confined and unconfined aquifers of glacial or pre-glacial origin (Subtypes 4b & 4c)
- Bedrock (Sedimentary rock, Subtype 5a-b); and
- Bedrock (Crystalline rock, Subtype 6a-b)

Unconsolidated aquifers consist of deposits of sand and gravel that occupy major river and stream valleys or lake plains and terraces. Bedrock aquifers consist of karstic and other sedimentary rock or fractured crystalline rock (volcanic, metamorphic, meta-sedimentary and meta-volcanic sub types) that can be located in most environmental settings. Unconsolidated aquifers are further divided into confined and unconfined. Unconfined unconsolidated aquifers start near the surface, with a shallow water table, and water can flow into these aquifers directly from the surface above. Confined unconsolidated aquifers are deeper and are capped by an impermeable layer of sediment (clay or till). Water flows into these aquifers from the sides, around the impermeable layer. Confined aquifers are typically of glacial or pre-glacial origin.

These general aquifer types are subdivided into a total of 12 separate subtypes based on aquifer medium and setting. The following table (Table 1) outlines the criteria for each aquifer subtype.

TABLE 1: AQUIFER TYPES

Aquifer Type	Criteria	
	Medium	**Setting**
1) Unconfined Aquifers		
a) Aquifers along higher-order rivers	Mostly sand and silt with some gravel and clay	High-order river valleys. Rivers with low gradient and low depositional energy
b) Aquifers along moderate-order rivers	Sand and gravel	Moderate-order river valleys. Rivers with high gradient and high depositional energy
c) Aquifers along lower-order streams	Sand and gravel	Low-order stream valleys with narrow flood plains
2) Deltaic aquifers	Sand and gravel	River and stream deltas
3) Alluvial or colluvial fan aquifers	Sand and gravel	Alluvial fans or colluvial fans
4) Aquifers of glacial or pre-glacial origin		
a) Unconfined glacio-fluvial aquifers	Sand and gravel	No specific setting is listed within the Wei system. However, on Vancouver Island, the locations of Type 4s are presumed to be found within areas of thick surficial sediment formed by glacio-fluvial activity and at relatively low elevations.
b) Confined glacial or pre-glacial aquifers	Sand and gravel	Located beneath glacial till or glaciolacustrine deposits
c) Confined glacio-marine aquifers	Sand and gravel	Near coastline and at low elevation. Located beneath marine deposits (sand, silt and clay).
5) Sedimentary Rock Aquifers		
a) Fractured sedimentary rock aquifers	Sandstone and conglomerate rock	Bedrock aquifers can exist within all settings and environments.
b) Karstic aquifers	Limestone	
6) Crystalline Rock Aquifers		
a) Flat-lying volcanic flow aquifers	Flat-lying volcanic rock	Bedrock aquifers can exist within all settings and environments.
b) Fractured igneous intrusive, metamorphic, fractured volcanic or metavolcanic aquifers	Other metamorphic or igneous rock	

Methods Summary

The Model used six data sets modified or used during the VMP. Five of these data sets were further modified and converted (if a polyline or polygon) to raster surfaces. The sixth was used to validate the Model. The final raster surfaces were used in various calculations within the ArcMap Model Builder Tool Set.

The first step in the model was creation of the data sets used to extract the medium and setting criteria for all 12 aquifer types. The data sets created for this Model included: Surficial Medium and Morphology shapefiles (polygons), Bedrock Medium shapefile (polygons), Stream Order (polylines) and Slope, Elevation and Drift Thickness raster surfaces. These data sets were created from the following:

- Ministry of Energy and Mines, Forest Renewal BC Digital Terrain Data (Polygons, complied and checked by VMP). This data set contains detailed information on surficial geomorphology;
- BCGS and GSC Geology Data (Polygons, complied and checked by VMP). This data set contains information on bedrock locations and types;
- BC Watershed Atlas (Polylines). This data set contains information on watersheds, water courses and water bodies;
- BC Integrated Land Management Bureau, Digital Elevation Model (DEM); and
- VMP Drift Thickness Raster. This data set was created from well bore logs recorded within rural and urban areas of Vancouver Island. It contains information on the thickness of surficial sediment above bedrock. It covers approximately 20% of the Vancouver Island study area.

A sixth VMP data set, Upper-most Aquifer Map (polygons), was used to validate the Model. The Upper-most Aquifer Map data set contained a field that classified 164 polygons as “Mapped” aquifers. These polygons are known aquifer locations (including aquifer type) and were used to validate the Model through a comparison process (See Model Validation Section below).

The next step was to determine which stream order, medium and morphology types and slope, elevation and drift thickness limits found in the shapefiles and raster surface corresponded to the criteria described in the Wei classification system.

Stream Order

All streams and rivers that exist on Vancouver Island have been ordered from one to six. The stream order classification used in the BC Watershed Atlas follows the Strahler system which defines stream size (order) based on a hierarchy of tributaries. Small streams are associated with low number values starting at one. Therefore, Streams labeled 1 to 3 were classified as low order streams, Streams 4 and 5 as moderate order streams and Stream 6 as a high order streams. The Stream Order shapefile was created by selecting the stream order field (L_Order: Class 1 to 6) from the BC Watershed Atlas (Polylines), eliminating all man-made water channels (Class 0) and exporting the selected data into a separate shapefile.

Surficial Medium and Morphology

The Surficial Medium and Morphology shapefile (Polygons) was created from Ministry of Energy and Mines, Forest Renewal BC Digital Terrain Data. This data set had been extensively modified during the VMP[1]. The modifications included edits to the Terrain Classification System for BC (Howes & Kenk, 1997) used in the data set for defining the surficial geomorphology (Texture, Surficial Material and Surface Expression) for each polygon. The editing process divided these surficial geomorphology characteristics into separate fields and ordered the fields by component and strata, where recorded.

The fields added during the VMP were examined to select those polygons that corresponded to our interpretation of the Wei classification criteria. An important method used was the preference for the second strata of the first component for each polygon. The first component field recorded the surficial geomorphology found within the majority of any given polygon. Second and third components represented far smaller areas and were ignored. The second or (preferably) the third strata field, where recorded, was used as this represented a more accurate indication of sediment composition suitable for containing an aquifer. If not available the first strata was selected.

The Model attempted to classify the upper-most aquifers only. For this reason Bedrock Aquifer Types (Types 5 and 6) could only exist in areas that had thin or no surficial sediment. Therefore an important aspect of the Model was to distinguish between Bedrock or Surficial type aquifers. Fortunately, a summary field, added during the VMP, identified which polygons contained no surface sediment or a veneer (less than 1 m) of surficial sediment and classified them as "Unmapped Bedrock" aquifers. The remaining polygons were classified as "Unmapped Surficial" as these contained evidence that sediment was thick enough to possess a surficial aquifer. This field was used by the Model to define the limits of both Surficial aquifer types (Types 1 to 4) and Bedrock aquifer types (Types 5 and 6).

New fields were added that contained numerical values which corresponded to various surficial medium and morphology criteria. The following table (Table 2) indentifies which fields were used to define specific criteria.

[1] A complete review of the methods used in the editing process is found in Newton, 2010.

TABLE 2: SURFICIAL MEDIUM AND MORPHOLOGY DATA SET (SELECTED FIELDS)

Surficial Geomorphology	Fields Selected (1st Component)	Records Selected	Corresponding Model Criteria
Texture	Ttex_1 (strata 1) or Sttex_1 (strata 2) or Tttex_1 (strata 3)	Any combination of Sand ('s'), Silt ('$'), Clay ('c') or Gravel ('g')	Surficial Medium
Surficial Material	Surfm_1 (strata 1) or Ssurfm_1 (strata 2) or Tsurfm_1 (strata 3)	Fluvial and Glacio Fluvial Polygons (F or FG); Lacustrine or Marine Polygons (L or W); Moraine (Till) Polygons (M); and Glacio-marine Polygons (WG)	Morphology, specific to Aquifer Type (see Table 3)
Surface Expression	Surf_E1 (strata 1) or Ssurf_E1 (strata 2) [2]	'f', 'fa', 'fl', 'fv', 'fs': coding for fans	Fan Location (Aquifer Types 2 and 3)

Bedrock Medium

Bedrock medium shapefile (Polygons) was created from the BCGS and GSC Geology Data set that had been compiled during the VMP. The "Type" field was selected to categorize each polygon to a specific bedrock type (Sand Stone & Conglomerate rock, Limestone, Flat Lying Volcanic rock or Other Metamorphic rock) as defined in the Wei Classification system (See Appendix A for a complete list of compiled rock types). A field was added that held the associated numerical code for each bedrock type.

