Physical Hydrogeology and Impact of Urbanization at the Waterloo West Side: A Groundwater Modelling Approach

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Anthony Jason Radcliffe

Abstract

In the last few decades protection of the environment has moved to the forefront of earth science research. Sustainable development is becoming more important to rapidly growing communities throughout southern Ontario including the City of Waterloo which has adopted an ecosystem planning approach toward future urban expansion.

The City of Waterloo is located in the Regional Municipality of Waterloo which relies mainly on local groundwater resources for its drinking water supply. The Waterloo West Side is a collective name for several new developments occurring at the western limit of the City of Waterloo. Development of the Waterloo West Side is encroaching on a potential regional groundwater recharge area. Recent studies have recommended that some of these developments will require artificial infiltration facilities to augment the reduction in infiltration rates at the post-development stage.

For this study, the pre-development groundwater flow system was characterized using a three-dimensional finite element model (WATFLOW). The regional Waterloo Moraine Model (approximately 750 km^2) was refined in the study area (approximately 25 km^2) so as to include the regional-scale influence on the local-scale groundwater flow. In addition, to approximate the complex groundwater flow system, within the study area, modifications were made to the current conceptual model. Several existing techniques were utilized in the numerical approach including three-dimensional parameterization and automated calibration methods. Simulations were completed to steady-state therefore results are averaged on a yearly basis.

The potential impact of urbanization on the groundwater flow system was investigated by modifying the surficial boundary condition to simulate post-development infiltration rates (increased runoff) in areas where development will occur. The impact to local surface water was investigated for each post-development scenario. In addition, the effect on the regional and local groundwater flow systems were compared for each scenario.

Acknowledgments

The first person I would like to thank is my advisor Emil O. Frind (for everyone who asked me, the "O" stands for Otto). I remember taking Emil's undergraduate modelling class in the fall of '96 and thinking, "Hey! this modelling thing isn't as bad as everyone says". Toward the middle of the course, Emil made an announcement that he was looking for some graduate students. I approached Emil about graduate work, and he agreed to give a short presentation outlining what I would be doing. A week later Emil had my papers signed and ready to go, and a few years later a finished thesis was produced on something quite different than what we originally agreed upon. Emil gave me an unique opportunity to do interesting and real-life applicable research. Thanks Emil, for this opportunity and the guidance along the way.

I would also like to thank my committee members Dave Rudolph and Ed Sudicky. Over the last few years the meetings with Dave provided insight and focus to this work and without his help this study would not have been possible. Ed deserves an extra thanks for coming into work during his vacation for my defence.

This next section is to thank the people that helped me along the way. A large thank-you goes to the modelling group (past and present) which includes, in no particular order, Dr. John Molson (Dr. sounds cool, huh John?), Michael Mößner, Rob McLaren, Connie Romano, Dawood Muhammad and finally, my good friend, Michelle Bester for reading three pages of my original draft and never returning them to me. Much of the work included in this thesis is an extension of previous work done by Dr. Jos Beckers and without his help I would still be trying to finish.

I would also like to thank the Water Services Division of the Regional Municipality of Waterloo for allowing me to pilfer their library. A special thanks goes to Tammy Middleton for her interesting phone conversations and to Hugh Simpson for supporting me during a certain presentation, where I became the target for misplaced hostilities, thanks Hugh.

Finally, I would like to thank two friends, with whom I have remained in-touch since undergrad: Barry (a.k.a. Red Dog) and Mel. I would *not* like to thank one person in particular, who didn't make it to my defence: Graham. Oh, by the way, was that a swimming group or a support group you signed up for in Toronto?

Dedication

I want to dedicated this thesis to my family, without their encouragement over the years I would not be here today. I would especially like to thank one family member in particular, for her support and love over the last three years, my best friend and wife, Karen. I consider myself lucky to have such a great family that has always been there for me when I needed them and never asked for anything in return.

A dedication to my family,

(the only picture I have with everyone in it).

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Chapter 1

Introduction

1.1 Background

Protection of the environment has moved to the forefront of earth science research in the last few decades. The move toward sustainable development has become necessary, for example, to ensure that natural resources are not compromised. Communities are discovering that the cost to develope sustainability is far less than the costs to repair damaged resources. These issues are becoming more important to rapidly growing communities throughout southern Ontario including the City of Waterloo which has adopted an ecosystem planning approach toward future urban expansion.

The Regional Municipality of Waterloo (RMOW), located in southern Ontario, is one of Canada's fastest growing regions with a current population of about 430,000 covering approximately 1360 km^2 (Figure 1.1). The Regions water supply is 75 percent groundwater and 25 percent surface water. The RMOW encompasses four townships: Wellesley, Wilmot, Woolwich and North Dumfries and three cities: Waterloo, Kitchener, and Cambridge. The study area is located within the City of Waterloo, and is referred to as the Waterloo West Side.

The City of Waterloo contains an environmentally sensitive area, the Laurel Creek Watershed (LCW). The LCW is not only ecologically important but is a part of the regional groundwater recharge area. Best Management Practices (BMPs) are being employed to reduce the impact on the watershed by encroaching urban expansion and in some cases returning sensitive areas to pre-agricultural conditions.

The *Laurel Creek Watershed Study* (LCWS) [1993] commenced in 1991 to address concerns of future impact on the Laurel Creek Watershed due to urbanization. The purpose of the LCWS was to identify and classify functional zones throughout the watershed into environmental Constraint Areas (CA). Based on recommendations from the *Laurel Creek Watershed Study* [1993], a regionally approved change to the Official Plan (Section 6.35.3.1) states that prior to district planning, subwatershed plans must be undertaken to ensure watershed goals and objectives are met. Further details outlining the purpose of these studies were included in *Requirements for Subwatershed Plans in the Laurel Creek Watershed* [*City of Waterloo*, 1994], which stated that the subwatershed studies are to provide a management plan in more detail than the *LCWS*.

Two subwatershed studies were commissioned under recommendations from the LCWS [1993] to investigate the potential impacts to the ecosystem as a result of urban expansion at the Waterloo West Side [*Planning and Engineering Initiatives Ltd.*, 1996] [*Dorfman*, 1996]. The purpose of these detailed studies was to develop a comprehensive plan utilizing an ecosystem approach, with the integration of biological and physical characteristics, to planning and land development. In these detailed subwatershed studies, several objectives must be achieved: to identify lands with environmental constraints and to determine impacts of development, to identify how the targets direct planning and implementation of land development, and to ensure that stormwater management will meet the targets for the subwatersheds. A major component of the subwatershed studies is to re-examine the CA identified in the LCWS at a subwatershed scale. The Waterloo West Side was subject to these conditions.

The Waterloo West Side is the primary study area for this research. The Waterloo West Side was in the planning stages for 15 years prior to construction. The planning stage involved partnerships with the City of Waterloo, Grand River Conservation Authority, Regional Municipality of Waterloo (RMOW), Ministry of Natural Resources (MNR) and developers. A collaboration of planners, hydrologists, hydrogeologists, ecologists and water resource engineers were included in the design stages of the Waterloo West Side so that an ecosystem approach to urbanization was possible.

The Waterloo West Side refers to the section of land bordered by Wilmot Line, Wideman Rd., Erbsville Rd. and Erb Street (Figure 1.2). There are four major developments currently under construction within the Waterloo West Side: Columbia Forest I and II, Clair Hills, and Rose Wood Estates (Figure 1.3). Trillium Estates started development in 1990 on the land that skirts the Laurel Creek Conservation area which is still under construction but is in the late stages of development. The

Waterloo West Side is at this time (summer 2000) in the early stages of construction where Columbia Forest I, Clair Hills, and Rose Wood Estates have started to build homes. Currently, land is being graded for Columbia Forest II and Erbsville Road developments but no construction has begun. Land at the southeast corner of the Waterloo West Side was developed several years ago. Urbanization adjacent and to the west of Wilmot Line is still in the preliminary stages of design but is conceptually included in Figure 1.3. Green areas shown in Figure 1.3 that trend northsouth though the middle of the Waterloo West Side are Environmentally Sensitive Protected Areas (ESPA) which will remain undeveloped.

1.2 Purpose of Study

Recent studies have utilized conceptual models and surface flow models to predict future impacts of urbanization within the Waterloo West Side. This study focuses on the characterization of the Waterloo West Side using a groundwater modelling technique to investigate these future impacts. Detailed local scale information from subwatershed studies is incorporated into the regional Waterloo Moraine Model in order to simulate pre-development regional and local groundwater flow patterns. The future impact to the groundwater flow system is evaluated by considering several scenarios with modified surface boundary conditions that imitate urbanization within the Waterloo West Side.

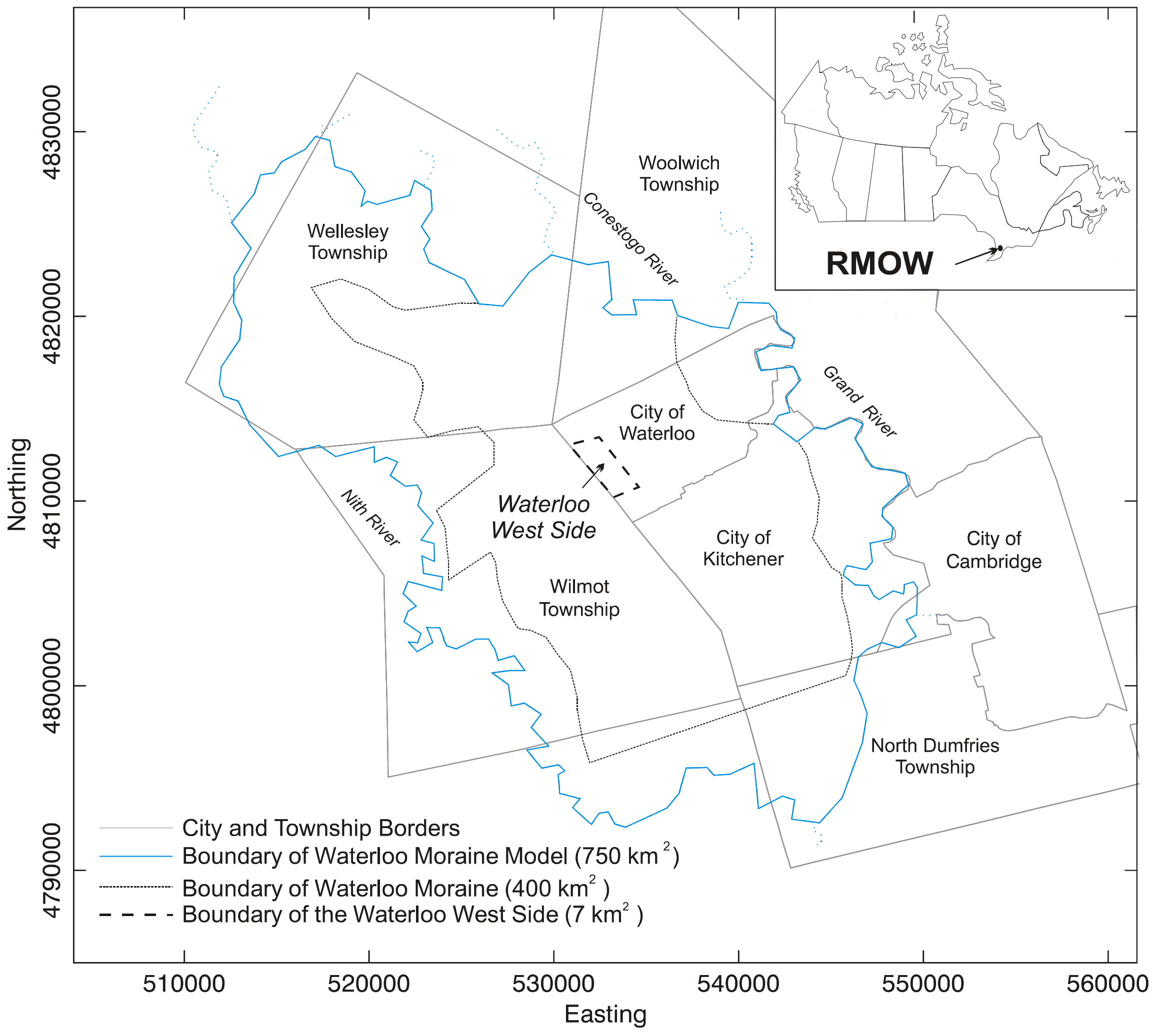

Figure 1.1. Location of Waterloo West Side within the Regional Municipality of Waterloo (RMOW). Township and city boundaries are illustrated. The Waterloo Moraine Model is outlined in blue and the Waterloo Moraine is indicated by a black line.

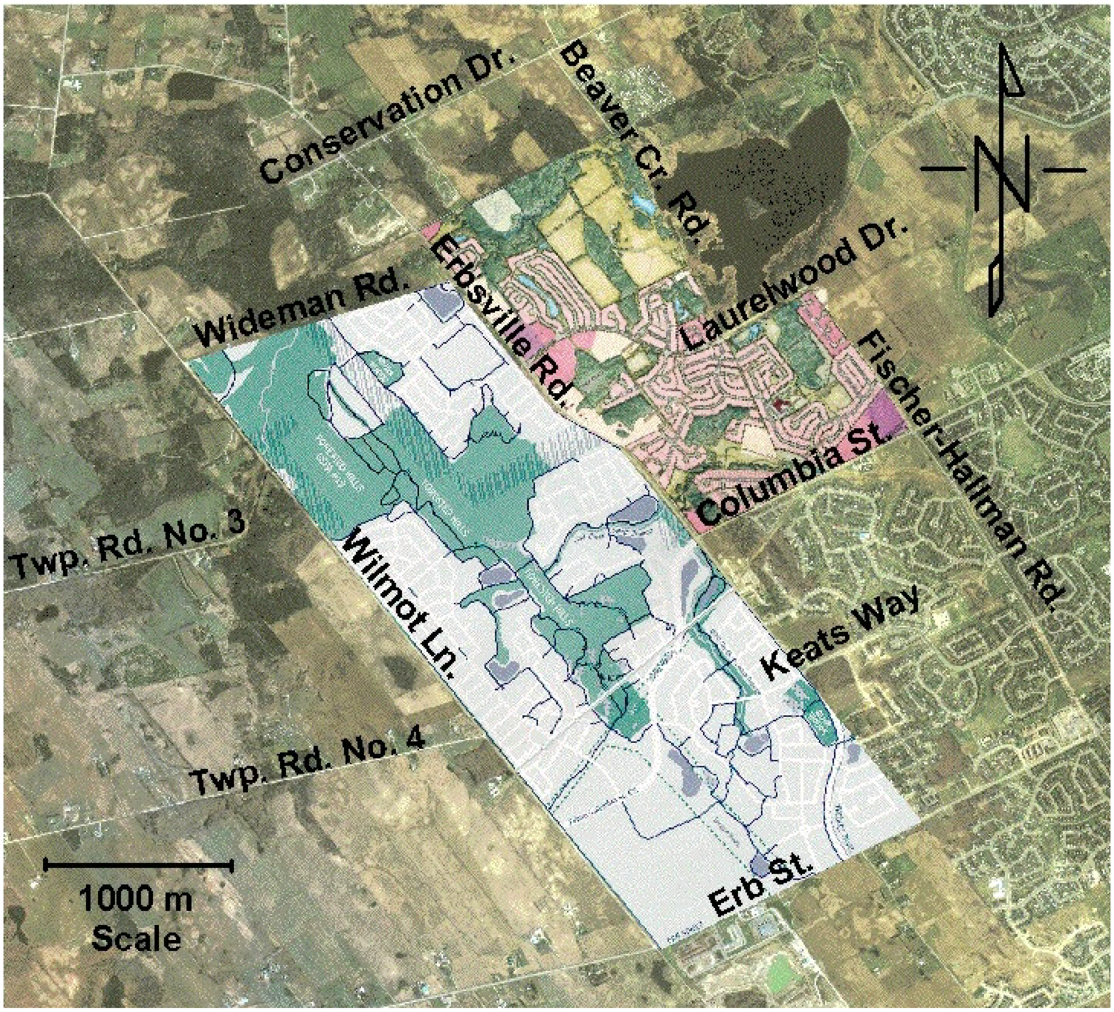

Figure 1.2. Waterloo West Side site map - surounding roads. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

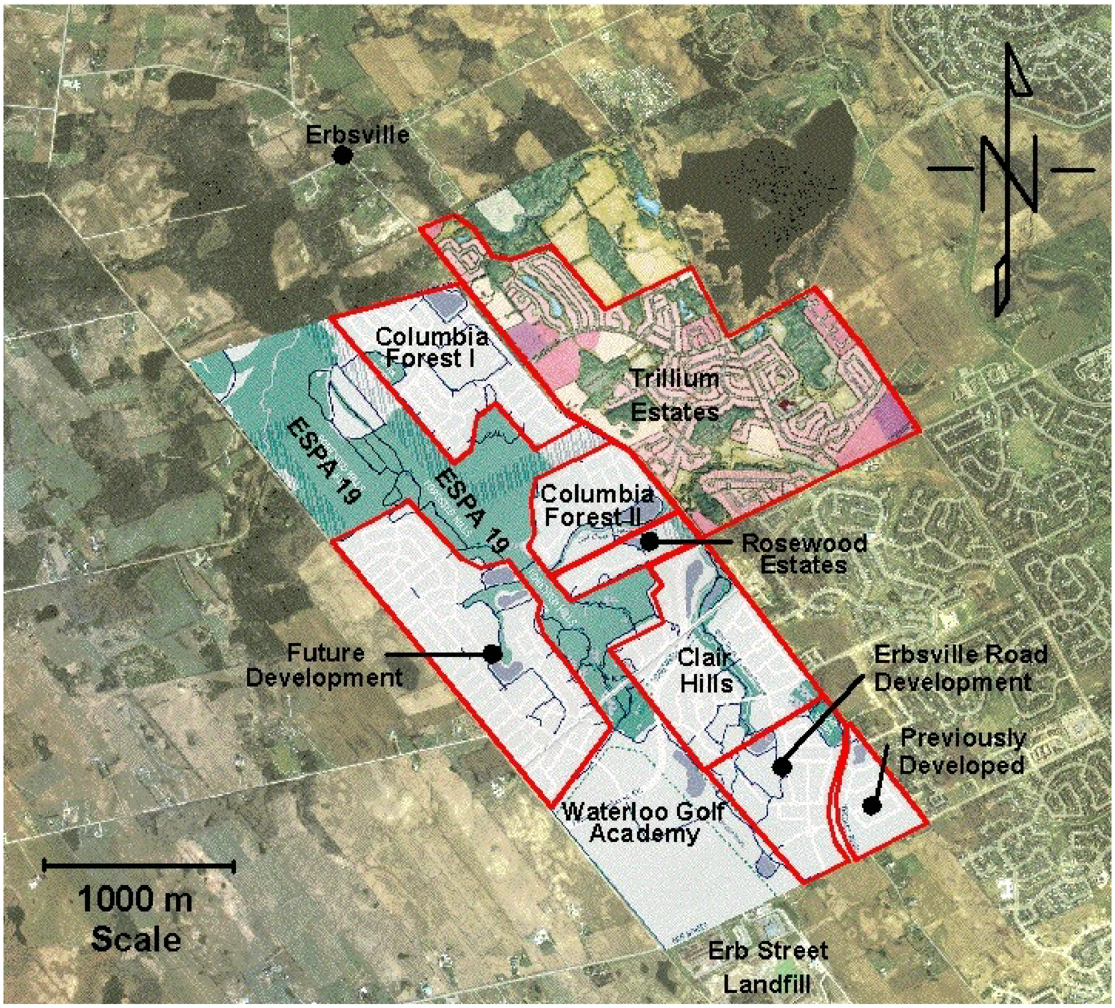

Figure 1.3. Waterloo West Side site map - areas of new urbanization. Areas of urbanisation are outlined in red. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

Chapter 2

Physical Background for Study Area

2.1 Regional Geology and Bedrock

The regional geological setting for the Waterloo region has been intensely studied over the last 30 years. Earlier work focused on the importance of surficial resources [*Presant and Wickland*, 1971], where the Region's surficial geology was classified by parent material (clay or gravel), weathering (chemical or mechanical), and drainage ability. Later work primarily examined the regional formation of the Quaternary geology [*Karrow*, 1986a] [*Karrow*, 1986b][*Farvolden et al.*, 1987].

The region has been altered by several glacial events including the last, the Wisconsinan Glacial Episode. Several advancing and retreating glacial lobes intersect within the Region of Waterloo. These glacial lobes include the Georgian Bay Lobe (from the northwest), Huron Lobe (from the west), and the Erie/Ontario Lobe (from the south and east). Terminal moraines were formed where these glacial lobes intersect. The largest of these moraines is the Waterloo Moraine which consists of glacio-fluvial deposited sands and gravels with interfingering till units and covers an area of approximately 400 km^2 (Figure 1.1).

Six major till units can be mapped across the region and were deposited during separate glacial advances. These units include, from youngest to oldest, Tavistock Till, Port Stanley Till, Maryhill Till, Catfish Creek Till, and Pre-Catfish Till [*Farvolden et al.*, 1987]. In the center of the Waterloo Moraine, the overburden thickness is at its maximum of 105 metres along the crest of the Waterloo Moraine in Wilmot township, to a minimum of zero along the Grand River in Cambridge where bedrock is exposed.

The bedrock beneath the Region of Waterloo is an eastern portion of the Michigan Basin [*Sanford*, 1969]. Bedrock in the Waterloo Region has been mapped using limited outcrops and water well records [*CH2M Gore and Storrie Limited*, 1997]. The regional bedrock topography ranges from 220 masl to 350 masl. The Michigan (depositional) Basin is saucer shaped with bedrock topography dipping to the southwest. The Michigan basin is associated with Palaeozoic strata of sedimentary origin with the younger deposits found toward the west.

The major subcropping formations include the Guelph and Salina Formations. The Salina Formation is a buff to brown coloured dolostone interbedded with grey and green shales. The Guelph Formation consists of cream and brown, fine to medium crystalline dolostone. Bedrock valleys are considered possible locations for groundwater resources due to the presence of permeable sand and gravel deposited from glaciofluvial outwash and glacial erosion of the underlying bedrock. Bedrock wells are only found in the Cambridge area where local recharge to the bedrock outcrops is common.

2.2 Physiography and Climate

Most of the study area consists of hummocky terrain and is dominated by the Waterloo Moraine (Figure 1.1). Within the moraine, topographic relief greater than 10% is common, increasing to 15% within the Waterloo West Side. Topography within the Waterloo West Side ranges from 400 masl in the southwest to 350 masl at the intersection of Erbsville Road and Clair Creek and forms the Clair Creek Valley. Figure 2.1 illustrates the topographic lows and highs of the area. Much of the Waterloo West Side consists of isolated wetlands of stagnant water where the local water table reaches the surface.

The Waterloo West Side is located within the Laurel Creek Watershed (LCW) (Figure 2.2a) which covers an area of 74.4 km^2. The LCW is characterized by 27 subwatersheds numbered 301 to 327 (Figure 2.2a). The subwatersheds are outlined in the *Laurel Creek Watershed Study* [1993] and were determined from landuse planning, terrestrial conditions and results from GAWSER (Guelph All Weather Storm Event Runoff) modelling. This study is focused on the Waterloo West Side which is in the western edge of the LCW and includes subwatersheds 308, 309, 313 and 314 (Figure 2.2b).

The Waterloo Region climate is semi-humid with an average annual precipitation of 917 mm between 1966 to 1990. Table 2.1 shows the precipitation normals for the Waterloo Wellington area between 1961-1990 [*Environment Canada*, 1993].

Precipitation	Dec	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	20.2	26.5	49.2	64.4	75.8	79.5	90.4	93.3	89.6	69.8	71.8	43.1	*774*
Snow (cm)	39.9	33.4	21.9	8.1	0.4	0	0	0	0	0.6	12.7	41	158
Total (mm)	54.3	55.6	72.7	72.6	76.3	79.5	90.4	93.3	89.6	70.4	83.1	79.2	917

Table 2.1. Precipitation normals for the Waterloo-Wellington area between 1961-1990 [*Environment Canada*, 1993].

2.3 Subwatershed Studies

Two subwatershed studies were undertaken prior to development of the Waterloo West Side. These two reports examined in detail four subwatersheds: 313, 309, a portion of 308, and 314 (Figure 2.2b) [*Planning and Engineering Initiatives Ltd.*, 1996][*Dorfman*, 1996]. The watershed studies were intended to determine management practices utilizing an ecosystem approach which includes both physical and biological processes.

The methodology adopted by the *LCWS* [1993] and the subsequent subwatershed studies is to characterize the land into environmentally sensitive areas or constraint areas (CA). The different constraint areas range in levels from CA-1 to CA-3. The classification of each constraint area is as follows: CA-1 classified lands that are to be preserved and maintained, CA-2 areas can be altered providing that the outlined functions can be maintained during pre- and post-development stages, and CA-3 areas are the lowest level of environmentally sensitive where development can occur subject to Best Management Practices.

For example, lands designated as CA level 1 are wetlands and densely forested areas such as ESPA #19 lands (see Figure 1.3). CA level 2 areas include buffer zones around CA-1, and areas of suspected groundwater recharge. Initial Constraint Areas were designated by the *LCWS* [1993]. The main purpose of subsequent subwatershed studies was to re-evaluate the *LCWS* [1993] CA designations on a subwatershed scale.

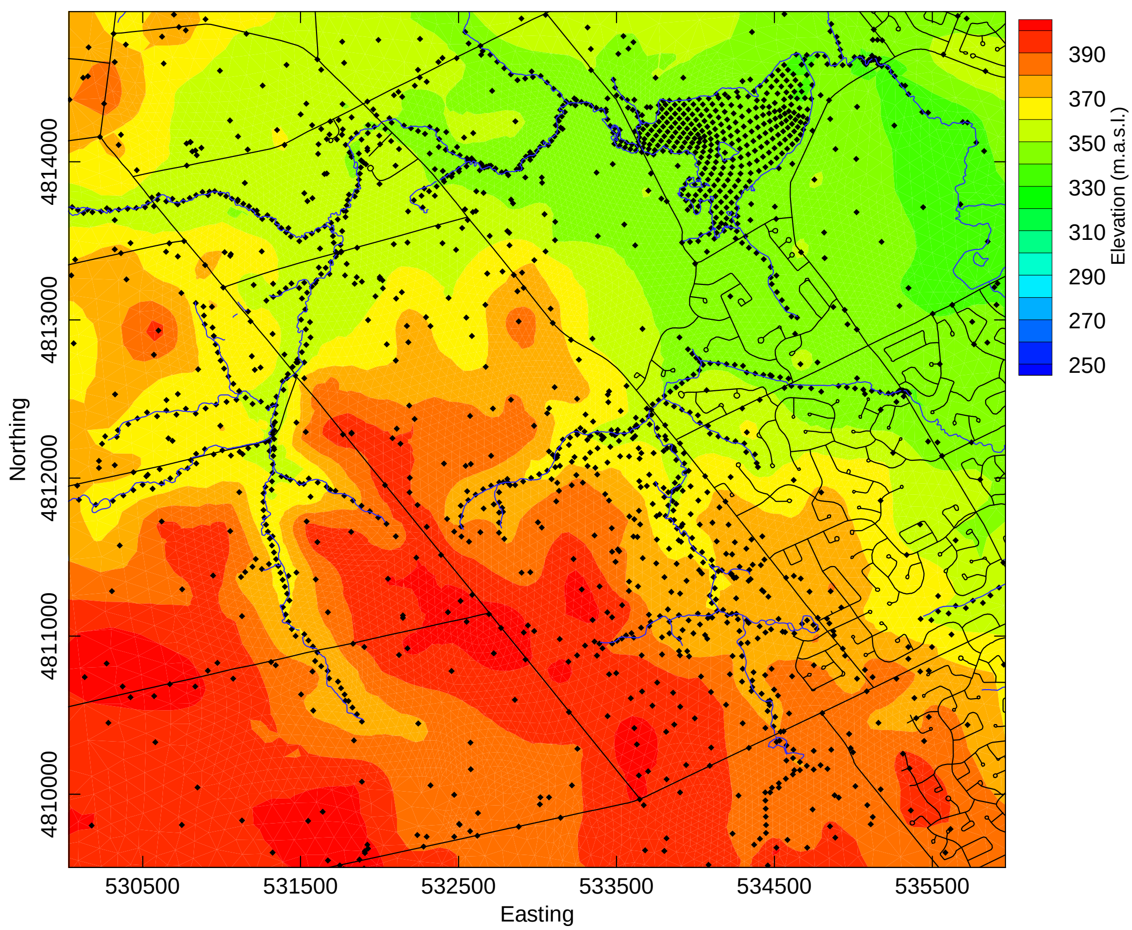

Figure 2.1. Waterloo West Side site map - topography of the study area. Generated using 2D Kriging of local survey data, stream valley morphology, and borehole data. Observed data points shown as black dots.

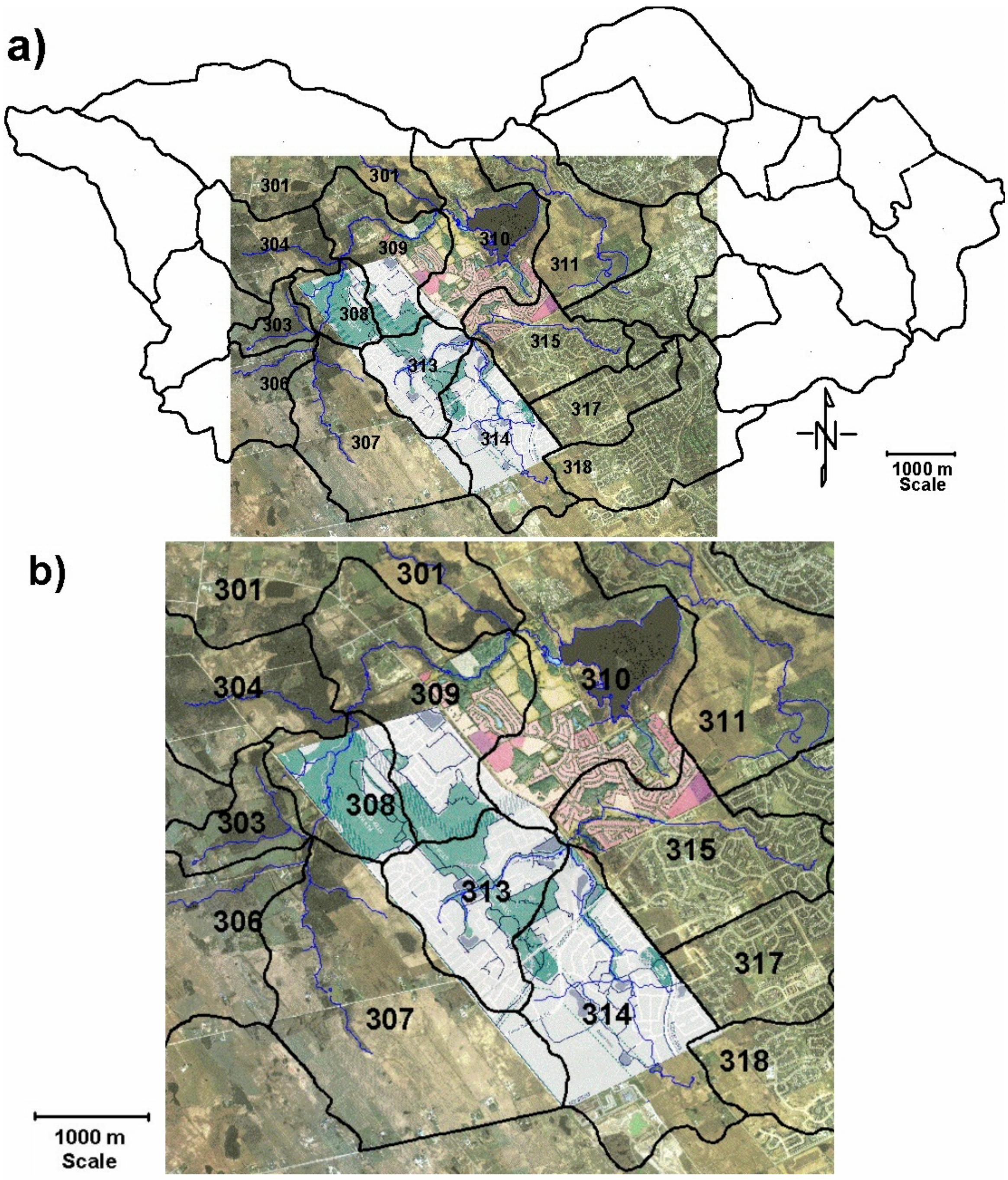

Figure 2.2. Waterloo West Side site map - a) Laurel Creek Watershed, b) Subwatersheds and major water courses. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

The constraint areas for the Waterloo West Side and the adjacent Trillium Estates land as recommended by the watershed studies are outlined in Figure 2.3. With reference to Figure 2.3, the major CA level 1 includes ESPA #19 lands, the north branch of Clair Creek and the Grand River Conservation Authority lands to the north which include the Laurel Creek Reservoir. These sections are prime areas for natural habitats which are either wetlands or forest. The CA level 2 lands include the south branch of Clair Creek and two larger portions of lands, first surrounding ESPA #19 and the second in the northern section of Laurel Woods (Trillium Estate) subdivision. Smaller portions of areas that are CA level 2 are linkage lands between CA level 1 lands.

2.4 Study Area Hydrology

The major water courses are shown in Figure 2.4. The northwest portion of the LCW is drained by Laurel Creek and its main tributaries Beaver Creek and Monastery Creek. Laurel Creek feeds the Laurel Creek Reservoir and Columbia Lake, both of which are man-made flooded lands used by the Grand River Conservation Authority (GRCA) for flood control and recreation. In the southwest portion of the LCW, drainage is directed along Clair Creek which flows south to north then crosses Erbsville Road and eventually flows into Laurel Creek to the east.

Subwatershed 314 covers the most southerly section of the Waterloo West Side (Figure 2.2b). The subwatershed is drained by the southern branch of Clair Creek (see Figure 2.3). The topography in the subwatershed is hummocky and has a low runoff potential [*Dorfman*, 1996]. In addition, the baseflow into Clair Creek is relatively low. The upper portion of Subwatershed 314, which is located south of Erb Street includes the Erb Street Landfill, drains into Dutton Pond and the surrounding wetland. Figure 2.3 shows that Dutton pond is classified as CA level 1 and the surrounding land is CA level 2. Dutton Pond is hydraulically connected to the southern branch of Clair Creek by a 375 mm culvert running 850 metres to the north (Figure 2.3). Regardless of the amount of the stormwater entering the wetland, the outflow from the culvert is maintained due to the high storage capacity of the wetland, and the outlet size of the pipe [*Dorfman*, 1996]. South of the confluence of the culvert and Clair Creek, channels are poorly cut and flow only occurs during storm events, although pools of standing water can be found along the drainage path.

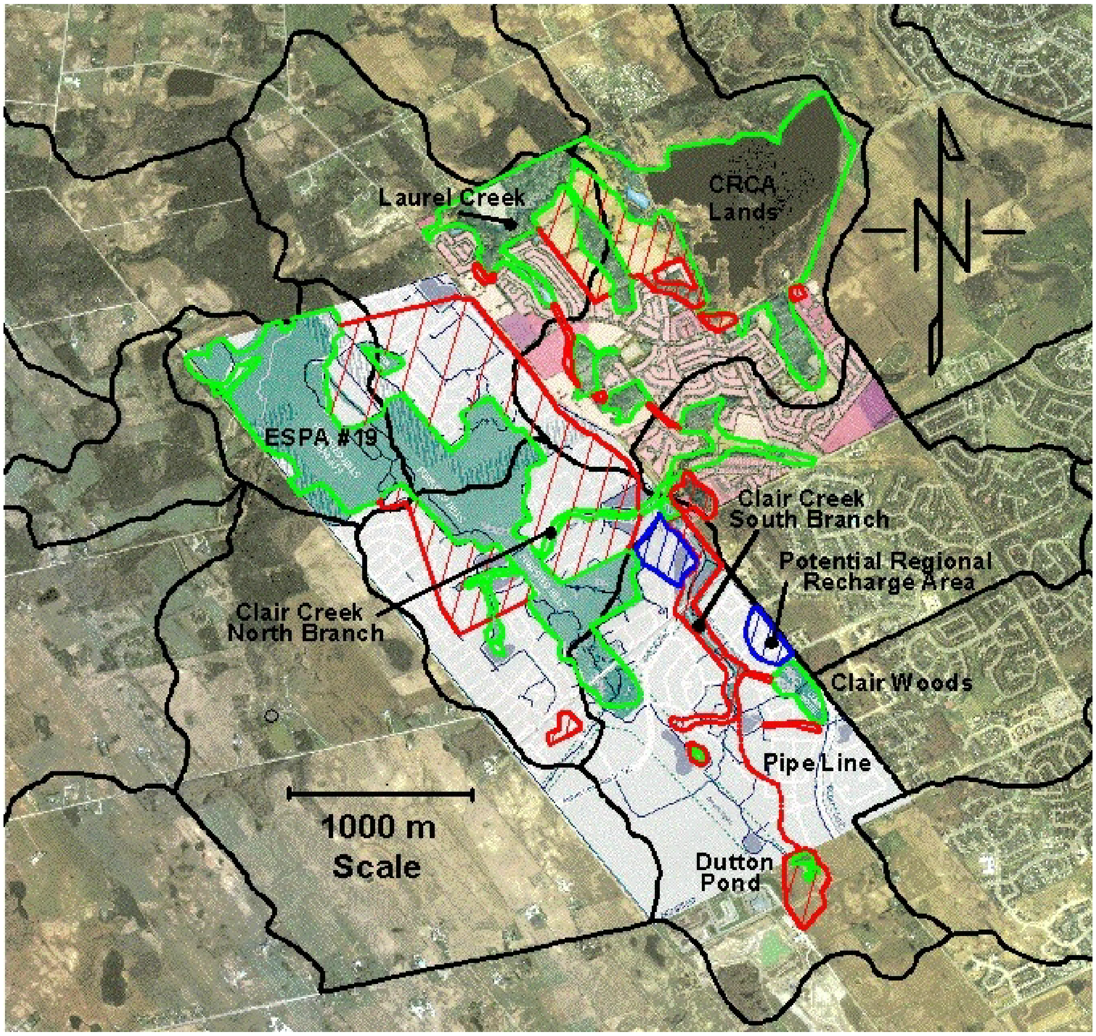

Figure 2.3. Waterloo West Side site map - constraint areas (CA) outlined for the Waterloo West Side and Trillium Estates super-imposed on subwatersheds. CA-1 is outlined in green and CA-2 is outlined in red [*Dorfman*, 1996][*Planning and Engineering Initiatives Ltd.*, 1996]. Potential regional recharge areas are indicated in blue [*Dorfman*, 1996]. CA-3, lowest level of environmental sensitivity, is land which is not outlined. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

Seepage meter data compiled during the *LCWS* [1993] and subsequent subwatershed studies are qualitatively represented in Figure 2.5. Also, vertical gradients at stream bottoms were measured from mini-piezometers and the data are included in Figure 2.6. Figure 2.7 shows surface water temperatures measured in early summer for local water courses. These measurements are snapshot data taken in the early summer months (approximately June-July) and therefore long-term trends cannot be determined. Even though surface water temperature is often a good indicator of baseflow direction, data can be misleading and results depend on various factors. For instance, sediment loads in creeks, shading from vegetation, flow rate, and depth of water all affect a waterbody temperature. These spot measurements from seepage meters and mini-piezometers often give contradictory results. The temporal variations in flow characteristics for stream bottoms are highly complex and more long-term average data sets are required such as stream gauging stations monitored for longer time periods. Therefore, no *quantitative* results can be inferred from these data.

Qualitatively, these data can indicate whether standing water is likely to be found or not and that a base flow does or does not exist. Baseflow at Dutton pond is relatively slow downward and is classified as warm water. Clair Creek and it tributaries to the south of the confluence of the Dutton Pond culvert are often dry. Most of the creek beds have been cultivated and are part of the agricultural landscape; therefore, the creek beds are no longer steep walled channels but subdued valleys. Farther down stream, at and beyond the culvert, creek channels show high erosion and flood plains up to one metre wide. Often during storm events, flow in the creek spills onto the flood plains. Figures 2.5 to 2.7 indicate Clair Creek has a complex flow path. Toward the north, the creek shows increasing gaining characteristics but from gradient data flow is stagnant (Figures 2.5 and 2.6). Surface water temperatures tend to indicate that the creek is losing water or recharging the underlying sediments. The upper 600 metres, down stream of the confluence of the north and south Clair Creek branches, is classified as CA level 2 due to its regional importance [*Dorfman*, 1996]. The upper 300 metres is an assumed regional recharge area and the lower section is a discharge zone for local groundwater. Clair Creek has been designated as a CA level 2 so that post-development function of the land can be improved.

Subwatersheds 313 and 309 cover the northern lands of the Waterloo West Side (Figure 2.2b). Subwatershed 313 is part of the rural headwater basin and contains the northern branch of Clair Creek where flow is eastward toward the confluence of the north and south branches of Clair Creek (Erbsville Road). The *LCWS* [1993] classified this stream as perennial but later studies showed flow to be intermittent

[*Planning and Engineering Initiatives Ltd.*, 1996]. The creek channel is well defined along its entire length. Figure 2.5 shows a losing nature in the upper section of the creek but gradient data indicates no flow at the base of the creek. Surface water temperature measurements suggest that groundwater is entering the creek up stream (Figure 2.7). West of Forested Hills (ESPA #19), Clair Creek is well defined but flow is constrained to storm events but East of Forested Hills, Clair Creek flows more consistently. The last 200 metres at Erbsville Road is assumed to intersect with the regional aquifer system where the creek becomes gaining (groundwater discharge) [*Planning and Engineering Initiatives Ltd.*, 1996].

Subwatershed 309 is considered a rural flow-through or lateral inflow basin, where a majority of the subwatershed extends above the Waterloo West Side and through the Hamlet of Erbsville. Surface water is drained into a section of Laurel Creek west of Laurel Creek Reservoir (see Figure 2.2b). Laurel Creek is a perennial creek which drains a large area and has many tributaries to ensure flow including Beaver Creek to the north and Monastery Creek to the southwest. The portion of Laurel Creek in Subwatershed 309 is mostly a gaining creek as indicated by the seepage meter data and surface water temperature data (Figures 2.5 and 2.7).

Subwatershed 308 includes the northwest corner of the Waterloo West Side but is almost entirely CA level 3 lands which ensures no development will occur and thus watershed conditions should not change. In addition, Subwatershed 308 is upstream from the Waterloo West Side development; consequently the watershed will be unaffected by development. Subwatershed 308 contains a portion of Monastery Creek which flows year round. The section of creek through Subwatershed 308 is a gaining stream.

2.5 Study Area Hydrogeology

The subsurface conditions in the area have been studied extensively. Smaller scale investigations, below the subwatershed scale, provide shallow subsurface information [*Presant and Wickland*, 1971][*CH2M Hill Engineering Ltd.*, 1991] [*Lotowater Ltd.*, 1991][*Planning and Engineering Initiatives Ltd.*, 1992][*AGRA Earth and Environmental*, 1997][*Planning and Engineering Initiatives Ltd.*, 1997][*England Naylor Engineering Ltd.*, 1998] [*Planning and Engineering Initiatives Ltd.*, 1998a][*Planning and Engineering Initiatives Ltd.*, 1998b]. Additional work in the area was done on the subwatershed scale [*Dorfman*, 1996][*Planning and Engineering Initiatives Ltd.*, 1996]. Larger-scale investigations include watershed studies and regional water resource inventories [*Lotowater Ltd.*, 1991][*Terraqua Investigations Ltd.*, 1992][*Grand*

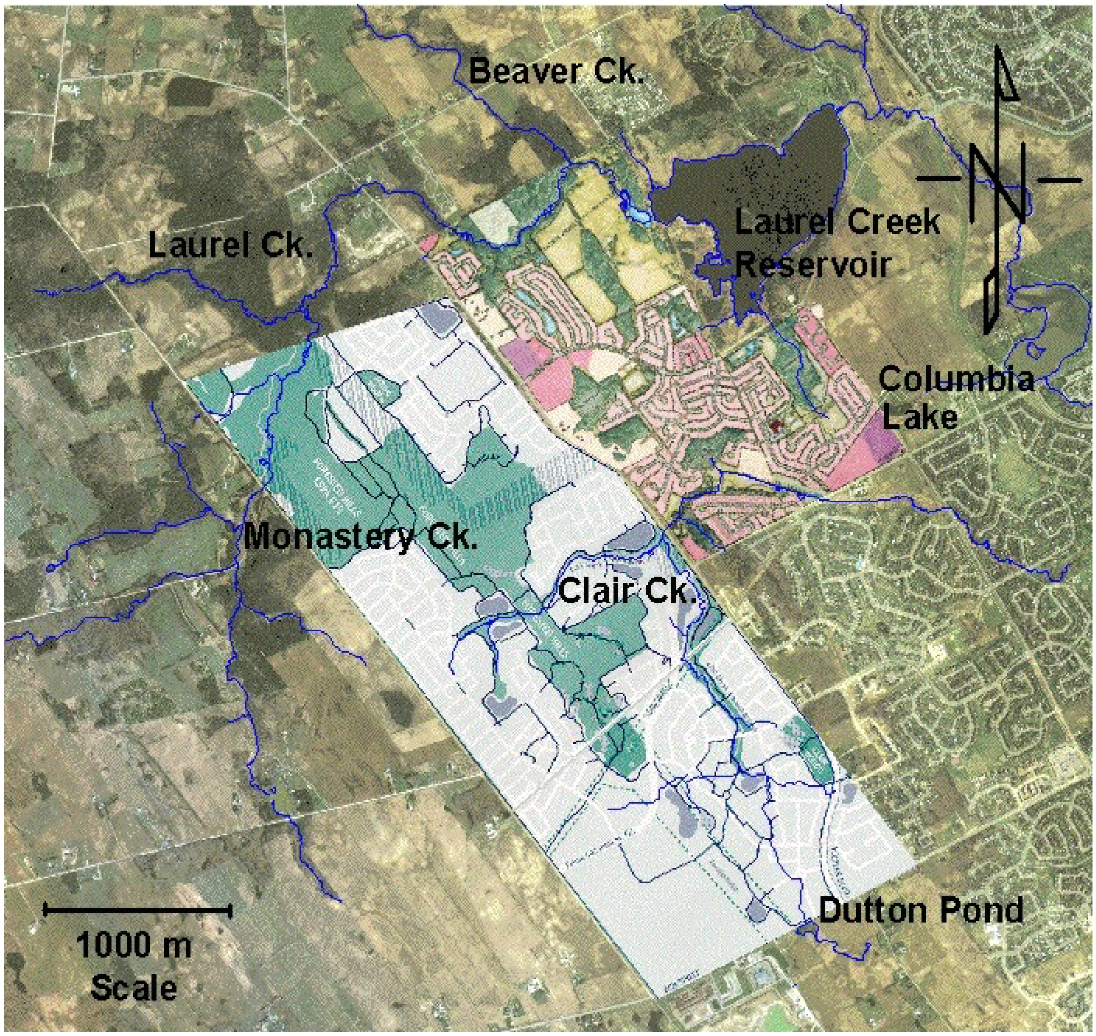

Figure 2.4. Waterloo West Side site map - water courses in and surrounding the Waterloo West Side. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

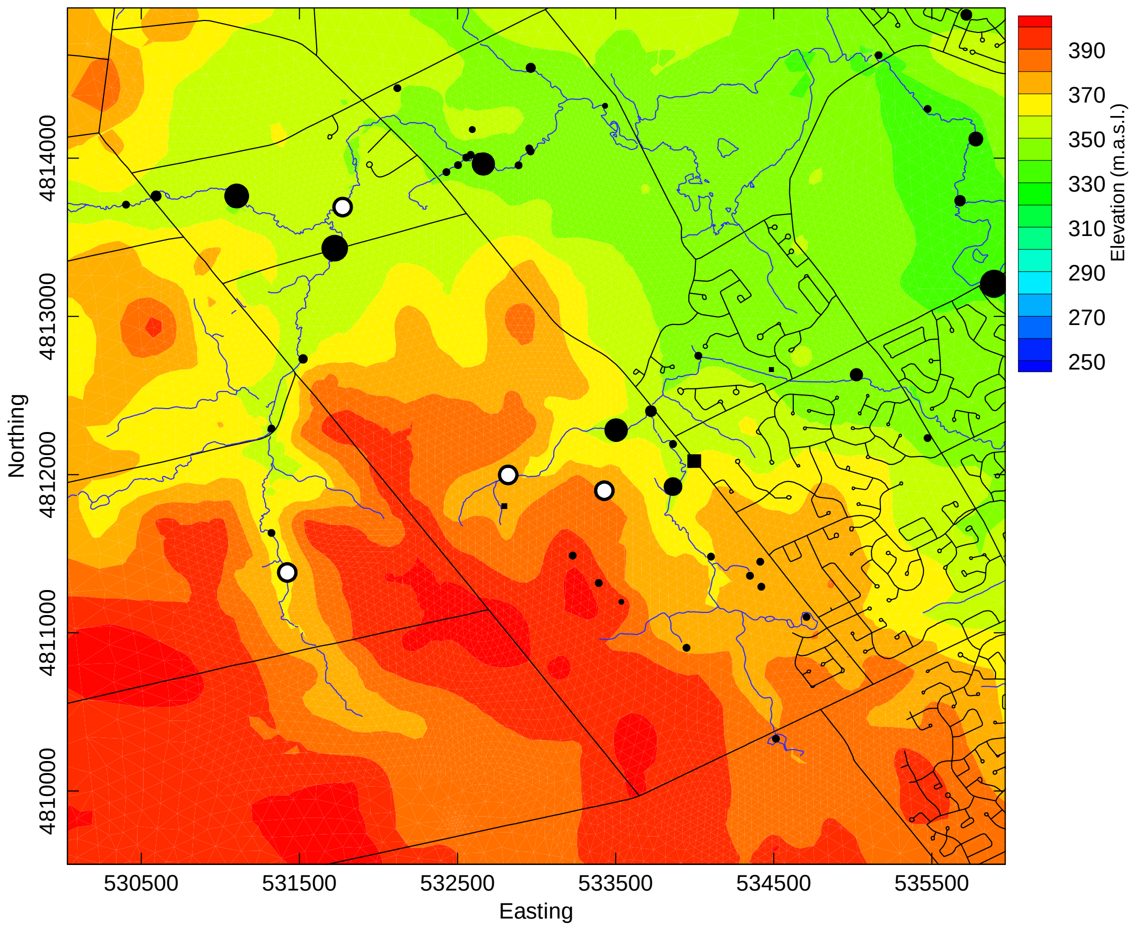

Figure 2.5. Waterloo West Side site map - qualitative seepage meter data distribution superimposed on topography. Symbol size corresponds to the relative magnitude of seepage. Circles represent locations of gaining water bodies and squares represent locations of losing water bodies. White circles represent neither gaining nor losing water bodies. Data were compiled from various studies and was measured in early summer.