Slope

The Slope raster was created from the BC Integrated Land Management Bureau, DEM using the Slope Tool in ArcToolbox and the Reclassify Tool which divided the raster surface into pixels ≤20% or >20%. This raster was used to set the limit for Surficial Aquifer Types (Types 1 to 4) to 20% slope. The limit of ≤20% slope was based on the angle of repose for sand which is approximately 30%. Aquifers technically could exist above a 30% slope however, water saturated sand will be subject to an increase in pressure and reduction in shear strength and lower the angle of repose to between 15% and 30%. Based on this, a slope cut off of 20% was selected to be reasonable limit for a productive, surficial aquifer.

Elevation

The Elevation raster was created from the BC Integrated Land Management Bureau, DEM using the Reclassify Tool to divide the DEM into pixels that were either ≤315m or >315 m a.s.l[3]. This raster was used to set an elevation limit of 315 m a.s.l for Type 4 Aquifers only. The limit of ≤315m a.s.l was based on the horizontal and vertical limits of the VMP Drift Thickness raster. Dr. Gilchrist determined that the Drift Thickness raster encompasses the region where Type 4's

[2] Note: there were only three records that had a 3rd stratum and these did not record surface expression.
[3] Above Sea Level

are more likely to occur. It is unlikely for Type 4s to be found outside of this region of thick surficial sediments. The vertical limit was determined by analyzing the elevation ranges within the Drift Thickness raster. The maximum elevation for the Drift Thickness Raster is 1,254 m a.s.l. However, that elevation is an anomaly as 98% of the Drift thickness raster lies below 320 m a.s.l. Therefore we determined the elevation limit for Type 4s to be no more than 3 Standard Deviations (315 m) from the mean elevation of 79 m a.s.l.

Drift Thickness

The VMP Drift Thickness raster was Reclassified into pixels that were either <10.5m or ≥10.5 m. Drift thickness was added to improve the model results in differentiating between bedrock and surficial medium in those areas where well depth information had been collected and compiled during the VMP. Based on the results of the VMP a cut off of 10.5 m thickness (minimum) was selected to allow for the presence of surficial aquifers (Types 1 to 4) otherwise the raster cell was coded as a bedrock aquifer type (Type 5 or 6).

Model Formulas and raster calculation

All polyline and polygon shapefile data sets were converted into a raster surface of the same cell size (100 m). Each raster data set was then used in the criteria formulas (Table 3); one formula for each aquifer type.

TABLE 3: REVISED FORMULAS

Aquifer Type	Formula
1) Unconfined Aquifers	
a) Aquifers along higher-order rivers	Stream Order 6 + ≤ 20% Slope + Surficial Medium (Any combination of Silt, Sand, Clay or Gravel) + Morphology: Fluvial and Glacio Fluvial Polygons (F or FG) + ≥ 10.5 m drift thickness
b) Aquifers along moderate-order rivers	Stream Order 5 or 4 + ≤ 20% Slope + Surficial Medium + Morphology: Fluvial and Glacio Fluvial Polygons (F or FG) + ≥ 10.5 m drift thickness
c) Aquifers along lower-order streams	Stream Order 1 to 3 + ≤ 20% Slope + Surficial Medium + Morphology: Fluvial and Glacio Fluvial Polygons (F or FG) + ≥ 10.5 m drift thickness
2) Deltaic aquifers	≤ 20% Slope + Surficial Medium + Morphology: Lacustrine or Marine Polygons (L or W) + ≥ 10.5 m drift thickness
3) Alluvial or colluvial fan aquifers	≤ 20% Slope + Surficial Medium + Morphology: Fan Coded Surface Expression ('f', 'fa', 'fl', 'fv', 'fs') + ≥ 10.5 m drift thickness
4) Aquifers of glacial or pre-glacial origin	
a) Unconfined glacio-fluvial aquifers	≤ 20% Slope + Surficial Medium + Morphology: Glacio-fluvial Polygons (FG) + ≤ 315 m a.s.l + ≥ 10.5 m drift thickness
b) Confined glacial or pre-glacial aquifers	≤ 20% Slope + Surficial Medium + Morphology: Moraine (Till) Polygons (M) + ≤ 315 m a.s.l + ≥ 10.5 m drift thickness

Aquifer Type	Formula
4) Aquifers of glacial or pre-glacial origin	
c) Confined glacio-marine aquifers	≤ 20% Slope + Surficial Medium + Morphology: Glacio-marine Polygons (WG) + ≤ 315 m a.s.l + ≥ 10.5 m drift thickness
5) Sedimentary Rock Aquifers	
a) Fractured sedimentary rock aquifers	Bedrock Medium classified as Sand Stone & Conglomerate rock
b) Karstic aquifers	Bedrock Medium classified as Limestone
6) Crystalline Rock Aquifers	
a) Flat-lying volcanic flow aquifers	Bedrock Medium classified as Flat Lying Volcanic rock
b) Fractured igneous intrusive, metamorphic, fractured volcanic or metavolcanic aquifers	Bedrock Medium classified as Crystalline or other Metamorphic rock

Each raster formula was additive process with each criteria assigned an arbitrary value. The total of these criteria values produced a final number that was assigned to one of the 12 aquifer types. Classification of each raster cell was an all or nothing process. If the cell failed to meet any of the requirements of the formula it failed to be classified as that specific aquifer type.

Bedrock Aquifer Types (Types 5 and 6) formed the foundation layer of the raster model and where overlapped by surficial aquifer types (Types 1 to 4). Also, Type 1 (a, b & c), Type 3 and Type 4a Aquifers overlapped with each other as they used the same morphology polygons. Therefore, a ranking system was developed by Dr. Gilchrist with the top most rank absolutely dominant (see Table 4). No overlaps occurred between Type 2 or Types 4B and 4C.

TABLE 4: RANKING SYSTEM FOR OVERLAPPING AQUIFER TYPES

Overlapping Aquifer Type	Rank
Type 4A	1
Type 1C	2
Type 3	3
Type 1A	4
Type 1B	5
Type 5 & 6 (Bedrock Aquifer Types)	6

Classification Model

Due to the complexity of the Model it was decided to separate it into two; one for creation of the Aquifer Medium raster surface and one for creation of the Aquifer Classification raster surface. Both Models were assembled in the ArcMap Model Builder Tool.

Aquifer Medium Model

The Aquifer Medium raster surface was created from the Surficial Medium and Morphology and Bedrock Medium shapefiles and the Drift Thickness raster. The Surficial Medium and Bedrock Medium shapefiles were converted into raster surfaces with each cell given a unique value based on sediment or bedrock type. These rasters were then combined together with the Drift Thickness raster which was used to restrict the locations of surficial aquifer type sediments (where the Drift Thickness raster existed) to those areas with greater than or equal to 10.5 m drift thickness[4]. The final raster output was a surface categorized by sediment and bedrock types coded to a unique value. A figure of the Aquifer Medium Model is presented in Appendix B.

Aquifer Classification Model

The Aquifer Classification raster surface was created from the Aquifer Medium raster and the other data sets listed previously with the exceptions of the Drift Thickness raster and the Bedrock Medium shapefile. These two data sets were used in the creation of the Aquifer Medium raster. The first step in the Model process was to create the Stream Order raster surface used for Type 1 Aquifers (A, B and C). Unlike other criteria which have defined boundaries (polygons, drift thickness or elevation limits), streams are linear features for which buffers had to be created. It was determined early on that any buffer would have to be flexible enough to capture the width of the valleys that the streams flow through. Considering the extreme variation in valley widths it was decided to set arbitrary and overly large buffers around each stream and create a raster surface that covered the entire study area. Other criteria such as slope and aquifer medium were then used to restrict the limits of Type 1 Aquifer locations.

Buffers were added to the streams and then converted and combined into a raster surface. The process followed was to first convert the Stream Order shapefile into a raster surface with cell values linked to stream classification (1 to 6). The buffer was added (2, 5, 8 or 90 pixels) via the Expand Tool. Each pixel represents $100m^2$. The number of pixels used in the buffer was determined by the class of the stream. Class 1 was expanded to 90 pixels, Class 2 and 3 to 2 pixels, Class 4 to 5 pixels and Class 5 and 6 to 8 pixels. The number of pixels chosen was

[4] Note that most of the Vancouver Island lacked this data and it would have no effect on a majority of the Aquifer Medium raster surface.

determined by the extent and expected valley width of each Stream Order. For example: Stream Order 1 is the most common order and is found throughout so a huge buffer was selected (90 pixels or 9,000 m) to insure that all areas were captured. Stream Order 5 and 6 were the least common but occupied the widest valleys and an 8 pixel width (800 m) was chosen. These extreme widths ensured that the entire valley bottoms and sides were captured. Once raster surfaces for each Stream Order were prepared they were added together. Where overlaps existed higher stream orders trumped lower stream orders. This created a raster surface, classified by stream order, which covered the whole of the Vancouver Island study area.