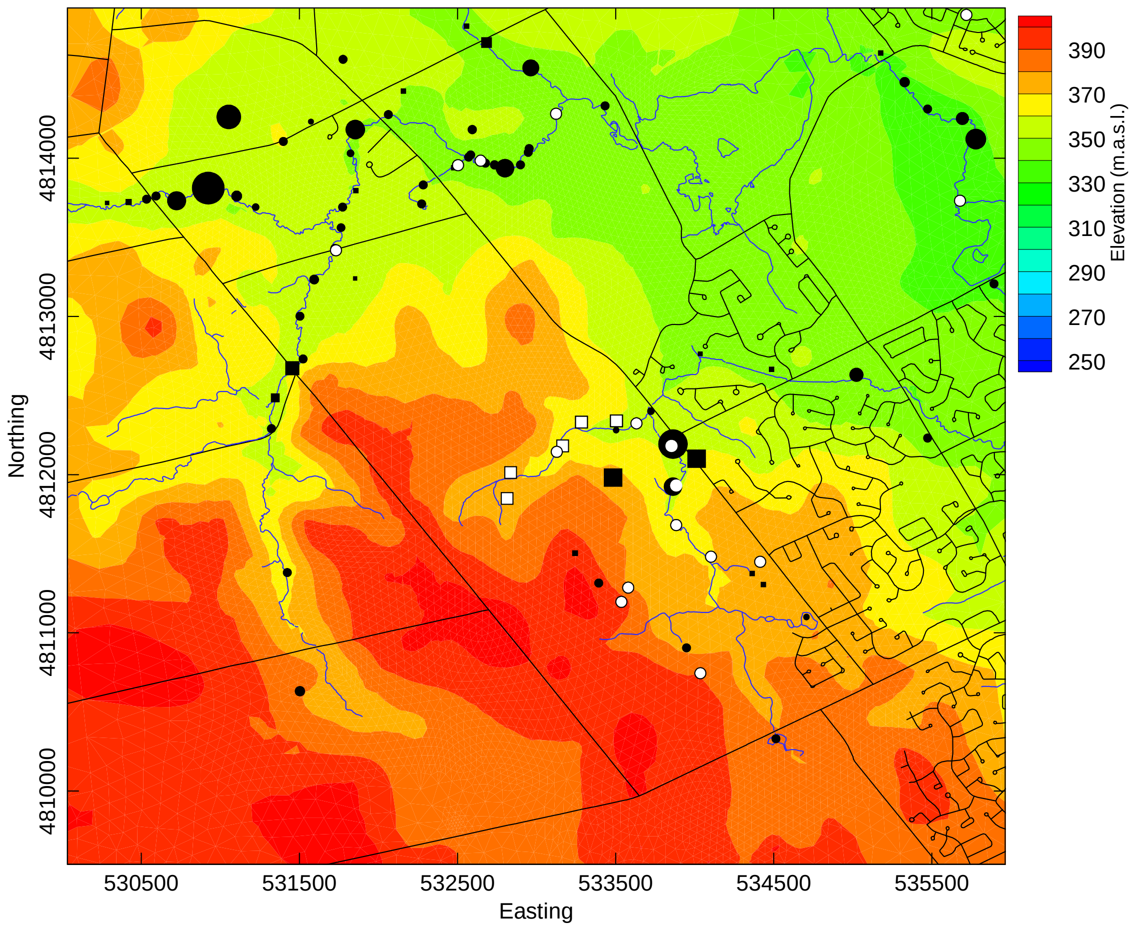

Figure 2.6. Waterloo West Side site map - qualitative hydrological gradient distribution superimposed on the topography. Symbol size corresponds to relative magnitude of the gradient. Black circles represent locations of gaining water bodies. Black squares represent locations of losing water bodies. White circles represent neither gaining or losing water bodies. White squares represent areas where dry conditions were encountered.

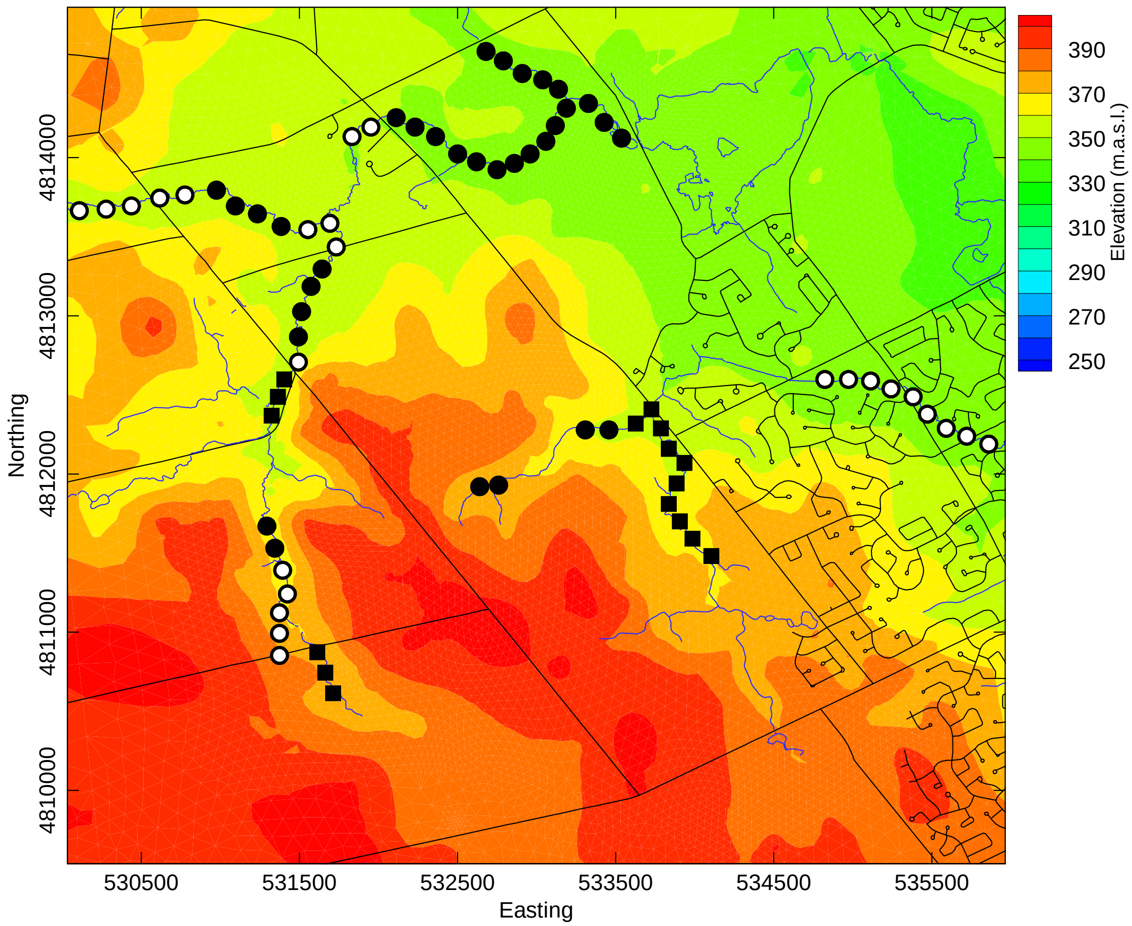

Figure 2.7. Waterloo West Side site map - surface water temperature data superimposed on topography. Black squares represent temperature measurements greater than 20 °C. Temperatures between 15 and 19 °C are indicated by white circles. Temperatures closely matching groundwater temperature (10 to 14 °C) are indicated by black circles. (Modified from [*Terraqua Investigations Ltd.*, 1993]).

River Conservation Authority, 1993][*Terraqua Investigations Ltd.*, 1993][*Terraqua Investigations Ltd.*, 1994][*CH2M Gore and Storrie Limited*, 1997]. Additional subsurface data was compiled for the Waterloo Moraine Model from the MOE water well records [*MOE*, 1981][*Martin*, 1994].

In the Kitchener-Waterloo area, bedrock water is characterized by elevated salinity, chloride, hydrogen sulphide, iron sulphate and hardness [*Woeller and Farvolden*, 1989]. Nevertheless, deeper wells that are hydraulically connected to the bedrock (for example W5-Waterloo North Aquifer system) are being considered for water supply [*Terraqua Investigations Ltd.*, 1992].

Surface and subsurface information from all available sources was catalogued into a database. Figure 2.8 illustrates the locations of 289 surficial data points which include mini-piezometers, testpits, test holes (hand augered holes), seepage meters and Guelph Permeameter tests. Subsurface information was obtained from borehole logs compiled by consultant reports and well driller logs in the MOEE database. A total of 373 boreholes were identified in the area and are plotted in Figure 2.9. Field measured hydraulic conductivity data were also retrieved from consultant reports and in the Waterloo West Side database. Figure 2.10 indicates where hydraulic conductivity was measured seepage meters, slug tests and pumping tests.

Much of this discussion comes from the latest subwatershed scale studies [*Dorfman*, 1996][*Planning and Engineering Initiatives Ltd.*, 1996]. In general, the area is underlain by 80 to 100 metres of unconsolidated glacial sediments. Subwatershed 314 (Figure 2.2), as discussed earlier, is within and to the western edge of what is locally referred to as the Waterloo Sand Hills. The geology beneath Subwatershed 314 is complex. A majority of the subwatershed is underlain by a thick clay till, thought to be impervious. The till layer thins towards the north at Clair Creek Valley where it disappears. This clay till is believed to be Mary Hill Till which characteristically acts like an aquitard due to the high clay content and interbedded lacustrine clay. Mary Hill Till can be found throughout the region and outcrop desiccation cracks have been documented [*Karrow*, 1993]. Guelph Permeameter data from testpits throughout Subwatershed 314 indicate a saturated hydraulic conductivity of 10^{-7} m/s. Toward the south of Waterloo West Side, the clay cap reaches thicknesses greater than 30 metres. However, borehole logs show discontinuous sand and gravel lenses.

The upper portion of the clay till is assumed to be fractured in portions of the subwatershed to a depth of 4-6 metres. The upper 4-6 metres provide a significant amount of groundwater storage. Much of this water then moves horizontally, as interflow, through the fractured clay and discharges into Clair Creek at Erbsville Road. The flow rate has been estimated at 150 m/year horizontally and 1 m/year vertically [*Dorfman*, 1996]. According to *Dorfman* [1996] and *Planning and Engineering Initiatives Ltd.* [1996] perched conditions are evident throughout the Waterloo West Side. Perched conditions exists where infiltrating water is held in the weathered zone of relatively low hydraulic conductivity units and water level observations in the deeper units below indicate overlying unsaturated conditions. Figure 2.11 illustrates locations of identified perched water levels. Under these geological conditions, *Dorfman* [1996] estimated 100 mm/year will recharge the underlying aquifer.

The northern portion of the Waterloo West Side is contained within subwatersheds 313, 309 and a portion of 308. The Mary Hill Till seems to thin north of Clair Creek and ranges from 0-10 metres in thickness. Subwatershed 313 is underlain by thick sand units which dip under the upper till unit found in Subwatershed 314. The northern branch of Clair Creek cuts through the thin layer of Mary Hill Till exposing the massive sand layer.

The southern portion of Subwatershed 309 shows more of the same sandy aquifer outcropping and continues to a depth of 45 m.b.g.s. The northern portion of Subwatershed 309 is more complex with inter-fingering of sand and silty-clay material. An intermediate aquifer system is present toward the north which was once used for commercial bottled water [*Lotowater Ltd.*, 1991]. Testpits and Guelph Permeameter data throughout the subwatersheds indicate a surficial saturated hydraulic conductivity ranging from 10^{-10} m/s to greater than 10^{-5} m/s. These values are consistent with sandy to clayey materials.

Local groundwater flow is assumed to dominate over regional groundwater flow through Subwatershed 309 [*Planning and Engineering Initiatives Ltd.*, 1996]. Regional groundwater flow is toward the southeast toward the Grand River. Much of the discharge to Laurel Creek is thought to be in the Erbsville area. Local groundwater flow is toward the north and Laurel Creek. Toward the south of Subwatershed 309, groundwater flow becomes increasingly more regional and flow is directed to the southeast toward Subwatershed 313 and Clair Creek.

The large area outlined as Constraint Area level 2 in the southern area of Subwatershed 309 and the northern portion of 313 are considered recharge areas due to radial groundwater flow patterns [*Planning and Engineering Initiatives Ltd.*, 1996]. This land is designated CA level 2 which permits development, but post-development must maintain or enhance the functionality of the area. The northern section of the Waterloo West Side is scattered with wetlands which are assumed to be perched water underlined by clay lenses. Groundwater within the weathered zone of the surficial till will flow according to topography and infiltrate where the soil conditions permit (relatively higher-K). Much of the north branch of Clair Creek is a losing stream [*Planning and Engineering Initiatives Ltd.*, 1996]. The head waters are fed by surface runoff during storm events and interflow from water stored in low-lying areas.

Geology similar to that of Subwatershed 309 is found west of Erbsville road on the Trillium Estate property (Figure1.3) [*CH2M Hill Engineering Ltd.*, 1991]. The upper-most 15 to 40 metres of glacial sediments consist of layered clay and silt with occasional lenses of sand. Studies indicate this unit has low hydraulic conductivity with average values of about 10^{-7} m/s. Surficial testing, using the Guelph Permeameter, resulted in saturated hydraulic conductivities ranging from 10^{-10} to 10^{-4} m/s. Several factors contribute to complex recharge rates within this area including: low permeability surface soils, sloping topography, and significant agricultural activity. The recharge rates are estimated to be less than 20 percent of the total precipitation, or 180 mm/year.

2.6 Study Area Hydrostratigraphy

The conceptual groundwater flow model is based on that adopted for the Waterloo Moraine [*Rudolph*, 1985][*Martin*, 1994][*Callow*, 1996] [*Martin and Frind*, 1998], which includes four aquitards and four aquifers stacked in an alternating layer cake fashion (Figure 2.12). The bottom layer includes the top five metres of bedrock which is believed to be fractured as a result of glacial action. In reality, this model is likely highly simplified compared to the actual hydrogeological system. Within the study area, Aquifer 3 and Aquitard 4 are thin and interbedded and likely could be considered a single hydrogeological unit.

A total of 26 cross-sections were compiled for the Waterloo West Side (Appendix A). Each cross-section shows both the lithology and water level data (if applicable), for each well. In addition, the well screens are also included and colour matched for multi-level installations. Figure 2.13 illustrates a typical cross-section generated for this study. The location of the sample cross-section is given in Figure 2.14 and the legend for the cross-section is provided in Figure 2.15. Surficial data including testpits (less than 4 m.b.g.s.) are not included in the cross-sections.

The hydrostratigraphy was mapped using the conceptual model and the cross-sections. Perched water levels were identified and separated from the regional data set (Figure 2.11), water table maps were created for regional Aquifers 1 and 2. Water levels interpreted for the deeper aquifers confirm that the deeper units

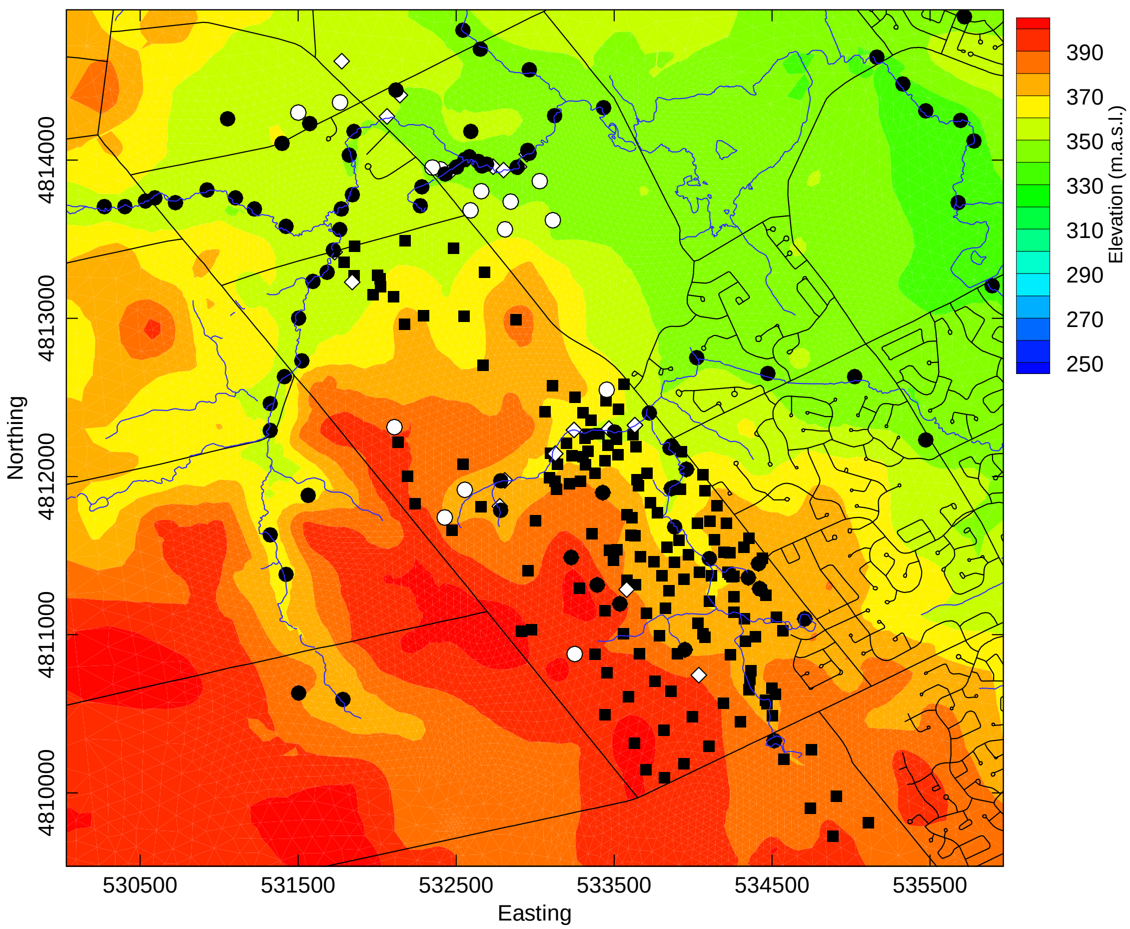

Figure 2.8. Waterloo West Side site map - locations of surficial data superimposed on topography. Squares are testpits. White circles are Guelph Permeameter tests. Black circles are seepage meter locations. White diamonds are mini-piezometers.

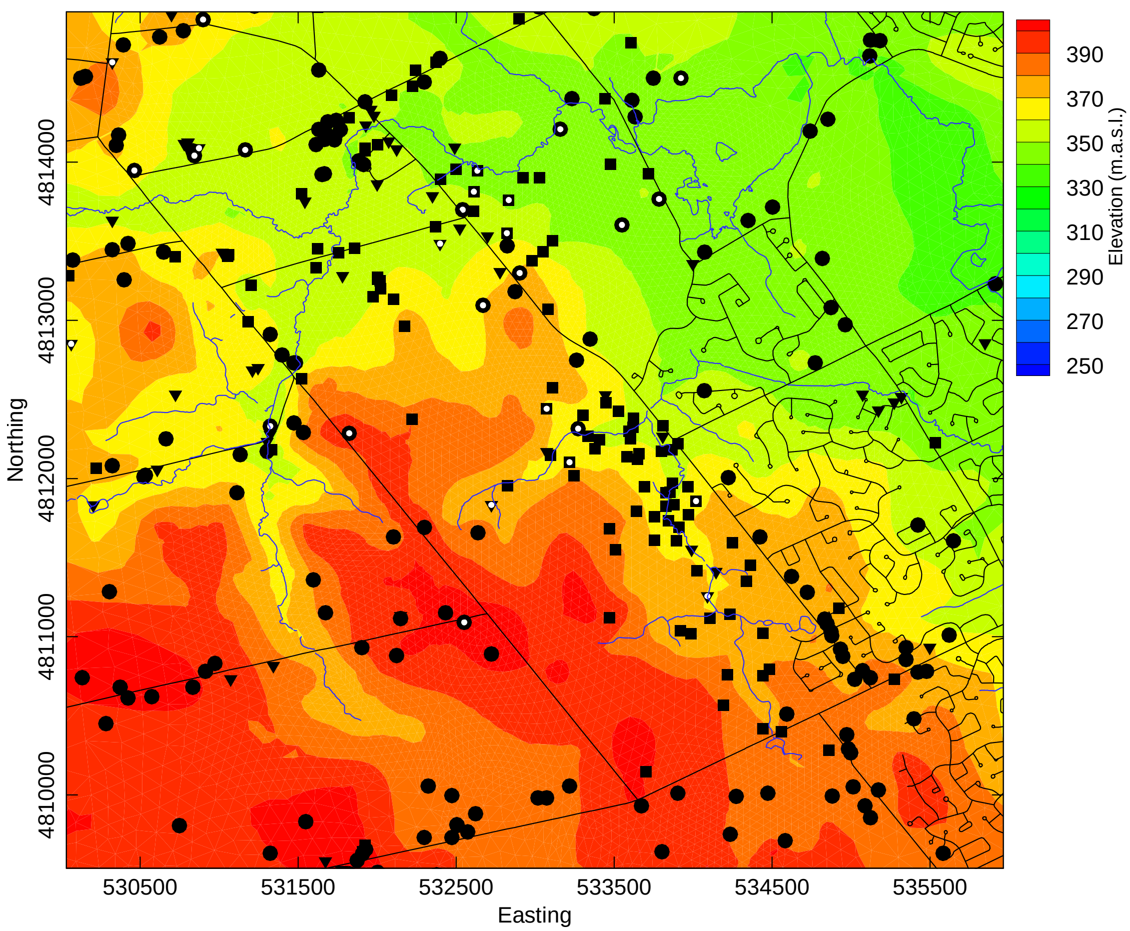

Figure 2.9. Waterloo West Side site map - locations of boreholes used for lithology cross-sections, superimposed on topography. Squares are boreholes 4 to 15 metres deep. Triangles are boreholes 15 to 30 metres deep. Circles are boreholes greater than 30 metres deep. Symbols with white centers represent multi-level installations.

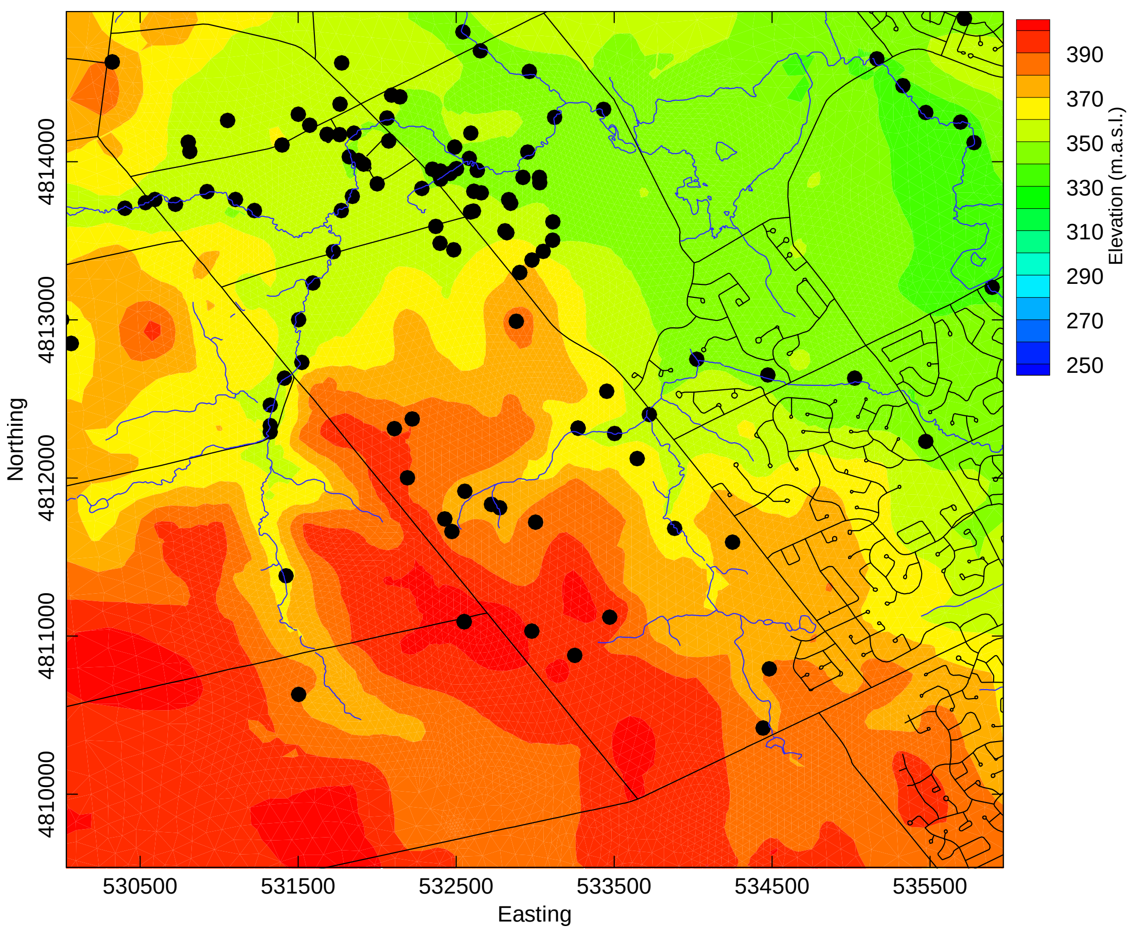

Figure 2.10. Waterloo West Side site map - locations of measured hydraulic conductivity superimposed on topography. Data includes results from falling head tests, pumping tests, Guelph Permeameter tests and seepage meters.

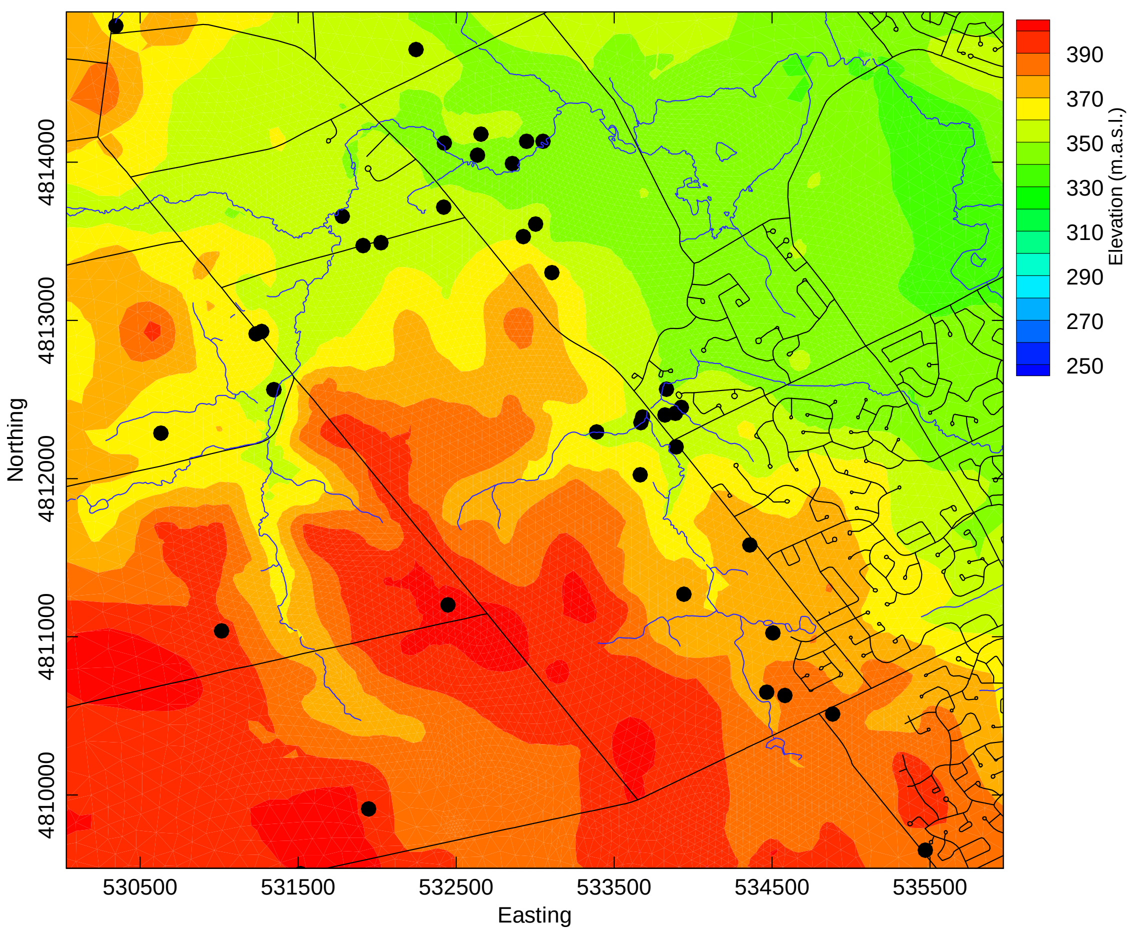

Figure 2.11. Waterloo West Side site map - locations of measured water levels under perched conditions, superimposed on topography.

are hydraulically connected (within the study area), and a single water table map was generated for the deeper units. Figures 2.16 - 2.18 show the piezometric head distribution for Aquifers 1, 2 and 3 from measured static water levels. Water level data from perched wells are not plotted but are included in the calibration database for the numerical model. Water level measurements used in the water table maps include data from early summer where transient conditions are still measurable but not dramatic.

Aquifer 1 is considered semi-confined and outcrops north of Clair Creek. Figure 2.16 shows higher levels to the west where a local topographic high occurs. Groundwater flow in Aquifer 1 is toward the east and discharges into Laurel Creek [*Planning and Engineering Initiatives Ltd.*, 1996]. Groundwater mounding is evident in the vicinity of Clair Creek indicating a local recharge area. Figure 2.17 indicates groundwater flow is toward the southwest for Aquifer 2. Again there is a slight mounding of hydraulic head around the center of the Waterloo West Side which shows a hydraulic connection to the upper aquifer and recharge from the north branch of Clair Creek. As discussed previously, the piezometric heads for the two deeper aquifers were combined and plotted in Figure 2.18. The southeast regional groundwater flow trend is dominant in the deeper units. Regional groundwater flow is to the south, and southeast toward the Grand River.

Groundwater flow in the area, as a whole, is assumed to be at, or near steady-state. From previous studies, observed flow transients are restricted to the upper 5 to 10 m of overburden where low surficial permeability exists. Much of the shallow work in the area, including testpits and test holes, showed intermittent groundwater seepage where water occurred in one testpit but not the next. A large portion of water is stored in the upper 4-6 m of fractured till in Subwatershed 314 which becomes interflow and discharges into local creeks [*Dorfman*, 1996]. Water pooled in low lying areas is referred to as Depressional Storage (DS). DS is an important factor in recharging groundwater even in areas of low surficial permeability.

The annual water level trends from a select number of multi-level wells are shown in Figure 2.19. The data for each well in Figure 2.19 are included in Table 2.2 and the locations of these wells are shown in Figure 2.20. The water levels are monitored by the Region of Waterloo [*Terraqua Investigations Ltd.*, 1994]. Measured water level data from June 1, 1993 to May 28, 1994 are included. These six wells were chosen because they are monitored regularly. Multi-level wells are important because they demonstrate the hydraulic connection between hydrostratigraphy. For instance, WM-08-93-I and WM-08-93-D are grouped into the same hydrostratigraphy because the hydraulic heads are similar while WM-08-S is clearly perched. The trends seen in Figure 2.19 seem to suggest that the groundwater in the area is at

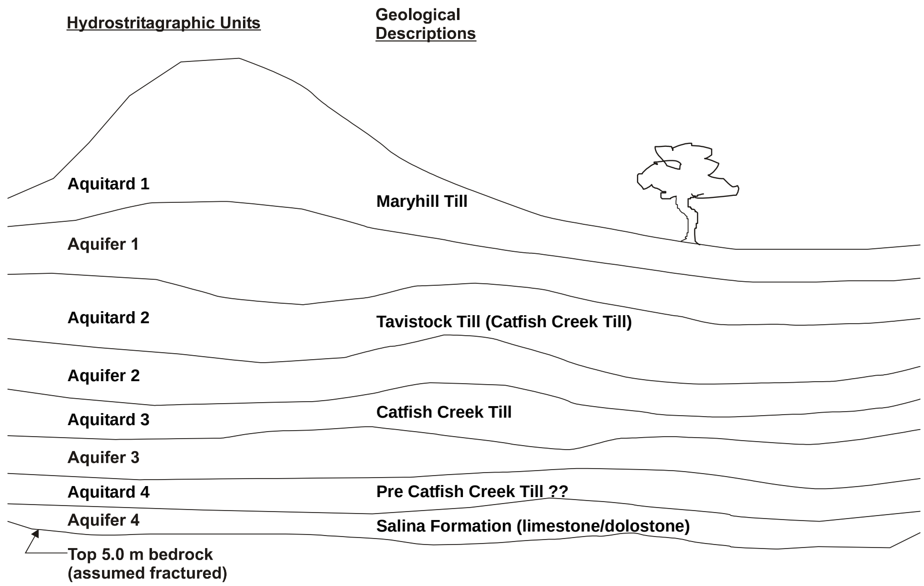

Figure 2.12. Conceptual model for hydrostratigraphy.

steady-state. As with past studies, this assumption that the lower more regional aquifers are at steady-state will be used in this research [*Rudolph*, 1985][*Martin*, 1994][*Callow*, 1996]. The other point to note from Figure 2.19 is that even in the more shallow wells such as TR 1-5 and WM-08-93-S, the water level fluctuations are less than 0.5 m over the year which suggests steady-state conditions. Storm events do not seem to be reflected in the monitoring wells. This is assumed to be the result of unsaturated flow which dampens the response [*Terraqua Investigations Ltd.*, 1993].

2.7 Municipal Well Fields

The Regional Municipality of Waterloo obtains 75% of its drinking water from groundwater wells and 25% from the Grand River. There are a total of 126 wells in the region that produce groundwater from the overburden throughout the Waterloo Moraine and from bedrock in the Cambridge area. The major well fields are indicated in Figure 2.21. There are no well fields within the Waterloo West Side although two well fields border the Waterloo West Side: the Waterloo North and Erb St. well fields. The Waterloo North well field is located to the northeast of the study area and includes W4, W5, and W10 (Figure 2.20). W5 was not in

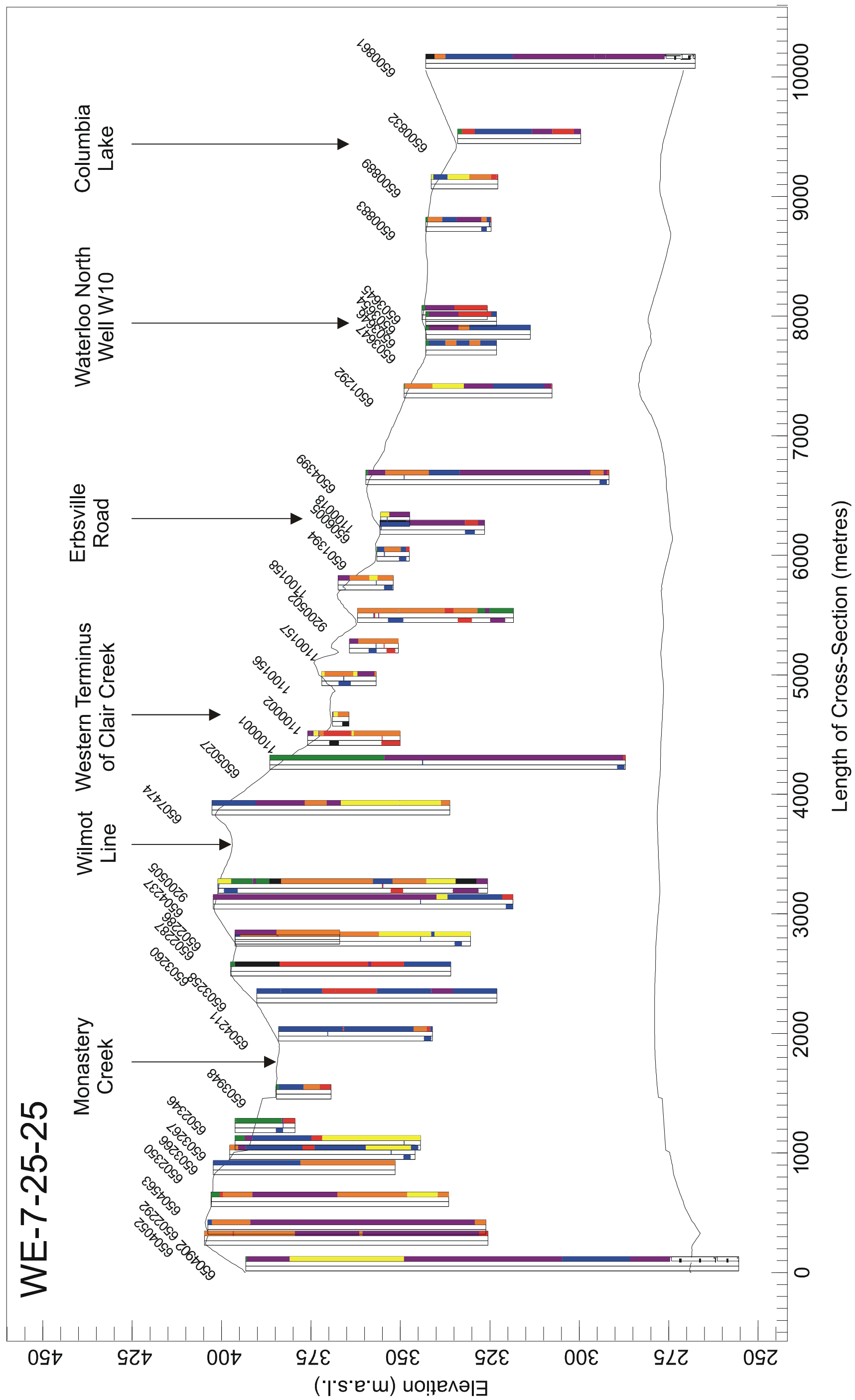

Figure 2.13. Sample cross-section, WE-7-25-25, showing top of model (ground surface) and base of model (unfractured bedrock). Three columns are given for each borehole; see Figure 2.15 for their description. Figure 2.14 shows the location of the cross-section.

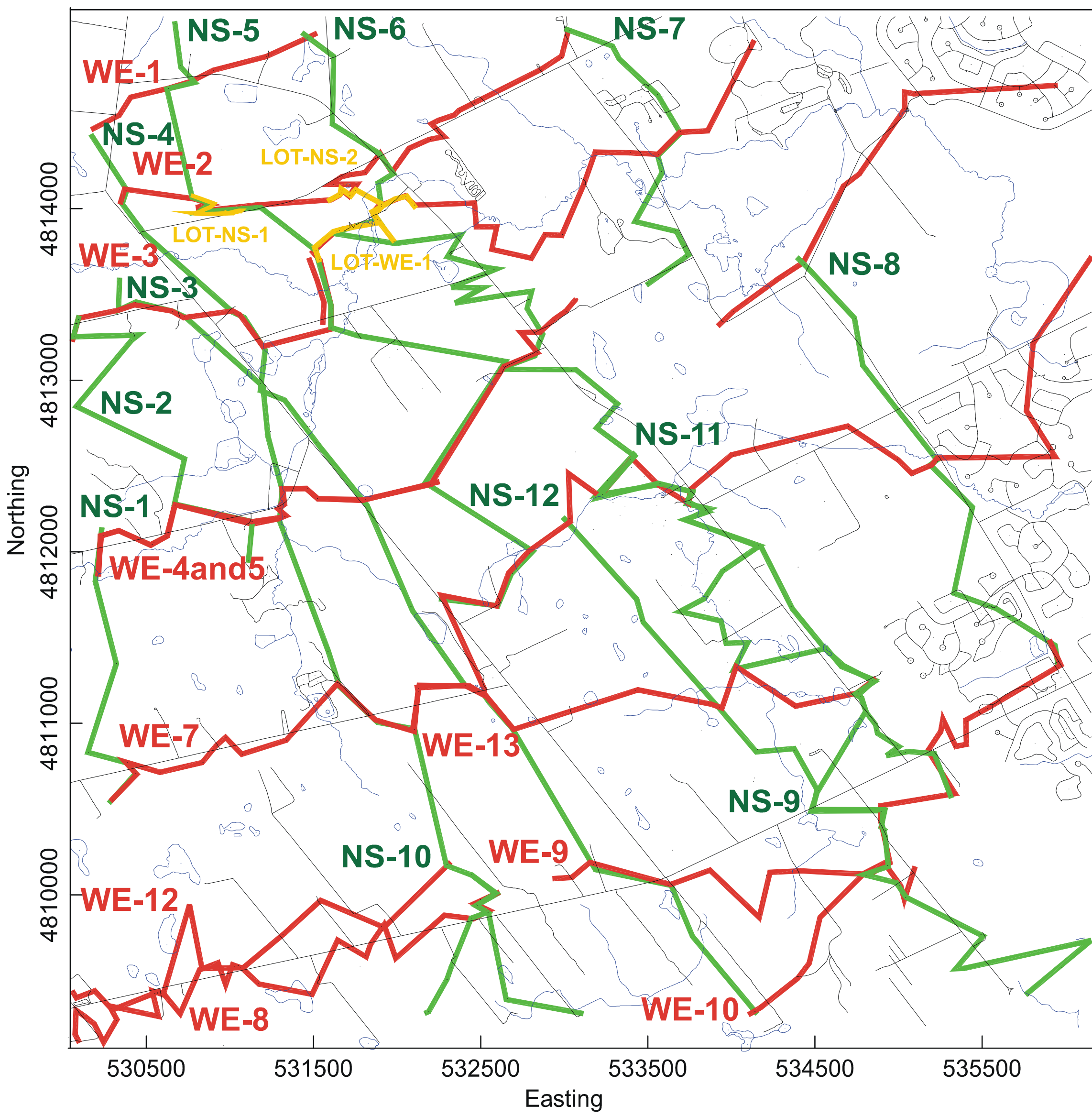

Figure 2.14. Cross-section locations in plan view for the Waterloo West Side. Cross-sections from north to south are in green, cross-sections from west to east are in red. Detailed cross-sections are labeled in orange.

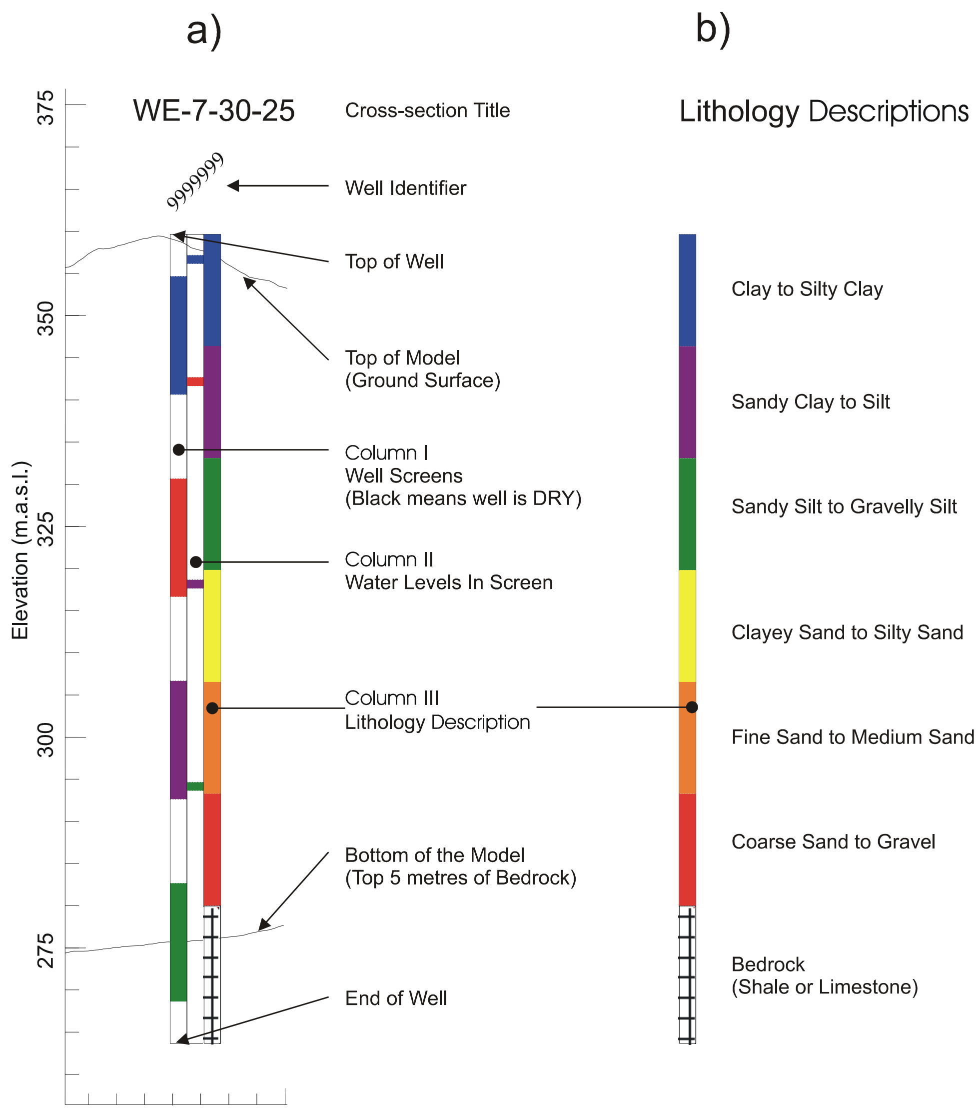

Figure 2.15. Lithology cross-section legend: a) attributes of the cross-section, and b) coresponding material types.