The second step was to extract the appropriate polygons from the Surficial Medium and Morphology shapefile and convert these into separate raster surfaces. Each surface would contain only those areas that corresponded to the morphology types listed in Table 3. These morphology rasters were then combined with Slope, Stream Order, Elevation and Aquifer Medium rasters through a process of Reclassify and Raster Calculation functions following the formulas listed in Table 3. The end result was a raster surface for each Aquifer Type.

The final step was to implement the ranking system to solve the problem of overlapping raster surfaces found for Type 1 (a, b & c), Type 3, Type 4a and bedrock aquifers Types 5 and 6. This was done through a systematic process of adding the rasters together (via Raster Calculator) one at a time and using the Reclassify Tool to insure that the higher ranked values remained while the lower ranked values were overwritten. A figure of the Aquifer Classification Model is presented in Appendix C.

MODEL RESULTS

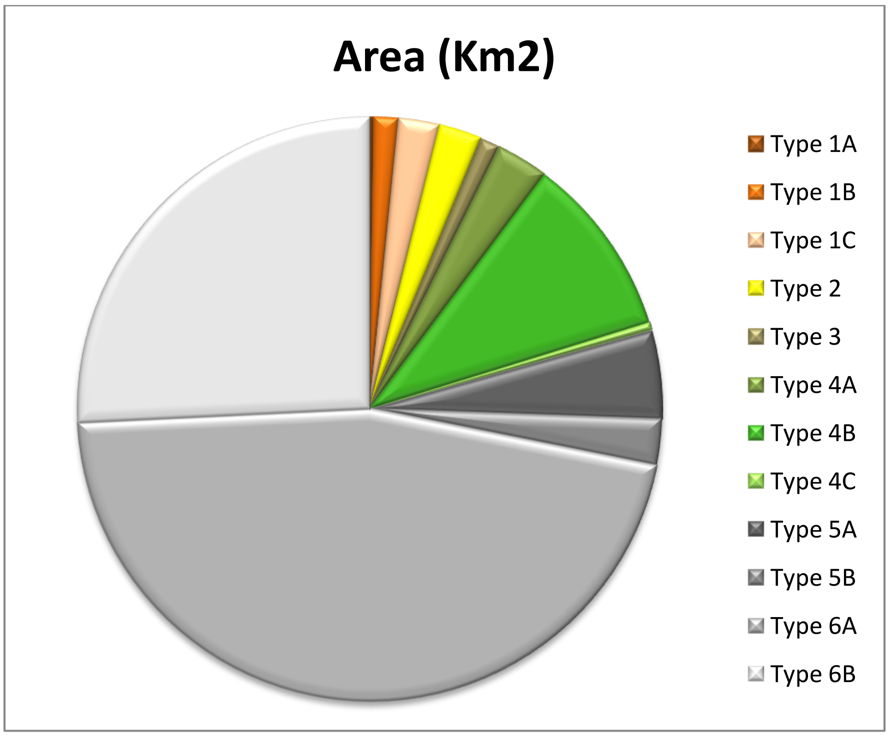
The Model successfully classified all areas of Vancouver Island into 12 aquifer types based on the Wei Classification System. The following table lists the total area for each aquifer type classified by the Model.

TABLE 5: MODEL RESULTS

Aquifer Type	Pixel (100m) Count	Area (Km^2)
Type 1A	7,306	730.6
Type 1B	44,437	4,443.7
Type 1C	76,020	7,602
Type 2	80,385	8,038.5
Type 3	34,984	3,498.4
Type 4A	97,111	9,711.1
Type 4B	336,389	33,638.9

Aquifer Type	Pixel (100m) Count	Area (Km^2)
Type 4C	15,219	1,521.9
Type 5A	162,683	16,268.3
Type 5B	85,548	8,554.8
Type 6A	1,542,393	154,239.3
Type 6B	861,454	86,145.4
Totals	*3,343,929*	*334,392.9*

FIGURE 1: AREA COMPOSITION PIE CHART



Bedrock aquifers (Types 5 and 6) are the dominant aquifer type on Vancouver Island. They account for 265,207.8 km^2 in comparison to 69,185.1 km^2 of Surficial Aquifer types (Types 1 to 4). Confined surficial aquifers (Types 4b and 4c) total 35,160.8 km^2, and account for more than half of the surficial aquifer types.

Model Assessment

The Model is a classification system based on previous study (Wei et al, 2009) and analysis by project sponsor Dr. Gilchrist. The Model is not "predictive" in that there is no interpolation;

however, it does attempt to estimate the type of upper-most aquifers that may be present in any given area on Vancouver Island. Therefore, its results need to be examined critically and a level of confidence determined. The method used to determine confidence was comparison of the Model results with the locations of 164 known and mapped aquifers identified in the VMP Upper-most Aquifer Map data set.

Model Validation

The Model was compared to the mapped and typed locations (n=164) of aquifers on Vancouver Island. Based on the results, the Model was adjusted until a high confidence level was obtained. The final version of the Model had only 11 “fails” where more than 80% of the raster cells were not of the mapped type and 65 “matches” where 80% or more of the raster cells matched the mapped aquifer type. The remaining 88 mapped aquifers coincided with raster cells of a type that “partially matched” (from 20% to 79%) with the majority of the 88 scoring a greater than 50% match to the mapped aquifer type (Table 6).

TABLE 6: MODEL RESULTS, COMPARISON WITH MAPPED AQUIFERS

Model Result	Mapped Aquifer Count	Area (Km^2)	%(Km^2)
fail	11	12	1%
match	65	647	27%
partial match	88	1,735	72%
Totals	164	2,394	

Five of the 11 fails were determined to be due to the Drift Thickness raster which, in areas where this data was available, limited the location of surficial aquifer types (Types 1 to 4) to those areas with greater than or equal to 10.5 m drift thickness. In these five areas the drift thickness was less than 10.5 m. As a consequence, the Model incorrectly labeled these surficial aquifer areas as bedrock aquifer types (Types 5 to 6). The remaining six fails were in areas classified by the Model as bedrock aquifer types in areas mapped as surficial. This was due to the Ministry of Energy and Mines, Forest Renewal BC Digital Terrain Data that identified these areas with a veneer of sediment (less then 1m thick) which the Model classifies as bedrock aquifer only areas.

In several cases the Model results produced a more detailed and believed to be a more accurate picture of the types of aquifers present within mapped areas. This interpretation is based on the method by which the 164 aquifers were mapped. The mapped aquifers classified an area based on the most common and productive type of aquifer present. Consequently, smaller and less productive aquifers types were not identified. The Model attempts to identify aquifer types, regardless of size. Therefore, within mapped areas, the Model identified a variety of smaller aquifer types in addition to the mapped aquifer type. For this reason, the majority of "partial matches" are not a concern as the majority of the raster cells produced by the Model matched the mapped aquifer type.

Based on this interpretation, the Model performed reasonably well on 72% of the mapped aquifer area and was very successfully on 27% of the mapped area with only a 1% failure rate. While these results cannot be extrapolated to the whole of the Vancouver Island Study area due to the limited coverage of the Drift Thickness raster data set, it does provide a high degree of confidence that the Model performs well.

Model Limitations

The strength of the Model is limited by the accuracy of the data sets used. For this Model the identified limitations are the scale, accuracy and coverage of the data sets. The scale of all data sets used, with the exception of BCGS Geology Data (1:250,000), is 1:50,000. This scale is relatively small and any variation in surface lithology or terrain morphology at a local level (such as 1:20,000 scale) would be missed. There are accuracy concerns for the BCGS and GSC Geology Data and Ministry of Energy and Mines, Forest Renewal BC Digital Terrain Data. Both were based on airphoto interpretation with limited field checking (Pers. Comm. Dr. Gilchrist, 2011). Also, this data was collected over several decades by geologists with differing levels of expertise. As such, the level of consistency is suspect. There are coverage concerns with the bedrock geology data as only the southeast of Vancouver Island had data at 1:50,000 scale and the rest of the island had to rely on bedrock data at 1:250,000 scale. The Drift Thickness data set (believed to be the most accurate as it is based on over 90,500 well bore logs) is limited to urban/rural areas of the Island and over 80% of the study area lacks this data. The elevation limit of 315 m a.s.l. for Type 4 Aquifers was derived from the Drift Thickness raster. Since the coverage of this data set is limited to a small area of Vancouver Island it is suspect when used to extrapolate to areas outside the Drift Thickness Raster surface (approximately 80% of the Island).

The Model is based on a straightforward and simple classification process that only takes into account stream order, slope, elevation, lithology, bedrock geology and terrain morphology. This simple Method combined with the relatively small scale of the source data limits the use of the Model to small scale planning and it is recommended that the Model be used for planning purposes at no smaller than 1:50,000 scale.