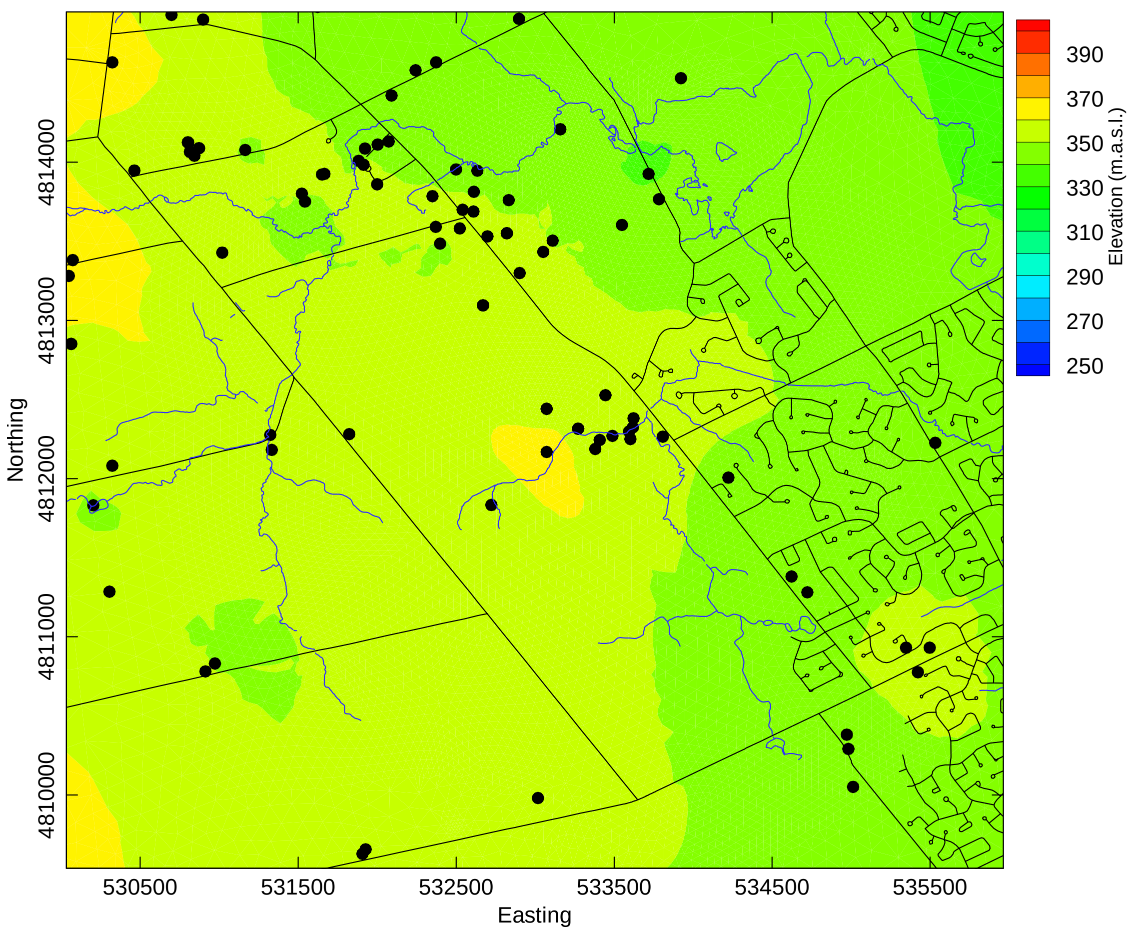

Figure 2.16. Waterloo West Side site map - piezometric head distribution for semi-confined Aquifer 1. Black circles represent locations of measured water levels.

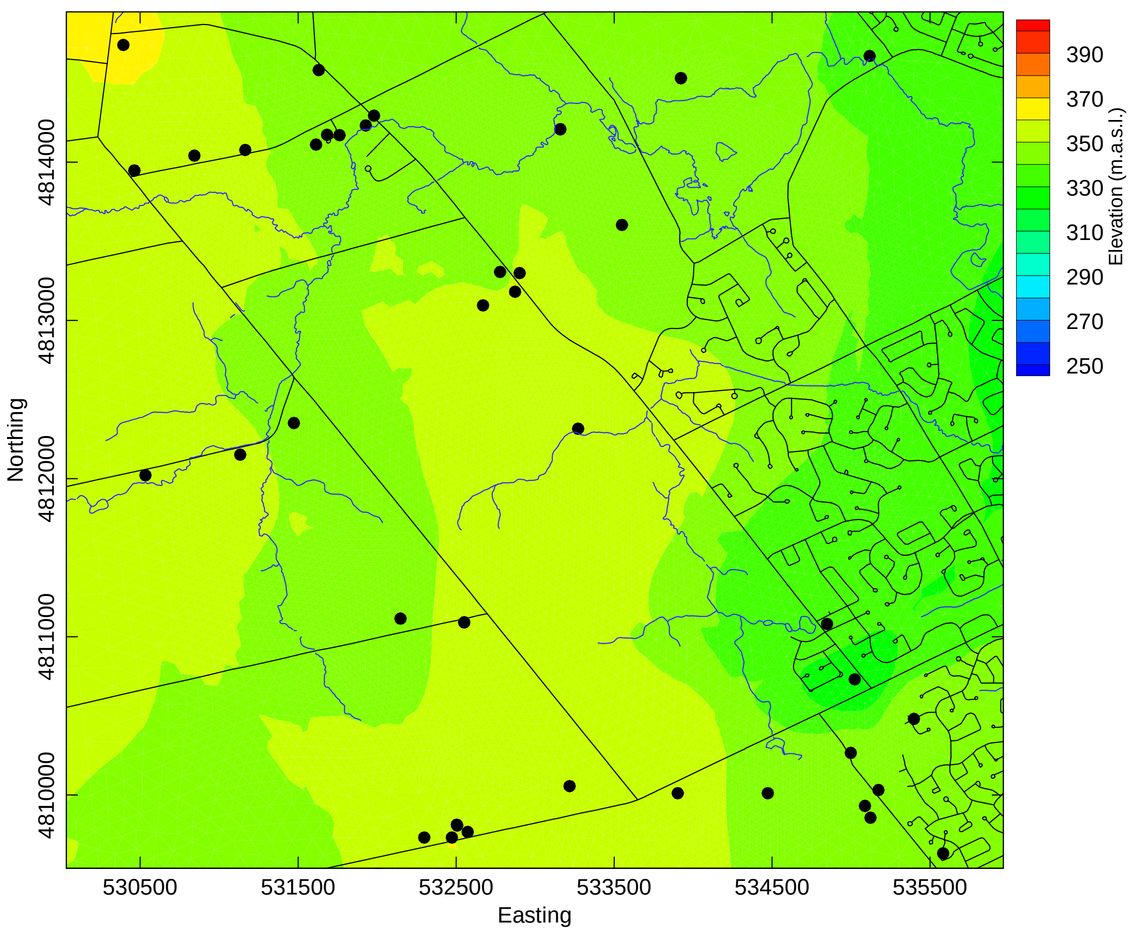

Figure 2.17. Waterloo West Side site map - piezometric head distribution for confined Aquifer 2. Black circles represent locations of measured water levels.

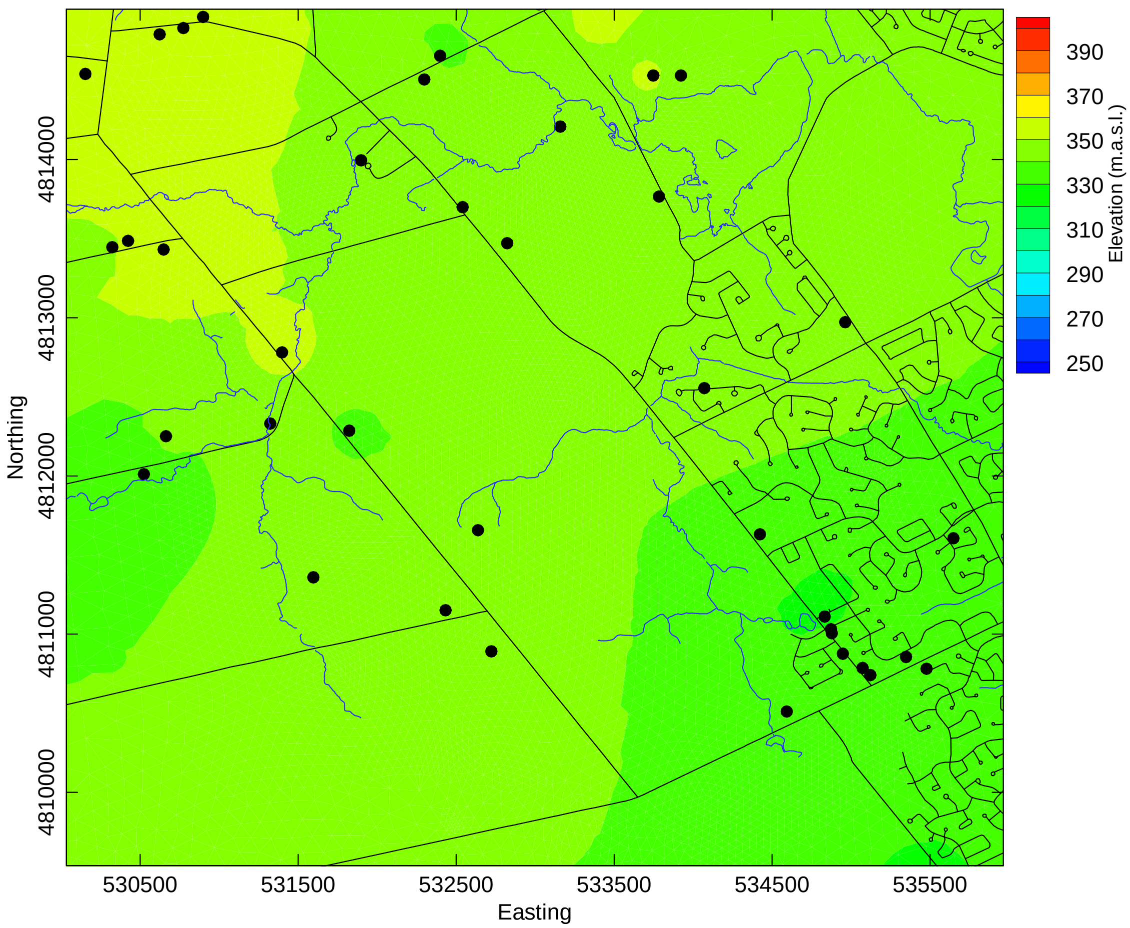

Figure 2.18. Waterloo West Side site map - piezometric head distribution for confined deep aquifers (Aquifers 3 and 4). Black circles represent locations of measured water levels.

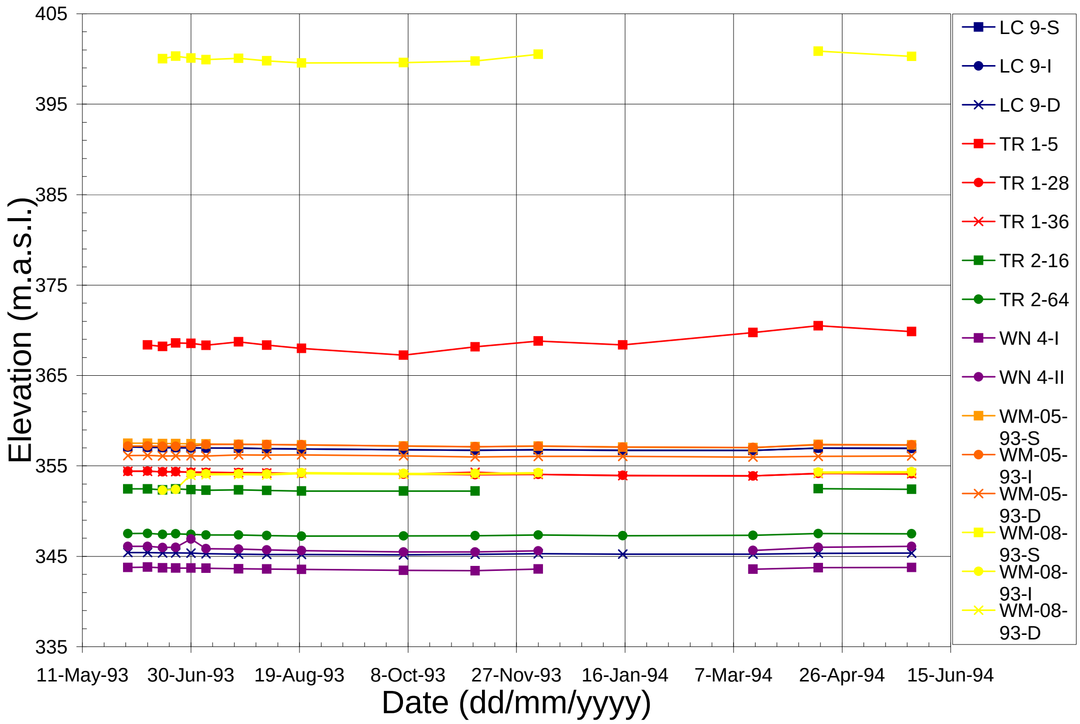

Figure 2.19. The annual trend of water levels for a select number of multi-level wells monitored in the Waterloo West Side. Installation data for each well are given in Table 2.2 and locations indicated in Figure 2.20.

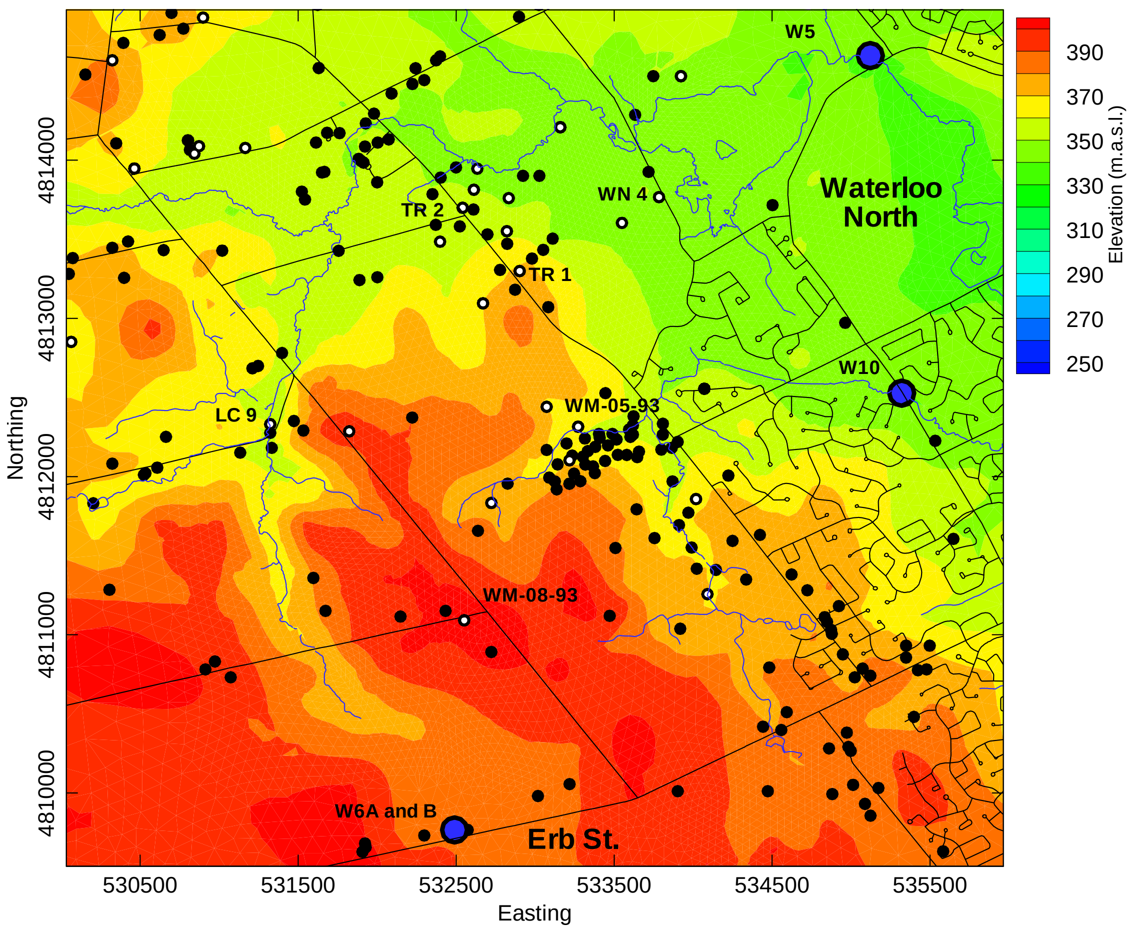

Figure 2.20. Waterloo West Side site map - locations of observation wells and municipal wells in the study area superimposed on topography. White centers represent multi-level installations. Multi-level wells used in Figure 2.19 are also labeled.

Well Name	Level	Well Number	Screened Interval (m.b.g.s.)	Hydrostratigraphic Unit	X-section
LC 9	S	9150022	6.0 – 9.2	Upper	WE-5
	I		14.0 – 18.5	Upper	
	D		70.0 – 76.0	Intermediate	
TR 1	5	9999008	1.5 – 6.1	Perched	NS-6
	28		22.9 – 30.2	Upper	
	36		37.3 – 37.1	Upper	
TR 2	16	9999011	12.8 – 18.3	Upper	NS-6
	64		60.1 – 66.5	Deep	
WN 4	I	9180002	5.0 – 7.0	Upper	NS-7
	II		58.0 – 61.0	Deep	
WM-05-93	S	9200502	8.6 – 12.8	Upper	WE-7
	I		28.0 – 32.0	Upper	
	D		37.1 – 41.3	Intermediate	
WM-08-93	S	9200505	1.7 – 5.5	Perched	WE-7
	I		48.3 – 51.7	Intermediate	
	D		65.7 – 72.8	Intermediate	

Table 2.2. Data for a select number of multi-level wells monitored in the Waterloo West Side. The screened interval and hydrostratigraphic unit numbers are included, as well as the cross-section identifier. Water level trends are included in Figure 2.19.

operation at the time of this study but is proposed for future water supply [*Terraqua Investigations Ltd.*, 1992]. W4 is to the east of the study area. The Erb St. well field is to the south of the study area and includes wells: W6A, W6B, W7 and W8. (Figure 2.20). The Erb St. and Waterloo North well fields extract groundwater from the upper two aquifers (Aquifers 1 and 2).

2.8 Infiltration Estimates

The total precipitation in the area ranges between 830 to 1000 mm/year which includes rainfall and snow melt [*Planning and Engineering Initiatives Ltd.*, 1996]. Typically, precipitation in the area averages 920 mm/year (Table 2.1) [*Dorfman*, 1996]. Much of the precipitation is absorbed by plant life and lost by evaporation. Evapotranspiration is close to 65 percent or approximately 590 mm/year for the study area (Figure 2.22) [*Planning and Engineering Initiatives Ltd.*, 1996][*Dorfman*, 1996]. The remainder of approximately 330 mm/year is defined the water surplus. The water surplus is distributed by three processes: overland flow (runoff), interflow and groundwater recharge. The potential recharge or infiltration is the water that enters the subsurface. Runoff does not enter the subsurface and is not considered part of the potential recharge. Runoff is a complex process which depends on a variety of surficial conditions. For this study, pre-development runoff is considered to be 10 percent of the total precipitation or 90 mm/year [*Planning and Engineering Initiatives Ltd.*, 1996][*Dorfman*, 1996]. The potential recharge (infiltration) for the area is therefore considered, for this study, to be approximately 240 mm/year when averaged over the entire year.

Many different infiltration rates have been estimated for the study area and are discussed. Subwatershed studies for 309, 308 and 313 characterize infiltration based on surficial soil descriptions [*Presant and Wickland*, 1971]. Soils are classified by parent materials, degree of weathering and drainage ability. An infiltration map was generated from this classification, where the infiltration estimates range from 245 to 182 mm/year. The average estimated infiltration for subwatersheds 313 and 309 are 193 and 204 mm/year, respectively. Values determined for Subwatershed 314 are considered potential recharge or infiltration which is quoted as 240 mm/year.

A two-dimensional groundwater model of the Trillium Estates area, estimated annual recharge rates ranging between 30 to 70 mm/year with an annual precipitation rate of 880 mm/year [*CH2M Hill Engineering Ltd.*, 1991]. These recharge

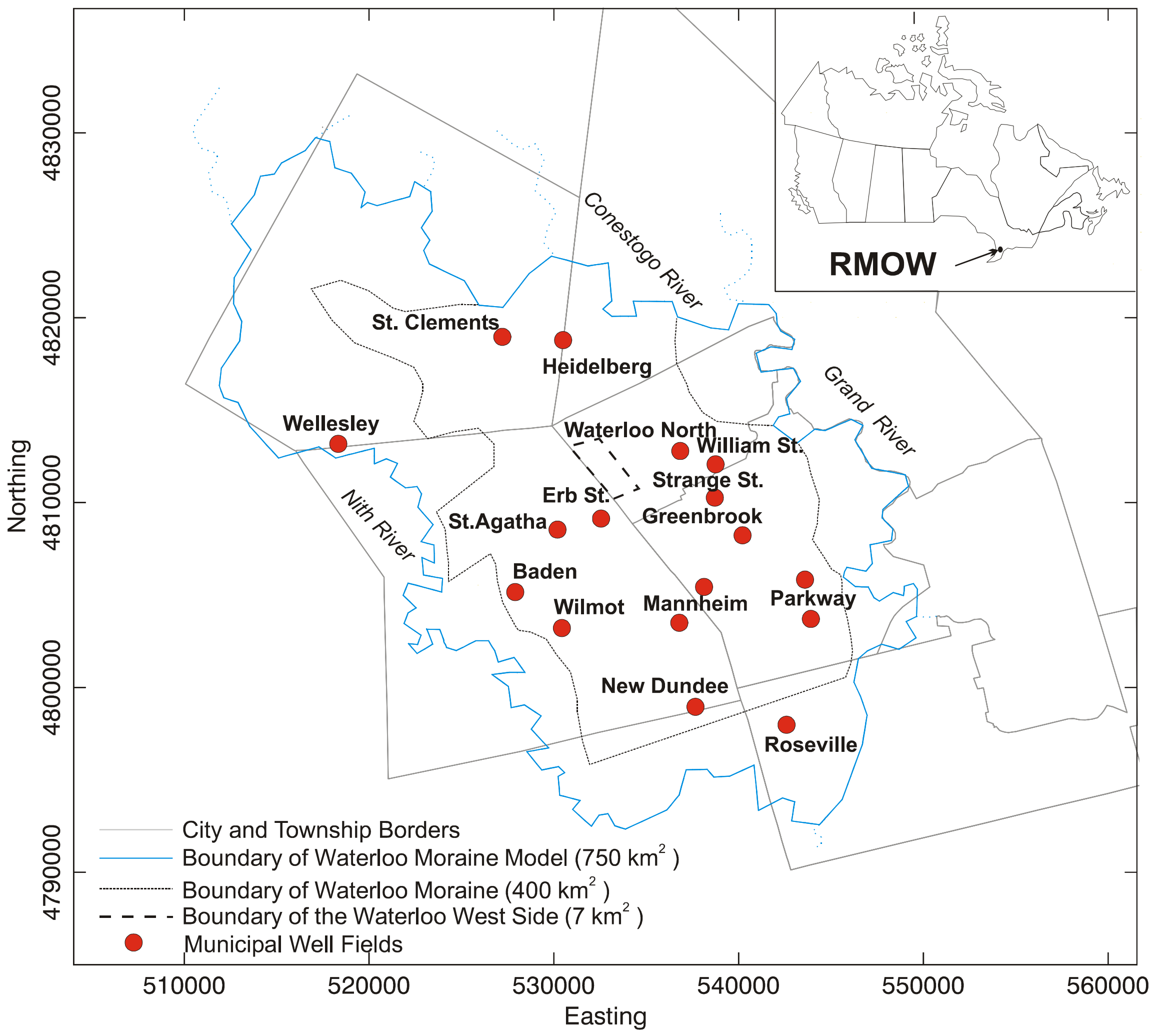

Figure 2.21. Location of municipal well fields within the Regional Municipality of Waterloo (RMOW).

rates are considered low due to assumptions made during modelling. The actual recharge rates are believed to be closer to 20%. Therefore, given 880 mm/year of precipitation, a recharge rate of 175 mm/year would be more reasonable.

Areas of potential and known recharge were estimated during the *Laurel Creek Watershed Study* [1993]. Recharge areas designated in the *LCWS* are illustrated in Figure 2.23. These boundaries are considered flexible and the *LCWS* recommends they should be re-examined on a subwatershed basis.

The complex nature of the hydrostratigraphy and hummocky terrain of the Waterloo West Side makes it difficult to map areas of recharge. Large-scale pumping tests conducted in the area showed recharge zones to be spatially complex [*Terraqua Investigations Ltd.*, 1992][*Lotowater Ltd.*, 1991]. Lands identified as potential recharge zones are designated as Constraint Areas level 1 or 2. As mentioned previously, the branches of Clair Creek, west and east of Erbsville Road, are thought to be important recharge areas. The functionality of the Clair Creek Valley is to be maintained with the designation of CA level 1 and 2 (Figure 2.3 on page 13). Much of the area to the east of ESPA #19 is designated CA level 2 and is considered a prime local and regional groundwater recharge area. This is based on the observed vertical gradients and the outcropping of Aquifer 1 in this area. Tritium dating of the groundwater below this recharge area indicates the groundwater to be 30 years old [*Terraqua Investigations Ltd.*, 1993][*Planning and Engineering Initiatives Ltd.*, 1996].

Land below the northern branch of Clair Creek and to the west of Clair Creek (southern branch) is part of Subwatershed 314. The surface is scattered with wetlands and unsaturated zones, the water table is 6 m below ground surface and is controlled by topography [*Dorfman*, 1996]. The subwatershed study recommends maintaining infiltration of approximately 240 mm/year over the entire Subwatershed 314.

2.9 Stormwater Management for the Waterloo West Side

Based on recommendations from the *LCWS* [1993], subwatershed plans are to outline Best Management Practices to ensure that pre-and post-development infiltration and surface water flows are maintained. Infiltration rates have been mapped and creek flows have been identified by the subwatershed studies. The subwatershed targets have been previously discussed.

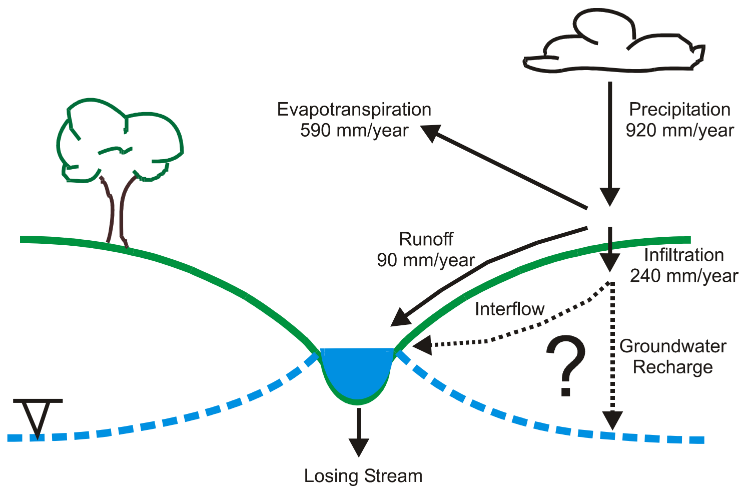

Figure 2.22. Conceptual model for water balance for the study area. Example illustrates a losing stream.

According to the *LCWS* [1993] stormwater runoff quality is to be maintained at pre-development conditions. For infiltration, contamination is of major concern especially where regional aquifer recharge is the focus, as urbanization reduces the quality of water and increases runoff in the watershed. Urban runoff is often of low quality due to contamination from a number of sources including metals, pathogens, nutrients, sediment, salts, pesticides/herbicides and petroleum products. Past practices would collect stormwater from urbanized areas into the city sewer system thereby removing all water from the watershed. Recent practices, on the other hand, utilize a complex system of managing urban runoff to maintain or enhance the watershed conditions.

Surface water flow, in local creeks, is controlled in post-development by the collection of urban runoff into Stormwater Management Ponds (SWMPs). In some cases, water is pretreated before entering the SWMPs using oil/water separators and/or sediment catchers. The purpose of the SWMPs is two fold: dampen flow rates to the creeks to match natural runoff rates and improve water quality through wetland pre-treatment. Water from SWMPs is cooled prior to introduction into the stream using a gravel cooling trench. SWMPs are designed to retain urban runoff and therefore are lined with local low permeability soils to ensure containment.

Infiltration rates or recharge are also artificially controlled and in some cases enhanced. Infiltration can be controlled on a small scale using soakaway pits and on a larger scale with infiltration galleries. Infiltration galleries are larger versions of soakaway pits. Soakaway pits are buried gravel-filled trenches, installed above

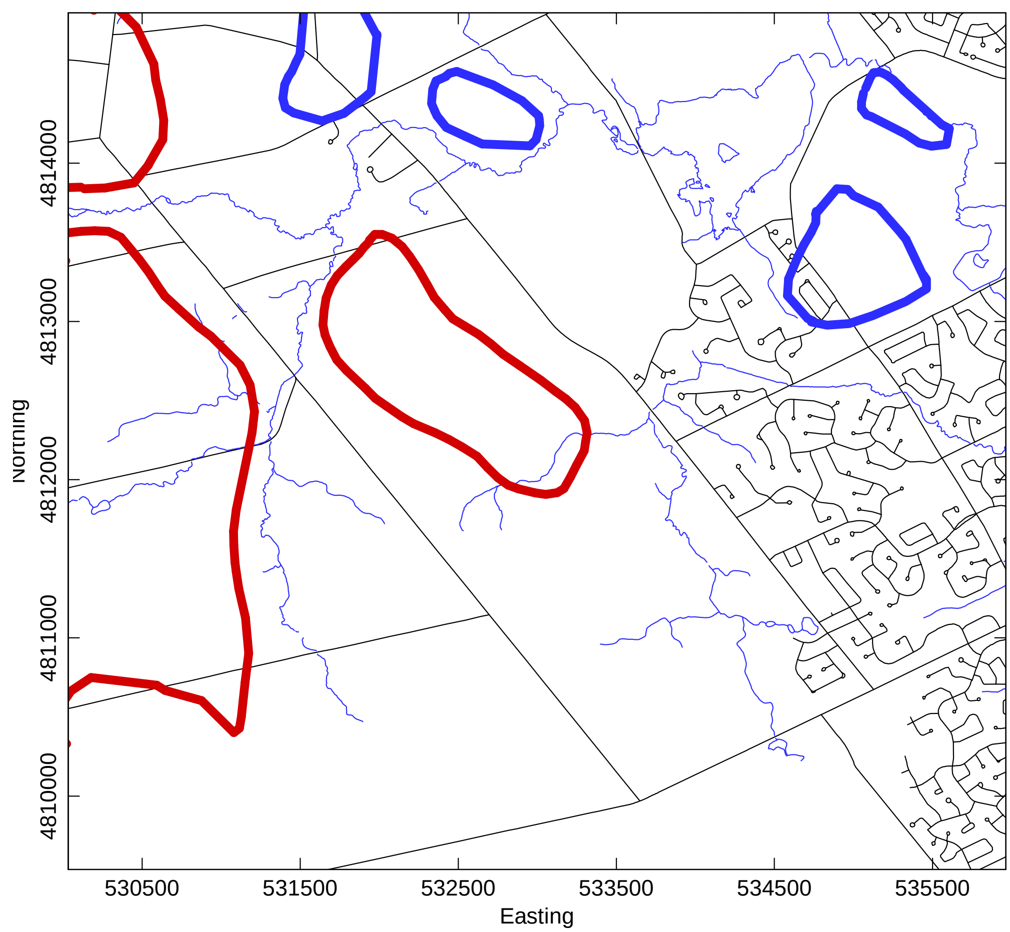

Figure 2.23. Waterloo West Side site map - known and potential recharge areas designated by the *Laurel Creek Watershed Study* [1993] for the Waterloo West Side. Known areas of recharge are outlined in red. Potential areas of recharge are outlined in blue.

the water table, where water drains by gravity into the underlying sediments and used to direct clean runoff from residential roofs. Infiltration galleries are used where runoff is captured from larger surfaces such as roofs of commercial buildings and road runoff.

Stormwater management is outlined in detail for each subdivision [*Paragon Engineering Limited*, 1997][*Planning and Engineering Initiatives Ltd.*, 1997][*Planning and Engineering Initiatives Ltd.*, 1998c]. The areas of Columbia Forest I and II have infiltration targets of 221 and 192 mm/year, respectively. Rosewood Estates are assumed to have similar infiltration rates as Columbia Forest I. Clair Hills and Erbsville Road Developments are required by subwatershed management plans to ensure infiltration of 240 mm/year.

Stormwater management plans for Columbia Forest I and II include artificial infiltration methods previously described. Each building will have a soakaway pit installed on public land (to ensure access) to infiltrate clean roof runoff. These soakaway pits will be designed to infiltrate the first 20 mm of roof runoff, any excess will over-flow into the sewer system. Studies show that this will be the equivalent of 675 mm/year of infiltration. Therefore, Columbia Forest I and II will have an average (based on area) of 117 and 103 mm/year of roof runoff as infiltration respectively [*Planning and Engineering Initiatives Ltd.*, 1997][*Planning and Engineering Initiatives Ltd.*, 1998c]. Pervious areas in each subdivision will provide 75% of the natural infiltration which results in an additional 83 and 75 mm/year of infiltration for Columbia Forest I and II respectively. The resultant infiltration totals fall short of the target values by 21 and 14 mm/year respectively.

To augment the infiltration deficit, runoff will be collected from roads and impervious areas for infiltration galleries. Prior to entering the infiltration galleries, runoff will be treated to remove sediment and petroleum products using oil/water separators. To avoid road salt contamination, the infiltration galleries will be disconnected in the fall.

Clair Hills and Erbsville Road developments are part of Subwatershed 314 where the surficial soils are of lower permeability. After a detailed geotechnical study, the stormwater management plans concluded that the soils are unable to effectively utilize soakaway pits [*Paragon Engineering Limited*, 1997]. Therefore, soakaway pits will be utilized only were soil conditions will permit. Where soakaway pits are ineffective, at-source control measures will be implemented where grading permits such as discharging downspouts to back yards.

Future development in the area is still in the design stages and information is not currently available. The previously developed area at the intersection of Erbsville Road and Erb St. has no infiltration measures and is considered impervious. Trillium Estates also does not have any infiltration systems in place.

Chapter 3

Numerical Modelling Theory

3.1 Numerical Model

3.1.1 Introduction

Large-scale hydrogeological systems involve many complex natural processes which are often difficult to simulate because of a lack of adequate field data and high computational effort. Choices must always be made with respect to the number and types of processes to include, and with respect to the amount of field data to incorporate.

In modelling groundwater systems, for example, one can choose either fully saturated models which eliminate the vadose zone or more complex models which include partially saturated media. Choosing a saturated model may reduce the complexity of a problem but at a cost of introducing greater uncertainty and error. Saturated models often have difficulty describing flow near the water table, and cannot accurately describe perched conditions.

On the other hand, variably saturated models allow for the coupling of unsaturated flow and saturated flow. These types of models have been in used for many years but most are limited to small-scale problems and have not been applied at the watershed scale. Also, variably saturated models require detailed parameters and are computationally demanding. Currently, an experimental variably saturated model (HTS) [*VanderKwaak*, 1999] is being applied to the Laurel Creek Watershed in Waterloo [*Sudicky et al.*, 2000].

The software chosen for this study is WATFLOW [*Beckers et al.*, 2000] , a fully-three-dimensional finite-element code developed at the University of Waterloo. A flow chart for WATFLOW is provided in Figure 3.1. GridBuilder [*McLaren*, 2000] was used to generate a two-dimensional grid that WATFLOW internally extends to three dimensions, under user specifications. Output from WATFLOW is visualized using either GridBuilder, GMS or Tecplot graphical utilities.

WATFLOW includes a pseudo-unsaturated model which approximates flow in the vadose zone by adjusting the relative permeability [*Bathe and Khosgoftaar*, 1979][*Desai and Li*, 1982]. This approach is somewhat simplified but applying a variably-saturated model at the watershed scale would require more detailed parameters and a significantly greater computational effort. The model is particularly suited for the Waterloo West Side which is characterized by complex hydrostratigraphy, large topographic relief, and thick unsaturated zones where perched water is common.

WATFLOW has other features that prove beneficial to this study, including use of prismatic elements which allow for a highly irregular mesh structure. A flexible mesh is important when mapping the hydrostratigraphic layering in glacial depositional environments where hydrostatigraphic units undulate and pinch out. In addition, WATFLOW has been shown to be stable with highly contrasting permeability fields typical of glacial terrain. Within the Waterloo West Side, the geological conditions are complex and clay deposits are often found adjacent to highly permeable materials.

Interflow is simulated within WATFLOW using a recharge spreading layer (RSL). A RSL is a layer of relatively higher permeability that is artificially blanketed over the top layer of the finite element mesh to allow infiltration to move throughout the surface from areas of low permeability to areas of higher permeability or to streams. By using a RSL, one can apply a uniform recharge along the surface of the entire model and flow is distributed according to permeability allowances. Without a RSL, infiltration would have to be spatially adjusted to eliminate water table mounding.

WATFLOW is a proven numerical model for glaciated environments and has been used in a variety of studies which include the Laurel Creek Watershed in Waterloo, Ontario [*Martin*, 1994]; the Waterloo Moraine Study in the Region of Waterloo, Ontario [*Martin and Frind*, 1998]; pumping-well optimization in Kitchener, Ontario [*Callow*, 1996]; the Oro Moraine Study in Halton Region, Ontario [*Beckers*, 1998] and capture zone studies for well head protection [*Muhammad*, 2000].

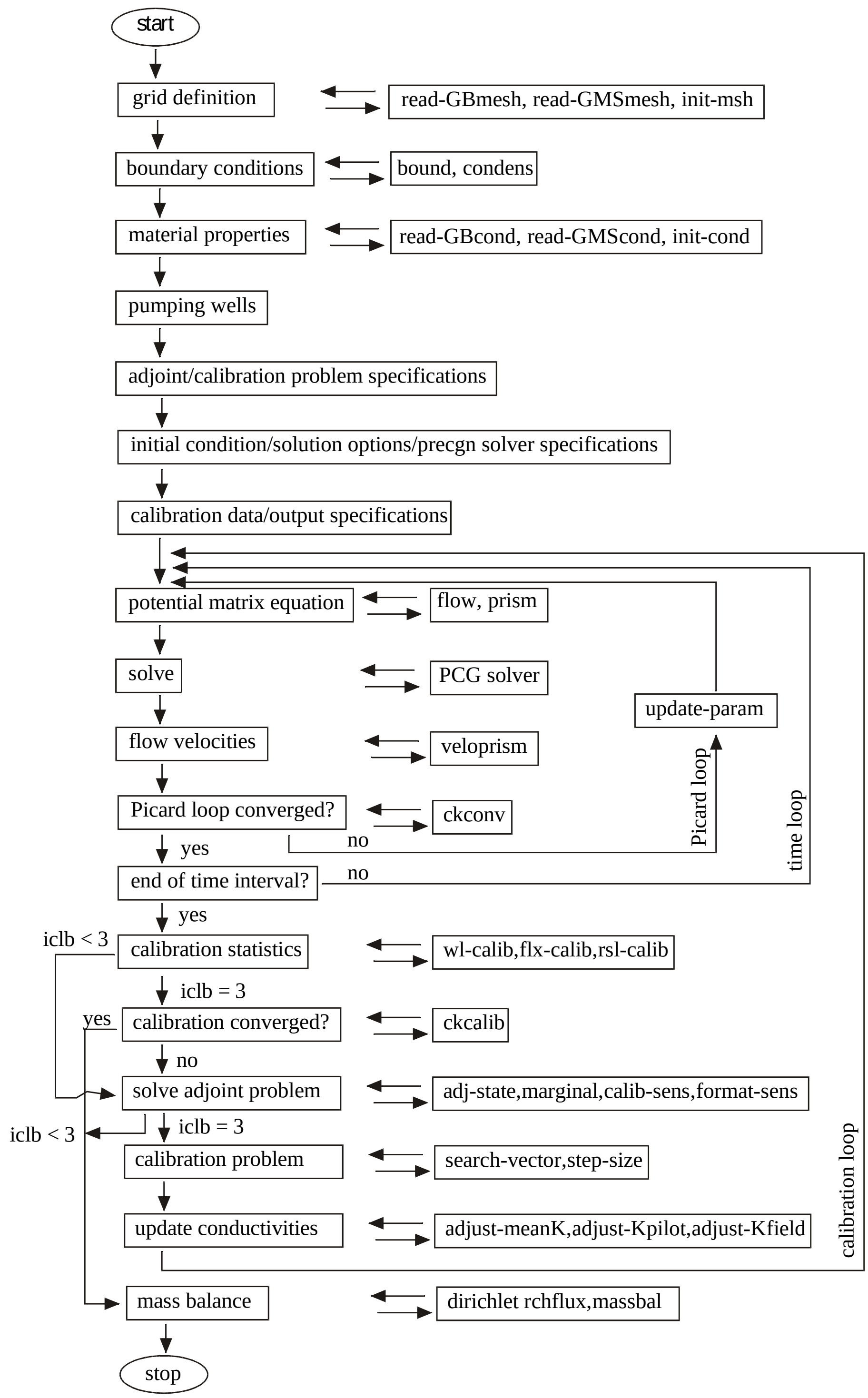

Figure 3.1. Flowchart for WATFLOW [*Beckers, Molson, Martin, and Frind*, 2000]

3.1.2 Governing Groundwater Flow Equation

The model is based on the general form of the differential equation for transient saturated flow in a homogeneous anisotropic porous medium [*Bear*, 1972]:

$$-\frac{\partial}{\partial x_i}\left[-K_{i,j}\left(\frac{\partial h}{\partial x_j}\right)\right]-\sum_{k=1}^{n}Q_k\cdot(x_k,y_k,z_k)=S_s\frac{\partial h}{\partial t} \tag{3.1}$$

where the Darcy flux is given by:

$$q_i=-K_{i,j}\left(\frac{\partial h}{\partial x_j}\right) \tag{3.2}$$

where h is the hydraulic head, x_i are the spatial coordinates, $K_{i,j}$ is the hydraulic conductivity tensor, t is time, Q represents sources or sinks, and S_s is the specific storage of the porous medium. Although WATFLOW is capable of solving transient flow, only steady-state flow was considered in this study. Equation (3.1) therefore becomes:

$$-\frac{\partial}{\partial x_i}\left[-K_{i,j}\left(\frac{\partial h}{\partial x_j}\right)\right]-\sum_{k=1}^{n}Q_k\cdot(x_k,y_k,z_k)=0 \tag{3.3}$$

since $S_s\frac{\partial h}{\partial t}=0$. WATFLOW utilizes the two standard boundary conditions for the solution of equation (3.1): Dirichlet or Type I, and Neumann or Type II given by:

$$\begin{aligned} h &= \widehat{h} \qquad on \quad \Gamma_1 \\ q_i\cdot n_i &= \widehat{q} \qquad on \quad \Gamma_2 \end{aligned} \tag{3.4}$$

where h is a specified head along a boundary Γ_1 for the Dirichlet condition, q_i is the specified Darcy Flux and n_i is a unit vector both normal to boundary segment Γ_2. For this study, surface water conditions are represented using Dirichlet boundaries.

To numerically solve the governing flow equation (3.1), WATFLOW utilizes a number of numerical techniques. A three-step process is used to discretize the domain. A triangular finite-element grid is first generated in two-dimensions using the pre-processor GridBuilder [*McLaren*, 2000]. Each geological contact (aquifer/aquitard or ground surface) is then interpreted onto the two-dimensional mesh. These contact surfaces are then stacked by WATFLOW using user-specified options to create a three-dimensional grid of triangular prismatic elements. The advantage of using this method of discretization allows irregular and complex contacts to be included. To simulate pumping/injection well-bores, WATFLOW uses 1D line elements following the approach of *Sudicky et al.* [1995].

For this work, the standard Galerkin finite element method was used to solve the governing flow equation [*Huyakorn and Pinder*, 1983]. The matrix equation is solved using an efficient pre-conditioned conjugate gradient solver with a block-line relaxation procedure to manage high vertical aspect ratios for the elements [*Braess and König*, 1995].

WATFLOW uses a Picard loop, shown in Figure 3.1, to obtain covergence of the flow solution. Within the Picard loop, the location of the water table is found, parameters are updated, and the flow solution is tested based on user-determined criteria for the hydraulic head update:

$$|h_{i,k} - h_{i,k-1}| < \triangle h_{crit} \qquad i = 1, 2, ...nn \tag{3.5}$$

where $h_{i,k}$ is the head solution for node i and iteration k, nn is the number of nodes in the domain, and $\triangle h_{crit}$ is the user defined maximum change in head between iterations.

3.1.3 Recharge Spreading Layer

Often in groundwater flow simulations, the upper boundary is set as a Neumann (Type II) boundary to simulate recharge. *Knupp* [1996] showed that a specified flux condition is an approximation of a true free-surface boundary. However, at steady-state, the specified flux condition and the kinematic conditions are equal. The main advantage of using a Type II boundary condition is that the water table is allowed to fluctuate to some equilibrium with the specified recharge.

The disadvantage in fixing the upper boundary as Type II is that the entire domain is forced to accept a user-defined flux. For elements that contain relatively low permeability material, high gradients are required to achieve the specified flux. The hydraulic head above these elements therefore can build up, causing local water table mounding. Flow problems can also become unstable and difficult to solve and often have unrealistic solutions. In glacial terrain, this becomes even more of a problem as the surficial permeability can vary over several orders of magnitude (e.g. 10^{-3} m/s to 10^{-10} m/s).

Methods often implemented to avoid water table mounding include using specified head or Type I boundary conditions, seepage face routines, and scaling the flux to underlying permeability, all of which are subjective and problematic to implement. WATFLOW uses a recharge spreading layer (RSL) for redistributing recharge from areas of relatively low permeability to areas of relatively high permeability. This method has been used to redistribute surface flow above fractured media [*Therrien and Sudicky*, 1996] and above low-permeable glacial units [*Martin and Frind*, 1998]. The recharge spreading layer is a thin blanket of relatively high-permeability material superimposed over the surface of the domain. This method conceptually imitates interflow. The potential recharge is applied uniformly over the surface of the domain allowing flow that cannot penetrate the lower conductivity units to move laterally through the RSL to units of relatively higher-permeability or to Type I boundaries. Any flow surplus is lost to Dirichlet boundaries, such as rivers, creeks, wetlands, and streams. The permeability and thickness of the RSL is user defined.

3.1.4 Pseudo-Unsaturated Module

A pseudo-unsaturated module was added to the WATFLOW code to account for flow above the water table [*Beckers*, 1998]. This is referred to as a pseudo-unsaturated model because the unsaturated flow is estimated by scaling the hydraulic conductivity based on the relative saturation of the element. This enables the mesh structure to remain constant and only the elemental conductivity needs to be updated.

The pseudo-unsaturated model (see Figure 3.2) uses an empirical relationship to determine the saturation on an elemental basis between the pressure head $p = h - z$ and the saturation of the porous medium S:

$$\begin{aligned} S(p) &= S_r + (1 - S_r)e^{\varepsilon p} \qquad && p < 0 \\ &= 1 && p \geq 0 \end{aligned} \tag{3.6}$$

where S_r is the residual saturation of the porous medium, and ε controls the relationship between saturation and residual saturation, where:

$$\begin{aligned} K_{i,j} &= S(p)K_{sat} & p < 0 \\ K_{i,j} &= S_r K_{sat} & p << 0 \\ K_{i,j} &= K_{sat} & p \geq 0 \end{aligned} \tag{3.7}$$

where K_r is the relative permeability and K_{sat} is the saturated permeability.

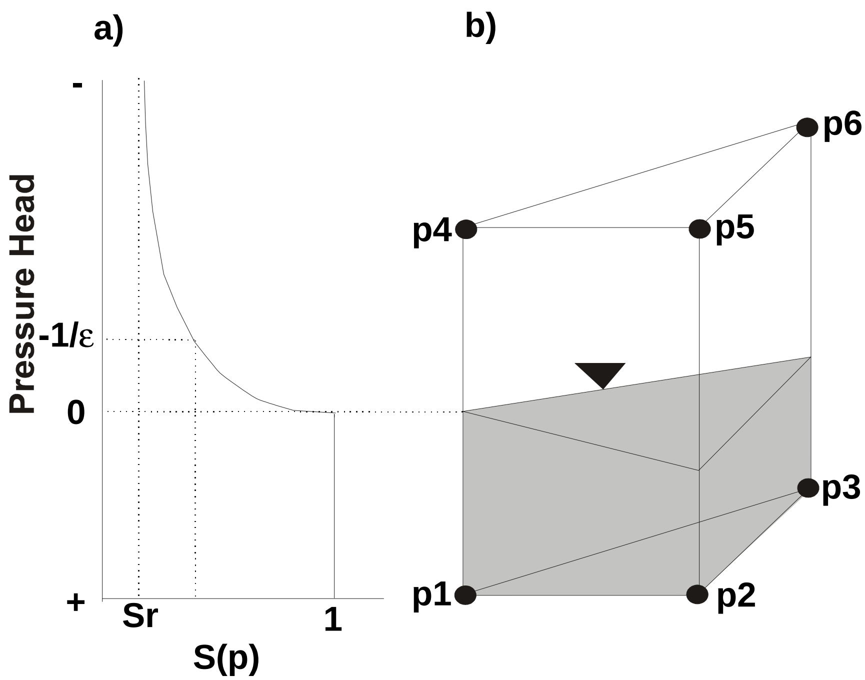

Figure 3.2. Pseudo-unsaturated curve relationship (a) exponential pseudo-unsaturated relationship and (b) partially saturated element (grey portion is below the watertable) [*Beckers, Molson, Martin, and Frind*, 2000].

The convergence of the numerical solution is controlled by equation 3.5. In addition to ensuring convergence of the head solution, WATFLOW ensures the saturation update has also converged using:

$$\left|\overline{S}_{i,k} - \overline{S}_{i,k-1}\right| < \triangle S_{crit} \qquad i = 1, 2, ...ne \tag{3.8}$$

where $\overline{S}_{i,k}$ is the saturation solution for element i and iteration k, and ne is the number of elements in the domain, and $\triangle S_{crit}$ is the user defined maximum change in saturation updates between iterations.

3.1.5 Flux Calculations

Flux calculations are determined on an elemental basis and are applied at the element centroid. Gradients across the elements are calculated using all six nodes of the element. To determine the flux through a specified element the elemental velocity is first calculated using:

$$V_x = \frac{-K_{xx}}{2\Delta\theta} \sum_{i=1}^{6} h_i b_i \tag{3.9}$$

$$V_y = \frac{-K_{yy}}{2\Delta\theta} \sum_{i=1}^{6} h_i b_i \tag{3.10}$$

$$V_z = \frac{-K_{zz}}{2\Delta\theta} \sum_{i=1}^{3} \left[h_i \left(\frac{-a_i - b_i x_c - c_i y_c}{h} \right) + h_{i+3} \left(\frac{-a_{i+3} - b_{i+3} x_c - c_{i+3} y_c}{h} \right) \right] \tag{3.11}$$

where V_x, V_y, and V_z are three-dimensional velocity components; K_{xx}, K_{yy}, and K_{zz} are the elemental hydraulic conductivities in the x, y, and z, directions; Δ is the surface area of the triangular element; θ is the elemental porosity; ϕ_i is the calculated hydraulic head at each of the six nodes of the three-dimensional element; h is the average height of the element; x_c and y_c are the element centroid coordinates; and a_i, b_i, and c_i are geometric parameters derived by counter-clockwise cyclic permutations over the nodes [*Huyakorn et al.*, 1986] . In WATFLOW, porosity is mapped to the hydraulic conductivity as outlined by *Domenico and Schwartz* [1990].

The elemental flux is directly determined from the elemental velocities calculated in equations 3.9 to 3.11 using:

$$q_i = -V_i \theta S(p) \tag{3.12}$$

where q_i is the directional flux, V_i is the corresponding directional velocity, and $S(p)$ is the elemental saturation.

3.1.6 Automated-Calibration Module

As the complexity of numerical models continue to grow, they can also become more difficult to calibrate. To facilitate calibration, WATFLOW incorporates an automated method for calibration and was developed by *Beckers* [1999]. This automated-calibration module is based on the work of *Neumann* [1980] and *de Marsily* [1984]. The routine was used here to adjust the hydraulic conductivity until the simulated heads matched the observed heads. A full description of the automated-calibration routine is given by *Beckers* [1999].

Inverse methods minimize an objective function that describes the fit of the model to a set of observations. An often-used performance measure is the weighted least squares residual between the predicted (h) and observed (h^*) hydraulic heads:

$$J_h = \sum_{i=1}^{NH} c_i [h_i - h_i^*]^2 \tag{3.13}$$

where NH is the number of point head data c_i are the calibration weights. If flow measurements are know then an additional performance measure can be used to constrain the hydraulic conductivity solution.

For an optimal fit, the objective function J_h must be minimized. The simplest approach to parameterization is to divide the domain into discrete 'zones' or grouping of elements which are believed to have similar flow properties, an aquifer and aquitard, for example. This is called the zonation approach. For the zonation method, the objective function (J_h) is minimized by changing the average hydraulic conductivity of a zone. The effect on the objective function of a uniform change in the hydraulic conductivity for a zone is calculated by a direct sum of the elemental sensitivity coefficients.

The automated-calibration routine is solved in a non-linear inner iteration, (see Figure 3.1). The calibration parameters are adjusted until convergence is achieved.

The automated-calibration routine requires an initial set of parameters: a value for each zone or grouping of elements. Unity is often chosen for the first calibration attempt. After the initial flow solution has converged, the objective function J_h, is computed. The gradient of the objective function is used to determine the direction of update to minimize the objective function. This is done using the Fletcher-Reeves conjugate gradient method. An optimum advance step (parameter update length), is determined using a Newton iterative search subject to user specified constraints. The user specifies the upper and lower bounds on the final update parameters to ensure realistic final updates.

3.2 Parameterization

3.2.1 Introduction

Geological deposits and their corresponding physical parameters are spatially complex due to dynamic processes which control deposition. Defining a realistic distribution of these parameters is therefore an important step in the formation of a numerical model. Different methods of parameterization, however, will produce different distributions and ultimately different simulation outcomes. Defining the spatial distribution of hydraulic conductivity, for example, is particularly problematic.

Although direct hydraulic conductivity measurements are included from pumping tests, the majority of the data for this study were inferred from well drillers' logs. Previous work in the area has enabled the direct correlation of the data from lithology descriptions. It is also important to realize the direct hydraulic conductivity measurements included in this study are only focused on lithology of higher permeability, where these lithologies are often the target of interest.

It has been shown that the vertical distribution and interconnection of the high-permeability units play a significant role in the behaviour of groundwater flow [*Fogg*, 1986]. Hydrogeological 'windows' (areas where confining units pinch out), for example, have been shown to be particularly important, and have been shown, in a conceptual sense, to have a critical effect on groundwater flow patterns [*Martin and Frind*, 1998]. This concept is most evident in well head protection and capture zone studies where vertical gradients can become very high [*Martin and Frind*, 1998] [*Muhammad*, 2000].

Definition of the subsurface hydrostratigraphy is a crucial step in numerical modelling and requires a hydrogeologic insight [*Martin and Frind*, 1998]. Fully automated structure-imitating procedures which interpret well logs to generate a conductivity field would not have performed well due to the complex distribution of data. Professional insight involves generating and interpreting cross-sectional correlations between the well logs to map hydrostratigraphic features based on geologic and hydrographic trends. The same procedure was adopted by *Martin* [1998] for the Waterloo Moraine Model, and by *Beckers* [1999] for the Oro Moraine, near Barrie, Ontario.

Hydraulic conductivity can often vary laterally over several orders of magnitude within a single unit, and sharp vertical contrasts of several orders of magnitude are not uncommon. This type of complex distribution is typical of glaciated terrain. To reduce uncertainty in the interpolation method, the subsurface is therefore grouped into 'similar' geologic materials where the variability within the unit is constrained.

In order to develop a geologic distribution for the numerical model, the conductivity variations within each unit need to be included. This information is generated from the water well records. Parameterization requires the combination of two methods: first, a method of generating the structural understanding of aquifer and aquitard units, and second, a structure-imitating method is used to define the heterogeneity within each hydrostratigraphic unit. Therefore, a database of two sets of spatial data will be required; one describing the contact boundaries of the units, and a second containing the distribution of observations for the lithology-derived hydraulic conductivity values.

Traditional methods of spatial interpolation for discrete observations include minimum curvature procedures, moving averages routines, least squares polynomials and splines. These methods are not appealing because they assume uncorrelated data. Geological data have inherent trends which are more closely represented by spatial statistical techniques, which make use of the auto-correlation exhibited by regionalized variables [*Davis*, 1986]. These methods often reproduce spatial trends found in geological systems without including the dynamics of the depositional environment [*Koltermann and Gorelick*, 1996]. Therefore, spatial statistical methods are well suited for defining the conductivity distribution in complex glacial deposits. Kriging, for example, has become a popular tool used to distribute geological data [*Delhomme*, 1978][*Delhomme*, 1979][*Martin*, 1994][*Beckers and Frind*, 1998]. Kriging allows the user to determine the uncertainty within estimated parameters, which can be beneficial for calibration modelling. In addition, kriging ensures that the observations are preserved in the final interpreted distribution field.

Methods for the spatial interpretation of the hydrostatigraphic contacts and the hydraulic conductivity are discussed in the next two sections. For more detailed information of these methods the reader is referred to *Davis* [1986] and the studies preceding this work, including *Martin* [1994] and *Beckers* [1999].

3.2.2 2D Kriging of the Hydrostratigraphic Contacts

A map of the hydrostratigraphy was created from well driller's logs defining the boundaries for each unit. This information is grouped together based on similar geological features, for example, aquifers and aquitards. The database includes point contact information defining each unit surface $z(x, y)$. Surfaces defining aquifer and aquitard interfaces are kriged in two-dimensional space by using these data.

Ordinary kriging or simple kriging is utilized where data are first-order stationary. In the case of geological deposits, however, as with most natural phenomena, datasets are not considered to be completely random and exhibit natural background trends. This background trend is referred to as drift. A dataset with an underlying trend is, by definition, not first-order stationary. Simple and ordinary kriging of data with a non-first-order stationary dataset can result in unnatural highs and lows in the interpolated field where no control points exist. Therefore, any large-scale trend(s) should be removed. One method is to remove drift from the dataset and then use ordinary or simple kriging. This can be difficult, however, if the trend is complex and low-order simple polynomial approximation is not valid over the entire domain. Universal kriging is a more efficient method of removing drift where the low-order polynomial is incorporated into the kriging equations. In practice, the entire dataset is not used, under the assumption that distant points will have a negligible effect on the estimated values. In this study, universal kriging is used to generate hydrostratigraphic layers.

3.2.3 3D Kriging of Hydraulic Conductivity Fields

Hydraulic conductivity values are inferred from litho-descriptions [*Martin and Frind*, 1998]. These values are combined in a database by hydrostatigraphic unit. Hydraulic conductivity values are then interpolated in three-dimensional space, by hydrostratigraphical unit, using kriging.

Hydraulic conductivity has been proven to be normally distributed in its log-transform state [*Sudicky*, 1986][*Woodbury and Sudicky*, 1991]. As outlined by *Beckers* [1999] and briefly mentioned here, earlier work by *Martin* [1994] used a two-dimensional kriging method for the K-field distribution. *Martin* [1994] determined a single horizontal ($K_{xx} = K_{yy}$) and vertical (K_{zz}) hydraulic conductivity at each well using the lithologies that were contained within the hydrostratigraphic unit boundaries using the arithmetic and harmonic averages, respectively. The K-field was generated in two dimensions resulting in a laterally heterogeneous distribution but vertically the hydrostratigraphic units were homogeneous. This averaging method was found to produce extremely high local anisotropy (K_{xx}/K_{zz}) often in excess of 10^6. As with any method that uses averaging, heterogeneities become somewhat smoothed. In addition, this method may not be appropriate for a three-dimensional numerical model (i.e. a 3D model should have 3D parameterization).

In an improved approach, *Beckers* [1999] incorporated a three-dimensional approach to determine the K-field within each hydrostratigraphic unit. A three-dimensional database was created from well logs for each hydrostratigraphic unit. Ordinary kriging equations were used to interpolate the hydraulic conductivity fields onto a three-dimensional mesh. The kriged log conductivity values are smoothed single realizations of the actual random functions. The same methodology was used in this study.

Chapter 4

Numerical Groundwater Model Development

4.1 Introduction

The Waterloo Moraine Model was chosen as the base numerical model for this study. The numerical methodologies were first applied to the Laurel Creek Watershed [*Martin*, 1994], and the same approach was later applied on a larger, more regional scale, to the Waterloo Moraine [*Martin and Frind*, 1998]. The objectives of the regional model were to delineate well head capture areas. The complex nature of the regional geology warranted a fully three-dimensional model. *Beckers* [1999] refined the previous approach with the introduction of three-dimensional parameterization when modelling the Oro Moraine. This work combines the two approaches in generation of the Waterloo West Side Model.

In this chapter, the formation of the Waterloo West Side Model is outlined and the conceptual model is developed. Refinement of the current Waterloo Moraine Model within the Waterloo West Side study area is detailed and a new hydrostratigraphic interpretation is proposed.

4.2 Physical Model Boundaries

The area of interest for this study is the Waterloo West Side and the immediate surrounding area (Figure 1.1 to Figure 1.3). In designing a numerical groundwater model, defining the boundaries is a crucial step since they are artificial constraints which can have a significant influence on the groundwater flow system.

In designing boundaries for this work, reference is made to recent studies that involved delineating well head protection areas for the Greenbrook well field in Kitchener, Ontario [*Gartner Lee Limited*, 1998]. To maintain the regional scale influence, in this study, a steady-state hydraulic head solution was extracted from the large-scale Waterloo Moraine Model and super-imposed on a smaller-scale so that computational limitations could be avoided. The authors found that a Type I boundary imposed on small-scale model constrained the solution and made calibration non-unique. Boundary effects were observed not only in the flow solution but also in the transport simulation.

In further studies [*Muhammad*, 2000], a different approach was used in which the area of interest was refined within the large-scale model. The latest approach was used in the Waterloo West Side study.

4.3 Assumptions and Limitations

The major assumption in this work is that the groundwater flow in the study area is at steady-state. At steady-state, boundary conditions, which include surface water (fixed head) and infiltration rates, are integrated over a period of one year. Temporal events such as spring melt and late summer dry periods are not represented explicitly and local surface water is assumed to flow continuously all year. At steady-state, interflow is also assumed constant over the entire year but in reality, interflow occurs primarily during the wet season and for short periods following storm events. Unsaturated flow is simplified using this model and is represented as a linear function under steady-state flow.

4.4 Conceptual Model

The conceptual model describing the regional geology, and more specifically the Waterloo Moraine, has been refined in the last 30 years. The current conceptual model of the subsurface includes a layer-cake geometry of highly discontinuous layers of alternating aquifer/aquitard materials (Figure 4.1). Similar conceptual models have been adopted for the majority of groundwater flow models within the region [*Rudolph*, 1985][*Martin*, 1994][*Callow*, 1996][*Martin and Frind*, 1998] and outside the region [*Beckers and Frind*, 1999].

Included in Figure 4.1 is the corresponding geology as interpreted within the Waterloo West Side. Aquitard material is linked to silts and clays which are evident in the local till units. Aquifer materials (sands and gravels) are the result of reworked till and glaciofluvial deposits. The hydrostratigraphic units are numbered sequentially from top to bottom resulting in four aquifers and four aquitards. There are seven overburden units and one bedrock unit. The bedrock comprises the lowest unit and is considered the fourth aquifer because it is believed that the top five metres are fractured. Within the study area, Aquitard 4 and Aquifer 3 are very thin and could be considered one single unit, but to conform to the regional model, two layers were incorporated.

Figure 4.1 shows the corresponding grid layers in the finite element model. In the original moraine model [*Martin and Frind*, 1998], thirteen elemental layers were used, a level of discretization which was suitable for the regional study and 2D parameterization. For this work and other recently completed studies [*Muhammad*, 2000], the vertical discritization was increased from 13 to 30 element layers including the RSL. Increased vertical discritization was important in this study to capture the 3D heterogeneities within a single hydrostratigraphic unit. Also, a fine vertical discretization increases the accuracy of the pseudo-unsaturated flow solution.

4.5 Hydrostratigraphic Interpretation

Information about the subsurface is commonly interpreted from water well records and other local studies. The MOEE database was used for the Waterloo Moraine study which included UTM-located wells, ground surface elevation, static water levels measured at the time of installation, and the description of the lithological materials encountered, including contacts measured from ground surface. The lithologies are classified according to closest fit to a standard list of criteria which include: 52 material types (clay, gravel, bedrock), 33 material descriptors (hardness, grain size, sorting) and 9 colours.

The MOEE data base includes borehole logs prepared by well drillers, professional hydrogeologists and researchers. There are 4500 borehole logs in the Region of Waterloo. Due to the suspect reliability of some elements of the database, *Martin* [1998] conducted an exhaustive screening procedure that reduced the number of reliable logs to 2044. A total of 317 cross-sections were used to create a new database that includes the interpreted contacts and lithologic sub-unit descriptions for each hydrostratigraphic unit for each well (Figure 4.2). The lithologic sub-units for each hydrostratigraphic unit were lumped into 16 categories, and characterized

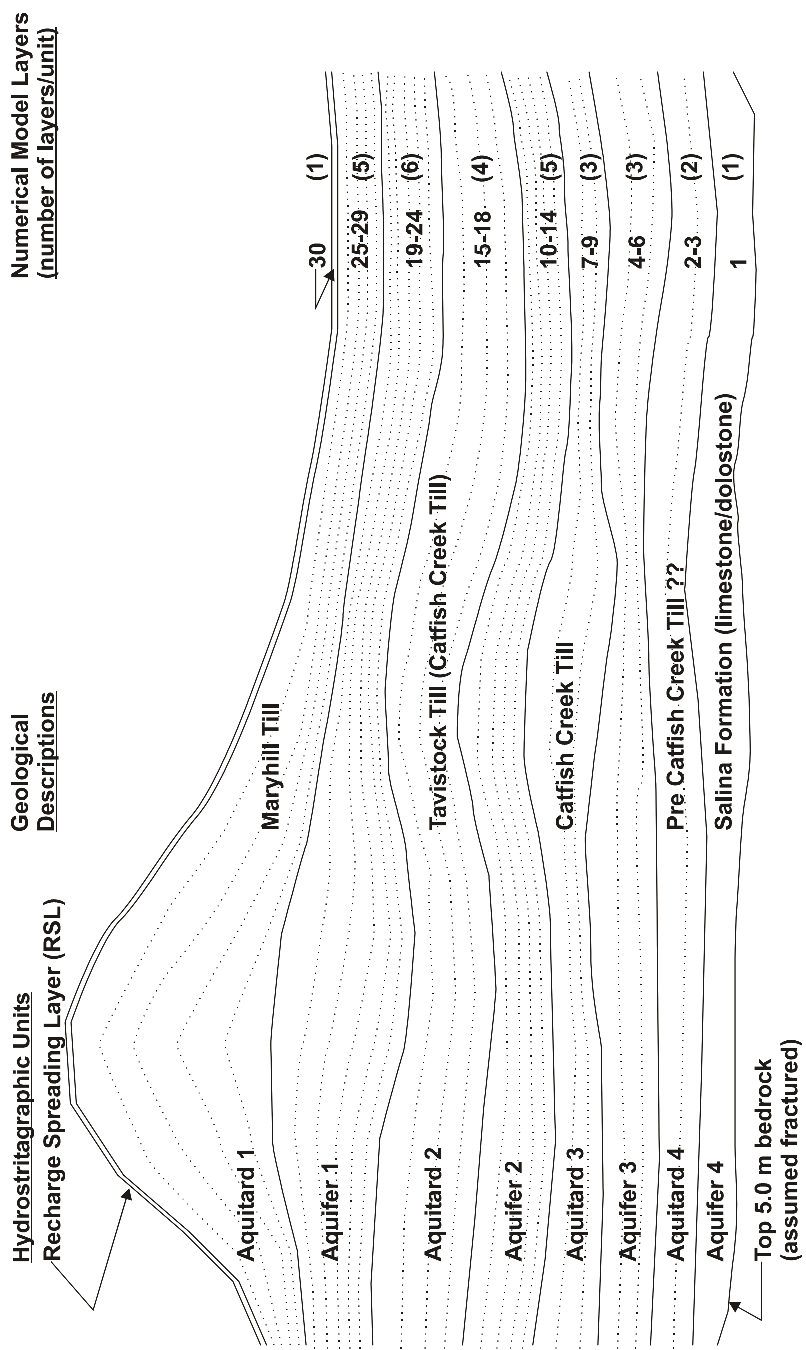

Figure 4.1. Conceptual model showing the layer-cake nature of hydrostratigraphic units. The assumed lithofacies for each hydrostatigraphic unit and element layer numbering are provided.

based on the given qualitative descriptions. Table 4.1 indicates the initial hydraulic conductivity values used for each sub-unit in previous models. Also included in Table 4.1 is the final average hydraulic conductivity determined from the calibrated Waterloo Moraine Model (column I). For this study, the average K-values from the Waterloo Moraine Model were used for the initial K-field, and new data were introduced from new sources as discussed in section 2.5 (page 15). The new data includes more surficial information such as shallow boreholes (<10 metres), test pits, Guelph Permeameter K-values, and hand-augered boreholes. This new data was included in the large database.

The interpretation had to be revisited on a local scale and involved generating several new cross-sections. The new database (including shallow data) was linked to a visualization program (VIEWLOG) which is a Geographical Information System (GIS). The software allows direct visual interaction with the database so that data trends can be cross correlated. For instance, when mapping hydrostratigraphy, it is important to observe geological and hydrogeological trends. With GIS software, multiple data can be interpreted together and interactively.

The database includes information relating to the hydrogeological properties such as water levels and screen intervals (if available), as well as multi-level information. When mapping the subsurface, static water level trends can be interpreted on the same cross-section as the lithology. Using these cross-sections, eight continuous hydrostratigraphic units were created (Figure 4.1). When mapping the sub-surface units locally, not all eight hydrostratigraphic units were observed in every borehole. For instance, in Figure 2.13 (page 29) borehole 6504902 (far left) shows the top two units, Aquitard 1 and Aquifer 1, but no other aquifers are present. In this case, the adjacent boreholes would suggest that Aquifer 2 appears at the end of 6504052 and 6502292. Therefore, the contacts at well 6504052 for Aquifer 2 continue straight across well 6504902. The elemental values of hydraulic conductivity for Aquifer 2 in the model will be that of aquitard material. This method avoids highly irregular element shapes that would become evident in the final three-dimensional mesh construction. Although this method results in better mesh design, it increases the difficulty of model calibration.

Topography has an important influence on the distribution of recharge. Since one of the objectives of this study is to determine the effect of recharge disturbances on the regional groundwater system, the definition of the uppermost model surface is crucial. To represent the topography, three datasets were combined: top of the boreholes, digitized elevations from surveys, and digitized elevations from stream valleys on Ontario base maps [*Ministry of Natural Resources*, 1987]. Figure 2.1 (page 10) shows topographic relief, stream valleys and the locations of data points

Hydraulic Conductivity, K_{xx} (m/s)				
Material	Literature	Field Measurements	(I)	(II)
Clay	$10^{-12} - 10^{-9}$	$3 \cdot 10^{-11} - 2 \cdot 10^{-9}$	$1 \cdot 10^{-11}$	$9 \cdot 10^{-10}$
Silty Clay	$10^{-11} - 10^{-9}$	-	$1 \cdot 10^{-10}$	$3 \cdot 10^{-9}$
Sandy Clay	$10^{-10} - 10^{-7}$	-	$1 \cdot 10^{-8}$	$1 \cdot 10^{-8}$
Gravelly Clay	$10^{-9} - 10^{-7}$	$1 \cdot 10^{-10} - 1 \cdot 10^{-7}$	$5 \cdot 10^{-8}$	$8 \cdot 10^{-8}$
Clayey Silt	$10^{-9} - 10^{-7}$	$2 \cdot 10^{-8} - 3 \cdot 10^{-7}$	$1 \cdot 10^{-9}$	$2 \cdot 10^{-8}$
Silt	$10^{-9} - 10^{-5}$	$1 \cdot 10^{-10} - 1 \cdot 10^{-6}$	$5 \cdot 10^{-8}$	$5 \cdot 10^{-8}$
Sandy Silt	$10^{-8} - 10^{-6}$	$2 \cdot 10^{-9} - 4 \cdot 10^{-7}$	$5 \cdot 10^{-7}$	$1 \cdot 10^{-7}$
Gravely Silt	$10^{-7} - 10^{-5}$	$1 \cdot 10^{-7} - 1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	$1 \cdot 10^{-6}$
Clayey Sand	$10^{-7} - 10^{-5}$	-	$5 \cdot 10^{-5}$	$4 \cdot 10^{-6}$
Silty Sand	$10^{-6} - 10^{-4}$	$1 \cdot 10^{-6} - 1 \cdot 10^{-6}$	$5 \cdot 10^{-4}$	$1 \cdot 10^{-5}$
Fine Sand	$10^{-6} - 10^{-4}$	$3 \cdot 10^{-6} - 2 \cdot 10^{-4}$	$1 \cdot 10^{-3}$	$6 \cdot 10^{-5}$
Medium Sand	$10^{-6} - 10^{-2}$	$4 \cdot 10^{-6} - 4 \cdot 10^{-4}$	$5 \cdot 10^{-3}$	$2 \cdot 10^{-4}$
Coarse Sand	$10^{-4} - 10^{-2}$	$2 \cdot 10^{-4} - 5 \cdot 10^{-3}$	$1 \cdot 10^{-2}$	$7 \cdot 10^{-4}$
Gravel	$10^{-3} - 10^{0}$	$4 \cdot 10^{-4} - 2 \cdot 10^{-3}$	$5 \cdot 10^{-2}$	$2 \cdot 10^{-3}$
Limestone	$10^{-9} - 10^{-2}$	-	$1 \cdot 10^{-4}$	-
Shale	$10^{-13} - 10^{-9}$	-	$1 \cdot 10^{-8}$	-

Table 4.1. Hydraulic conductivities, K_{xx}, (m/s) for the lithologic categories. Field measurements are from pumping and slug tests in the Waterloo Moraine as listed in *Martin and Frind* [1998]. Columns (I) and (II) are the final calibrated results for K-values from previous numerical models: *Martin and Frind* [1998] and *Beckers* [1999] respectively.

used to generate the topographic surface.

4.6 Elevation of Hydrostratigraphic Surfaces

After the sub-surface was mapped according to Figure 4.2 (page 64), a database of contact elevations was generated for each unit. Using these data, nine surfaces, including the topography and bottom of the fractured bedrock, were generated using universal kriging, as outline in Section 3.2.2. Only the Waterloo West Side and the immediate area within the Waterloo Moraine Model (Figure 4.7) is redefined for the new surface contacts. Universal kriging was completed for each surface dataset, using GridBuilder with the spherical model variogram option and first degree drift. Sample variograms for the first four contacts are included in Figure 4.3. The fitted model variogram parameters are given in Table 4.2 for all units.

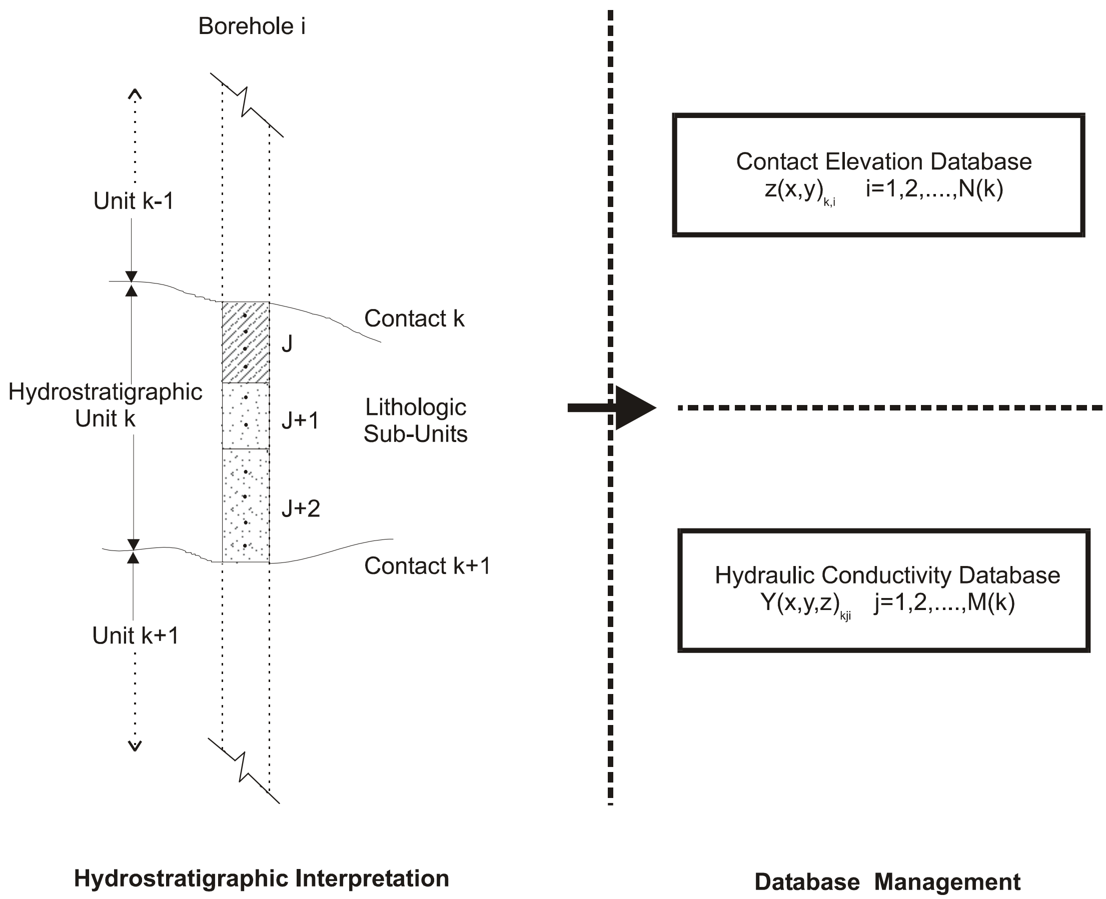

Figure 4.2. Relationship between the hydrostratigraphic interpretation and database management.

Contact Surface	Number of Data Points	Sill m^2	Range m	Nugget -
Topography	663	23.4	1380	0.0
TAQ1	298	123	1420	0.0
BAQ1	214	73.4	653	0.0
TAQ1	172	103	505	0.0
BAQ1	103	82.9	414	0.0
TAQ1	79	37.6	378	0.0
BAQ1	61	36.0	766	0.0
TAQ1	50	40.7	1330	0.0
Bottom of Model	50	40.7	1330	0.0

Table 4.2. Parameters for spatial interpolation of the two-dimensional model surfaces.

Once the elevations of the contact surfaces were generated, the thickness of each hydrostratigraphic unit could be calculated by taking the difference in elevation of the two binding contact surfaces. Figures 4.4 to 4.5 show the thickness of Aquitard 1 and Aquifer 1, respectively. Both figures show the thickness of each unit where the white areas indicate pinch-outs. The contouring has been cut off at a minimum thickness of 2 metres.

4.7 Finite Element Mesh

The three-dimensional finite element mesh is generated by first defining several 2D horizontal meshes to represent each of the hydrostratigraphic contacts. The 2D meshes are then stacked vertically, and additional grid layers are added between contacts to represent each aquifer and aquitard.

The regional scale mesh is illustrated in Figure 4.6 with the Waterloo West Side area highlighted. The element size within the regional model ranges from tens of metres near the various well fields up to 500 metres near the domain boundaries. The Waterloo Moraine Model contains 8348 nodes and 16158 elements in the 2D horizontal plane. After locally refining the regional model within the study area, the average element size was reduced to 30 metres. The refinement is illustrated in Figure 4.7. The new 2D regional mesh contains 17590 nodes and 34642 elements. Discretization on this scale is considered sufficient to represent the local hummocky terrain where elevation changes are drastic; especially adjacent to drainage paths

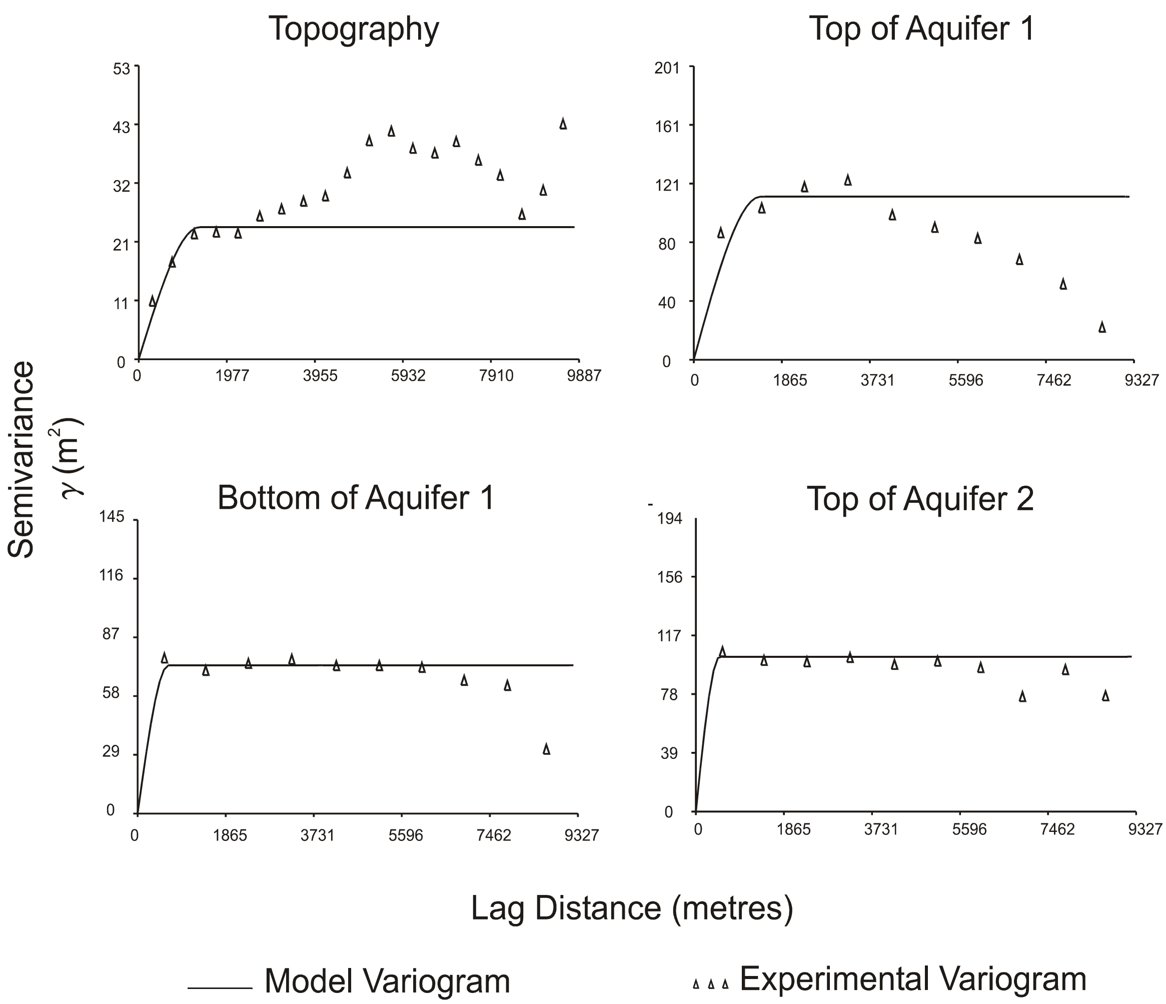

Figure 4.3. Variograms for the first four contact surfaces, showing the experimental and model variograms.

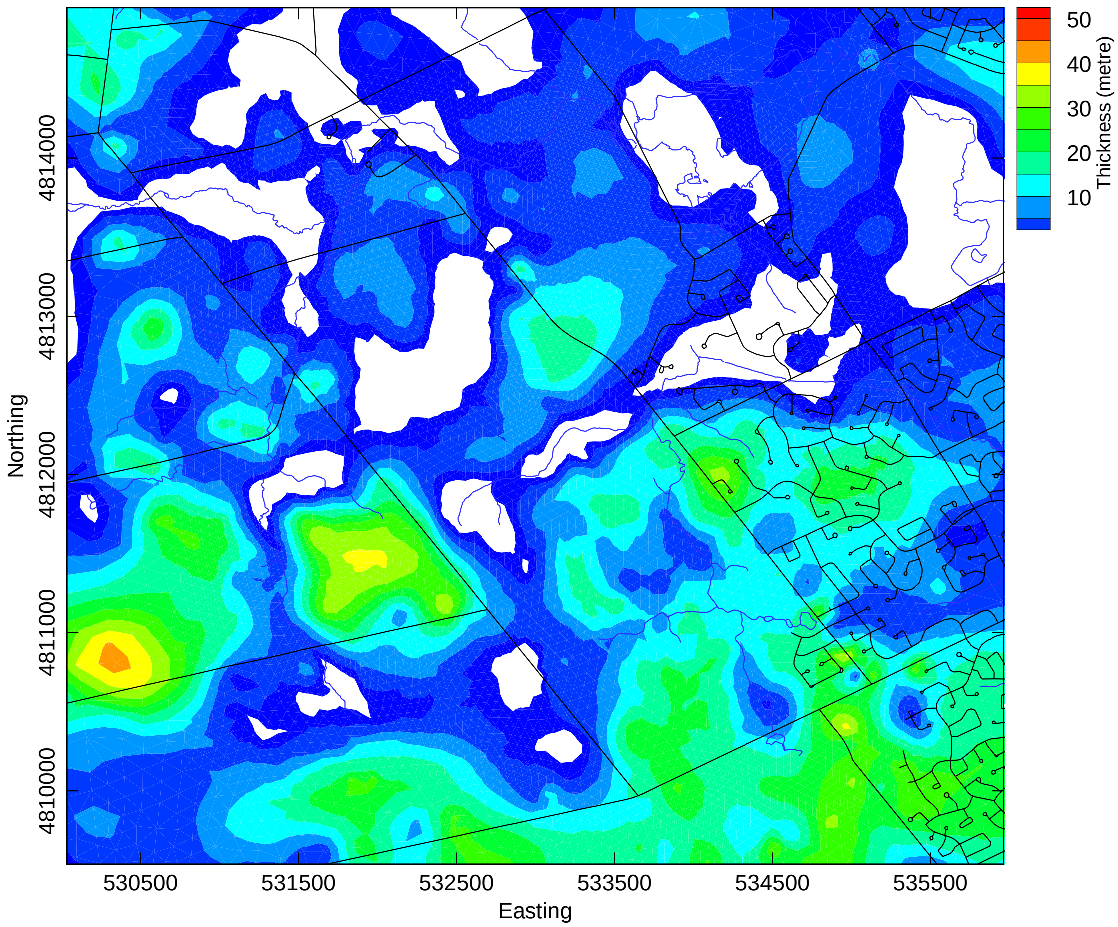

Figure 4.4. Thickness of Aquitard 1. White areas indicate regions where Aquitard 1 pinches-out (< 2 meters thick). Data is generated from the difference between surface topography and top of Aquifer 1.

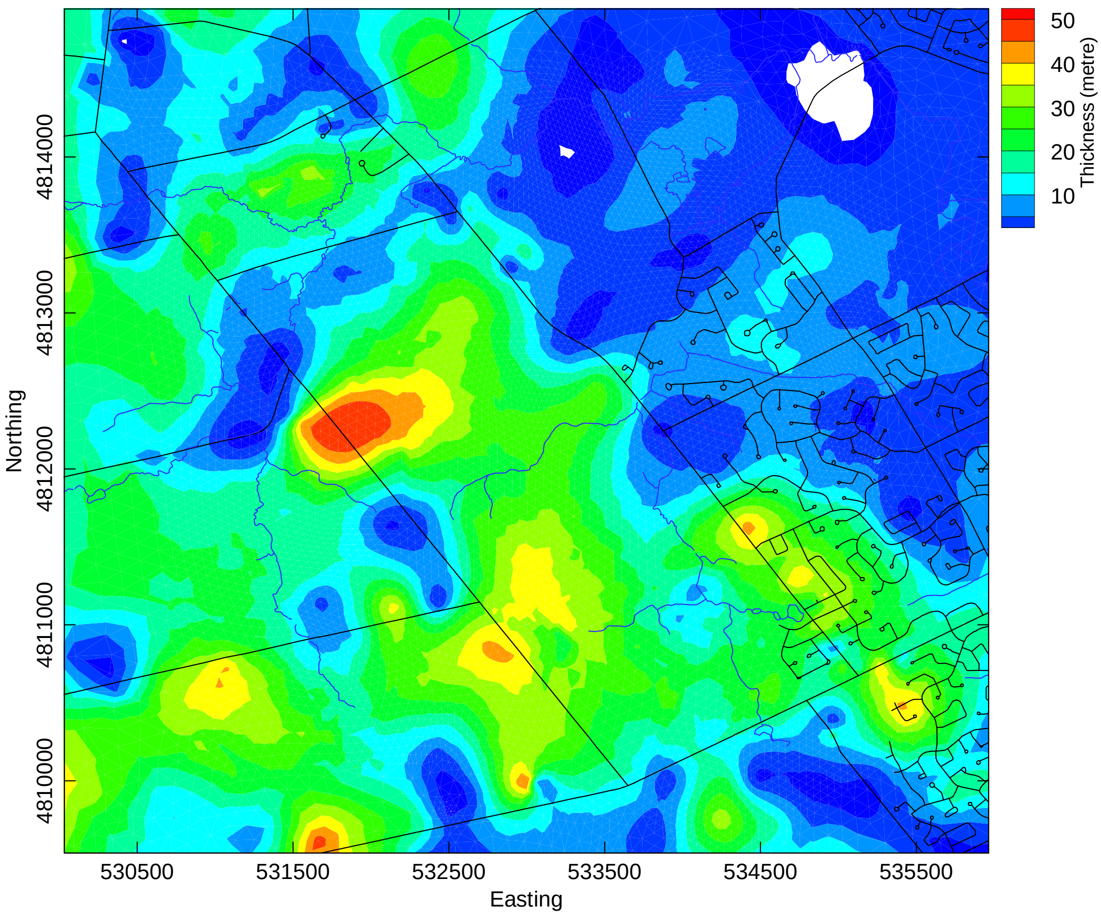

Figure 4.5. Thickness of Aquifer 1. White areas indicate regions where Aquifer 1 pinches-out (< 2 meters thick). Data is generated from the difference between the top and bottom of Aquifer 1.

(see Figure 2.1 on page 10). In addition, the near-surface hydraulic conductivity distribution from detailed watershed studies can be preserved at this scale.

WATFLOW incorporates a module (MESH3D) which generates a three-dimensional mesh by stacking several 2D triangular element meshes, each of which represents the interpreted contacts from borehole logs. The formation of these surfaces is discussed in the previous section (4.6). The final 3D mesh is composed of deformed triangular prisms.

The interpreted hydrostratigraphic surfaces of the Waterloo Moraine, especially the upper most units including the topography, are complex and often intersect. Since WATFLOW must have continuous elemental layers, however, a set of checks are used to avoid negative elemental thicknesses when contact surfaces cross. These rules include: (1) if the elevation is greater than ground surface elevation, it is corrected to ground surface, (2) if a contact is below the bedrock surface, the elevation is corrected to the bedrock surface, and (3) if two intermediate surfaces intersect then they are both corrected to the mean surface. For the Waterloo West Side Model, a minimum elemental thickness of 0.1 metres is enforced to maintain accuracy.

The entire three-dimensional mesh for this study contains 30 elemental layers (including the RSL) with a total of 1,039,260 elements.

4.8 Hydraulic Conductivity Parameterization

Hydrostratigraphic boundaries have been generated according to Section 4.5 and Figure 4.2. Using these hydrostratigraphic contacts for each well, a database of sub-unit lithology was created and linked to a corresponding K-value (Table 4.1). Using the three-dimensional parameterization outlined in Section 3.2.3, the hydraulic conductivity of the sub-units is interpolated onto a three-dimensional mesh.