Recommendations For Improvement

The Model is based on sound study and expertise. Improvements can only occur by either providing additional data or improving the accuracy of the data sets already in use. Currently, it is recommended that the Model be limited to a scale of 1:50,000 or smaller. If larger scale data sets become available they could replace those currently in use and the overall accuracy of the result would be on a larger scale. The addition of other data sets would improve the model. Recommended additions include more well borehole logs as they become available, which can be used to create a drift thickness for areas not currently covered by the Drift Thickness Raster. The addition of this data set has shown to improve the results of the Model in differentiating between surficial and bedrock aquifer types. There is also the possibility of further refinement of the Model by adjusting the effect of elevation on the location of Glacial Aquifers.

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Appendix A

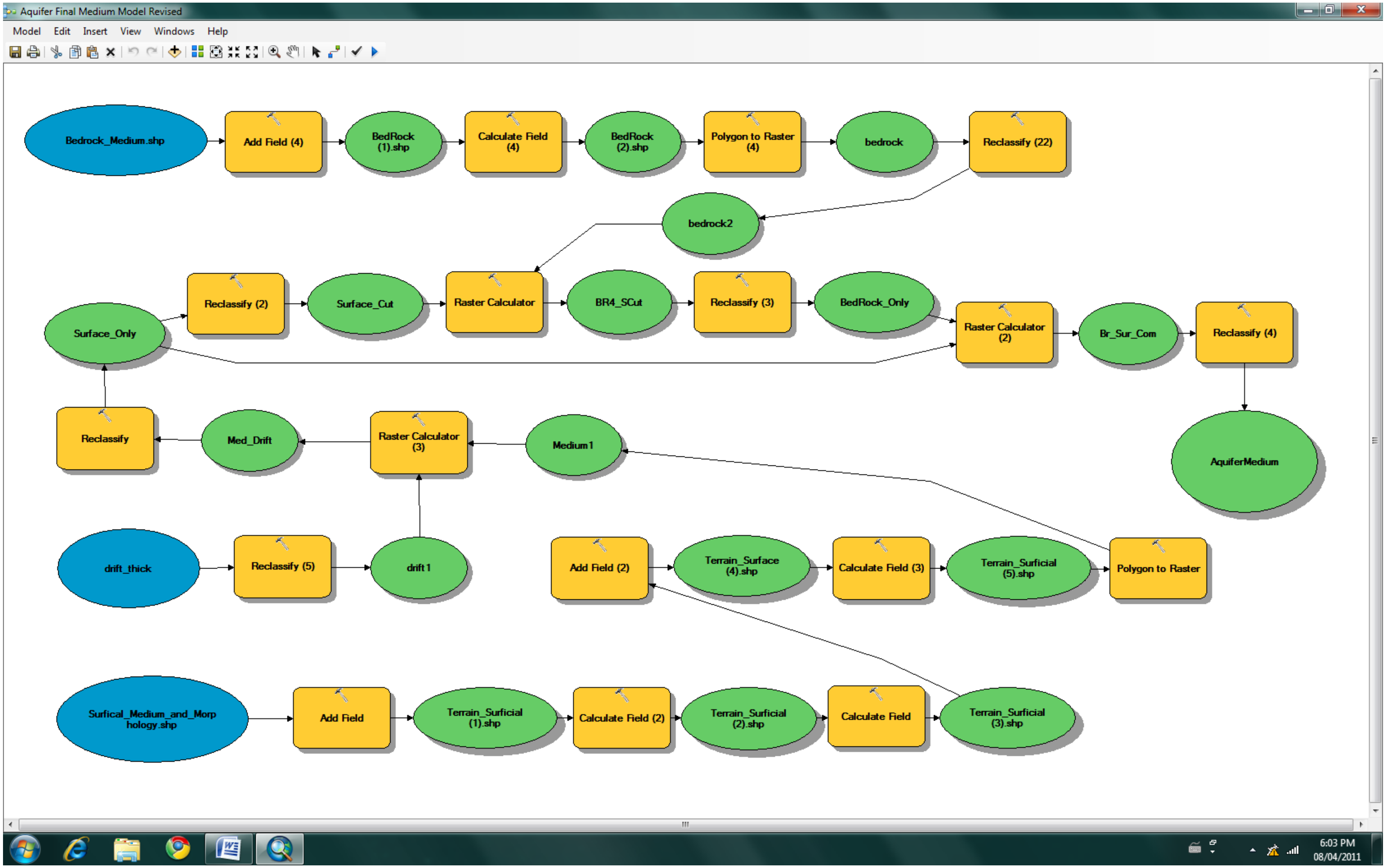
Bedrock Type Reclassification

Type 5A (Sand Stone & Conglomerate)	Type 5B (Limestone)	Type 6A (Flat Lying Volcanic)	Type 6B (Other Metamorphic rock)
mudstone, siltstone, shale fine clastic sedimentary rocks	limestone bioherm/reef	undivided volcanic rocks	amphibolite, metadiorite, metagabbro, paragneiss
undivided sedimentary rocks	limestone, marble, calcareous sedimentary rocks	bimodal volcanic rocks	biotite granodiorite, feldspar porphyry, quartz-feldspar porphyry
coarse clastic sedimentary rocks	limestone, slate, siltstone, argillite	volcaniclastic rocks	chlorite schist, metarhyolite, metabasalt, volcaniclastic sandstone, cherty argillite, rib*
conglomerate, arkosic arenite, lithic arenite, mudstone, siltstone		calc-alkaline volcanic rocks	greenstone, greenschist metamorphic rocks
conglomerate, sandstone		metabasaltic flows, breccia, lapilli tuff, lithic tuff, chert	intrusive rocks, undivided
conglomerate, coarse clastic sedimentary rocks		metabasalt flows, breccia, tuff	lower amphibolite/kyanite grade metamorphic rocks
conglomerate, sandstone, coal		crystal tuff, lapilli tuff, volcaniclastic wacke	quartz dioritic intrusive rocks
conglomerate, sandstone, silstone		marine sedimentary and volcanic rocks	quartz-feldspar paragneiss
conglomerate, sandstone, siltstone		rhyolite and dacite tuff, lithic tuff, crystal tuff, lapilli tuff, breccia, chert	quartz-mica schist, slate, argillite, metagreywacke, tuffaceous metagreywacke
conglomerate, siltstone		basalt flows, chert	
conglomerate, siltstone, sandstone		basaltic flows, breccia	
gravel, clay, silt, sand		basaltic volcanic rocks	
mudstone, siltstone, arkosic arenite		diabase, basaltic intrusive rocks	
mudstone, siltstone, conglomerate		andesite-rhyolite flows, breccia, tuff, conglomerate, greywacke, siltstone, argillite	
mudstone, siltstone, sandstone, argillaceous limestone		diorite, granodiorite, quartz diorite	
mudstone, siltstone, sandstone		dacite porphyry, quartz diorite	
mudstone, siltstone, sandstone, conglomerate		diorite, granodiorite, quartz diorite	
mudstone, siltstone, shale fine clastic sedimentary rocks		diabase, gabbro leucogabbro, diorite	
sandstone		gabbro, quartz diorite, tonalite, trondhjemite, diabase, pyroxenite	

Type 5A (Sand Stone & Conglomerate)	Type 5B (Limestone)	Type 6A (Flat Lying Volcanic)	Type 6B (Other Metamorphic rock)
sandstone, conglomerate, siltstone		dioritic intrusive rocks	
sandstone, argillite, shale, conglomerate		granodioritic intrusive rocks	
sandstone, conglomerate, siltstone, arkosic arenite		gabbroic to dioritic intrusive rocks	
sandstone, conglomerate, siltstone, mudstone			
sandstone, lithic arenite, siltstone			
sandstone, siltstone			
sandstone, siltstone, conglomerate			
sandstone, siltstone, coal			
sandstone, silstone			
shale, siltstone, sandstone			
shale, sandstone, conglomerate			
sandstone, siltstone, shale, coal			
siltstone, sandstone			
shale, siltstone, sandstone, coaly shale			
undivided sedimentary rocks			
siltstone, shale coal			
siltstone, sandstone, arkosic arenite			
volcaniclastic siltstone, sandstone, tuff, conglomerate, limestone			
argillite, volcaniclastic sandstone, basalt, rhyolite, conglomerate			
arkosic arenite, conglomerate			
arkosic arenite, conglomerate, sandstone			
conglomerate, carbonaceous shale, coal			
chert, siliceous argillite, siliciclastic rocks			
ribbon chert, marble, quartzite, basalt, tuff, greenstone, phyllitic slate			