To constrain the variability of the dataset and to ensure that the vertical heterogeneity is maintained, parameterization of the hydraulic conductivity field was completed on a hydrostratigraphical unit basis. In this way, smoothing of the K-field is observed only within a hydrostratigraphic unit. With any kriging procedure, the dataset must first be classified statistically. In this case, a three-dimensional statistical definition is required in the horizontal and vertical directions. *Beckers* [1999] found that a reliable method of determining the horizontal semivariograms

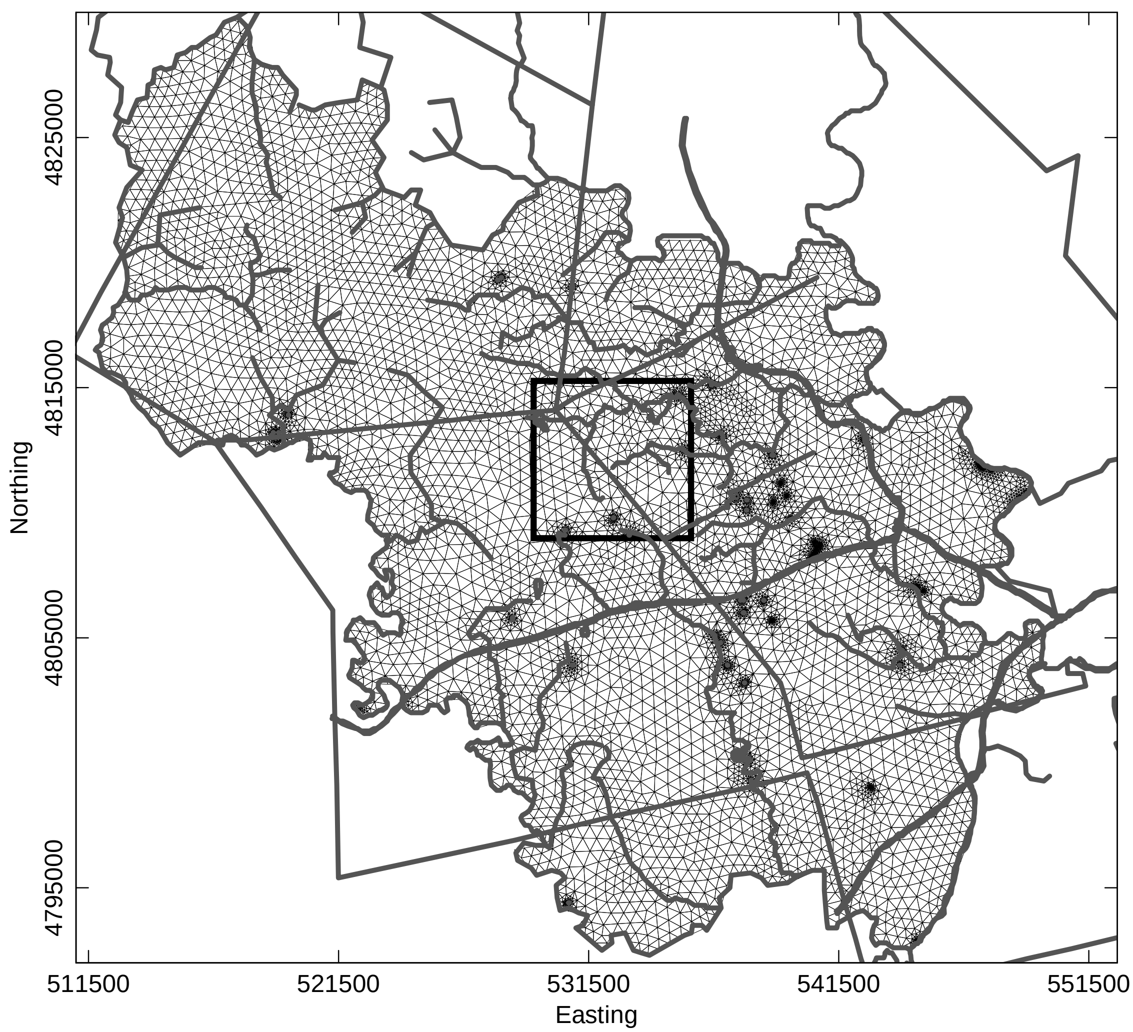

Figure 4.6. 2D finite element mesh for the Waterloo Moraine Model with regional roads and major water courses shown. The box in the center of the mesh indicates the area to be refined for the Waterloo West Side.

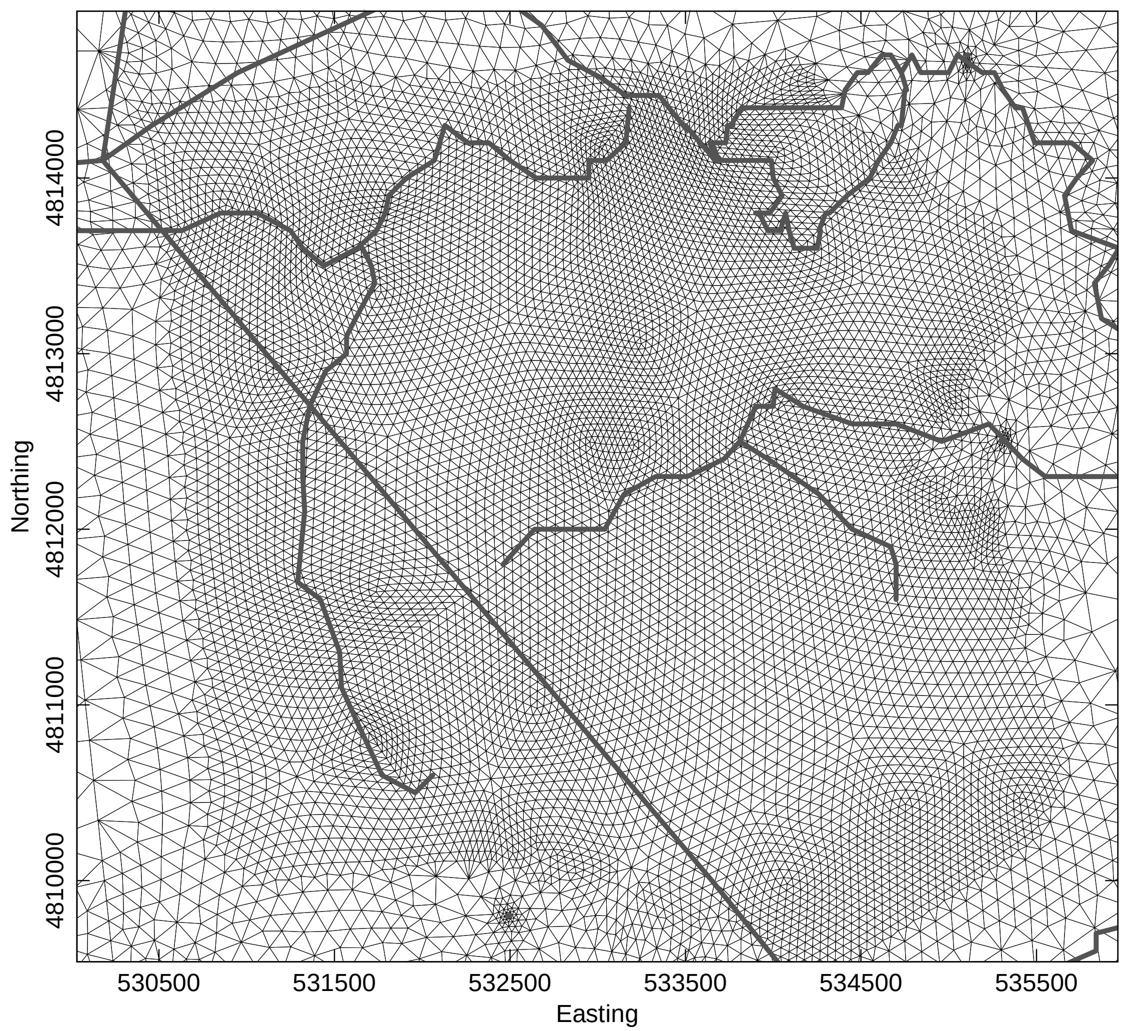

Figure 4.7. 2D refined finite element mesh for the Waterloo West Side study area. Regional roads and major water courses shown.

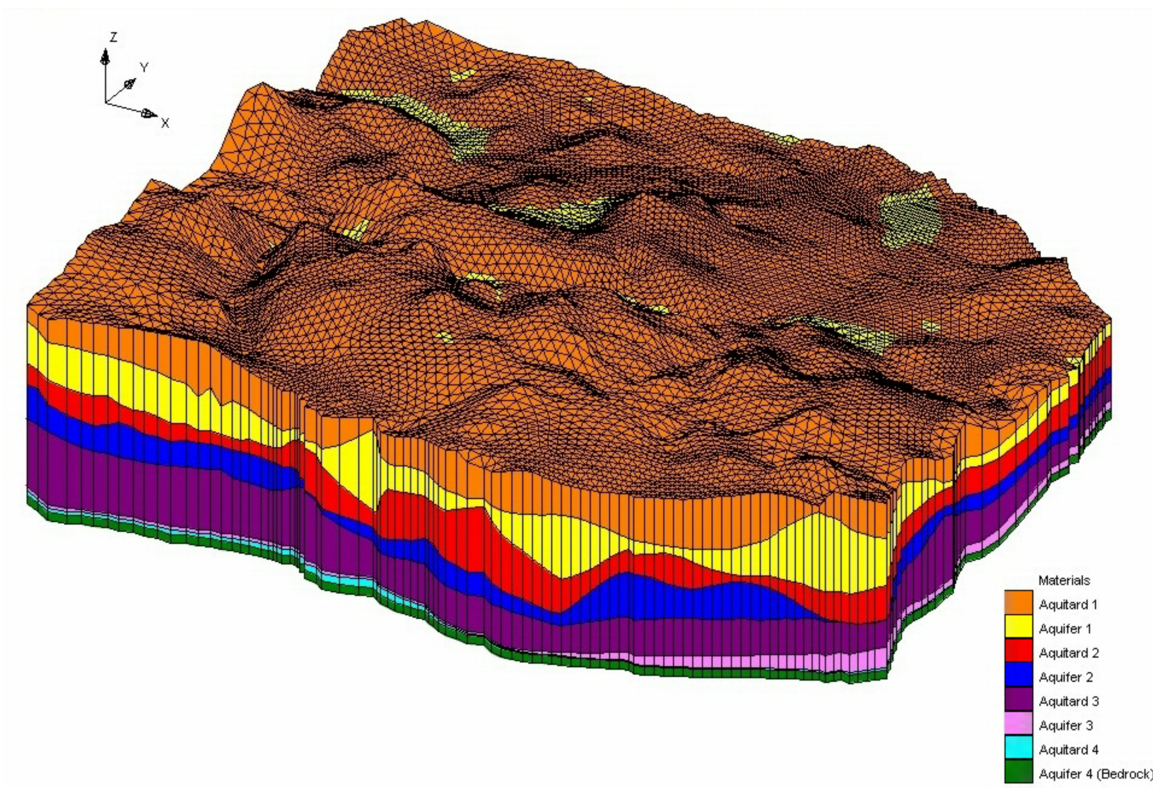

Figure 4.8. Three-dimensional mesh (Waterloo West Side refined area only) illustrating the complex structure of the hydrostratigraphy including areas where pinch-outs occur; Aquifer 1, for example, is seen exposed at the surface. Vertical exaggeration of 10x. Vertical discretization within each hydrostratigraphical unit is not illustrated.

was not available. It can be shown, however, that the variation in the horizontal range has a minor effect on the horizontal distribution of the hydraulic conductivity field. The initial K-distribution for a recent calibration of the Waterloo Moraine Model, which formed the basis for this work, used a standard 100 metres for the horizontal range; this same range was adopted here. For the vertical correlation, vertical semi-variograms were found to be better constrained as the number of data points along the axis of the borehole increased. Data along the borehole length in most cases is irregularly spaced, as the sub-units changed thickness.

To distribute the sub-unit lithology uniformly along the length of the boreholes, the lithologies were subdivided along the vertical axis. For *Beckers* [1999], the lithologies were subdivided into 5 metre intervals where any sub-unit less than 5 metres in length was disregarded. This approach was used for the initial sub-unit K-values outside the study area (most of the Waterloo Moraine Model). In the study area (Waterloo West Side) most of the new data is more detailed, especially in Aquitard 1. The average element thickness within the Waterloo West Side is approximately 3 to 5 metres but ranges up to 10 metres in some areas. Within the study area, a length of 1 metre was used for the sub-units and this was found to provide several data points over each element.

During the generation of the database for the sub-units, any values from Table 4.1 that intersected field-measured hydraulic conductivity were over-written with the field measured K. Surficial K-measurements included those from Guelph Permeameter tests, seepage meter data, pumping tests and single well tests. A total of 133 known measurements of K were included in the final database for the sub-units. Figure 2.10 on page 25 illustrates the location of measured K-values in the study area.

Figure 4.9 shows the initial hydraulic conductivity distribution along a cross-section after parameterization of the K-field. This cross-section was chosen to closely match the location of the cross-section in Figure 2.13 on page 29.

4.9 Numerical Model Boundaries

Figure 4.10 illustrates the boundary conditions used in the Waterloo Moraine Model. Major water courses, including the Nith and Grand Rivers, are represented by Dirichlet, or fixed head boundary conditions ($h = h_\Gamma$) and are applied to the top two layers of the model. Dirichlet boundaries are also used for minor waterways such as creeks and streams but are only applied to the uppermost nodes.

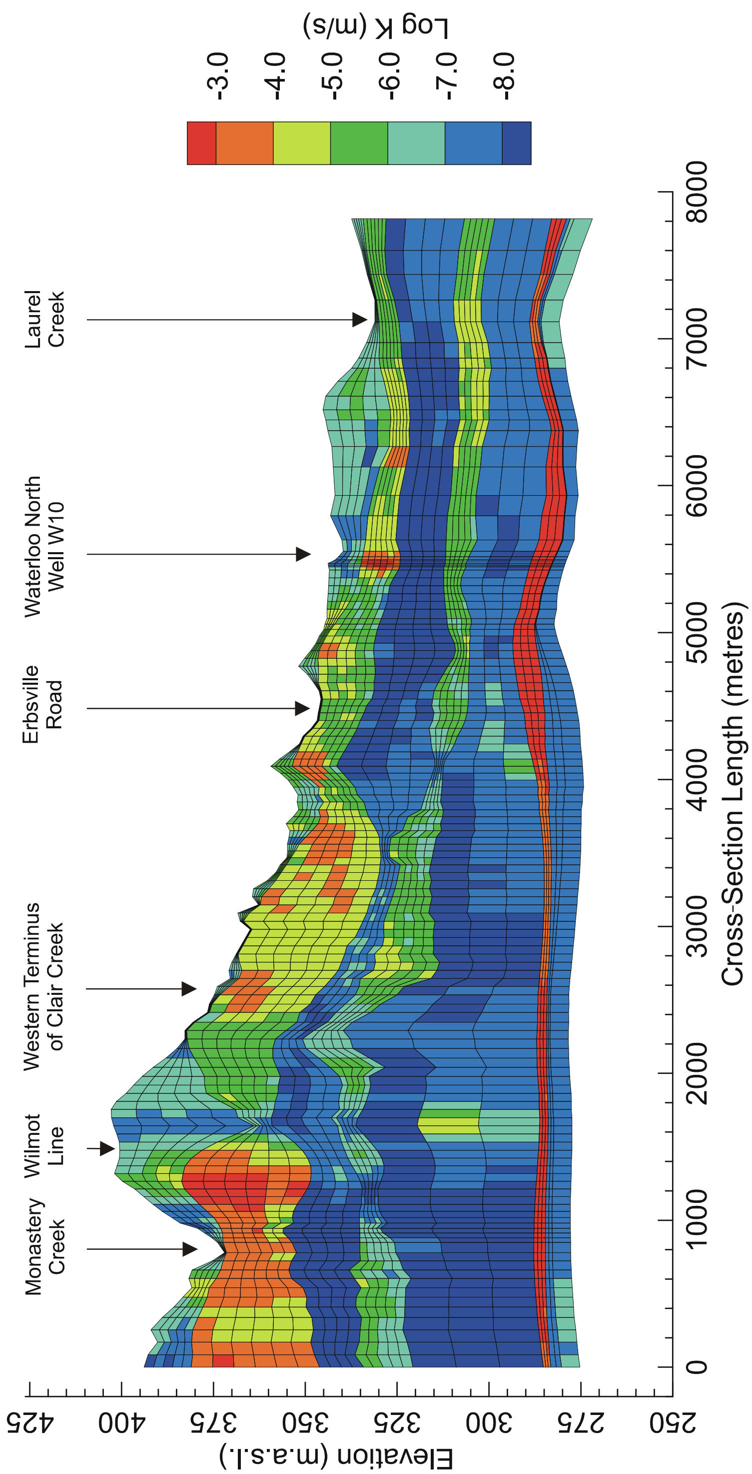

Figure 4.9. Cross-section from the numerical model, matching WE-7-25-25, illustrating the initial hydraulic conductivity (K_{xx}) distribution generated from the 3D kriging. See Figure 2.13 on page 29 for matching borehole cross-section and Figure 2.14 on page 30 for cross-section location.

All other lateral model boundaries are fixed as zero flux ($\frac{\partial h}{\partial \eta} = 0$) or equivalent symmetry boundaries beneath major rivers. Figure 4.11 indicates where Type I boundaries have been applied over the study area. A Neuman boundary is applied across the entire surface of the model to represent infiltration from rainfall.

The surface boundary condition for the model becomes an important factor when studying the effect of infiltration changes on the groundwater system. In a comparison of simulation approaches, *Beckers* [1999] compared WATFLOW to SWMS 2D [*Simúnek et al.*, 1992], a two-dimensional Galerkin-based model that simulates flow in variably saturated media. Both models were used to determine the flow through a semi-confined aquifer system where WATFLOW utilized the pseudo-unsaturated module and a recharge spreading layer. Results from WATFLOW were found to closely match results from SWMS. Introducing a RSL to the numerical model facilitated simulation of interflow, a natural component of infiltration, which distributes water from areas of low permeability (aquitards) to areas of higher permeability (aquifers). Infiltration becomes either groundwater (recharge) or leaves the system, via interflow, as baseflow to surface water (Type I boundaries). The combination of these techniques was found by *Beckers* [1999] to accurately handle the complex recharge mechanism of heterogeneous aquifer systems and was adopted for the current Waterloo West Side study.

In using the above approach, a constant infiltration rate is applied to the entire surface of the model. The flux applied to the surface is referred to as the 'potential recharge' but does not represent the actual recharge due to the redistribution through the RSL to areas of higher permeability (see Section 2.8).

Studies in the area show that recharge to the aquifers range from as low as 80 mm/year to as high as 250 mm/year. *Rudolph* [1985], for example, found that the average recharge to the aquifers was 100 mm/year when modelling groundwater flow for the Greenbrook well field. In some studies a variable recharge rate was found to be more realistic. For instance, *Fitzpatrick* [1993] used an average rate of 125 mm/year and 275 mm/year in rural areas and *Callow* [1996] assumed 50 mm/year in urban areas and 250 mm/year in rural areas.

The portion of the water surplus that is runoff is often estimated as 10 percent, or 95 mm/year for Waterloo [*Planning and Engineering Initiatives Ltd.*, 1996][*Dorfman*, 1996]. Models that use a RSL cannot simulate overland and interflow simultaneously. *Martin and Frind* [1998] used a variable potential recharge rate which ranged from 180 mm/year to a high of 310 mm/year in the Mannheim Sandhills, a known recharge area. Recent studies using the Waterloo Moraine Model used 535 mm/year for the potential recharge [*Gartner Lee Limited*, 1998][*Muhammad*, 2000], where a higher potential recharge was necessary to calibrate to known base flows in the local rivers. *Beckers* [1999] used a similar approach by calibrating to base flows and pressure heads with a range in potential recharge of 320 mm/year to 420 mm/year in the Oro Moraine. These higher values of potential recharge were required to match measured base flows in major water ways by including runoff.

The Waterloo West Side Model couples the RSL with the pseudo-unsaturated module. An yearly-averaged infiltration rate was chosen at 240 mm/year and applied over the entire model surface. The overland flow component is not included in the Waterloo West Side Model.

4.10 Groundwater Abstraction

The Regional Municipality of Waterloo currently extracts groundwater to supply 75% of the community's drinking water. The remaining 25% is taken from the Grand River. Well fields are scattered throughout the Regional Municipality of Waterloo and are depicted in Figure 2.21 on page 39. Well locations and pumping rates were not changed for the Waterloo West Side Model and remain the same as the Waterloo Moraine Model [*Martin and Frind*, 1998][*Muhammad*, 2000].

4.11 Model Calibration

4.11.1 Introduction

Calibration involves 'fitting' model parameters to a field-measured outcome. As a model becomes more complex and as the number of observed data points increases, the model becomes more difficult to calibrate [*Durrant*, 2000]. Recent work has been done to alleviate the difficulty in the calibration procedure by incorporating automated methods (see Section 3.1.6 on page 53).

Previous calibration of the Laurel Creek Watershed Model and the Waterloo Moraine Model was accomplished using manual trial and error methods [*Martin*, 1994][*Martin and Frind*, 1998] which involved adjusting the overall hydraulic conductivity of each hydrostratigraphic unit until a good match to observed static water levels was produced. In addition, *Martin and Frind* [1998] found it was necessary to use a variable infiltration distribution. Model results were matched to water level data extracted from the MOEE Water Well Drillers' Logs.

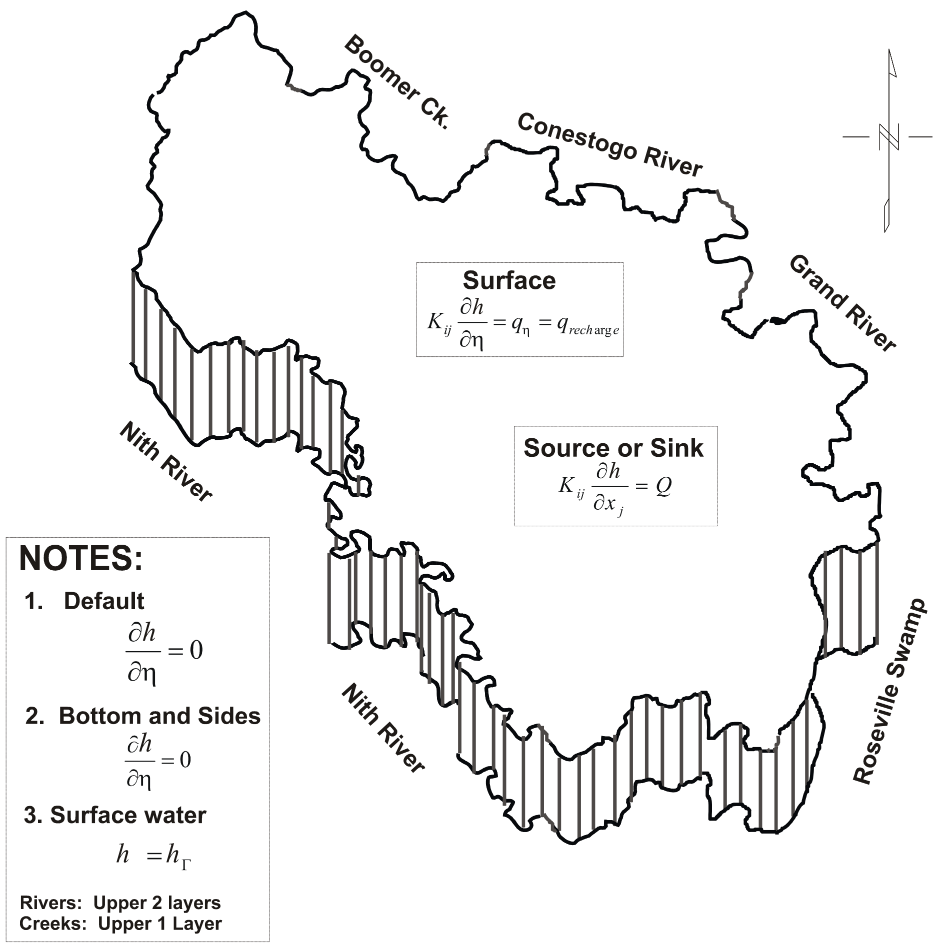

Figure 4.10. Numerical boundaries for the Waterloo Moraine Model. Dirichlet conditions are applied to natural water courses. The top boundary is a Neumann boundary. Bottom and sides of model are no-flow.

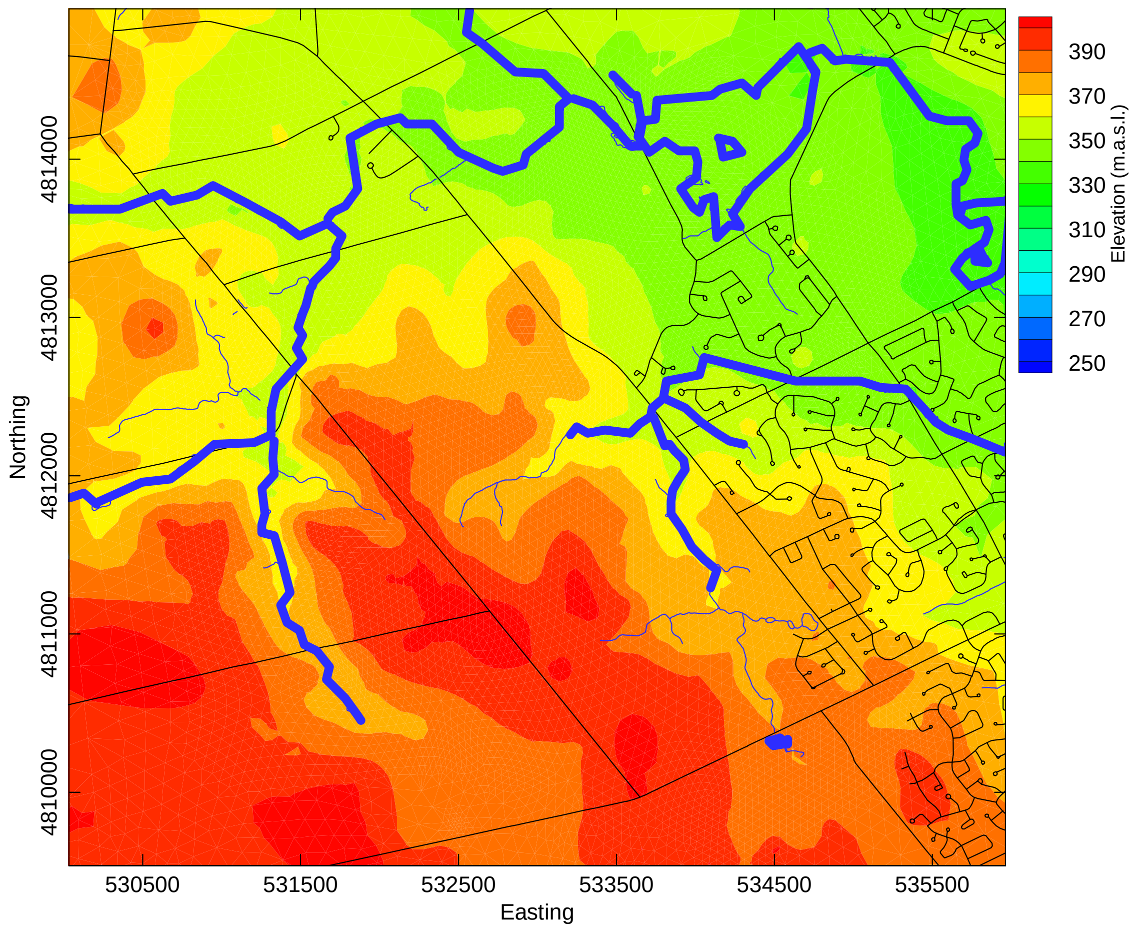

Figure 4.11. Waterloo West Side site map - locations of Type I boundary conditions (thick blue lines) super-imposed on topography. Thin blue lines indicate stream valleys.

Further work expanded on this technique of calibration for the Oro Moraine Model [*Beckers*, 1998][*Beckers and Frind*, 2000]. The Oro Moraine Model incorporated pseudo-unsaturated flow on a regional watershed basis. In addition to static water level data, the model was calibrated to field-measured base flow for major water courses. An automated calibration routine for WATFLOW was used to fit both datasets to the model at the same time. A best fit was accomplished by adjusting the permeability of pre-described zones within the model.

Automated calibration still requires professional insight and some degree of trial and error. While calibrating to a statistically sound fit, for example, automated parameter updates may lead to unrealistic values. Upper and lower bounds are therefore required to constrain the final solution. Also, the spatial organization of the calibration zones (elemental groupings) must be defined. Both have dramatic effects on the resultant fit.

4.11.2 Calibration Approach

More recent studies have utilized an automated approach to model calibration (see, for example, work by *Muhammad* [2000] and *Gartener Lee Limited* [1998]). In these more recent studies the calibration was made with respect to hydraulic head distribution and base flow measurements for the Nith River and Grand River. Any perched water levels were removed from the calibration database. Nine calibration zones were created, one for each hydrostratigraphic unit and one for the recharge spreading layer (RSL). The initial hydraulic conductivity of the RSL was set as an order of magnitude greater than the highest K-value in the entire domain and applied uniformly over the model surface. An infiltration rate of 535 mm/year was applied over the entire surface, and final calibration factors (CFs), which are the multipliers for each calibration zone, were determined. The final calibrated CF-value for Aquitard 1 was 2 orders of magnitude, while those for the deeper units were less than an order of magnitude. The final calibrated hydraulic conductivity for the RSL decreased from an initial value of 10^{-3} m/s to 10^{-5} m/s. However, base flows and rates of recharge were still considered too low for a perfect calibration.

Initial calibration runs for the Waterloo West Side Model were poor using the above approach, especially near locations of perched water which were added to the calibration database. Although *Beckers* [1999], validated the pseudo-unsaturated module in WATFLOW for the Oro Moraine, perched data were not included.

Subsequent runs altering the hydraulic conductivity of the RSL still proved problematic when calibrating to perched water level data. Efforts to remove the

RSL from the model were attempted but as was found with previous studies [*Martin*, 1994], excessive water table mounding could not be eliminated. Further simulations showed that as the RSL permeability was increased, the calibration to perched water levels became worse. A higher RSL permeability was clearly increasing runoff. This observation was quite significant where topographic relief was at its highest, i.e. where perched conditions are most likely. With such a high permeability for the RSL, both interflow and runoff were being simulated in the same layer; which is conceptually invalid.

The calibration was improved by changing the hydraulic conductivity of the RSL from a uniform to a variable value which was dependent on the underlying geologic material, thus ensuring that the permeability of the RSL remained within a realistic range. Conceptually, the RSL now represented a surficial weathered zone in the upper unit. In utilizing this approach, runoff is no longer simulated in the numerical model and only infiltration is applied to the model surface (Figure 2.22 on page 41).

The final calibration of the Waterloo West Side Model was completed in three steps. The first step involved calibration of the regional model with nine calibration zones (one for each hydrostratigraphic unit plus the RSL) and running the automated calibration module. The second calibration utilized nine additional zones within the Waterloo West Side study resulting in a total of 18 calibration zones. The results of the second automated calibration run formed the base condition for the third and final calibration step described below.

Additional calibration zones were created within the Waterloo West Side area for the third and final calibration step. Attempts at using the automated calibration for the final fit proved unrealistic due to the variability of the RSL and Aquitard 1. By increasing the number of calibration zones, the calibration became non-unique, and the final calibration was therefore accomplished through manual trial and error methods on the refined calibration zones.

Calibration zones were created for the RSL which matched the upper hydrostratigraphic unit (Aquitard 1). These zones were based on areas of known perched water conditions and on similar permeability values. Calibration zones were mapped for deeper hydrostratigraphic units based on similar permeability clusters.

4.11.3 Final Calibration Results

The final calibration statistics for Aquifers 1 to 4, and the perched water level data, are provided in Table 4.3. Figure 4.12 is a scatter plot of the numerically simulated hydraulic heads versus observed hydraulic heads. Table 4.3 and Figure 4.12 include observed data for the entire Waterloo Moraine. All observed data that were found to be perched were included in the observed hydraulic head database, even if the data provided a poor fit to the final calibration results. The distribution of the final relative hydraulic conductivity (scaled-K for unsaturated elements) and residuals for Aquitard 1 and Aquifer 2 are included in Figures 4.13 and 4.14. Figure 4.15 shows the final calibrated hydraulic conductivity for cross-section WE7-25-25.

The distribution of hydraulic conductivity in Aquitard 1 is very complex (Figure 4.13). Portions of aquifer material, for example, are found throughout Aquitard 1, due to the pinching-out of Aquitard 1 or from isolated hydraulic conductivity measurements from surficial field data. Aquitard 1 pinch-outs are common, for example, along portions of the northern branch of Clair Creek (Figures 4.13 and 4.15). The hydraulic conductivity for Aquifer 1 also exhibits a complex distribution (Figure 4.14) with hydraulic conductivity values toward the south of the Waterloo West Side higher than toward the north. Toward the Trillium Estates development, the K-values are much lower and represent aquitard-type material.

Final calibration residuals are also included in Figures 4.13 and 4.14. The residuals for the perched dataset (Aquitard 1) indicate an overall good fit. South of Clair Creek, the perched water levels were uniform due to the massive clay cap in Aquitard 1.

The northern section of the Waterloo West Side proved more difficult to fit to observed perched data. This was a result of the lack of geologic definition and because of drastic topography changes. For instance, the under-predicted value of 32 metres at well 1100003 is located above an isolated clay lens atop of a local topographic high (Figure 4.16). Adjacent wells, 6501392 and 1100006, east and west of 1100003 (Figure 4.16) indicate a massive sand layer and a deep water table. Wells 1100006 and 110002, to the north and south (Figure 4.17) also indicate a massive sand lens south of well 1100003, at Clair Creek, wells 1100002 and 1100001 are dry (Figure 4.17). The localized perching of well 1100003 is difficult to represent in the model without further lithological information to delineate the extent of the confining lens.

Further difficulty was found trying to fit the model to under-predicted residuals east of Erbsville Road on Trillium Estates lands (Figure 4.13). Figure 4.18 shows the perched wells in cross-section which includes wells 9999008, 1100012, and 1100013. Well 1100014 is part of Aquifer 1 and is included in Figure 4.14. The relief of the slope and the hydraulic gradient was difficult to match without affecting residuals for Aquifer 1. Vertical and horizontal mesh refinement in this area may result in a better fit to the observed data.

Unit	Standard Deviation (metres)	Mean Error (metres)	Absolute Error (metres)	Number of Data Points
Perched	7.8	-3.1	3.1	40
Aquifer 1	6.1	-2.8	4.5	323
Aquifer 2	6.1	-1.2	4.8	175
Aquifer 3	7.9	1.8	6.0	167
Aquifer 4	7.3	2.1	6.1	36

Table 4.3. Statistical information from final calibration.

4.11.4 Sources of Error and Uncertainty

Sources of error can be broadly grouped into those originating from errors in the observed data (e.g. heads and inferred K-values) and errors in the numerical model, for example due to simplified conceptual models. Uncertainties in the hydraulic conductivity distribution are related to estimation errors (interpretation of the well drillers' logs) and the 3D parametrization method. For instance, much of the regional scale K-values are derived from well drillers' logs which are highly subjective. Lithological contact locations are estimated during drilling; precise locations can only be found using coring techniques. The final K-values are inferred from the lithological descriptions and can be orders of magnitude from the real K-value. The greatest uncertainty is observed in the intra-formational hydraulic conductivity distribution where no observed data exists.

Model calibration was completed using observed water levels from well drillers' logs and observation wells. Although every effort was made to ensure that the observed water level data was taken at the same time of the year, much of these data are not consistent.

Uncertainty also exists in the applied infiltration rate which is based on estimated values of evapotranspiration and overland flow which are spatially and temporally variable. Data limitations reduced the accuracy of the topography and small-scale elevation variations are not represented. Locations of Type I boundaries are fixed which implies year-round flow, however some sections of these streams may become dry part of the year.

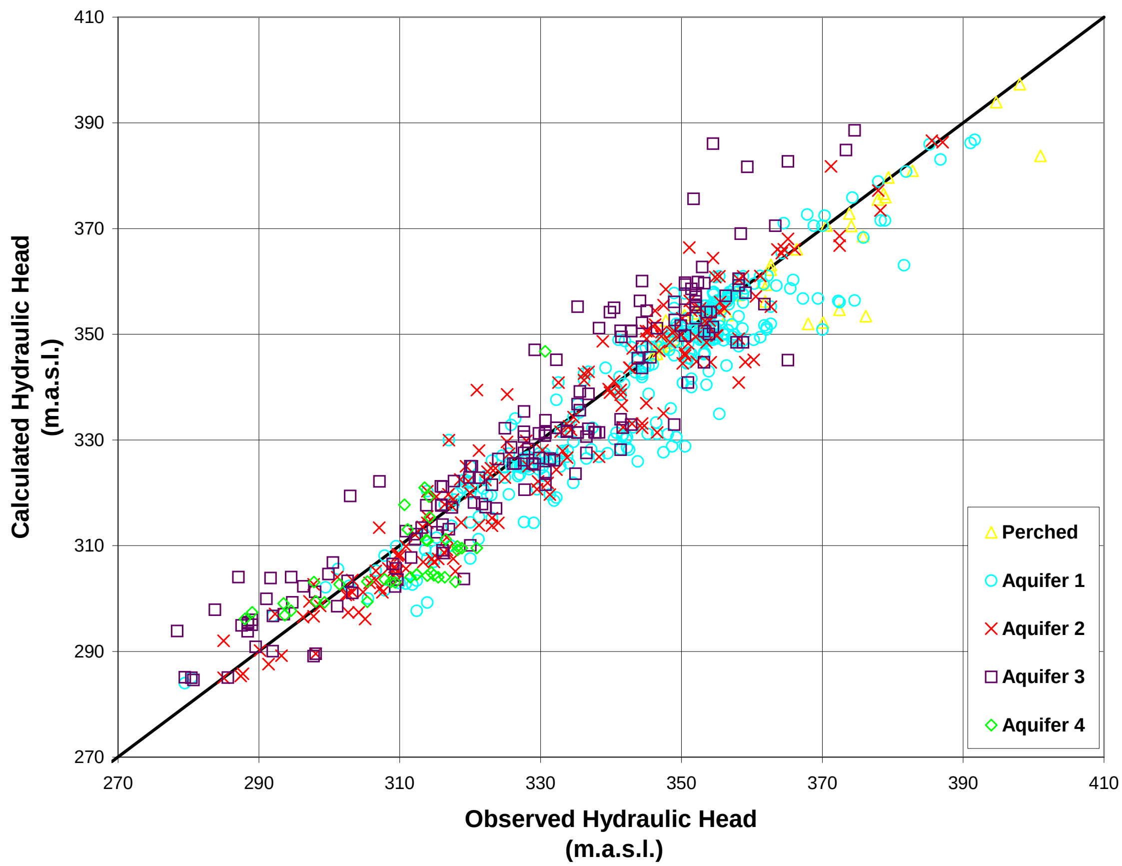

Figure 4.12. Residual plot for the calibrated Waterloo West Side Model.

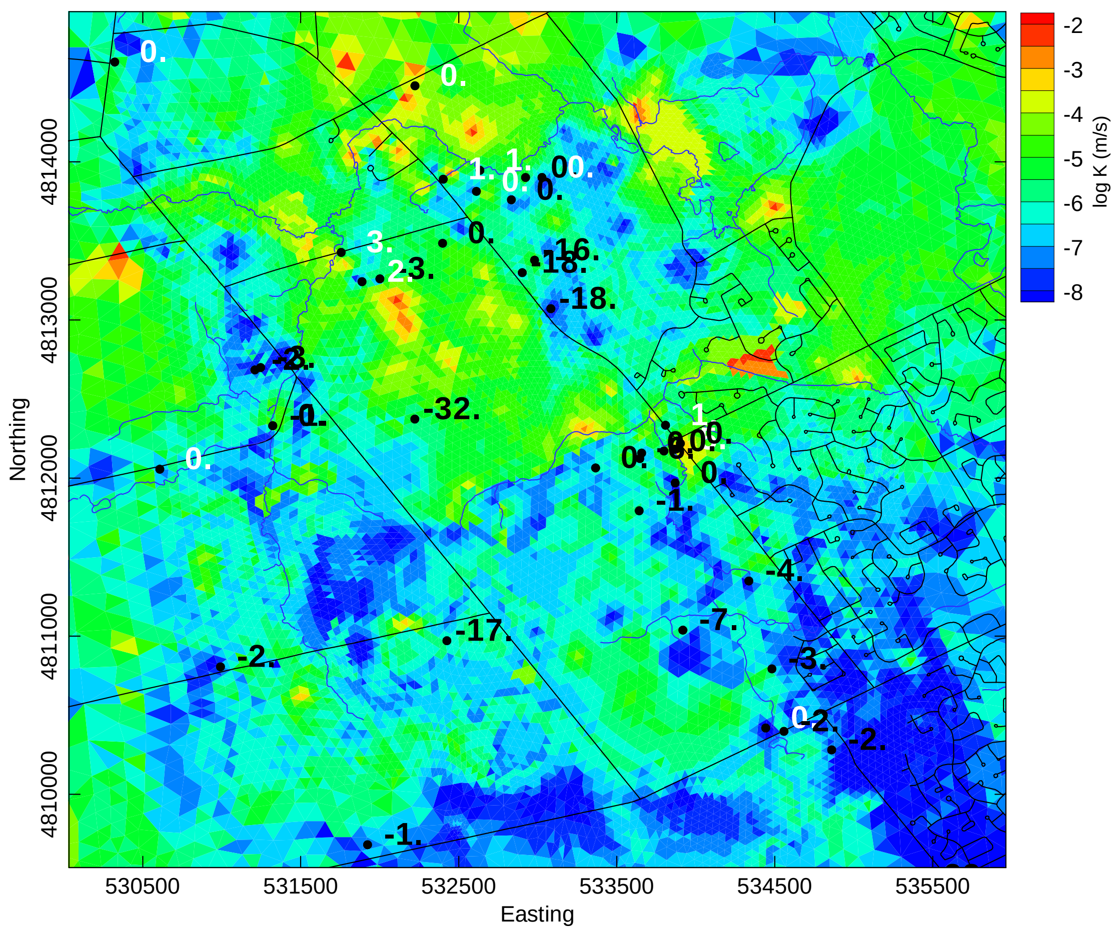

Figure 4.13. Distribution of final calibrated hydraulic conductivity (K_{xx}) and residuals for Aquitard 1, representing the perched observed hydraulic head data. Residuals are plotted in white for over-predicted heads and black for under-predicted heads.

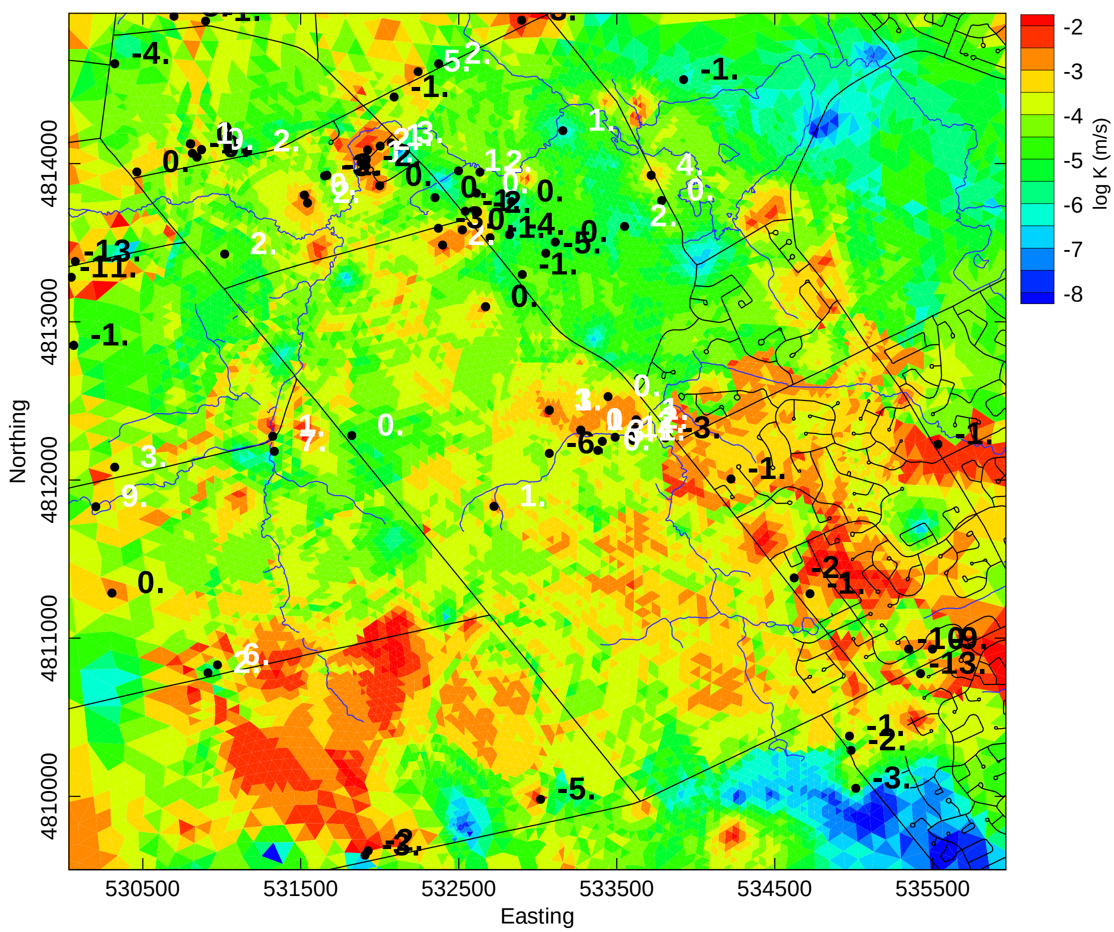

Figure 4.14. Distribution of final calibrated hydraulic conductivity (K_{xx}) and residuals for Aquifer 1. Residuals are plotted in white for over-predicted heads and black for under-predicted heads.

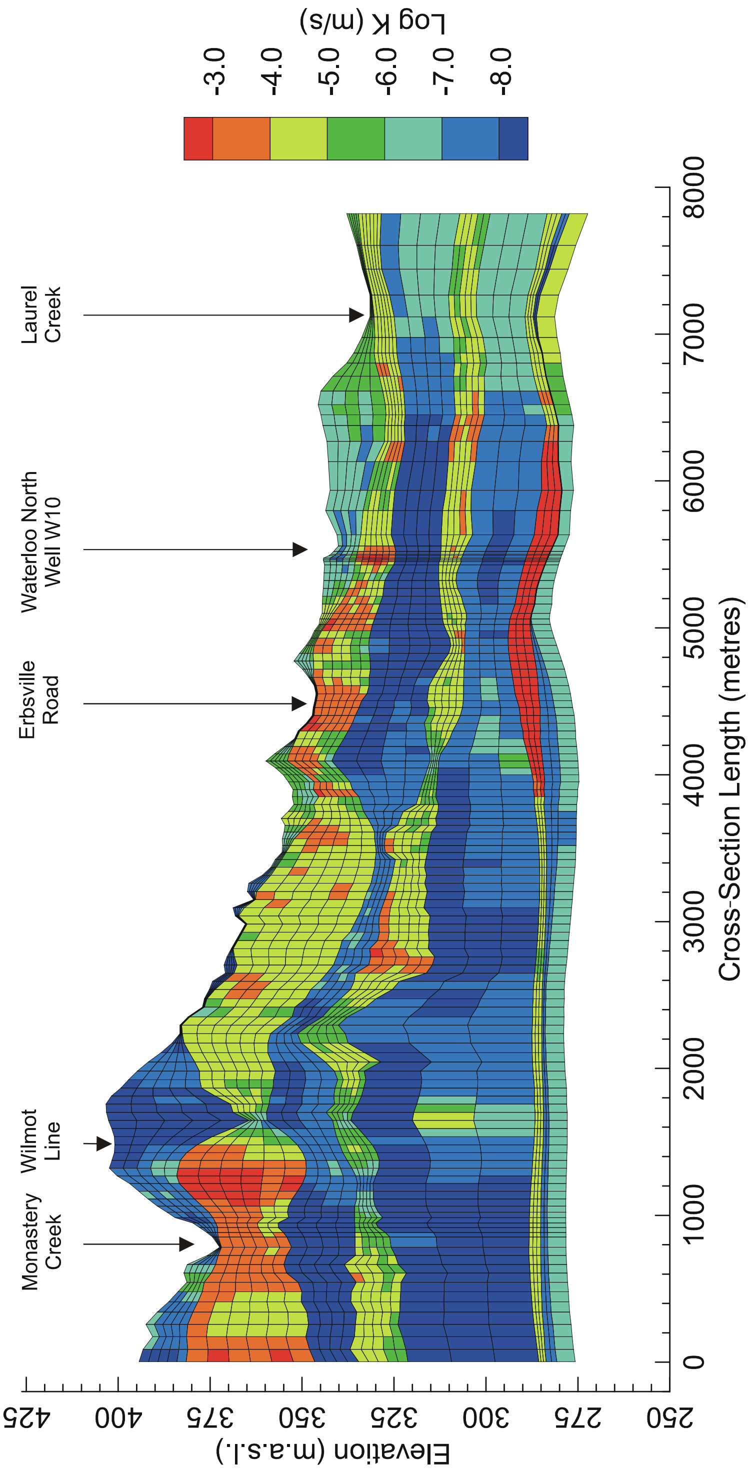

Figure 4.15. Cross-section from the numerical model, matching WE-7-25-25, illustrating the final calibrated hydraulic conductivity (K_{xx}) distribution. See Figure 2.13 on page 29 for matching borehole cross section and Figure 4.9 on page 74 for the initial K-values.