Appendix B

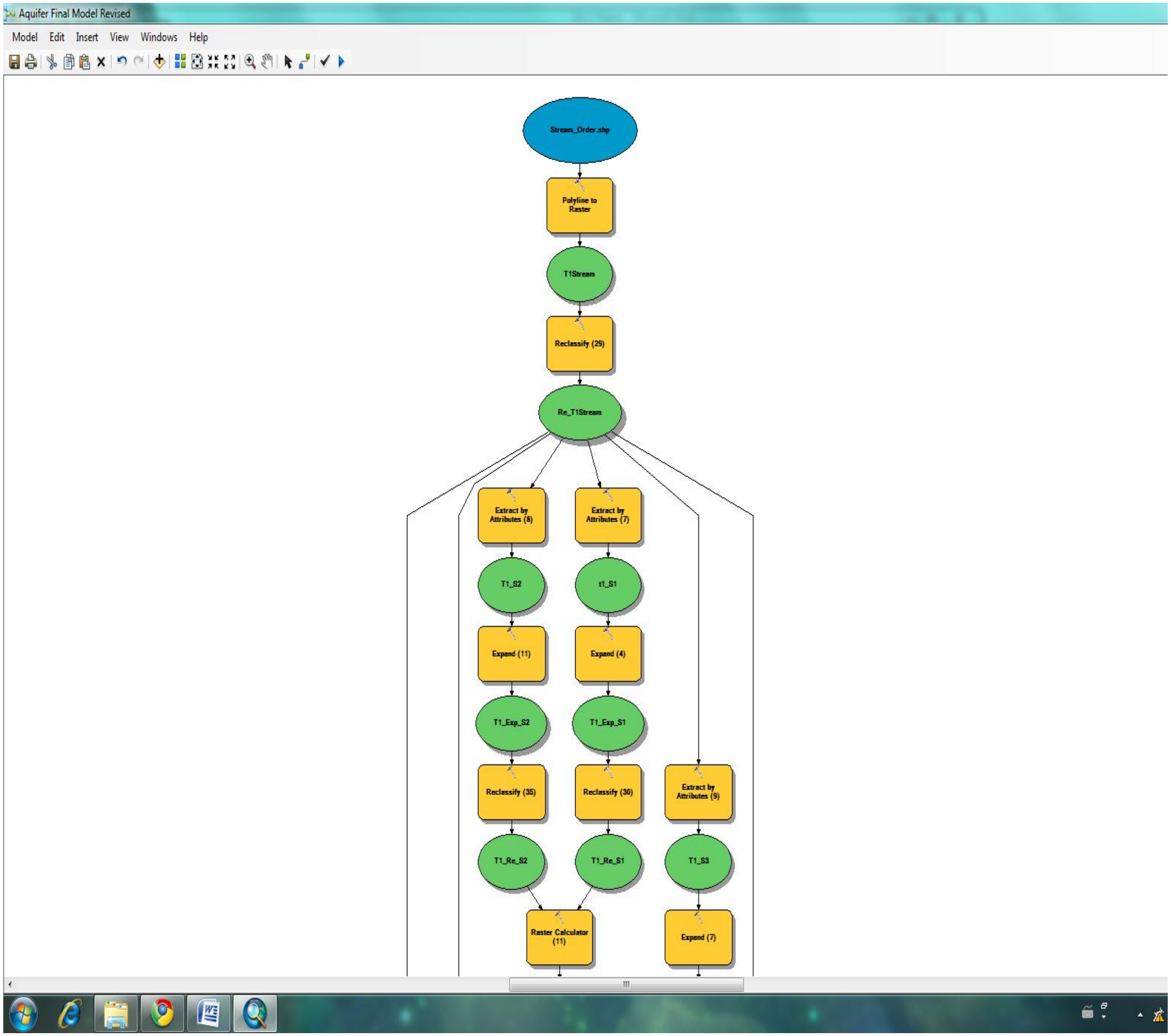
Aquifer Medium Model Schematic

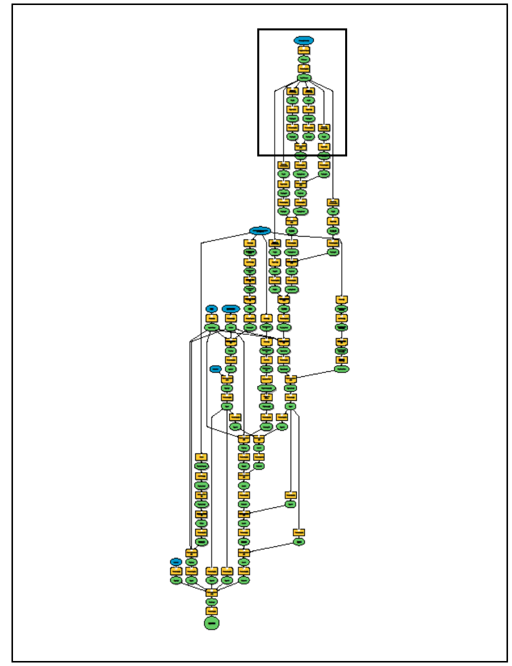


Aquifer Medium Model

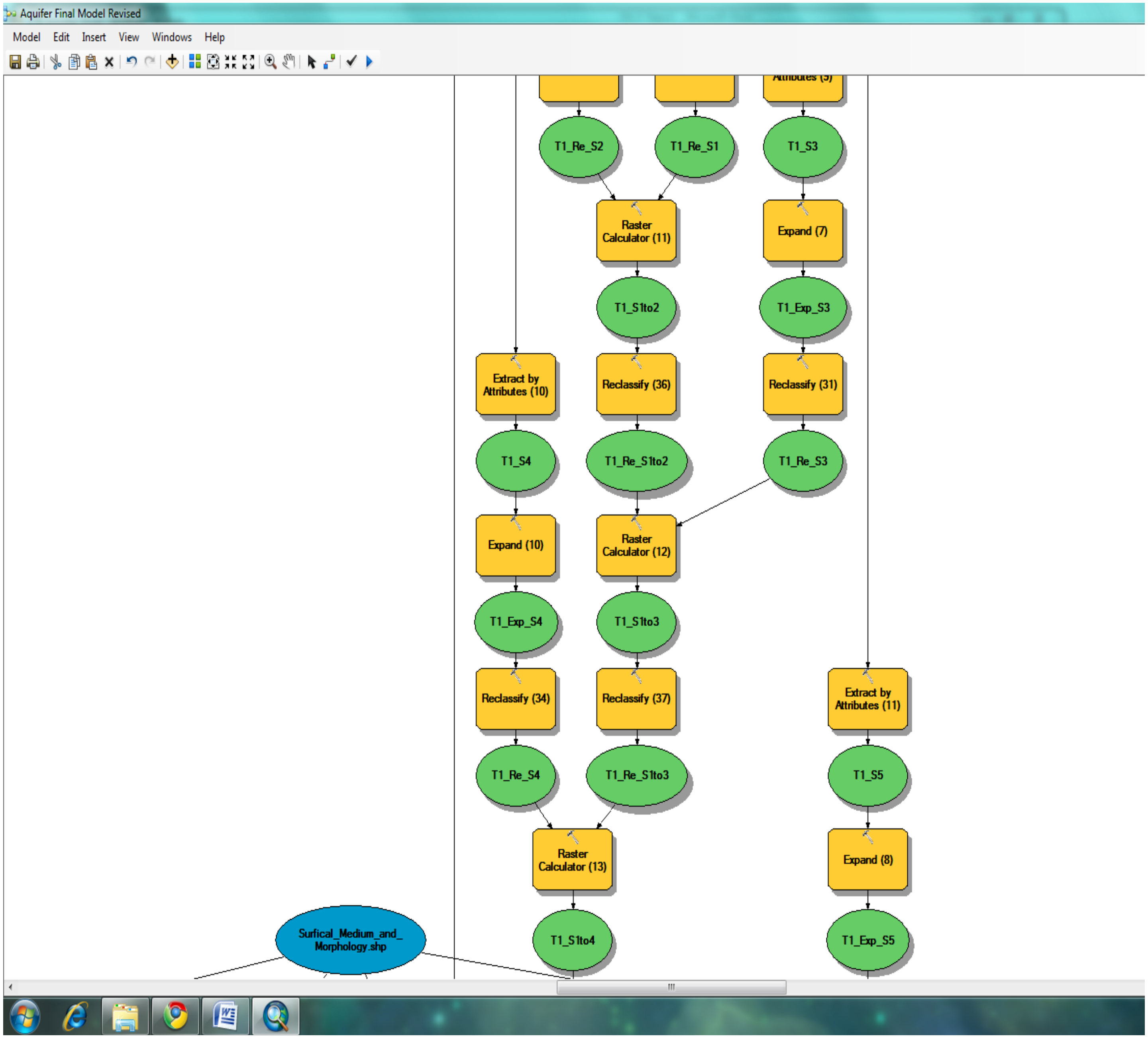
Appendix C

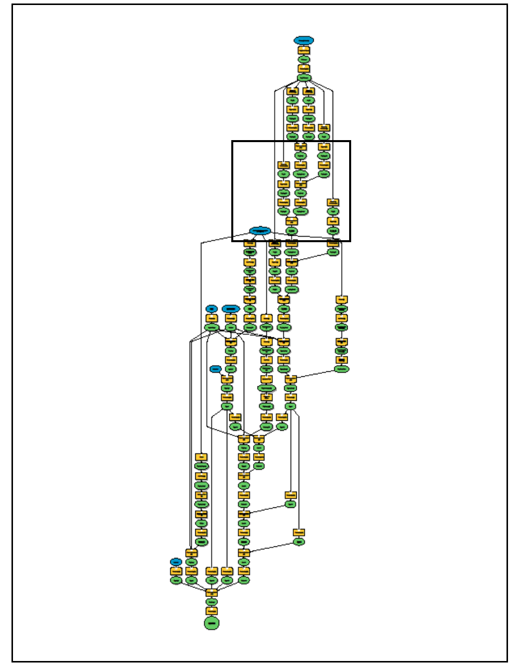
Aquifer Classification Model Schematic



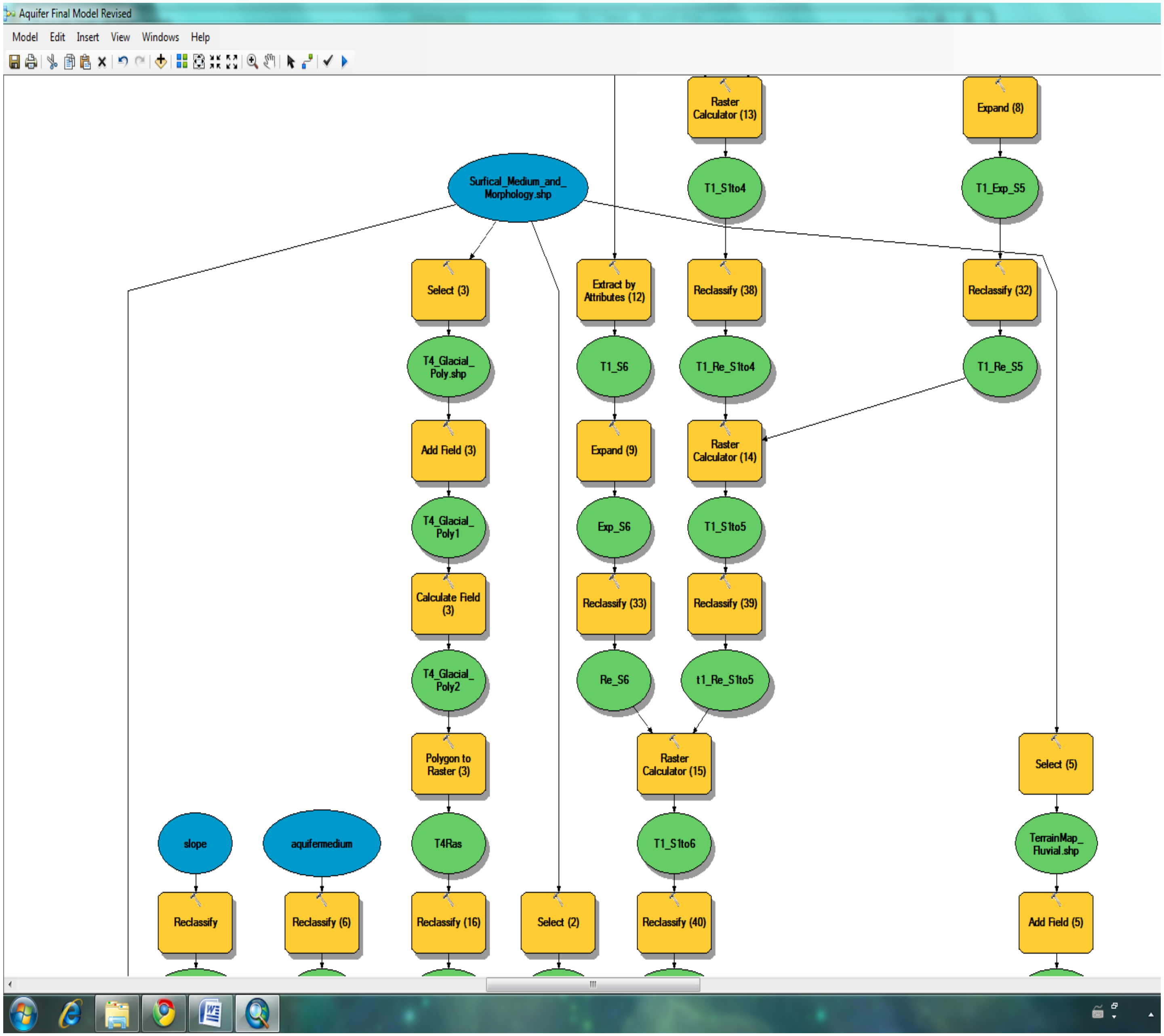


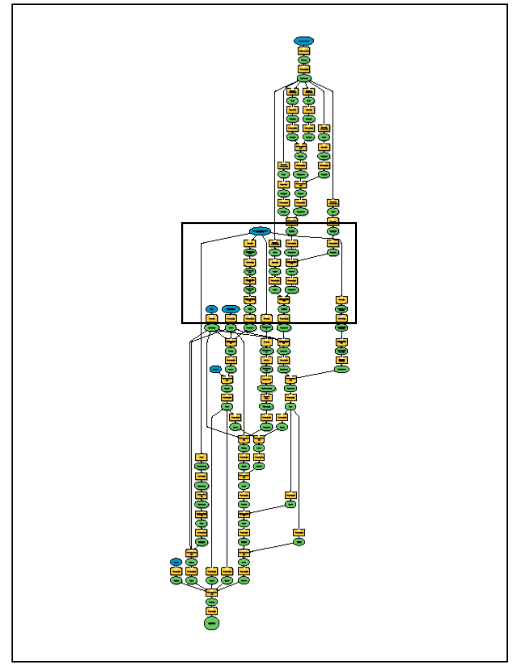
Total Model Schematic



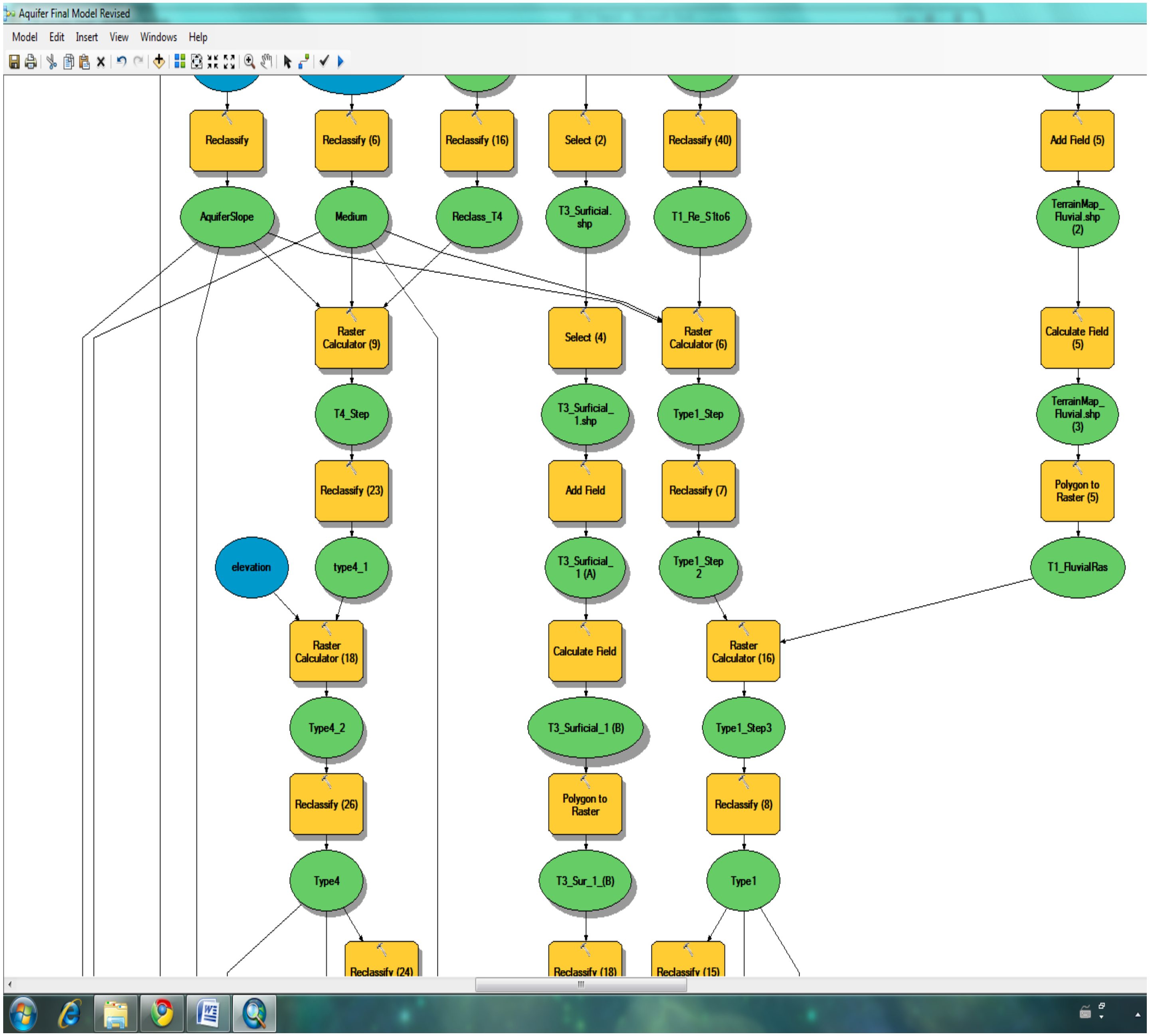