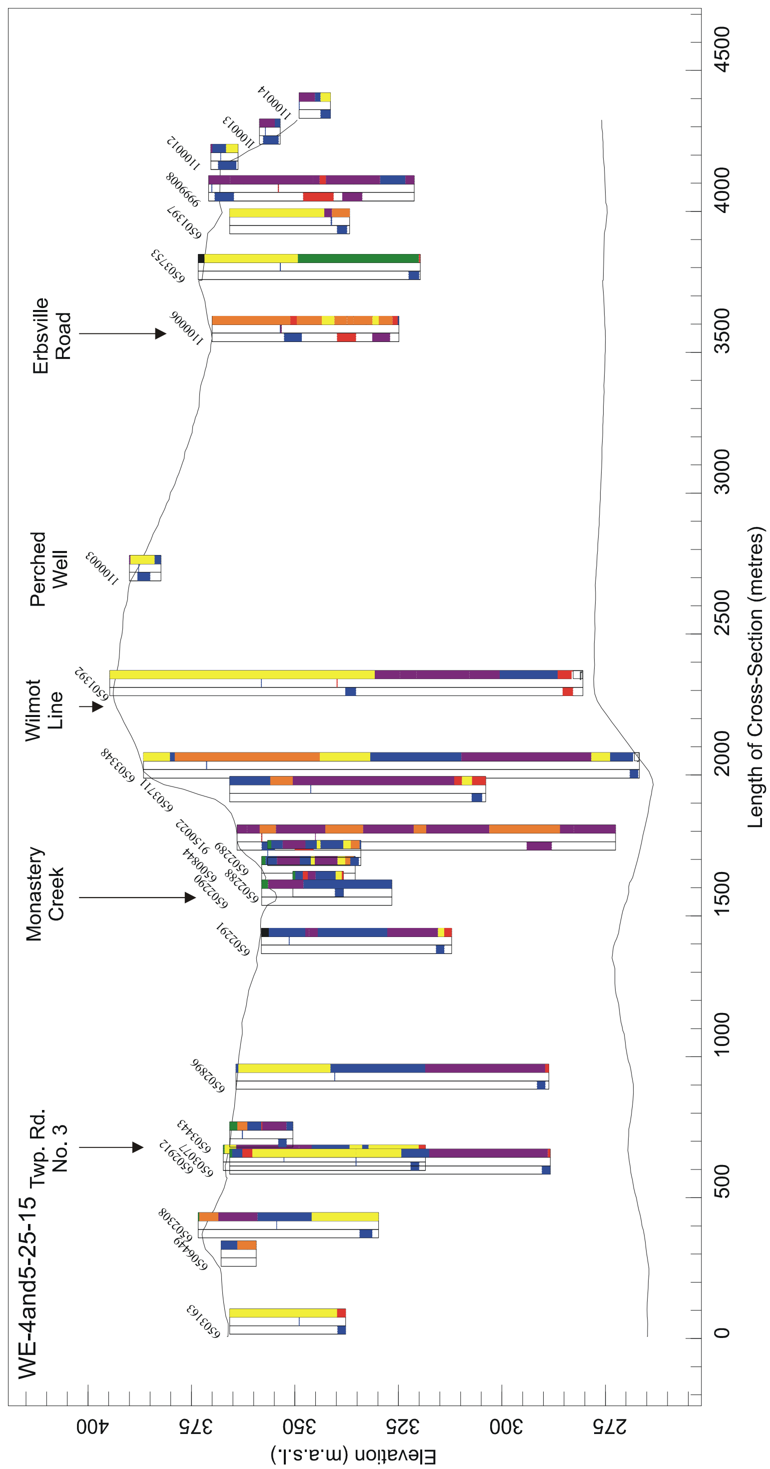

Figure 4.16. Cross-section WE-4and5-25-15. Three columns are given for each borehole, see Figure 2.15 for their description. Figure 2.14 shows the location of the cross-section.

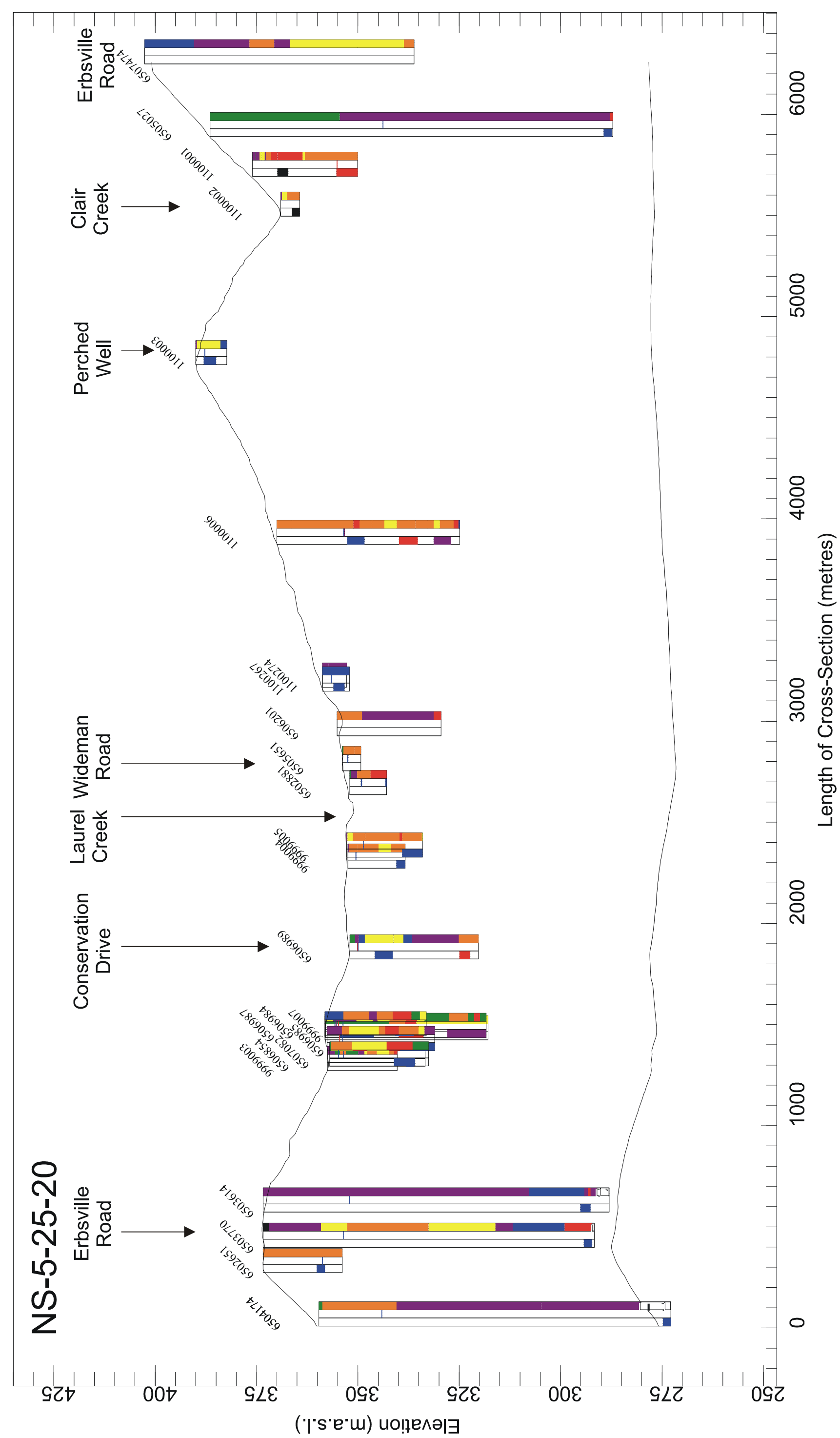

Figure 4.17. Cross-section NS-5-25-20. Three columns are given for each borehole, see Figure 2.15 for their description. Figure 2.14 shows the location of the cross section. (Note: Black screens indicate dry wells)

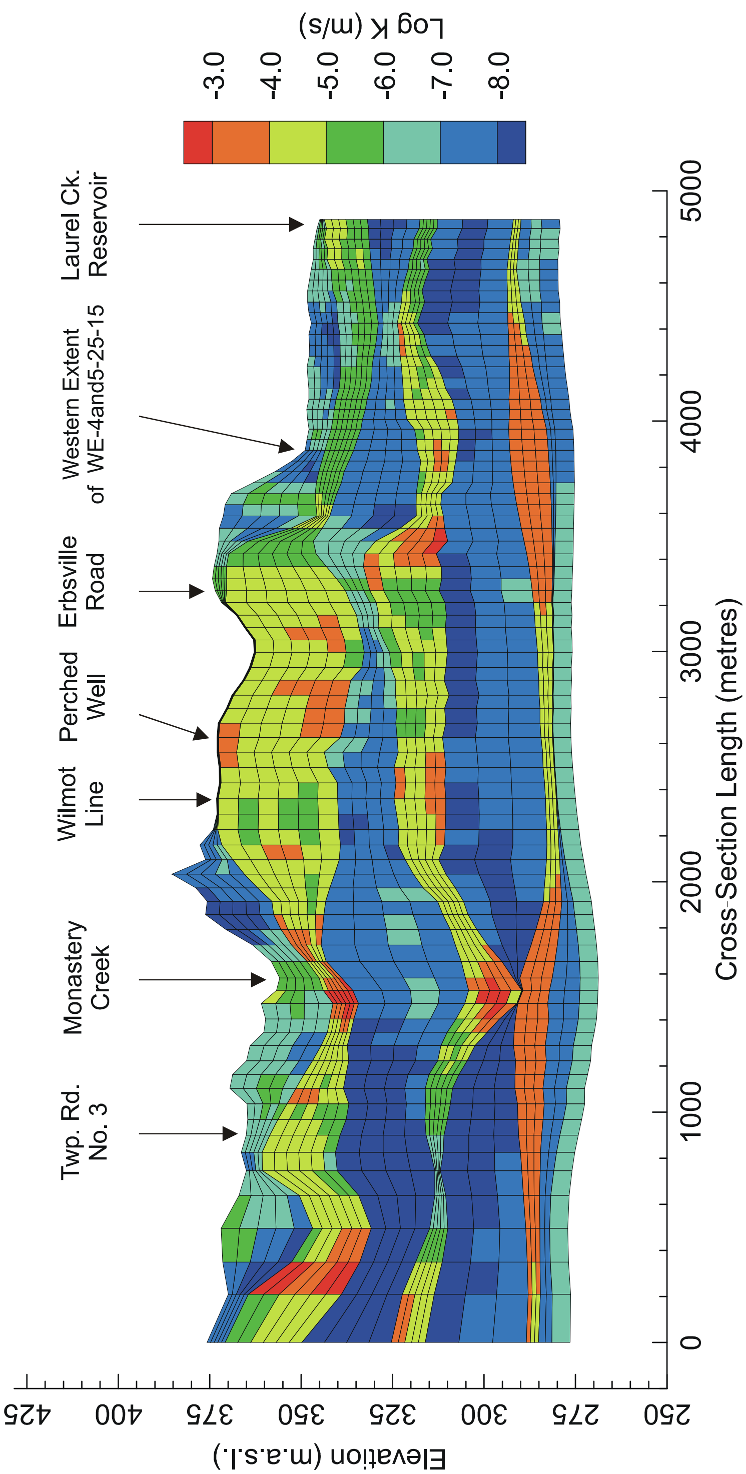

Figure 4.18. Cross-section from the numerical model, matching WE-4and5, illustrating the final calibrated hydraulic conductivity (K_{xx}) distribution. See Figure 4.16 on page 87 for matching borehole cross-section. For the cross-section location see Figure 2.14 on page 30.

Chapter 5

Impact of Urbanization

5.1 Introduction

Groundwater flow systems can be adversely affected by changes in landuse, including urban development. With urban sprawl, large areas of land are cleared and the vegetative cover is reduced and replaced with impervious surfaces such as roads, driveways, and parking lots. In addition, urban sprawl changes the topography due to construction grading and cut-and-fill practices. The alteration of the landscape can also reduce depressional storage, and surficial permeabilities by soil compaction. These alterations affect the fate of precipitation by increasing the rate and quantity of runoff. With increased overland flow, flooding and silting can occur in local drainage paths. An increase in runoff decreases infiltration, decreases base flow to surface water, and causes the water table to drop. Infiltration is also affected by weeping tiles used to dewater foundations.

On the other hand, urbanization can, in some cases, enhance the recharge to the water table. This is most evident in areas of arid conditions. In Peru, for example, infiltration has been increased from 0 to 700 mm/year as a result of leaky water mains and over-irrigation [*Geake et al.*, 1986].

In some communities, post-development recharge has been enhanced using artificial methods. Soakaway pits and infiltration galleries have been used since the 1970s to increase post-development infiltration by utilizing clean stormwater runoff from impervious areas and directly injecting it into the subsurface just above the water table through buried gravel trenches. Infiltration ponds have been effective at enhancing recharge rates in Nassau County, New York [*Ku et al.*, 1986]. Studies indicate that in urbanized areas where infiltration ponds were utilized, the water table had risen by approximately 1.5 metres [*Ku et al.*, 1986] . On the other hand, the water table dropped by almost a metre where runoff was directed into the ocean.

At the Waterloo West Side, artificial infiltration methods are being adopted to maintain natural infiltration rates in potential recharge areas within the new residential developments. Columbia Forest I and II utilize soakaway pits for clean runoff from individual homes and infiltration galleries for road runoff (Figure 1.3 on page 6). In Clair Hills and the Erbsville Road development areas, soakaway pits are to be used where surficial soils permit. Due to the high till content south of Clair Creek, surface conditions are poor for soakaway pits. The previously developed area located at the southwest corner of the Waterloo West Side at Erbsville Road and Trillium Estates lands do not have any post-development infiltration systems.

5.2 Post-Development Infiltration

Infiltration rates are difficult to determine due to the complex nature of the controlling factors. In addition, impacts to groundwater are often not observed until decades after urbanization has occurred. Numerical modelling gives the user an opportunity to compare effects on the groundwater flow system based on modified boundary conditions. The difficulty lies with how to change the boundary conditions to represent urban expansion.

For this study the urbanization impact will be evaluated by changing the infiltration rates applied to the model surface. Within the Waterloo West Side, previous studies have estimated that the natural runoff is 10 percent of the annual precipitation and estimates of infiltration were 240 mm/year [*Dorfman*, 1996][*Planning and Engineering Initiatives Ltd.*, 1996]. Stormwater management plans for the area show the average impervious area for developed lands is 50 percent [*Planning and Engineering Initiatives Ltd.*, 1997][*Planning and Engineering Initiatives Ltd.*, 1998a]. The remaining 50 percent of the land within the subdivision is assumed to allow 75 percent of the natural infiltration. Using these estimates, the post-development infiltration rates would be 90 mm/year.

The pervious lands within the subdivisions could on average allow less than 75 percent of the natural infiltration. These lands are graded to improve runoff and to reduce surface and foundation flooding. In addition, pre-development infiltration due to depressional storage will be greatly reduced once grading has occurred. Natural permeabilities of surficial soils will be reduced as a result of compaction during construction and grading. Often clay rich topsoil is used in the grading process which can reduce vertical movement of water. Therefore, a worst case scenario of 50 percent post infiltration will be assumed for the pervious lands, reducing the average infiltration rate of 90 mm/year to 70 mm/year, in subdivisions not utilizing any post-development-infiltration methods.

In three of the subdivisions, Columbia Forest I and II and Rose Wood Estates, soakaway pits and infiltration galleries will be used to augment the reduced post-development infiltration. The future effect of clogging or damage to these systems will also be investigated. It will be assumed that 60 percent of the post-development infiltration comes from soakaway pits and infiltration galleries and that the efficiency of these systems will be reduced by 50 percent thereby decreasing the post-infiltration from 240 mm/year to 160 mm/year.

To represent the post-development conditions, the surface flux boundary was altered as discussed but Type I boundaries were unchanged from pre-development conditions. The assumption is that water flow in the creeks will be maintained with storage release form the stormwater management ponds.

Three scenarios will be simulated for evaluation of post-development impact to the groundwater system, these include (see Figure 5.1):

1. For subdivisions where no post-development artificial infiltration methods will be used, the infiltration rate will be dropped from 240 mm/year to 90 mm/year.

2. For subdivisions where no post-development artificial infiltration methods will be used, the infiltration rate will be dropped from 240 mm/year to 70 mm/year.

3. Same as Scenario 2 but including future impact from damaged artificial infiltration facilities, therefore reducing post-development infiltration from 240 mm/year to 160 mm/year (where artificial infiltration systems will be utilized).

5.3 Post-Development Impact on the Groundwater Flow System

To quantify the impact on the groundwater flow system, the relative change in the hydraulic head distribution was compared for each post-development scenario.

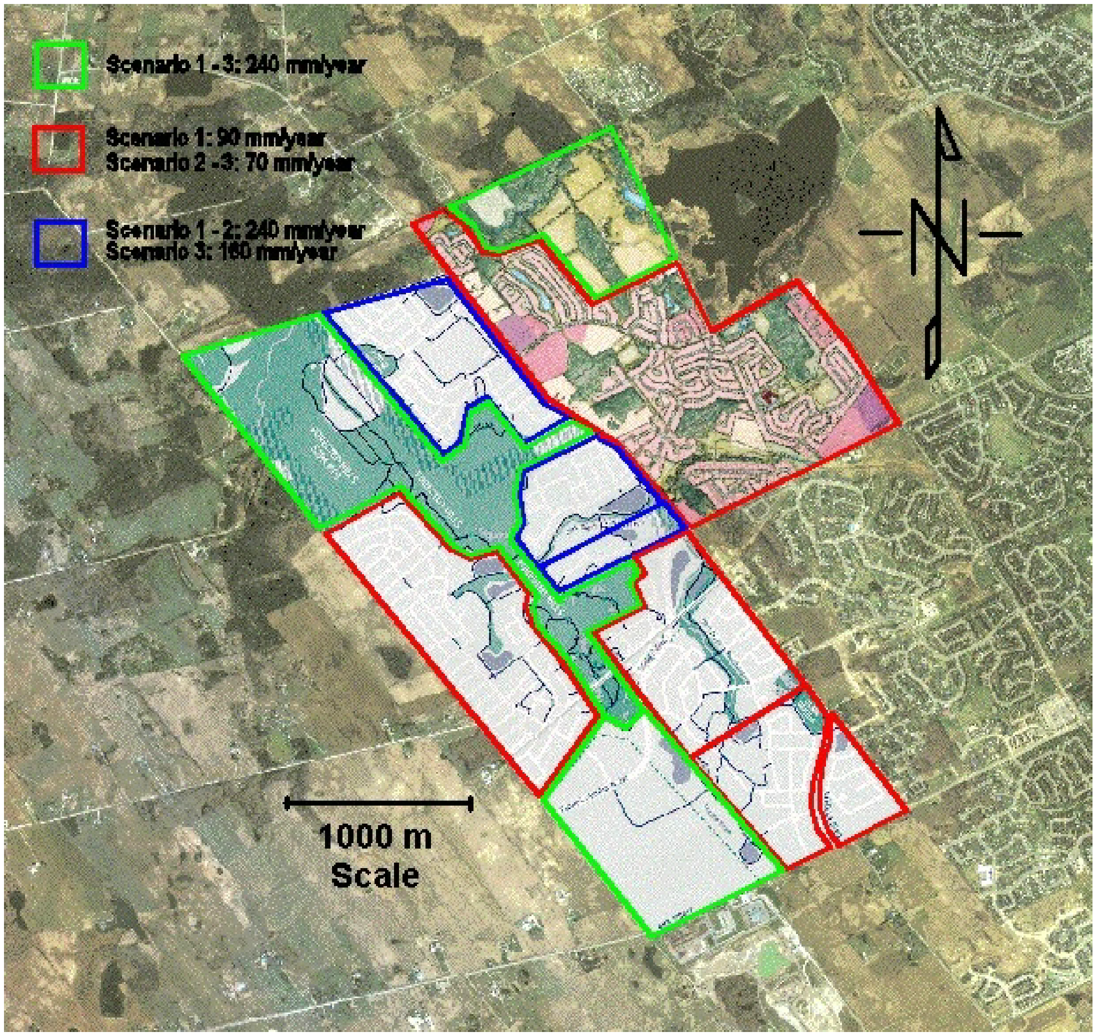

Figure 5.1. Post-development infiltration areas for Scenarios 1, 2 and 3. Red outlines are areas where no artificial infiltration will be used in post-development and correspond to Scenarios 1, 2 and 3. Blue outlines are areas where soakaway pits and infiltration galleries will be used and correspond to Scenario 3. Green outlines are for areas where pre-development infiltration rates were unchanged. Underlay of recent air photo and conceptual plans for urbanization (modified from [*Trushinski and Leedham*, 1998][*Trillium Estates Limited*, 2000]).

Figures 5.2 and 5.3 show the relative drop in the hydraulic head for Aquitard 1 and Aquifer 1 respectively, subject to Scenario 3. For post-development Scenarios 1 and 2, the relative drop in the water levels is similar to Scenario 3 and therefore plots are not included. The hydraulic head changes are minor for the deeper aquifers (less than 0.1 metres) and are also not included.

For Aquitard 1, in areas where perched water occurs, a large drop in the water table is observed (greater than 10 metres) subject to Scenario 3. For post-development Scenarios 1 and 2, the maximum change in hydraulic head in Aquifer 1 is just over a metre, and for Scenario 3 the head drops by almost 1.5 metres. For Aquifer 2, the maximum change in hydraulic head is less than 0.5 metres for all three scenarios. Three areas show a localized maximum effect on the water table: the most westerly portion of Clair Creek, the area south of Laurel Creek Reservoir on Trillium Estates land, and south of Erb Street close to Dutton Pond.

A significant drop in the water table is observed at the western limit of Clair Creek's northern branch. This area is part of the Clair Creek Valley which extents east to Erbsville Road (see topography in Figure 2.1 on page 10 and Figures 2.13 and 4.15). Clair Creek valley is believed to be a significant recharge area because the valley cuts through Aquitard 1 to Aquifer 1. The drop in the water table is limited to the western section of Clair Creek. The water table does not change to the east (closer to Erbsville Road) because stormwater management ponds will maintain flow in this section of the creek and the water table under this section should therefore not be effected.

The western section of Clair Creek does not flow all year but collects flow during storm events and is fed by seepage from infiltrating waters to the north, west and south. This portion of the Clair Creek Valley would seem to play an important role in groundwater recharge, at least at the local scale. If the stormwater management plans for the future development along Wilmot Line incorporate the western branch of Clair Creek for stormwater runoff, groundwater recharge may become locally and perhaps regionally enhanced.

The water table in Aquitard 1 and Aquifer 1 drops by approximately 1.5 metres and 3 meters respectively just north of Clair Creek on Trillium Estates Land (Figures 5.2 and 5.3). This area is in a topographic low with a local high to the west (Figure 2.1). Few geological data were included in the model for this area as indicated in Figures 2.8 to 2.11. In Figure 4.4 (page 67) Aquitard 1 ranges in thickness from 4 metres where the water table is most affected to over 20 metres at Erbsville Road where a topographic high occurs. The underlying Aquifer 1 has a uniform thickness of 10 metres (Figure 4.5). The topographic low and relatively low hydraulic conductivity of the underlying units may promote depressional storage which may not occur under post-development conditions.

In the vicinity of Dutton Pond (south of Erb Street), the water table is also affected in the post-development scenarios. All runoff south of Erb Street in Subwatershed 314 is stored in Dutton Pond which drains into Clair Creek to the north through a culvert (see Figure 4.4). Dutton Pond is assumed to be perched and is located above a relatively low hydraulic conductivity layer. At the pond, there is a downward gradient and but it is relatively low (Figures 2.5 and 2.6). As the local water table drops, the hydraulic connection between the pond and Aquifer 1 is broken, decreasing the recharge to the underlying aquifer, and dropping the water table.

Figures 5.4 and 5.5 illustrate the vertical distribution for hydraulic head and saturation observed in the model. The location of the cross-section is given in Figure 5.3. Perched water throughout subwatersheds 313 and 314 (Figure 5.4) in the pre-development scenario induce high vertical gradients through the upper till unit and increase the hydraulic head in deeper units. The regional flow pattern is from west to east (left to right) but local flow patterns exist in the upper units (Figure 5.4).

In the post-development scenarios, the vertical gradients are reduced in the upper till layer where infiltration rates have dropped over subwatersheds 313 and 314. The saturation profile is also affected under post-development conditions (Figure 5.5). The saturation at surface, for example, is greater where perched water is found and the majority of the upper till unit is at residual saturation (0.1). The saturation around Clair Creek decreases from 0.8 to 0.4 under post-development conditions even though the surface water is a fixed Type I boundary.

The impact of urbanization on the regional flow system was also investigated by comparing groundwater flow in the various hydrostratigraphic units under pre- and post-development scenarios. Table 5.1 shows the total applied infiltration within each of the subwatershed boundaries identified in Figure 5.6 as well as the percentage reduction of the infiltration under the three development scenarios. Table 5.2 shows the corresponding changes in the pre-development flow into Aquifers 1 and 2 (expressed as a percentage of infiltration) as well as the post-development flow under the three development scenarios (also expressed as a percentage of the pre-development flow for the same unit).

The average net vertical flow in Aquifer 1 is upward into Aquitard 1 in Subwatersheds 309 and 310 but in Subwatersheds 308, 313 and 314 Aquifer 1 is being recharged from Aquitard 1. The maximum net vertical flow was observed in Subwatershed 313, where 66 percent and 39 percent of the applied infiltration entered

Aquifer 1 and Aquifer 2, respectively. In Subwatershed 314, where there is a significant till layer, up to 50 percent of the applied infiltration is recharging Aquifer 1, this flow is assumed to come from depressional storage where perched water exists. High gradients observed in Aquitard 1 (see Figure 5.4) seem to have a significant effect on recharge rates to the underlying aquifer. The significance of depression-focused recharge has been well documented, for example, in western Canada small-scale wetlands underline by low-permeability material (Log K of 10^{-10} m/s) were found to facilitate increased recharge rates [*Hayashi*, 1996][Hayashi *et al.*, 1998] and also in La Plata, Argentina along coastal wetlands [*Logan and Rudolph*, 1996].

Under post-development conditions vertical flow into Aquifer 1 in Subwatershed 314 is most affected under Scenarios 1 and 2 but little change is observed under Scenario 3. Only a maximum 2 percent change to the recharge rates to Aquifer 1 is observed in Subwatershed 313 subject to all three post-development scenarios.

The regional groundwater flow system down-gradient from the Waterloo West Side is also affected by urbanization. Table 5.3 includes the net horizontal flow observed in the upper hydrostratigraphic units along the section identified in Figure 5.6. The greatest impact on the flow system is seen in the top two hydrostratigraphic units, Aquitard 1 and Aquifer 1, with respect to pre-development conditions while the deeper units (as seen in Table 5.3) are not significantly affected. Horizontal flow rates within aquitards are orders of magnitude less than observed in aquifers; therefore, the 3 percent change for Aquitard 1 is less significant than the 3 percent change in Aquifer 1. Aquifer 2 experiences a decrease of 2 percent in horizontal flow (Table 5.3). Over the entire depth represented in the numerical model, the flow drops by 1.5 percent or $1.2 \cdot 10^7$ litres per year, for each scenario.

Subwatersheds	Pre-Development Applied Infiltration m^3/s	Post-Development Percent Reduction in Applied Infiltration		
		Scenario 1	Scenario 2	Scenario 3
308	9.15E-03	2.4	2.9	4.0
309	2.19E-02	7.9	9.5	16.1
310	2.74E-02	17.3	20.9	21.7
313	1.37E-02	34.2	41.2	48.3
314	2.59E-02	28.2	34.0	34.2

Table 5.1. Comparison of applied inftration within subwatershed boundaries identified in Figure 5.6. For each post-development scenario the percent drop in applied infiltration is also given.

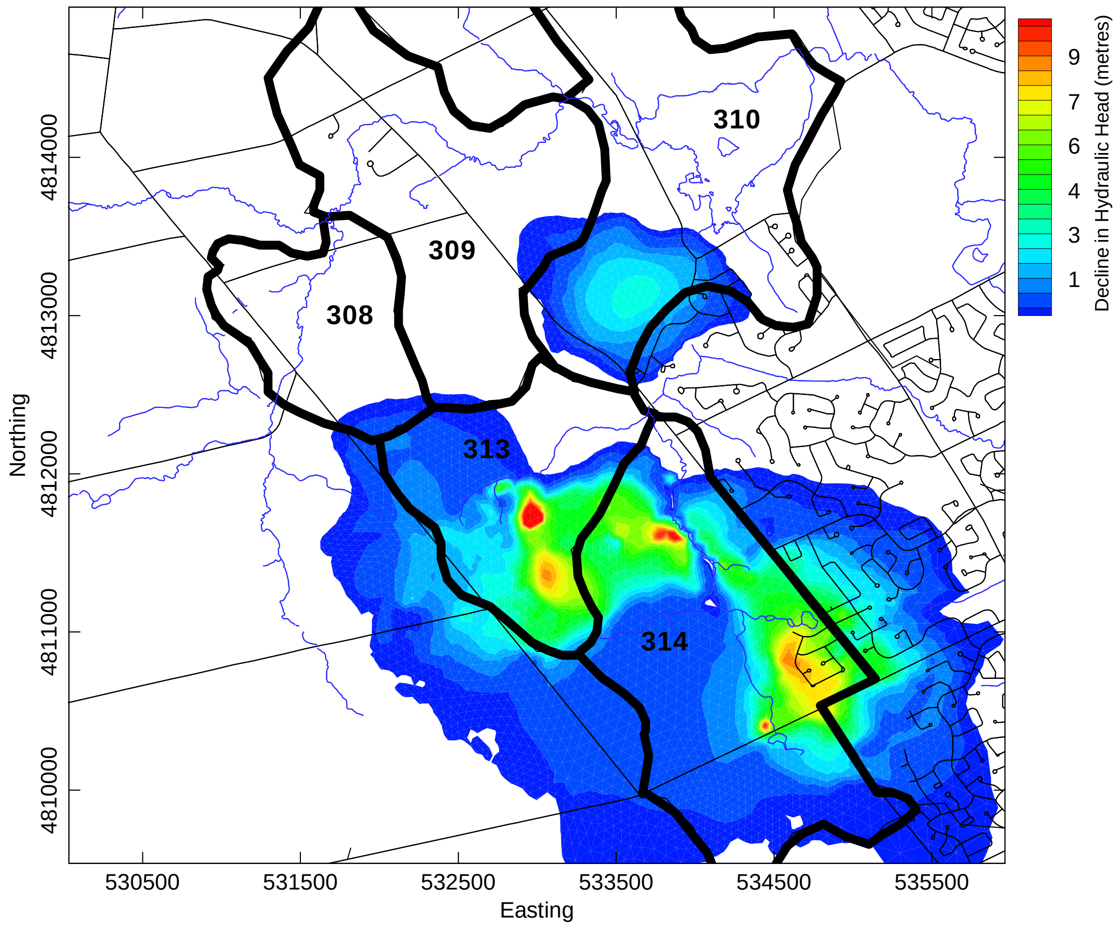

Figure 5.2. Relative hydraulic head change in Aquitard 1 as a result of post-development Scenario 3. Thick black lines outline the subwatersheds. Head changes less than 0.25 metres are not shown.

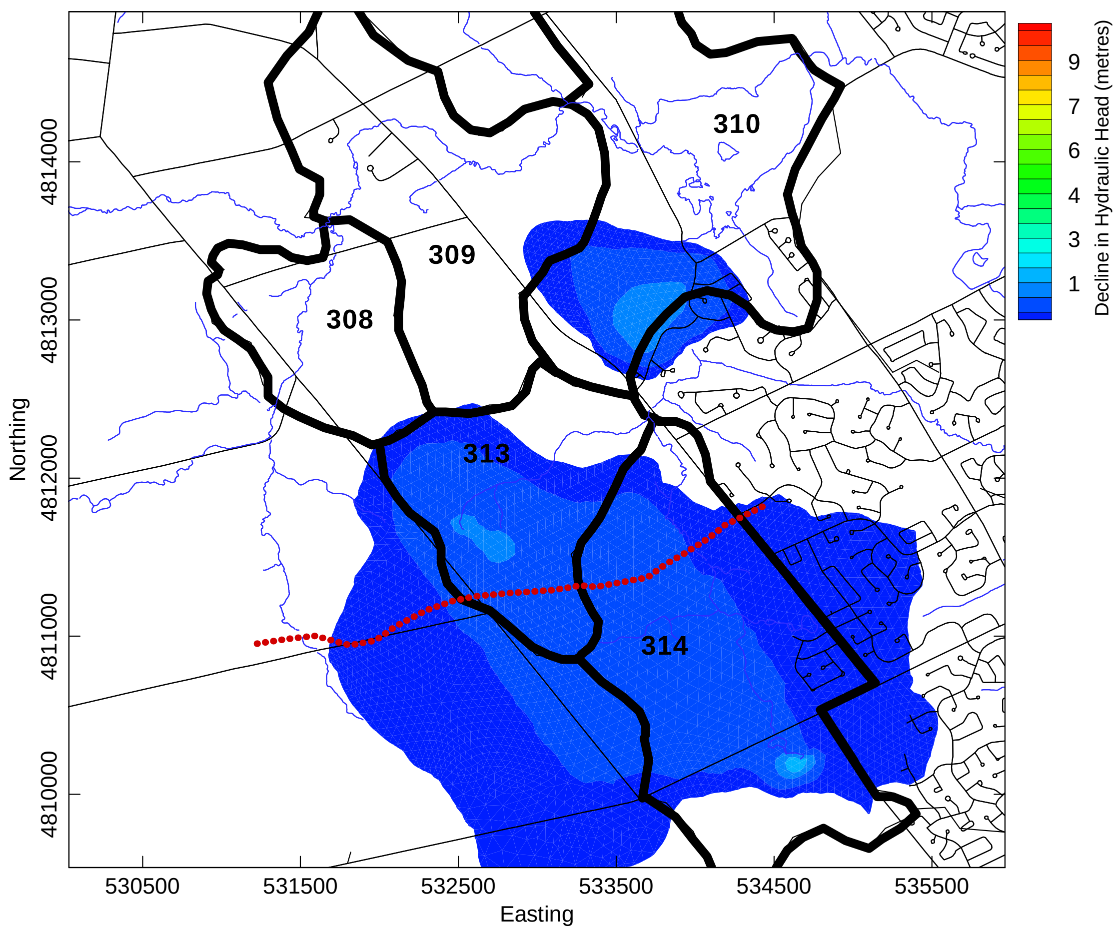

Figure 5.3. Relative hydraulic head change in Aquifer 1 as a result of post-development Scenario 3. Thick black lines outline the subwatersheds. Dotted red line represents cross-section location for Figures 5.4 and 5.5. Head changes less than 0.25 metres are not shown.

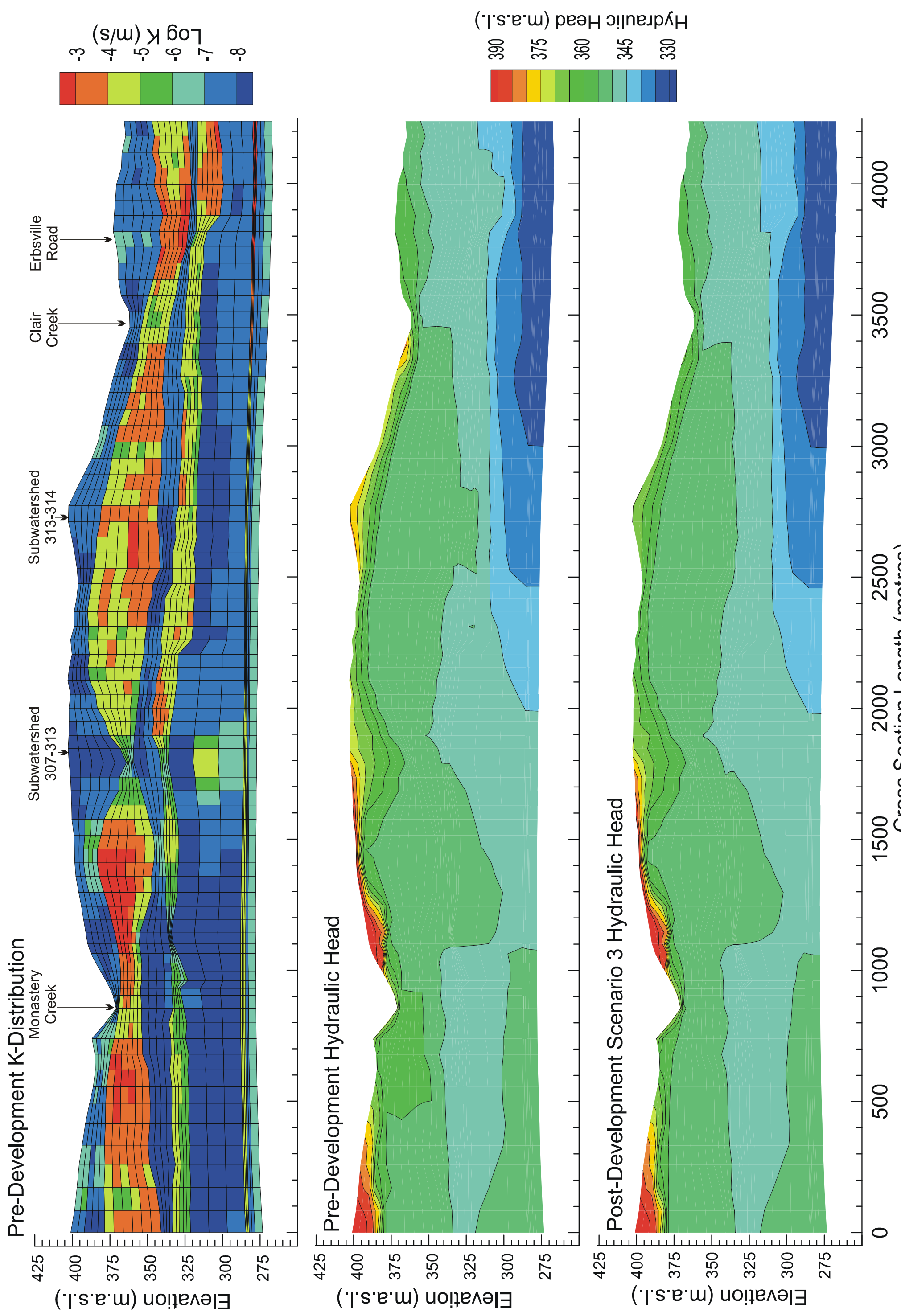

Figure 5.4. Cross-section showing the pre-development versus the post-development (Scenario 3) impact to the hydraulic head distribution. Cross-section location shown in Figure 5.3. Top of figure shows the hydraulic conductivity distribution (K_{xx}).

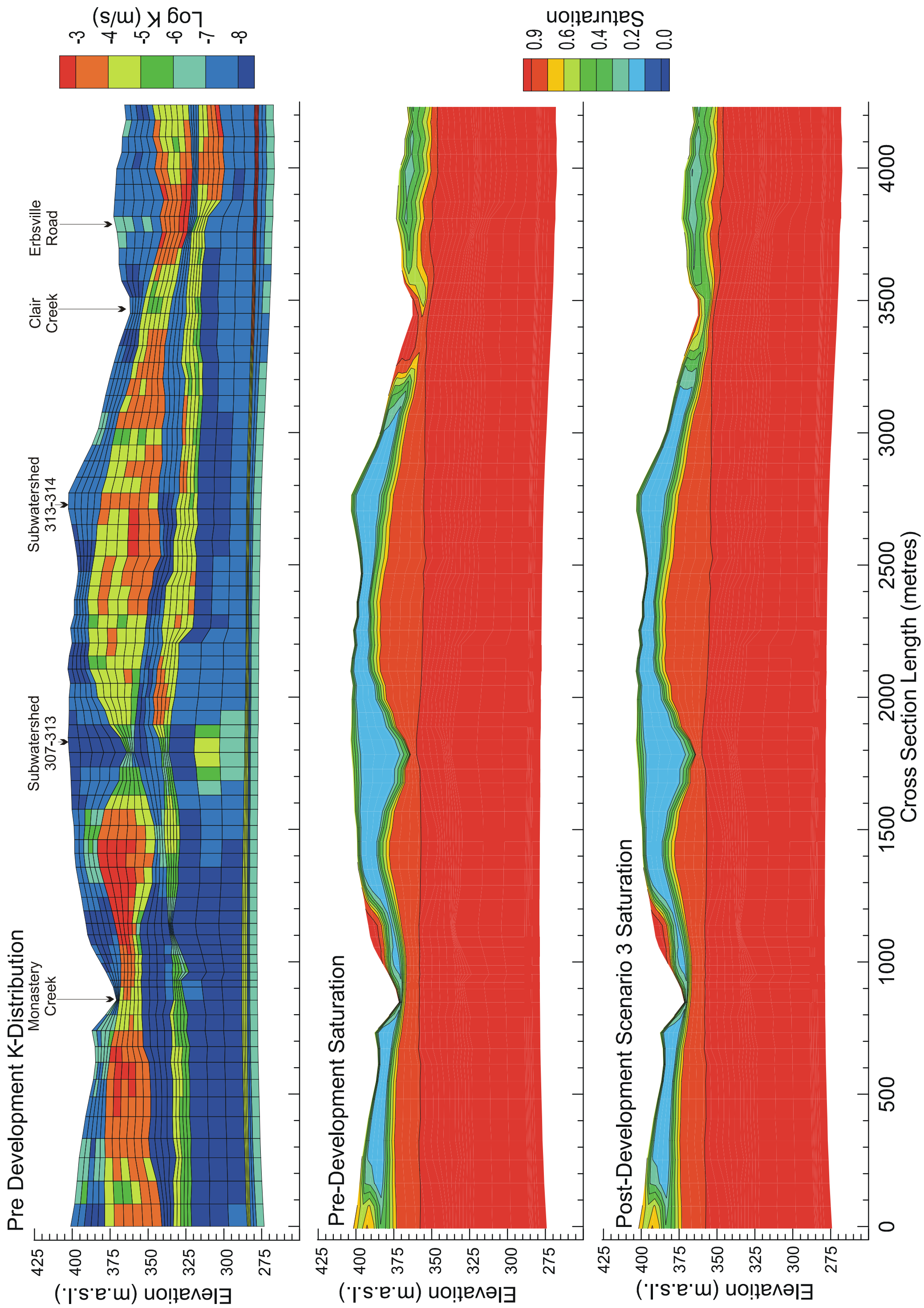

Figure 5.5. Cross-section showing the pre-development versus the post-development (Scenario 3) impact to the saturation profile. Cross-section location shown in Figure 5.3. Top of figure shows the hydraulic conductivity distribution (K_{xx}).

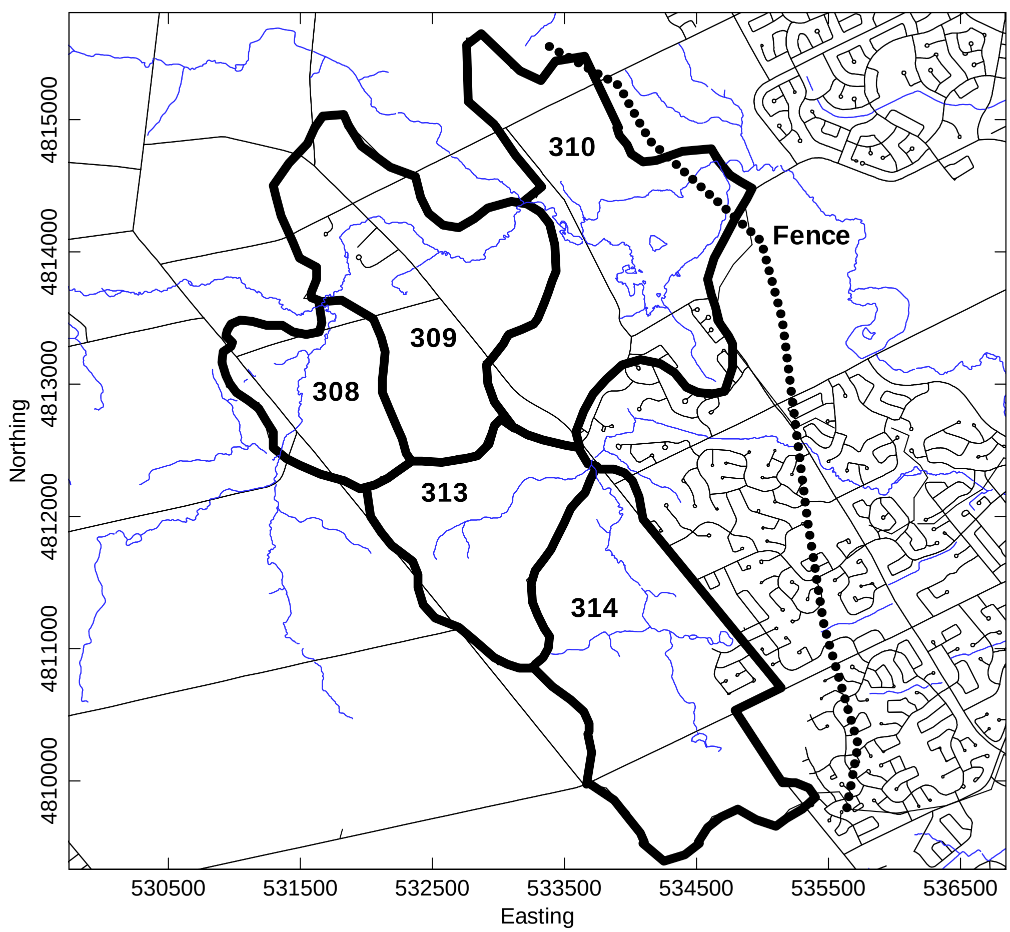

Figure 5.6. Waterloo West Side - locations of subwatersheds boundaries for vertical flow comparison (See Table 5.2 and Table 5.1). Location of fence for horizontal flow comparison (See Table 5.3).

	Pre-Development		Development Scenarios					
			Scenario 1		Scenario 2		Scenario 3	
Sub-watersheds	Vertical Flow m^3/s	% of Applied Infiltration	Vertical Flow m^3/s	% Change wrt Pre Flow	Vertical Flow m^3/s	% Change wrt Pre Flow	Vertical Flow m^3/s	% Change wrt Pre Flow
To Aquifer 1								
308	1.40E-03	15.3	1.47E-03	4.9	1.48E-03	5.9	1.49E-03	6.9
309	-1.51E-03	6.9	-1.47E-03	-2.8	-1.46E-03	-3.3	-1.51E-03	-0.6
310	-1.55E-03	5.7	-1.62E-03	4.2	-1.63E-03	5.1	-1.63E-03	5.1
313	9.06E-03	66.1	8.91E-03	-1.6	8.88E-03	-1.9	8.88E-03	-2.0
314	1.21E-02	46.6	1.14E-02	-5.5	1.13E-02	-6.5	1.13E-02	-6.6
To Aquifer 2								
308	6.43E-04	7.0	6.88E-04	7.0	6.97E-04	8.4	7.05E-04	9.6
309	3.16E-04	1.4	3.34E-04	5.9	3.38E-04	7.0	3.10E-04	-1.7
310	-1.06E-03	3.9	-1.11E-03	4.8	-1.12E-03	5.8	-1.12E-03	5.7
313	5.31E-03	38.8	5.24E-03	-1.3	5.23E-03	-1.6	5.22E-03	-1.7
314	6.72E-03	25.9	6.49E-03	-3.5	6.45E-03	-4.1	6.44E-03	-4.1

Table 5.2. Comparison of net vertical flow within subwatershed boundaries identified in Figure 5.6. The net vertical flow into Aquifer 1 and Aquifer 2 for the three post-development scenarios and the percent change with respect to the pre-development flows are given. Negative flow values indicate upward groundwater flow.