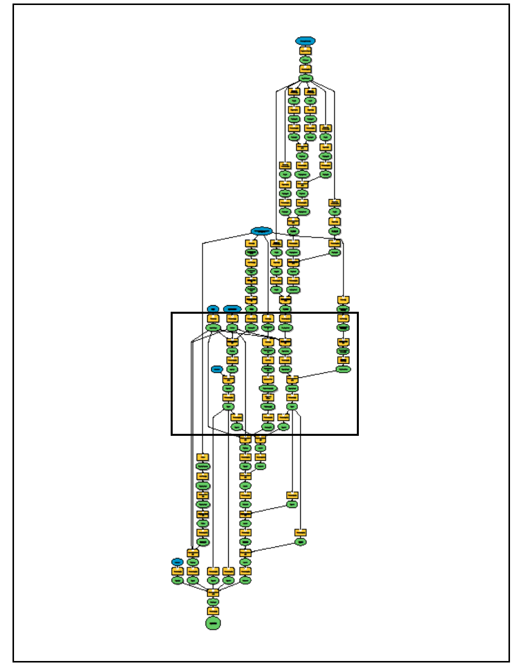
Total Model Schematic



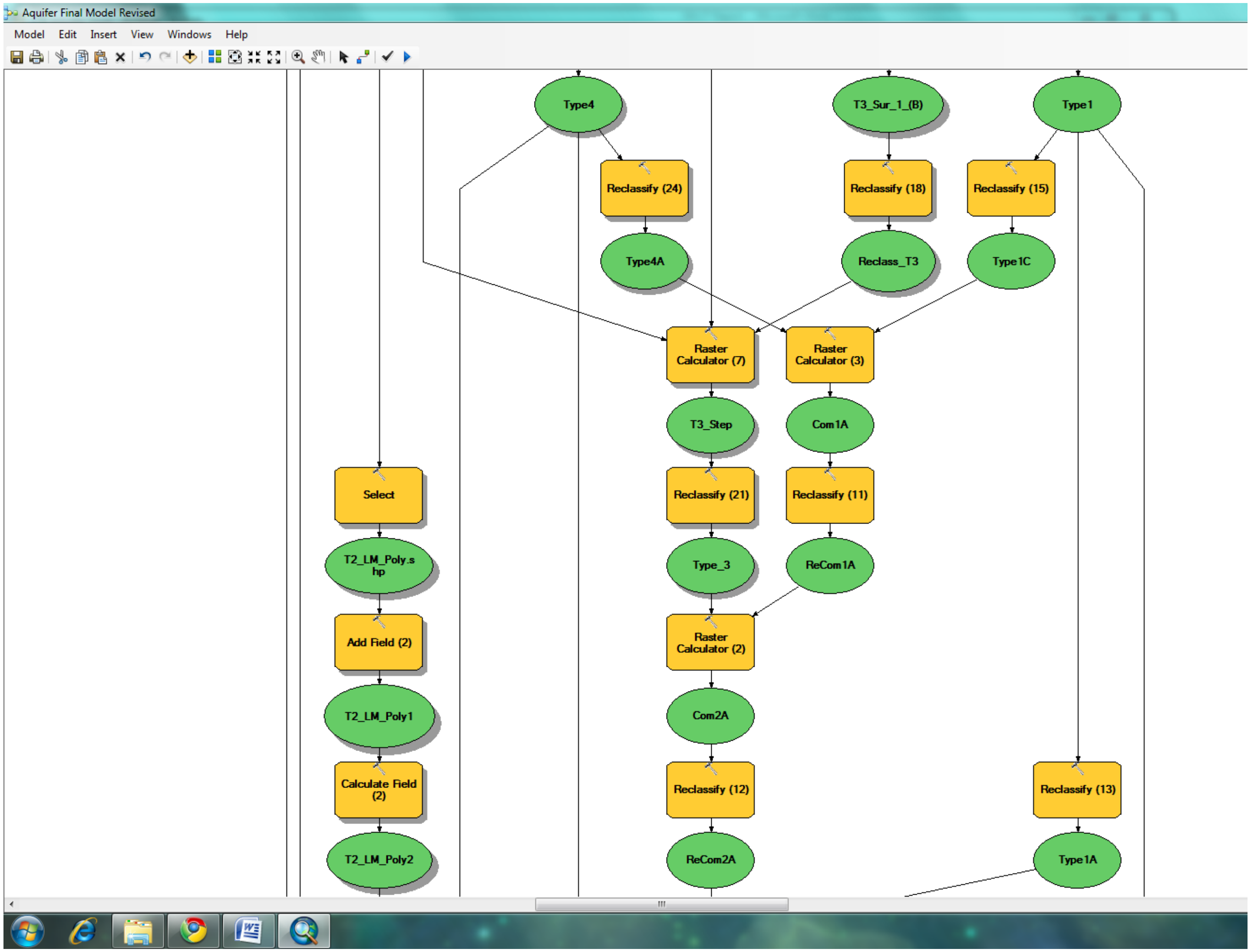


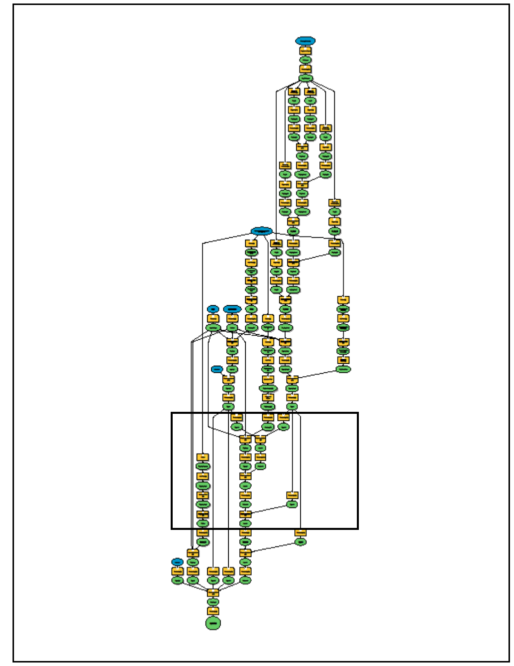
Total Model Schematic





Total Model Schematic





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