5.4 Post-Development Impact to Local Surface Water

The impact to surface water within the Waterloo West Side area was examined by comparing the flow at the Type I boundaries representing the water body. It is assumed that stream flow will be maintained in the post-development stage by supplementing flow from the stormwater management ponds. The assumption that Type I boundary conditions are preserved is therefore conceptually valid, but in reality some sections of the streams may become dry. Due to the limitations associated with the lack of small scale data, such as stream bottom K-values, the context of this discussion is related more to the relative change observed at Type I boundaries as opposed to the magnitudes.

Surface water segments were isolated according to subwatershed boundaries and are indicated in Figure 5.7. Table 5.4 lists the flow at the Type I nodes for each subwatershed segment for pre-development and post-development Scenarios 1 to 3. The flow along each segment has been subdivided according to input flow (into domain) and exit flow (out of domain). Included in Table 5.4 is the average net flow over all Type I nodes for the each surface water body.

	Pre-Development	Post-Development Scenario 1		Post-Development Scenario 2		Post-Development Scenario 3	
	Horizontal Flow	Horizontal Flow		Horizontal Flow		Horizontal Flow	
	m^3/s	m^3/s	% Change	m^3/s	% Change	m^3/s	% Change
Aquitard 1	6.81E-04	6.96E-04	2.3	6.99E-04	2.7	6.99E-04	2.8
Aquifer 1	1.34E-02	1.30E-02	-2.8	1.31E-02	-2.7	1.31E-02	-2.7
Aquitard 2	-3.21E-04	-3.18E-04	-0.9	-3.18E-04	-1.1	-3.17E-04	-1.2
Aquifer 2	2.01E-03	1.97E-03	-1.8	1.97E-03	-2.1	1.97E-03	-2.1
Net All Units	2.83E-02	2.78E-02	-1.5	2.79E-02	-1.5	2.79E-02	-1.5

Table 5.3. Comparison of net horizontal flow across the down-gradient boundary identified in Figure 5.6. The net horizontal flow across the fence boundary for the upper-most four hydrostratigraphic units and the net horizontal flow across all eight hydrostratigraphic units are given (deeper units are not significantly affected). Positive flow is toward the east in the direction of regional groundwater flow.

The creeks in the area are on average recharging the underlying sediments (Table 5.4). In all post-development scenarios, the recharge from the surface water for each subwatershed increases (Table 5.4). This is because as the surrounding water table drops, the downward gradient increases, inducing more flow from surface water to the underlying sediments (Figure 5.8).

Segment S-1 includes a portion of Monastery Creek that runs through Subwatershed 308 and on average contributes a large amount of water to the underlying sediments. This can be attributed to the high permeability of the sediments (see Figure 4.13 on page 84) and the thinness Aquitard 1 (Figure 4.4) below the stream bed. Surface water segments S-2 and S-3 are on average contributing little recharge as indicated in Table 5.4. All three segments (S-1 to 3) show a slight increase in recharge under post-development conditions but the impact to each segment is low. This can be linked to the fact that all three segments are up-gradient from developments.

Clair Creek is subdivided into two segments S-4 and S-5. Segment S-4 corresponds to the northern branch of Clair Creek and is located in Subwatershed 313. Field data indicate that this portion of the creek has both losing and gaining sections (Figure 2.7). Model simulations show a net recharge to the underlying sediments from the creek. The impact to S-4 increases for each subsequent post-development scenario (Table 5.4). Segment S-5 is affected by post-development Scenarios 1 and 2 but compared to Scenario 2 no additional change was observed in Scenario 3 (Table 5.4). Most of the south branch of Clair Creek is perched on clay which isolates the creek from Aquifer 1 but ensures that the stream is losing along its entire length. A change in the hydraulic head below this clay layer has a small effect on the amount of recharge to Aquifer 1 because the most of Clair Creek (S-5) was already perched in the pre-development base case.

	Subwatershed	Label	Flow At Type 1 Nodes		
			Into Domain m^3/s	Out of Domain m^3/s	Net m^3/s
Monastery Creek					
Pre-Development	308	S-1	0.7413	0.0674	0.6739
Post Scenario 1			0.7425	0.0673	0.6752
Post Scenario 2			0.7428	0.0673	0.6755
Post Scenario 3			0.7435	0.0672	0.6763
Laurel Creek					
Pre-Development	309	S-2	0.2836	0.2743	0.0093
Post Scenario 1			0.2843	0.2730	0.0113
Post Scenario 2			0.2845	0.2727	0.0118
Post Scenario 3			0.2847	0.2722	0.0125
Laurel Creek and Laurel Creek Reservoir					
Pre-Development	310	S-3	1.4070	1.3950	0.0117
Post Scenario 1			1.4090	1.3940	0.0144
Post Scenario 2			1.4090	1.3940	0.0150
Post Scenario 3			1.4090	1.3940	0.0150
Clair Creek west of Erbsville Road					
Pre-Development	313	S-4	0.0717	0.0389	0.0328
Post Scenario 1			0.0735	0.0379	0.0356
Post Scenario 2			0.0738	0.0377	0.0361
Post Scenario 3			0.0745	0.0373	0.0371
Clair Creek west of Erbsville Road					
Pre-Development	314	S-5	0.1684	0.0493	0.1191
Post Scenario 1			0.1701	0.0478	0.1223
Post Scenario 2			0.1706	0.0476	0.1230
Post Scenario 3			0.1706	0.0475	0.1231

Table 5.4. Flow determined at Type I boundaries identified in Figure 5.7.

5.5 Summary

The impact of urbanization within the Waterloo West Side was examined by decreasing the applied pre-development infiltration rates but the Type I boundaries representing creek flow were unchanged from pre-development conditions. The later assumption is justified in the sense that stormwater management ponds will be able to maintain stream flow. The impact on the groundwater flow system was quantified by comparing changes in observed hydraulic head distribution, and by

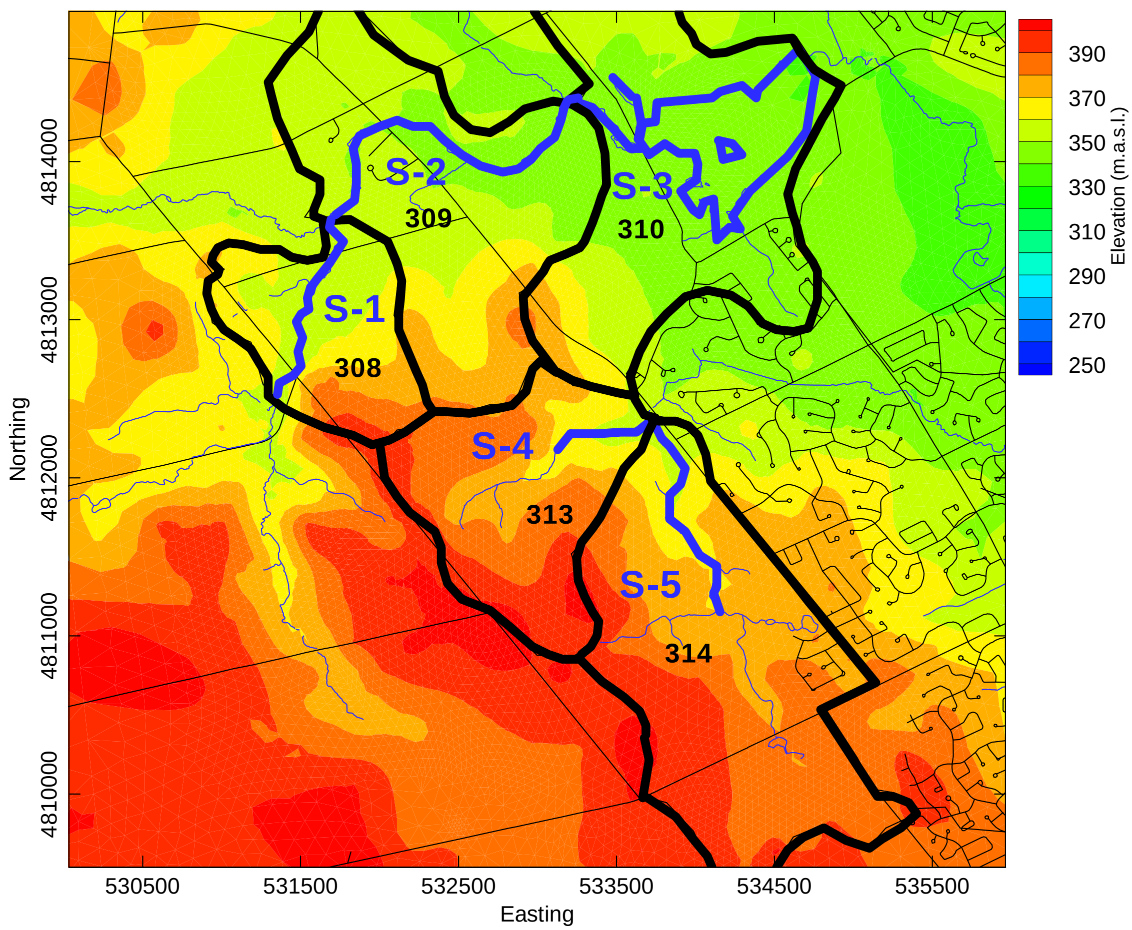

Figure 5.7. Waterloo West Side - locations of water courses where pre- and post-development impact was compared (super-imposed on topography). Thick blue lines represent segments of water courses where comparison was made. Thick black lines represent subwatershed boundaries.

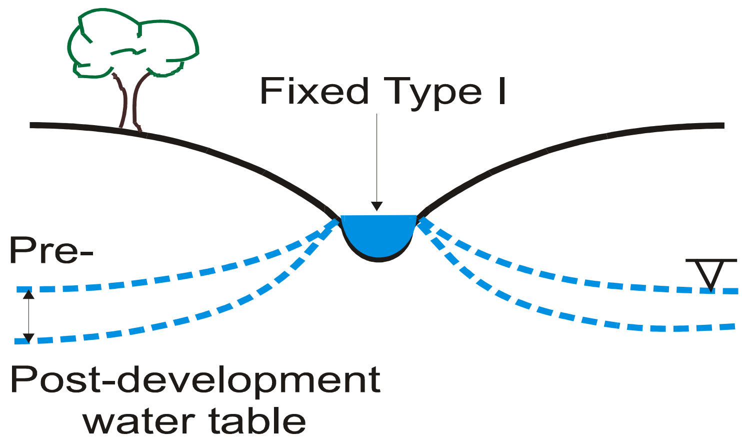

Figure 5.8. Conceptual model for post-development effect on the water table close to Type I boundaries.

comparing flow rates within the hydrogeological units. Simulations showed that measurable impacts were concentrated to the near-surface units including Aquitard 1 and Aquifer 1 whereas deeper units were relatively unaffected. Post-development simulations showed that downward vertical gradients were significantly reduced in Aquitard 1.

Simulations suggest that local groundwater flow within the Waterloo West Side is significantly controlled by surface water (i.e. wetlands, ponds and creeks). Post-development results, however, show that when surface water conditions are maintained there are only minor changes to the groundwater flow system. If surface water flows are not maintained, local groundwater recharge will be significantly affected which may then impact the regional groundwater flow system.

Chapter 6

Summary

6.1 Conclusions

The two objectives of this study were to characterize the hydrogeology of the Waterloo West Side and to determine the impact of urbanization on the groundwater flow system. The first objective was accomplished by utilizing existing techniques, which included 3D parameterization of the K-field and automated calibration of the 3D steady-state model. Further work involved modifying the current conceptual model for representing the complex heterogeneous aquifer systems within the Waterloo Region.

The second objective of examining the effect of urbanization within the Waterloo West Side was accomplished by changing the surficial boundary conditions to approximate post-development infiltration rates. The simulations compared three scenarios for post-development conditions to pre-development conditions. Results show that urbanization within the Waterloo West Side will affect both the local groundwater flow system and to a lesser degree the regional groundwater flow system, as well flows in local surface water.

Post-development impact was quantified locally with respect to the surface water and recharge to the local aquifer system as well as to the regional groundwater flow system down-gradient from the Waterloo West Side. Surface water in the area will be affected by urbanization where downward flow from the creeks will increase as the surrounding water table drops. Local recharge will also be affected by urbanization with a greater impact seen in areas where artificial infiltration methods are difficult to implement (where surficial permeability is low).

From this study it was determined that a decrease in infiltration rates does not directly correlate to an equal decrease in regional groundwater flow but on a local-scale, subsurface flow is significantly effected as observed at surface water boundaries. As expected, the impact to the regional groundwater system will increase as urban sprawl expands, but if the near-surface groundwater flow system is maintained at pre-development conditions, the impact on regional groundwater flow due to urbanization will be reduced. Within this study area, it was found that the local-scale groundwater flow system is significantly controlled by surface water conditions (i.e. creeks and wetlands) in pre-and post-development stages. It should be noted, however, that these conclusions are contingent on the assumption that post-development stream flows are maintained by using stormwater management ponds.

6.2 Recommendations

Approximations associated with the numerical technique utilized in this study limit the ability to accurately determine the effect of development on the near-surface flow system, especially close to surface water bodies. It is recommended that further studies be conducted using a more localized approach so that the complex near-surface flow system can be investigated in more detail. This includes determining the effect of unsaturated flow as a result of perched water and utilizing a numerical technique which directly simulates surface water and groundwater interactions and allows transient conditions to be taken into account.

Future investigations related to post-development impact on groundwater flow will require more detailed data. For instance, changes in topography will have a significant effect on runoff rates and depressional storage which will alter recharge rates to the underlying aquifer system. Detailed information regarding topography changes could be obtained from smaller-scale DEM's (10 metre) for pre- and post-development conditions. In addition, further field studies should be concentrated north of Clair Creek where the shallow hydrogeology has been poorly characterized, this could include, for example, information from shallow monitoring wells, testpits and Guelph Permeameter measurements.

From this study it is concluded that a majority of recharge to the underlying aquifers is controlled by surface water (creeks and wetlands). Impact to the subsurface flow system will be reduced if flow is maintained within local creeks using storage from stormwater management facilities. In addition, post-development impact to subsurface flow associated with future development along Wilmot Line can be reduced if the northwest branch of Clair Creek is incorporated in the stormwater management plans for this new development. In addition, in areas where buried artificial infiltration methods are not practical, for example at Clair Hills where Aquitard 1 thickens, infiltration ponds could be utilized to augment post-development infiltration rates and these facilities would be easier to maintain and monitor.

Future groundwater monitoring is suggested close to the artificial infiltration facilities (soakaway pits and infiltration galleries) to verify their effectiveness and to determine the post-development impact on the groundwater quality and water levels.

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Appendix A

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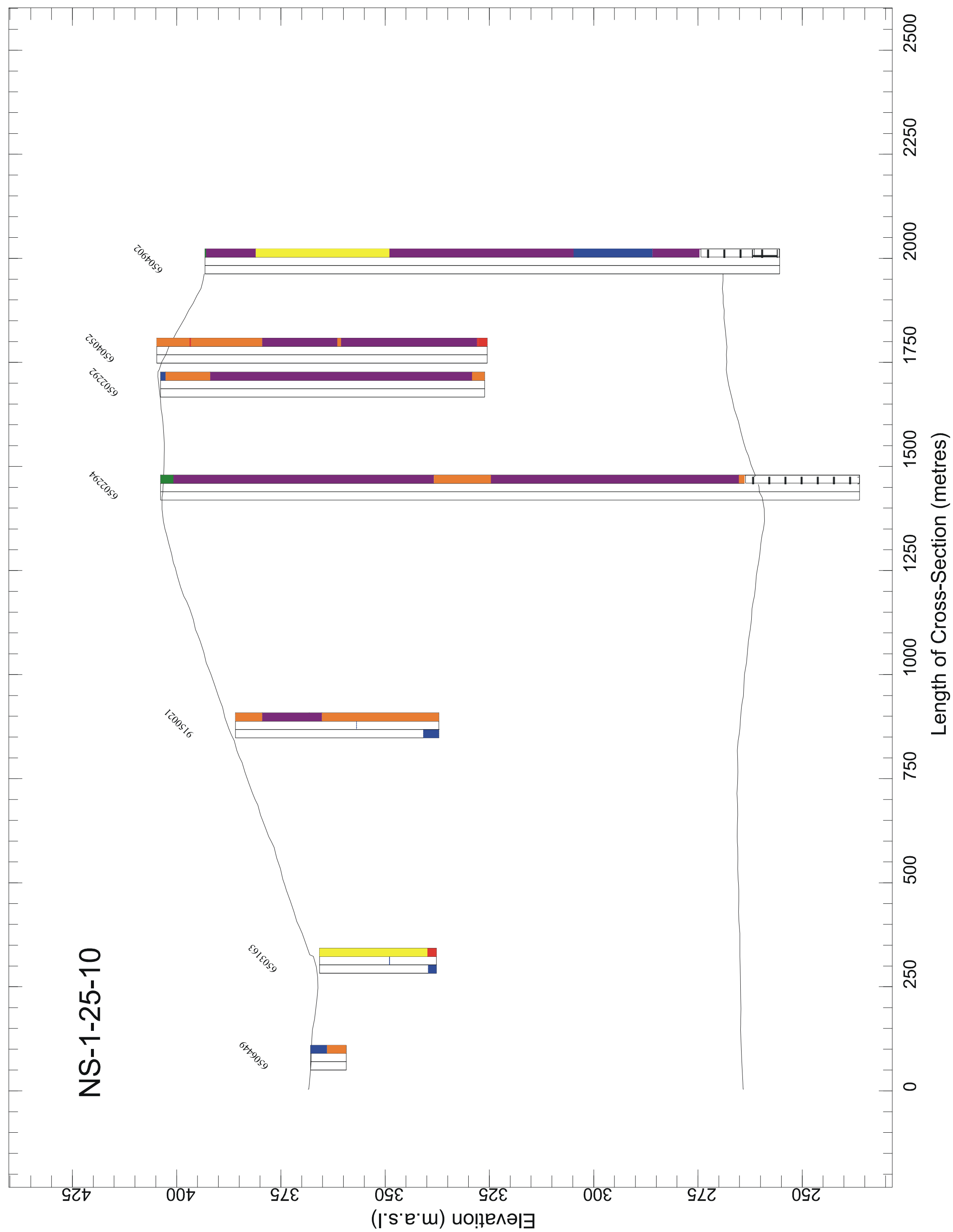
Hydrogeological Cross-Sections

A total of 26 cross-sections were used in the hydrostratigraphic interpretation for the Waterloo West Side and are given on the following pages. Figure 2.14 (on page 30) shows the location of the cross-sections. A legend describing the cross-section setup is given in Figure 2.15 (on page 31). Three columns are given for each borehole; see Figure 2.15 for their description. Three cross-sections are included in the text: NS-5 (page 88), WE-4and5 (page 87), and WE-7 (page 29).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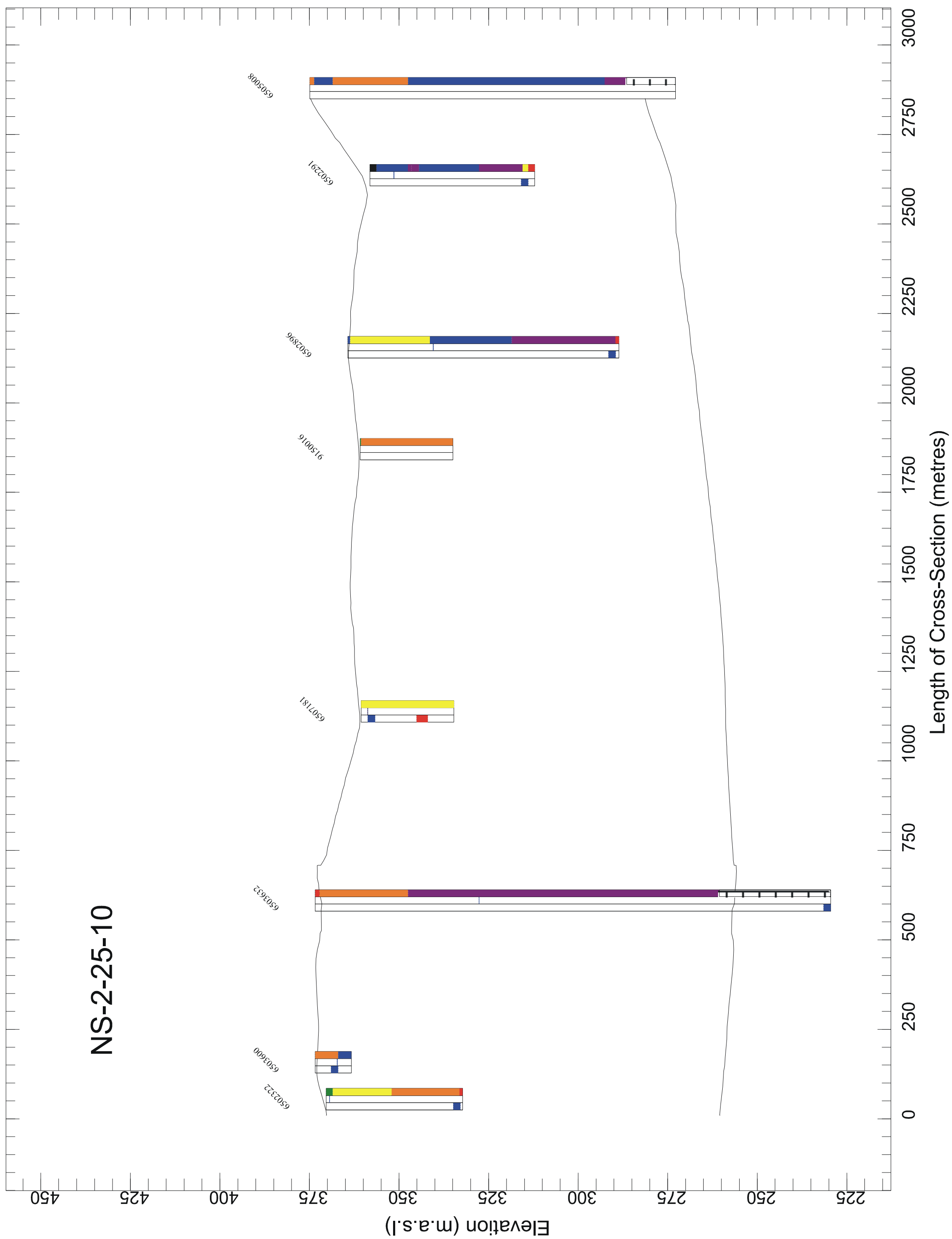
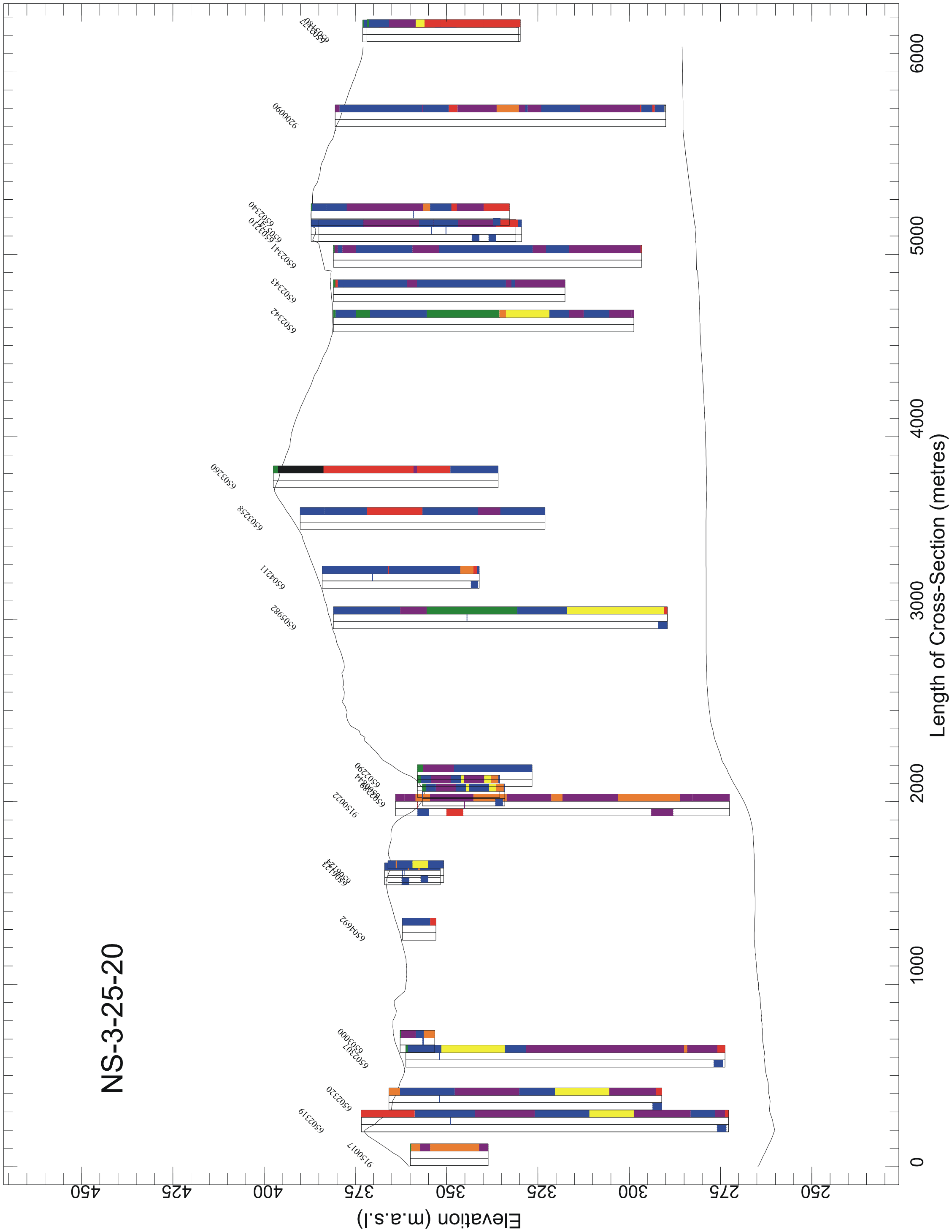
6503163
9150021
6502294
6502292
6504052
6504902


NS-2-25-10
Elevation (m.a.s.l)
Length of Cross-Section (metres)
450
425
400
375
350
325
300
275
250
225
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
2750
3000


NS-3-25-20
Length of Cross-Section (metres)
Elevation (m.a.s.l)
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1000
2000
3000
4000
5000
6000
450
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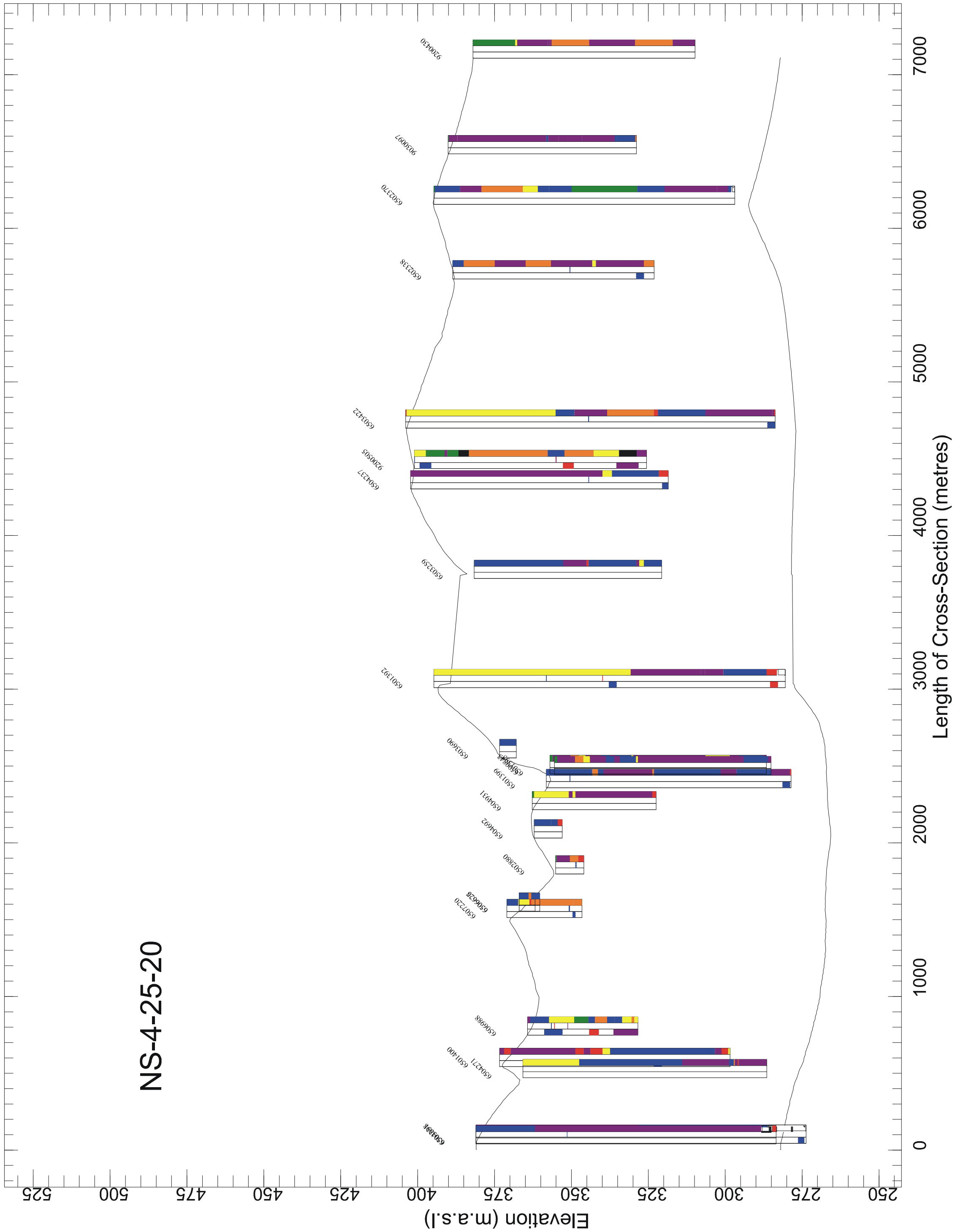
350
325
300
275
250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Elevation (m.a.s.l)
Length of Cross-Section (metres)
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275
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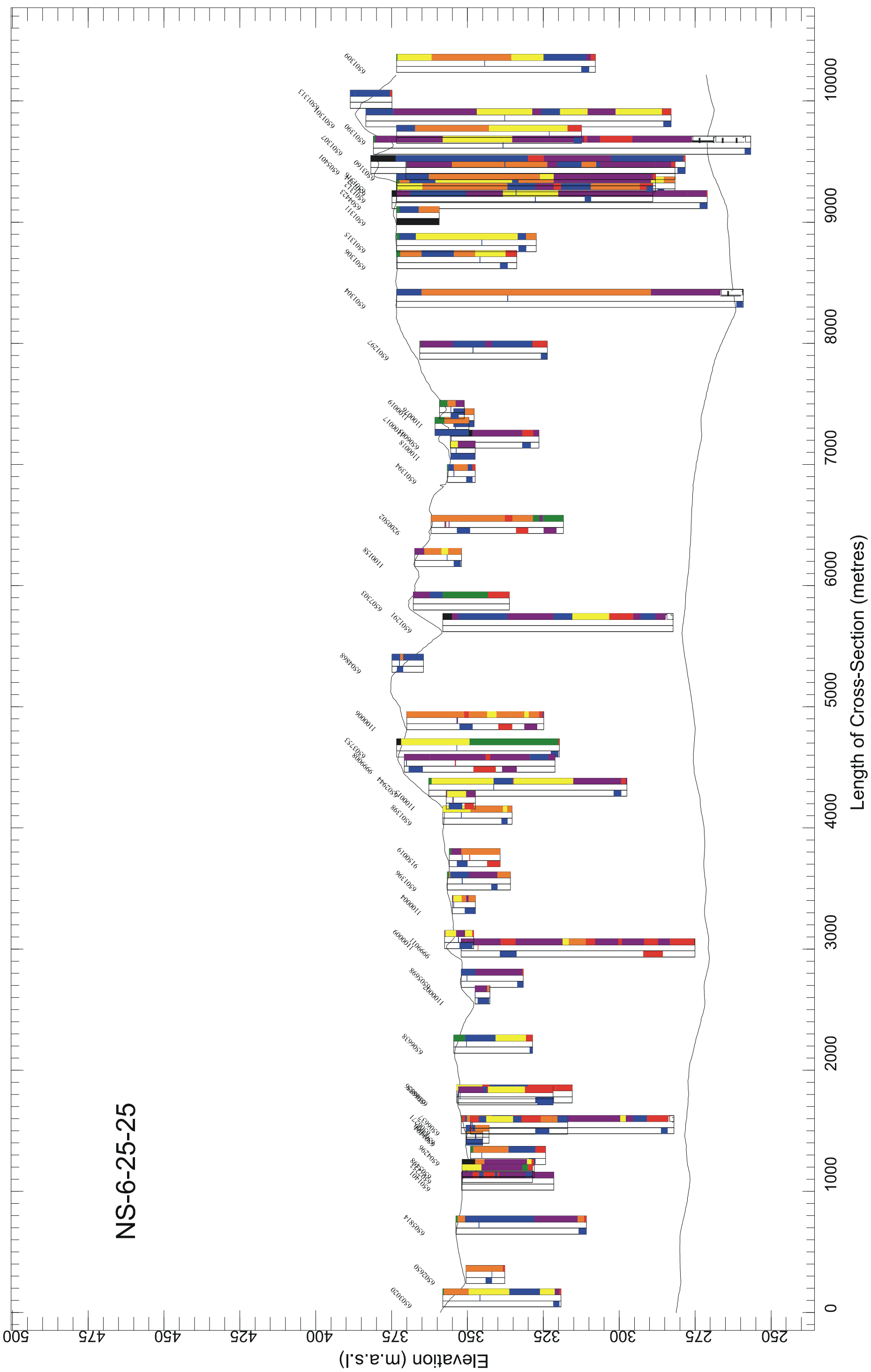
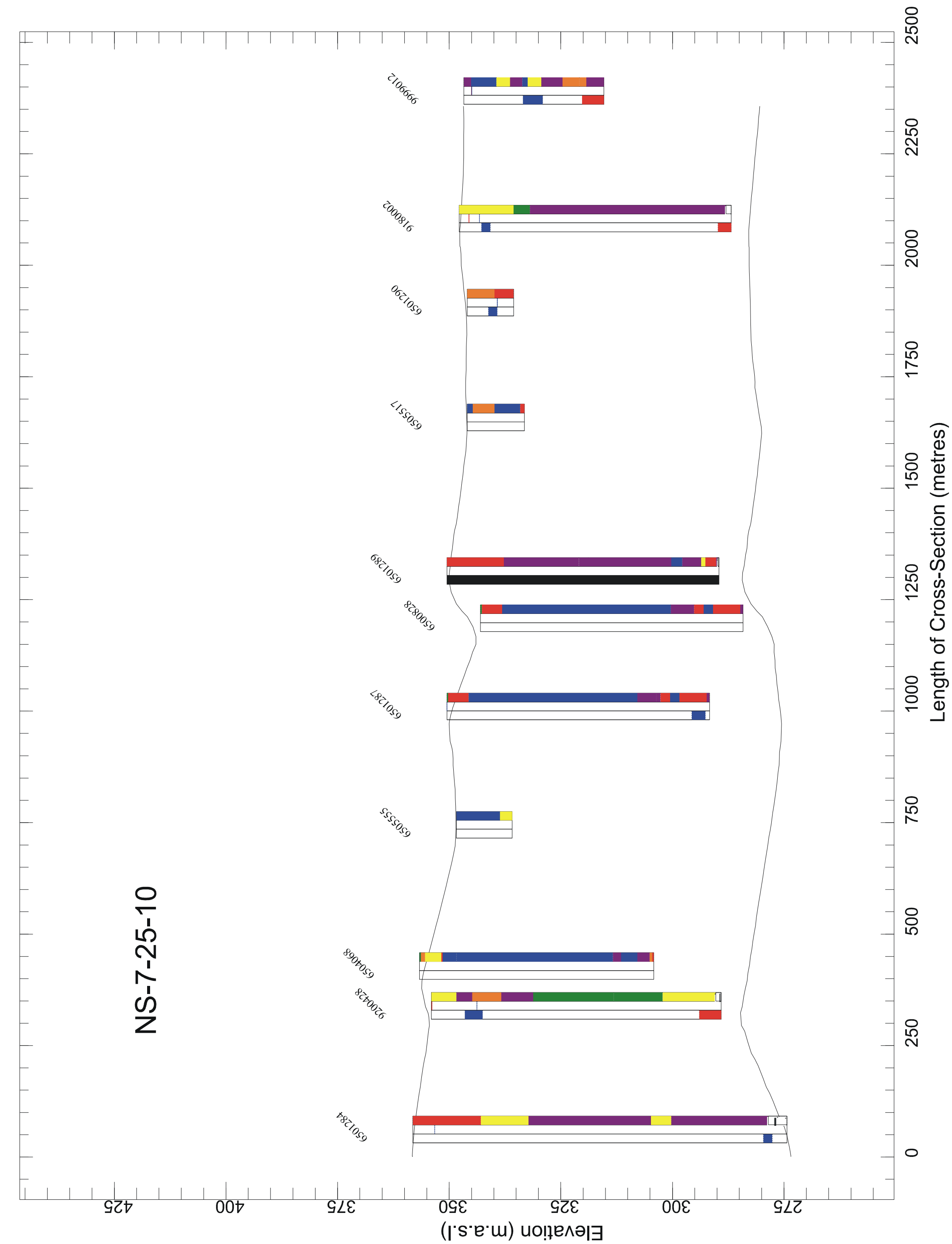
325
350
375
400
425
450
475
500
525
0
1000
2000
3000
4000
5000
6000
7000