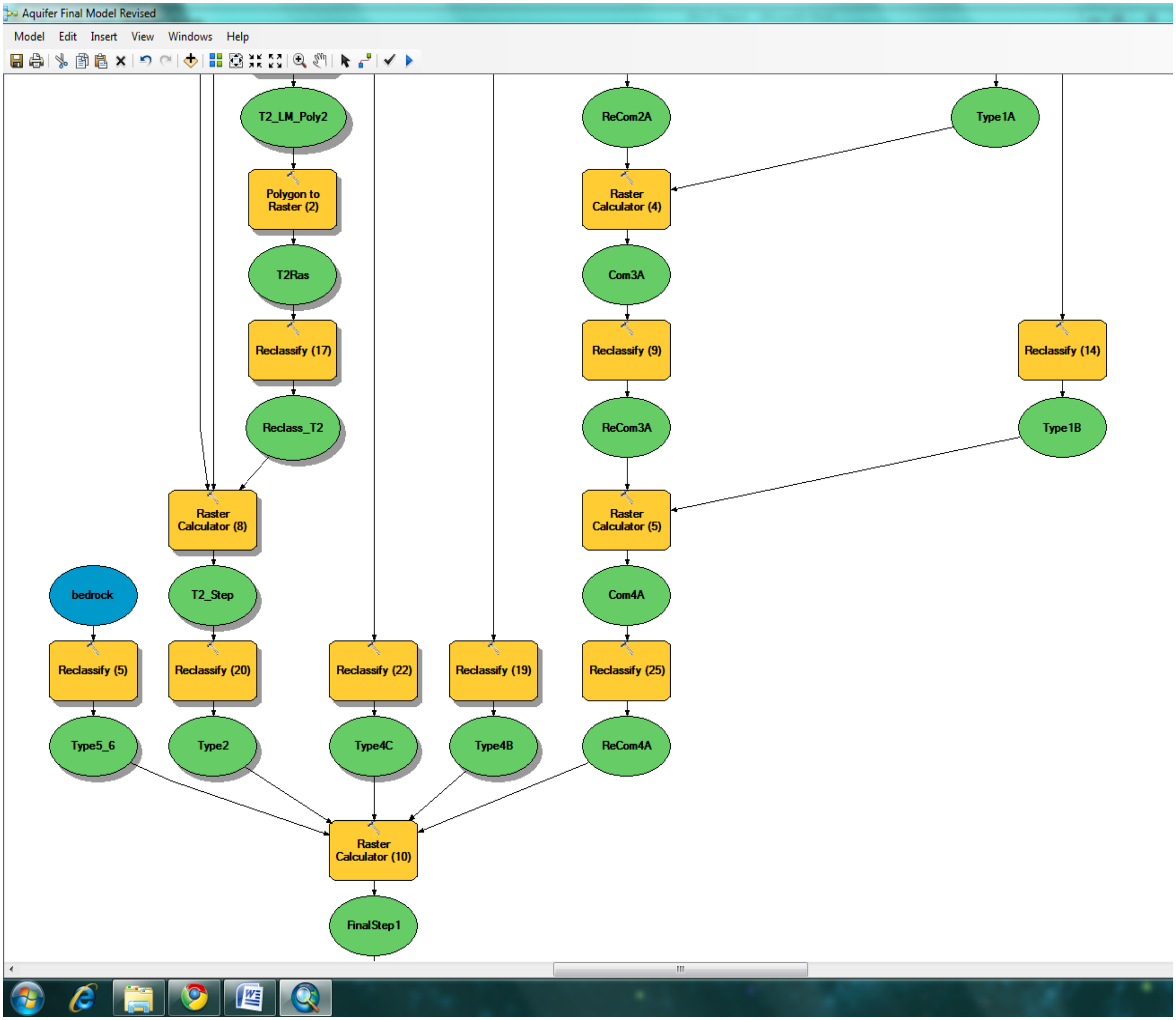
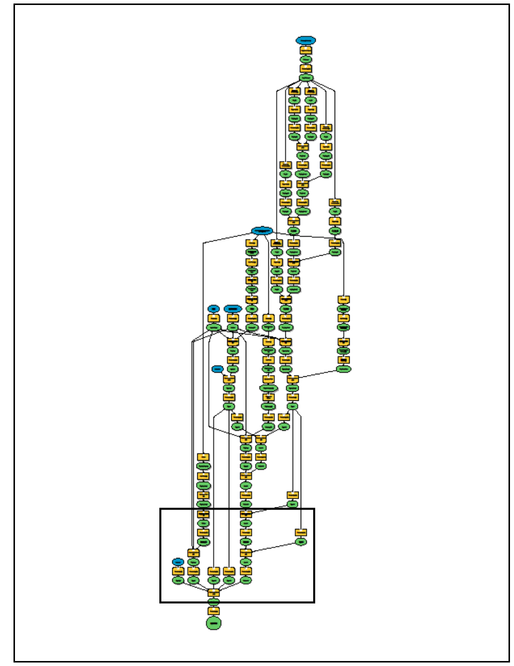
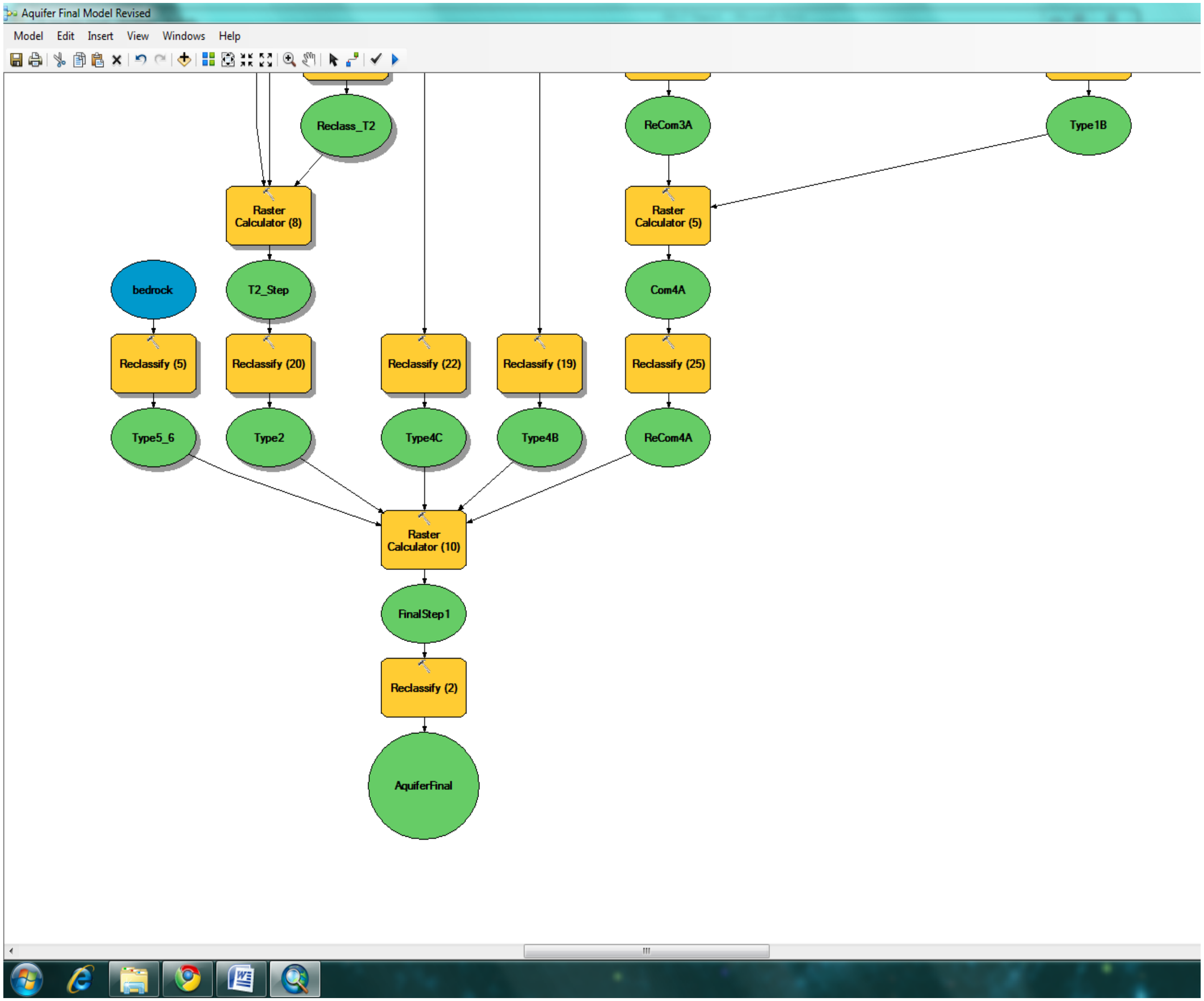
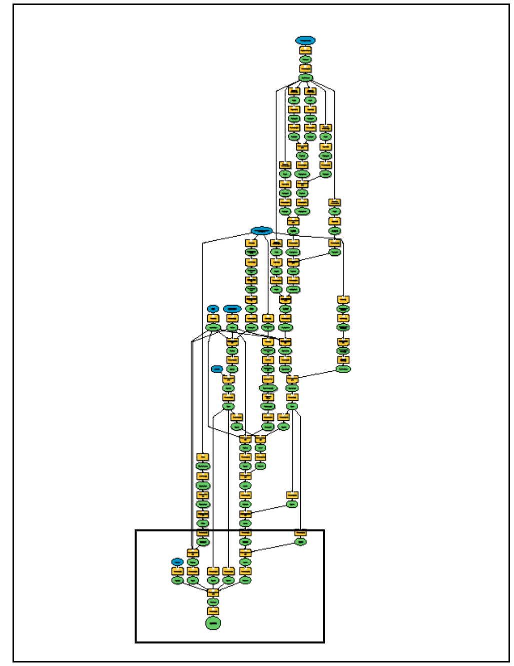




Total Model Schematic





Total Model Schematic