NS-6-25-25
Elevation (m.a.s.l)
500
475
450
425
400
375
350
325
300
275
250
Length of Cross-Section (metres)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000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Length of Cross-Section (metres)
Elevation (m.a.s.l)
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
275
300
325
350
375
400
425
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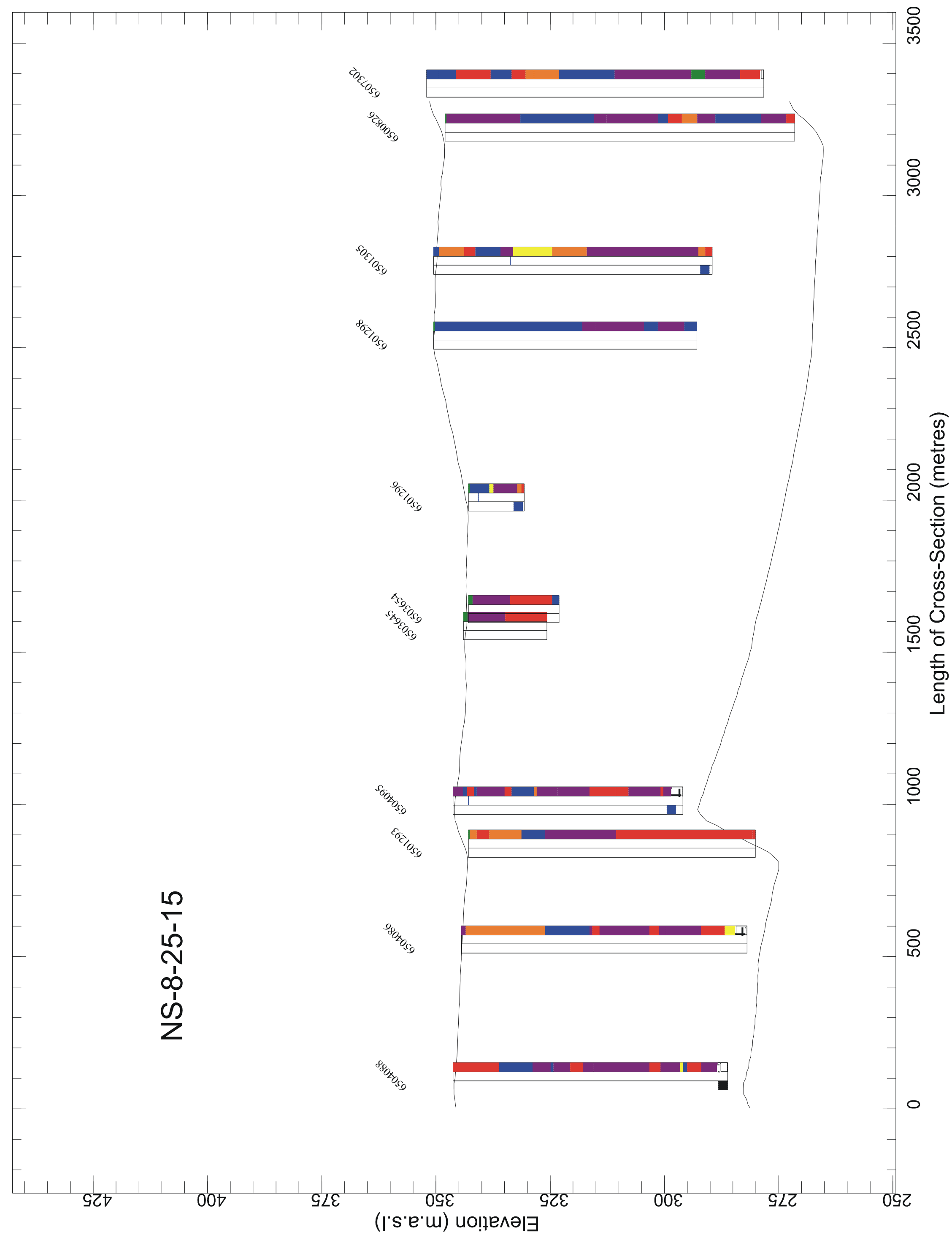
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Elevation (m.a.s.l)
Length of Cross-Section (metres)
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6501293
6504095
6503645
6503654
6501296
6501298
6501305
6500826
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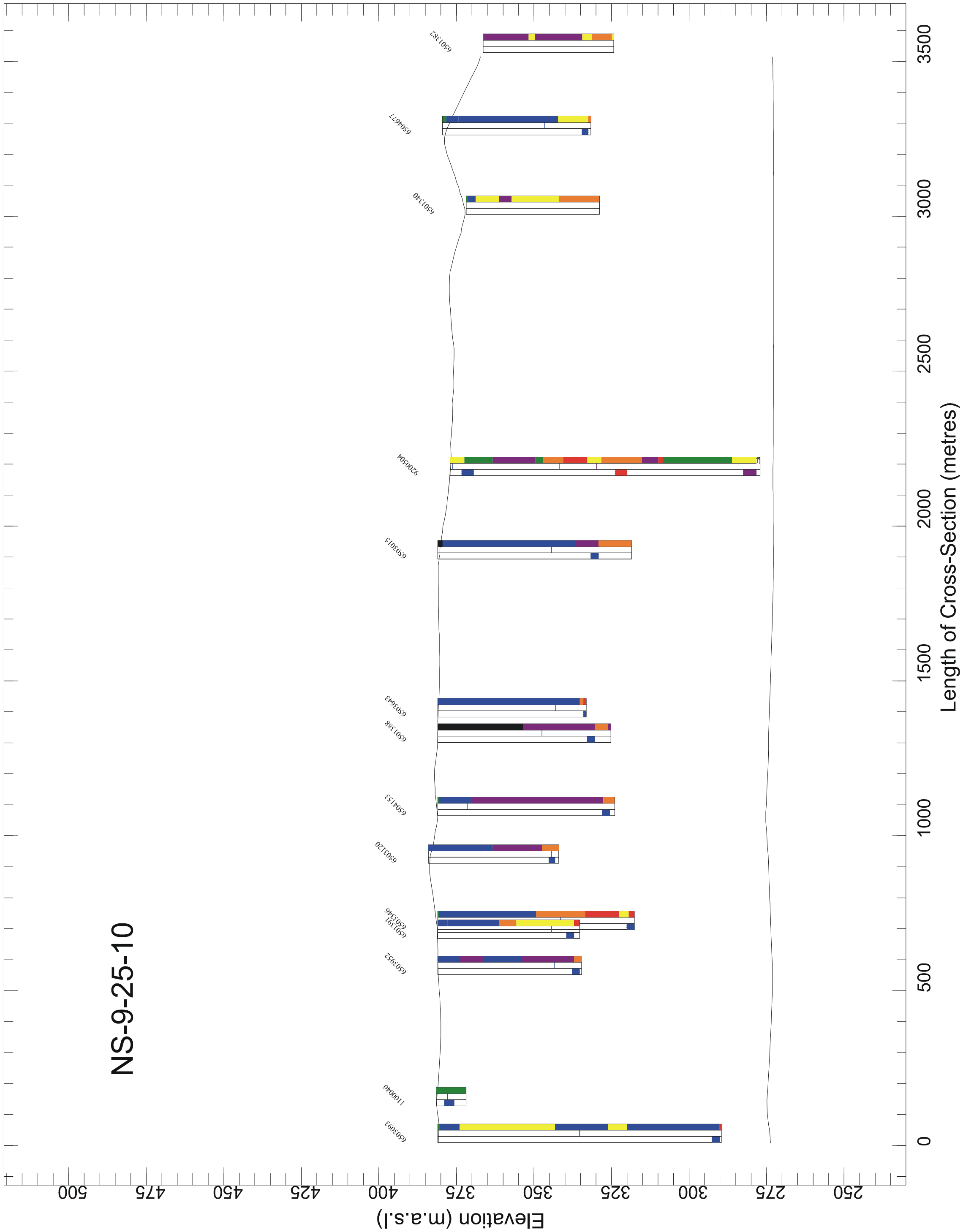
250
275
300
325
350
375
400
425
0
500
1000
1500
2000
2500
3000
3500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Length of Cross-Section (metres)
Elevation (m.a.s.l)
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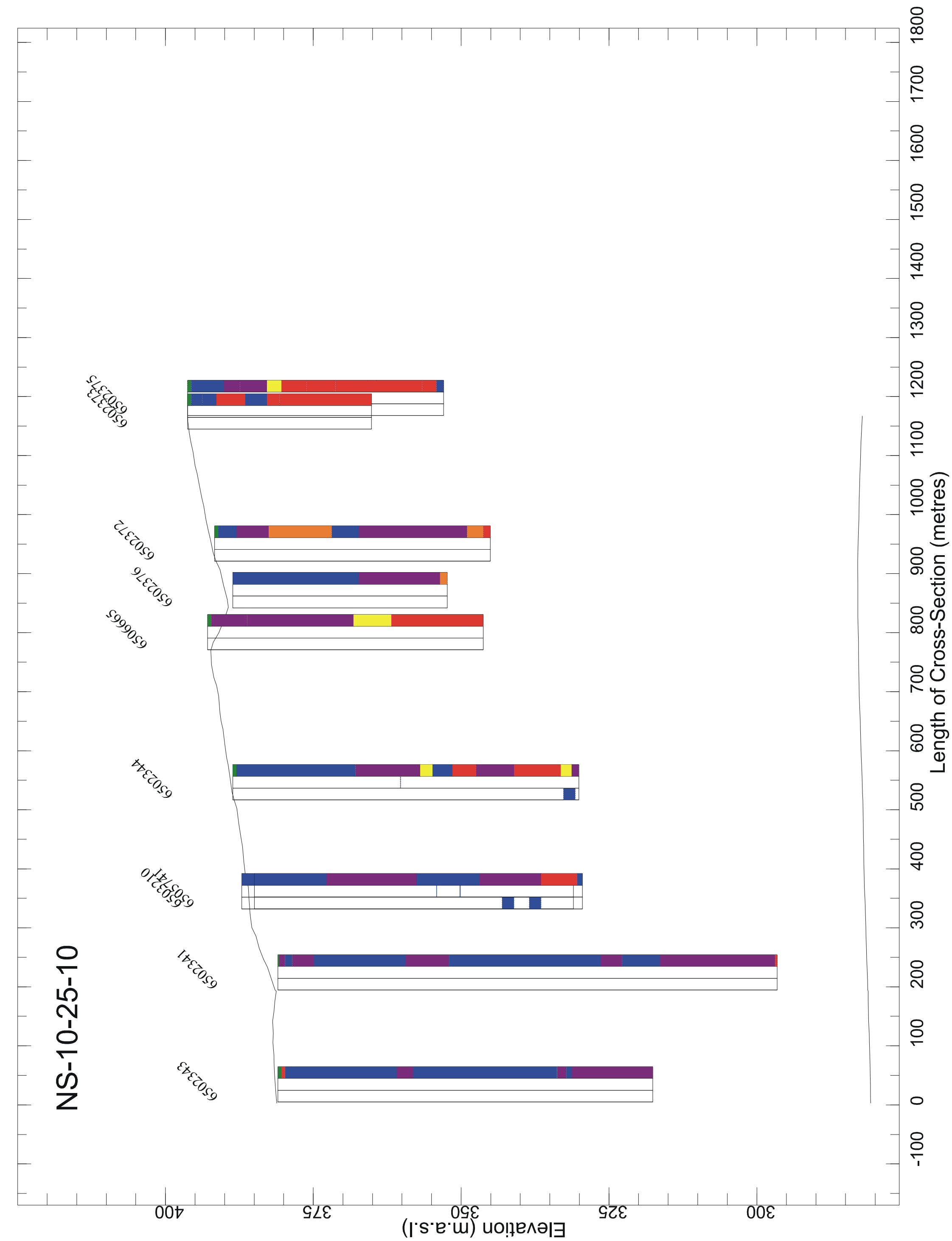
1500
2000
2500
3000
3500
250
275
300
325
350
375
400
425
450
475
500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Length of Cross-Section (metres)
Elevation (m.a.s.l)
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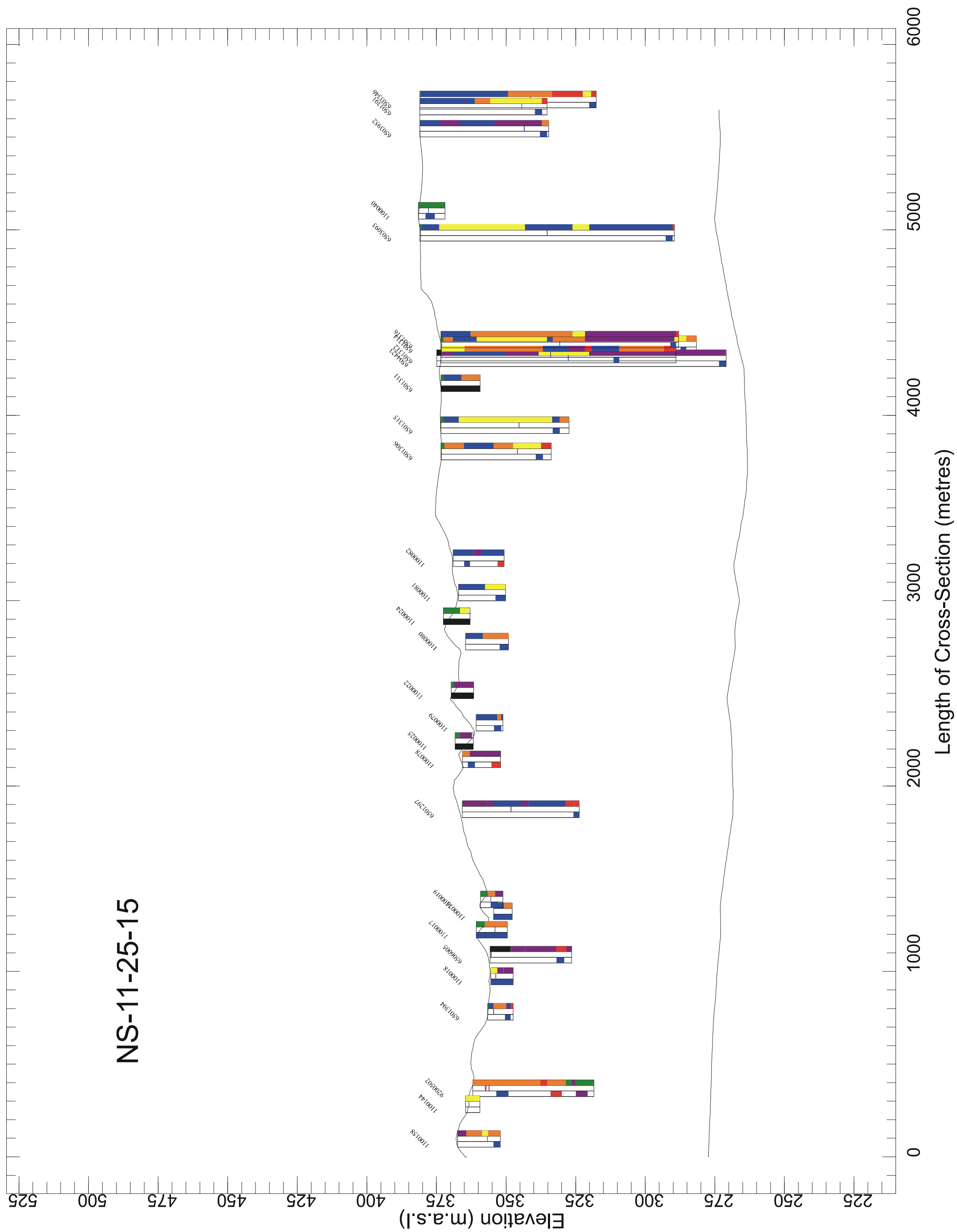
6502375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Elevation (m.a.s.l)
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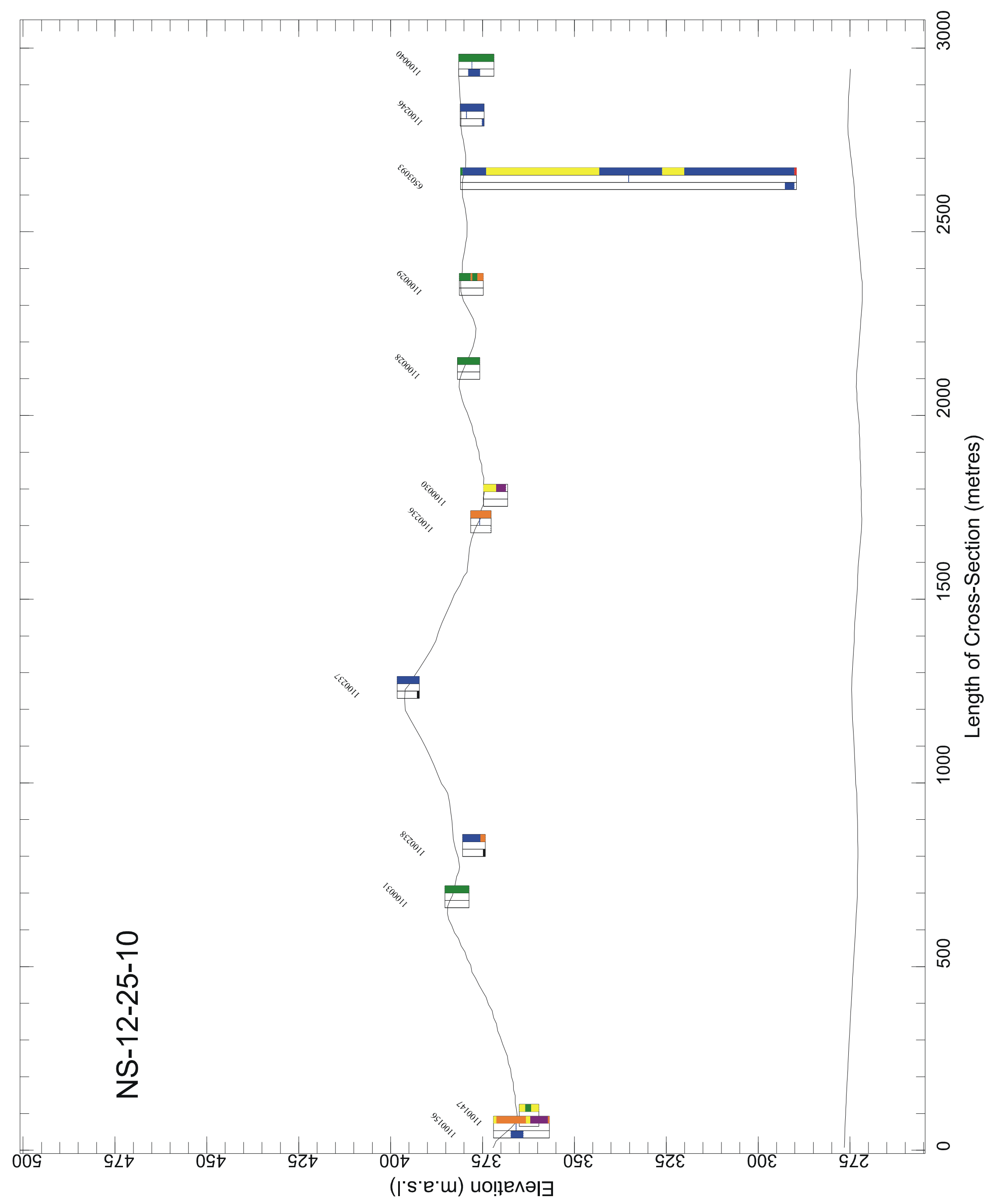
Length of Cross-Section (metres)
0 1000 2000 3000 4000 5000 6000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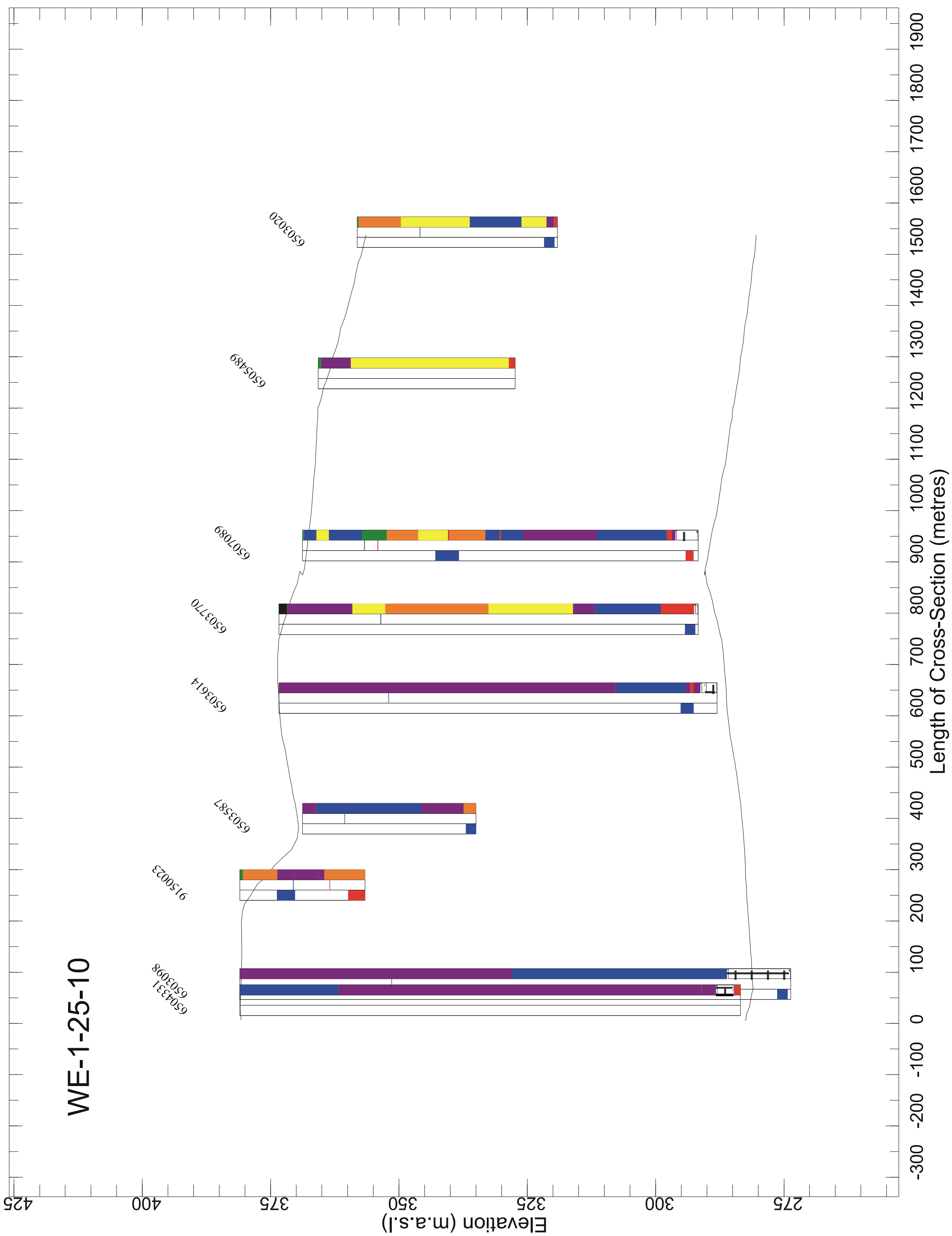
Length of Cross-Section (metres)
Elevation (m.a.s.l)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6504331
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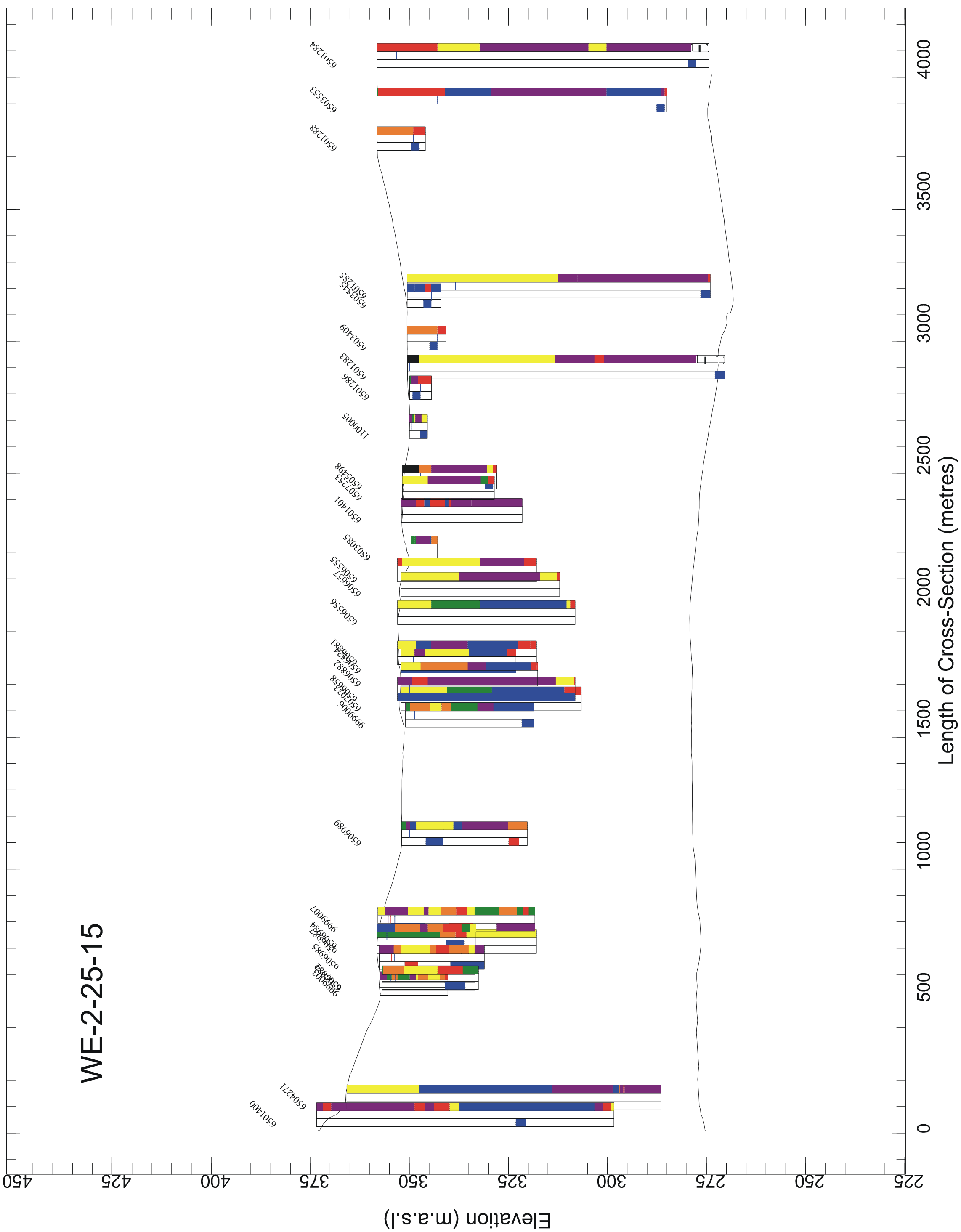
6503614
6503770
6507089
6505489
6503020
Elevation (m.a.s.l)
Length of Cross-Section (metres)


WE-2-25-15
Length of Cross-Section (metres)
0
500
1000
1500
2000
2500
3000
3500
4000
Elevation (m.a.s.l)
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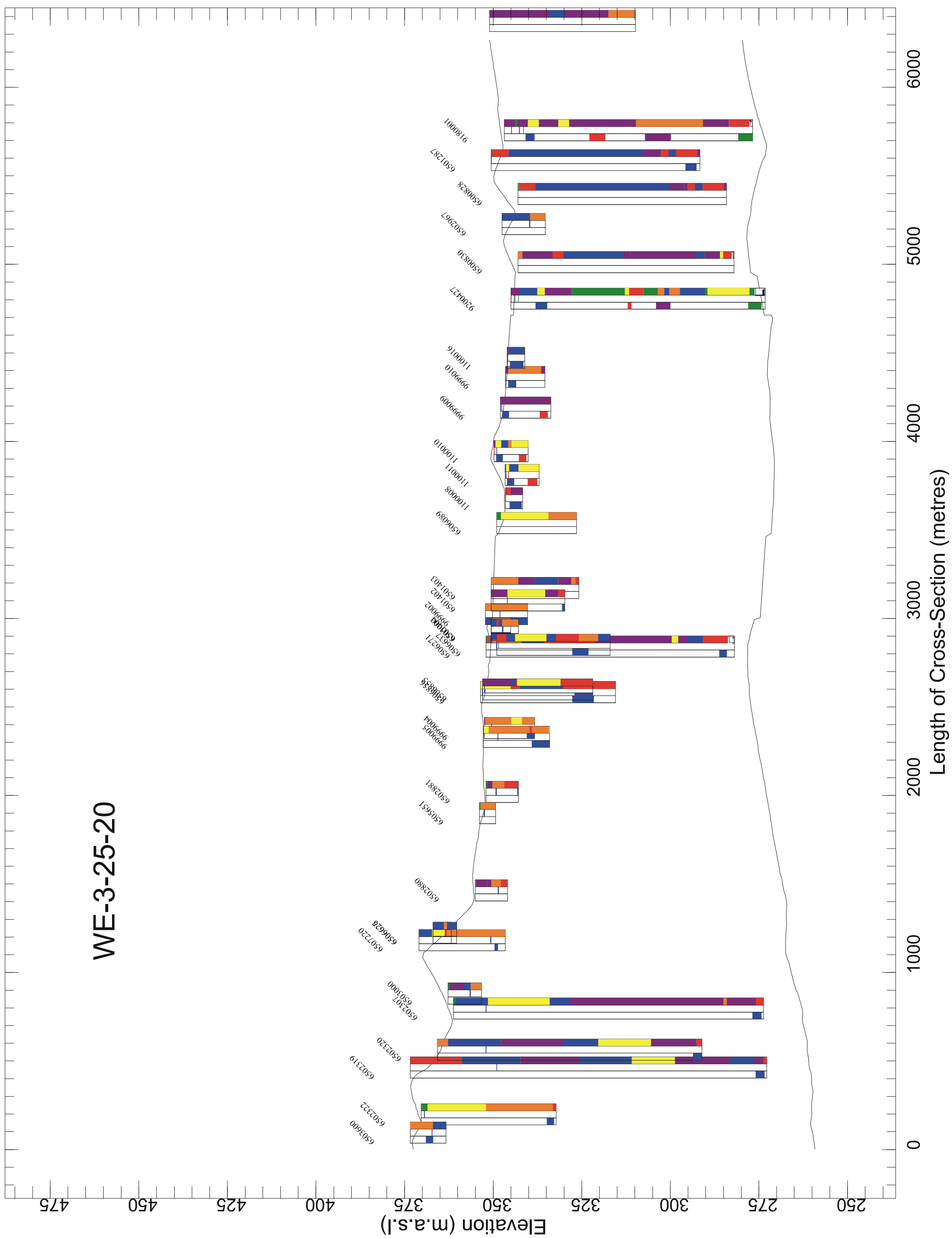
425
400
375
350
325
300
275
250
225



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Elevation (m.a.s.l)
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375
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325
300
275
250
Length of Cross-Section (metres)
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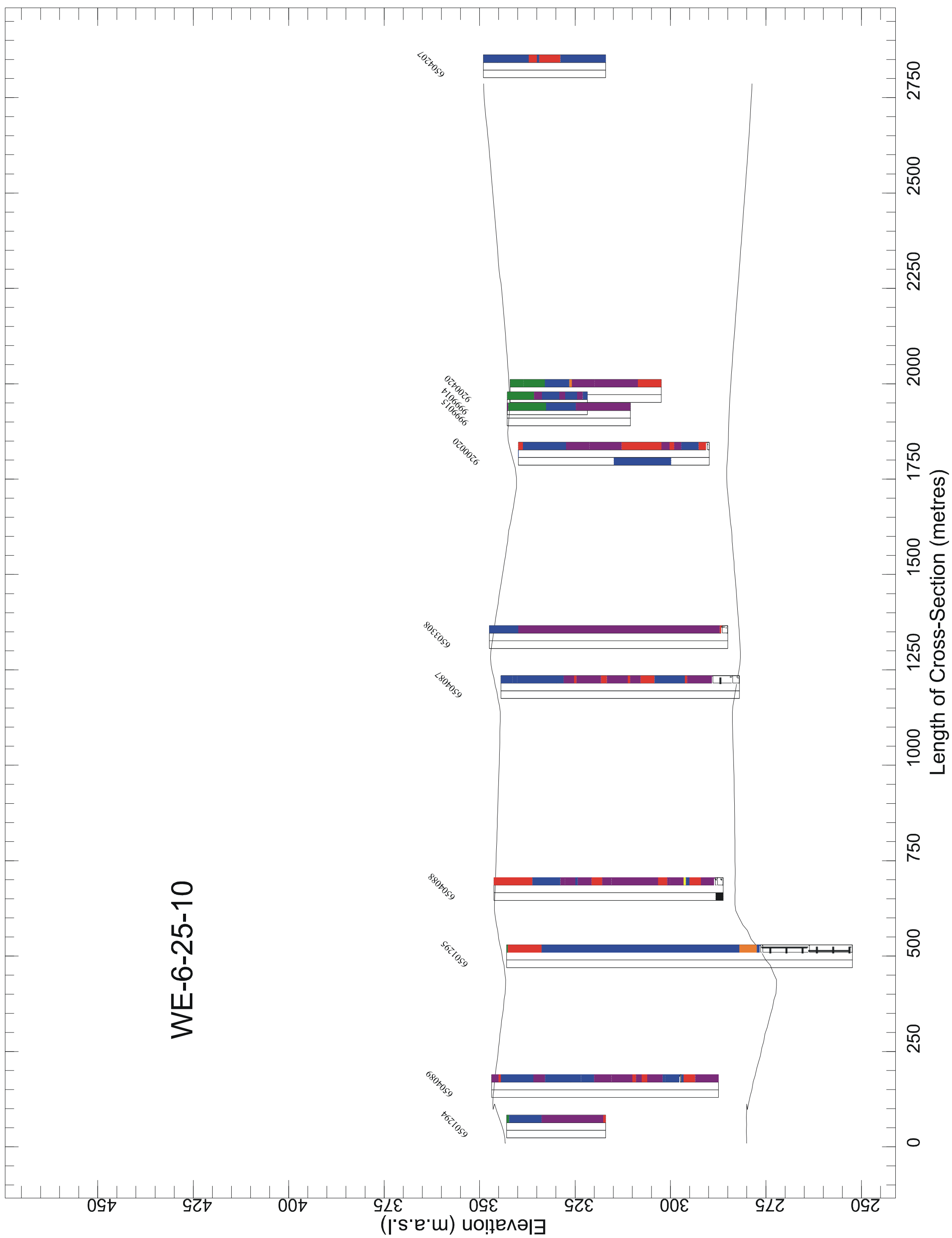
2000
3000
4000
5000
6000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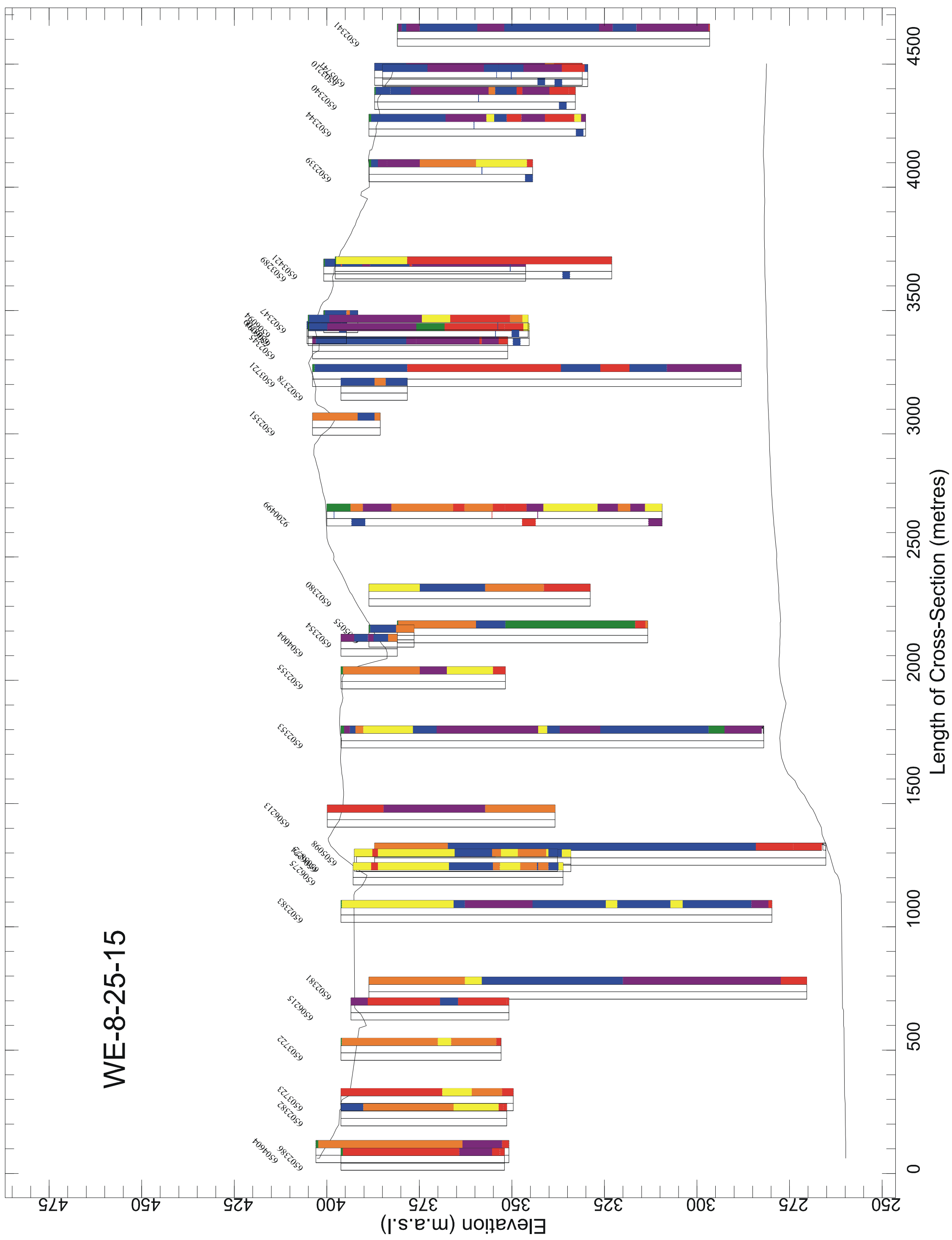
Elevation (m.a.s.l)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300
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1000
1500
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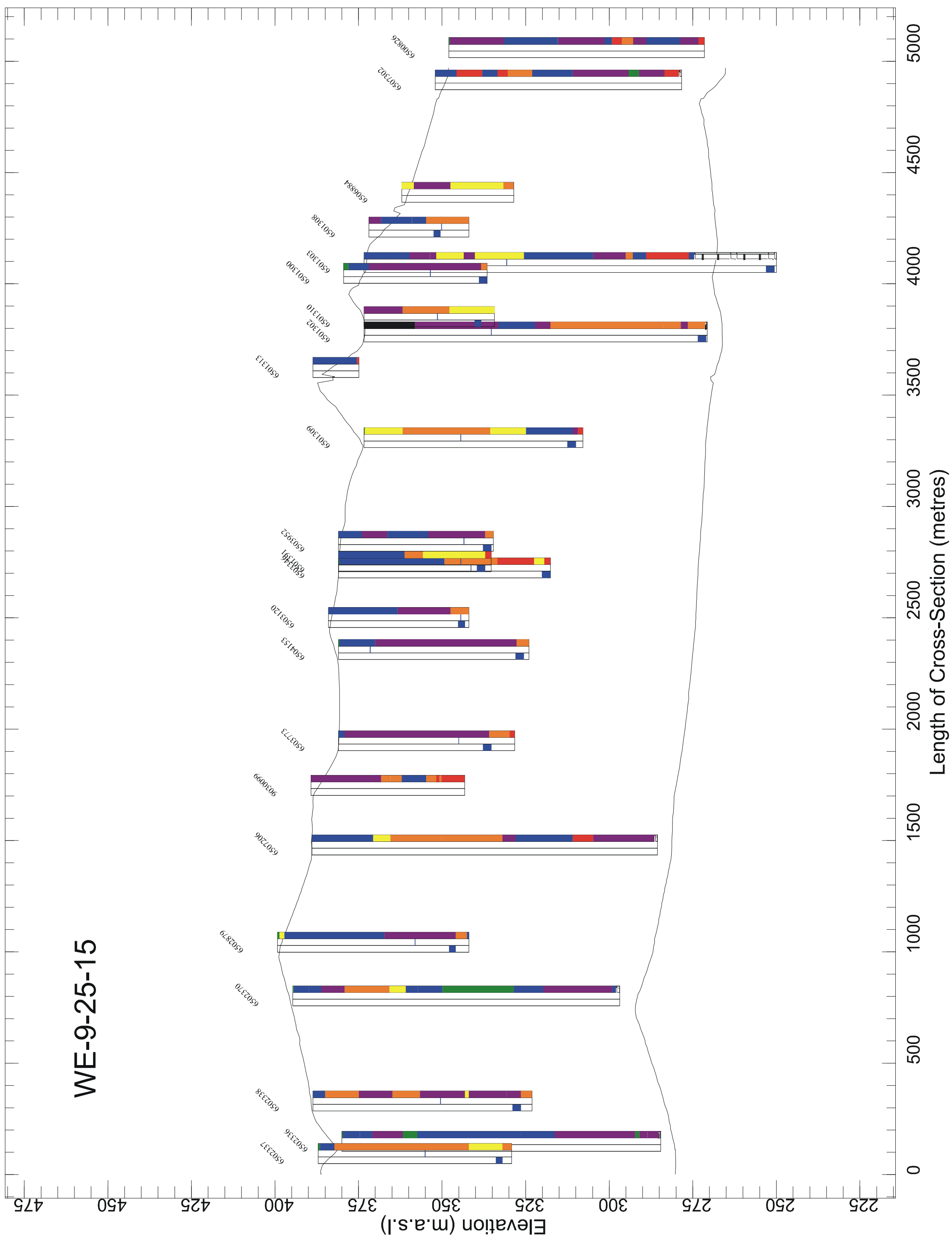
3000
3500
4000
4500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Elevation (m.a.s.l)
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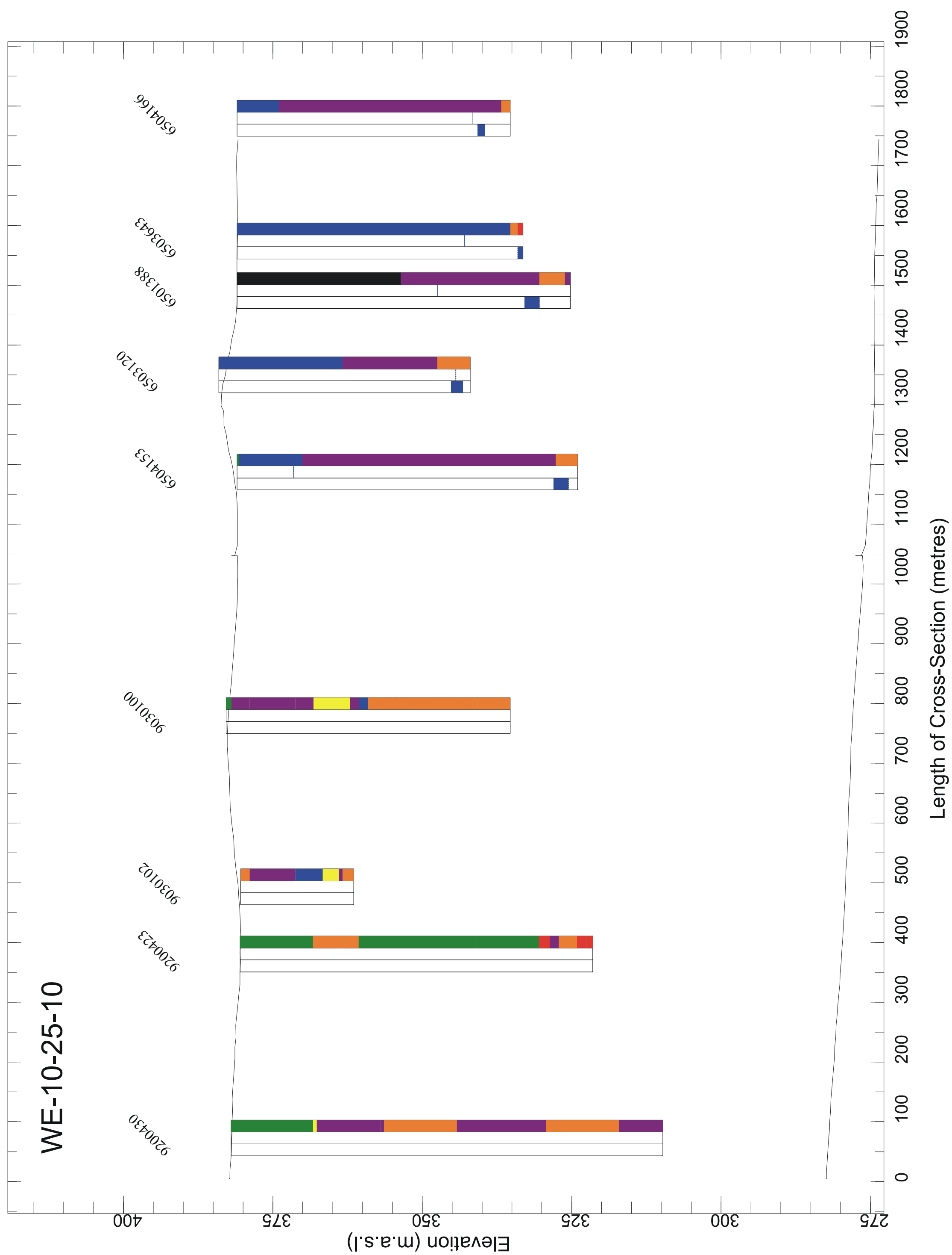
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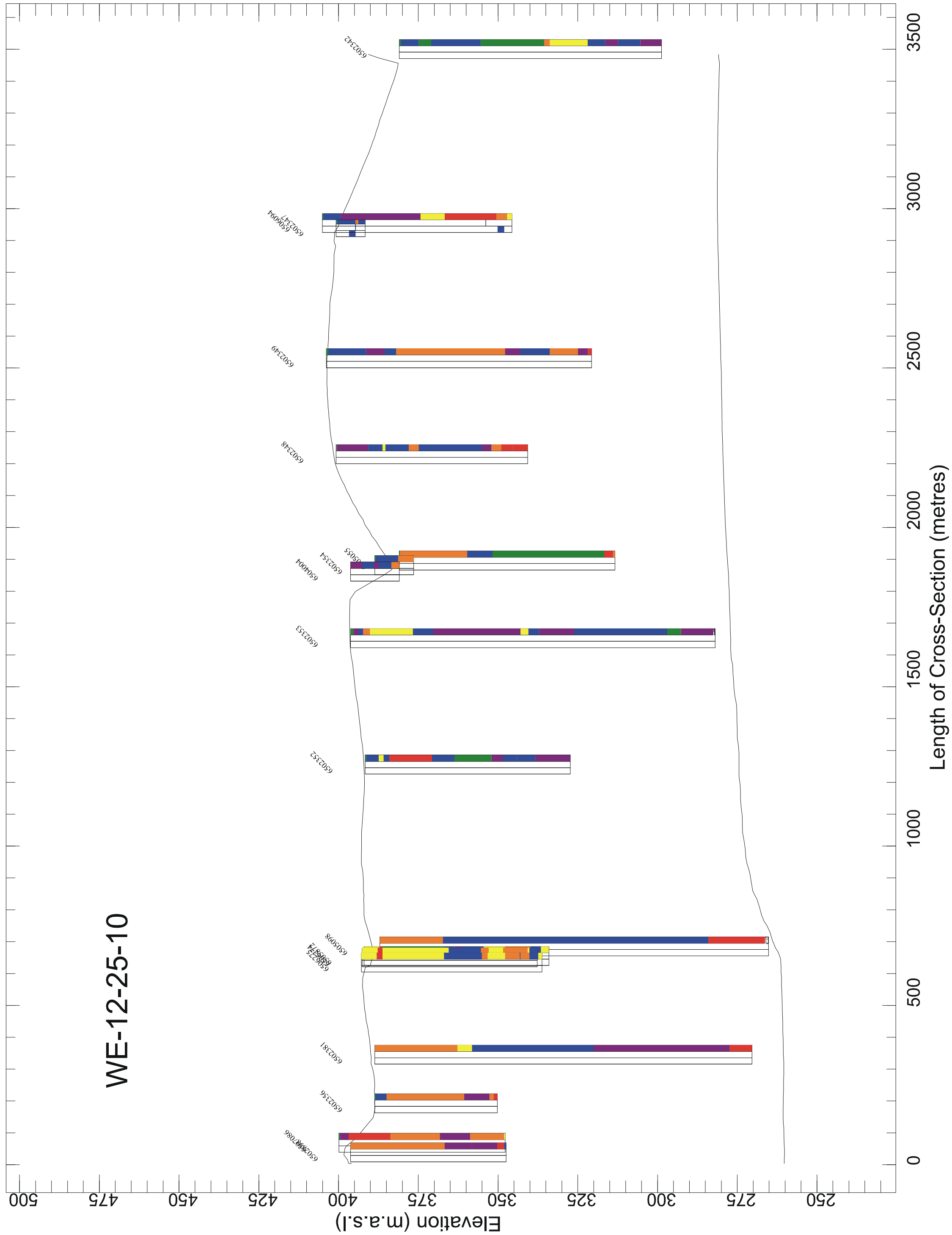
Length of Cross-Section (metres)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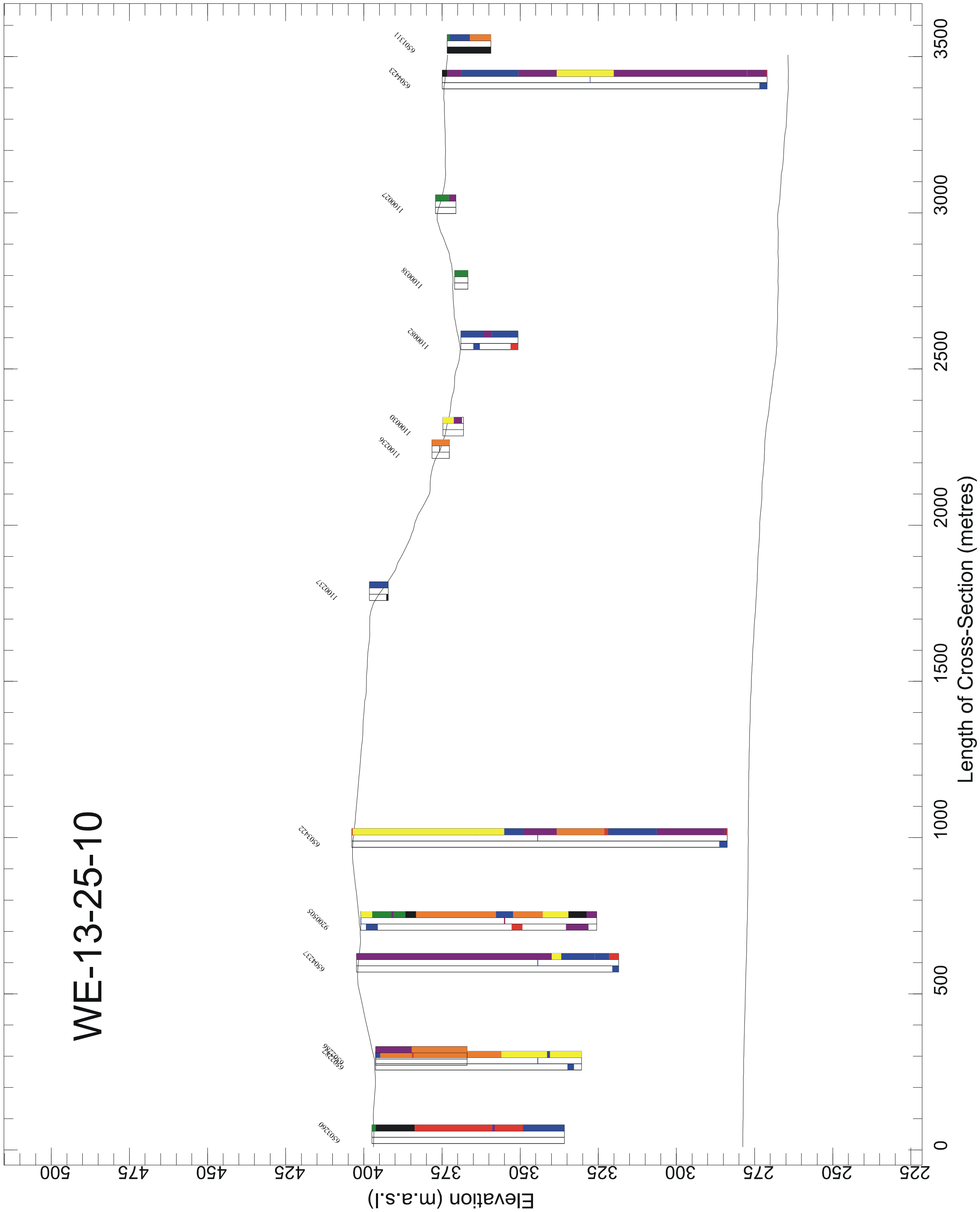
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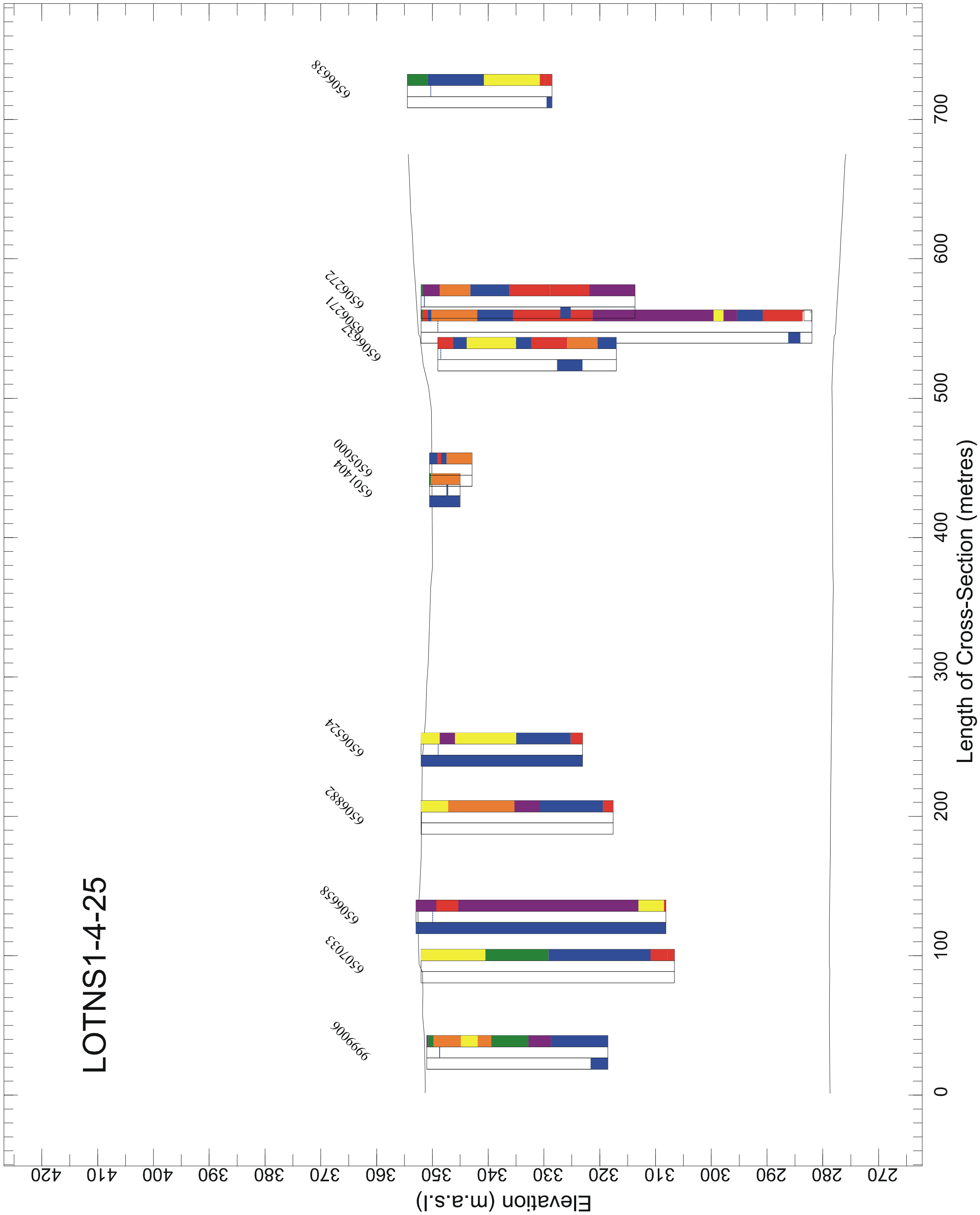
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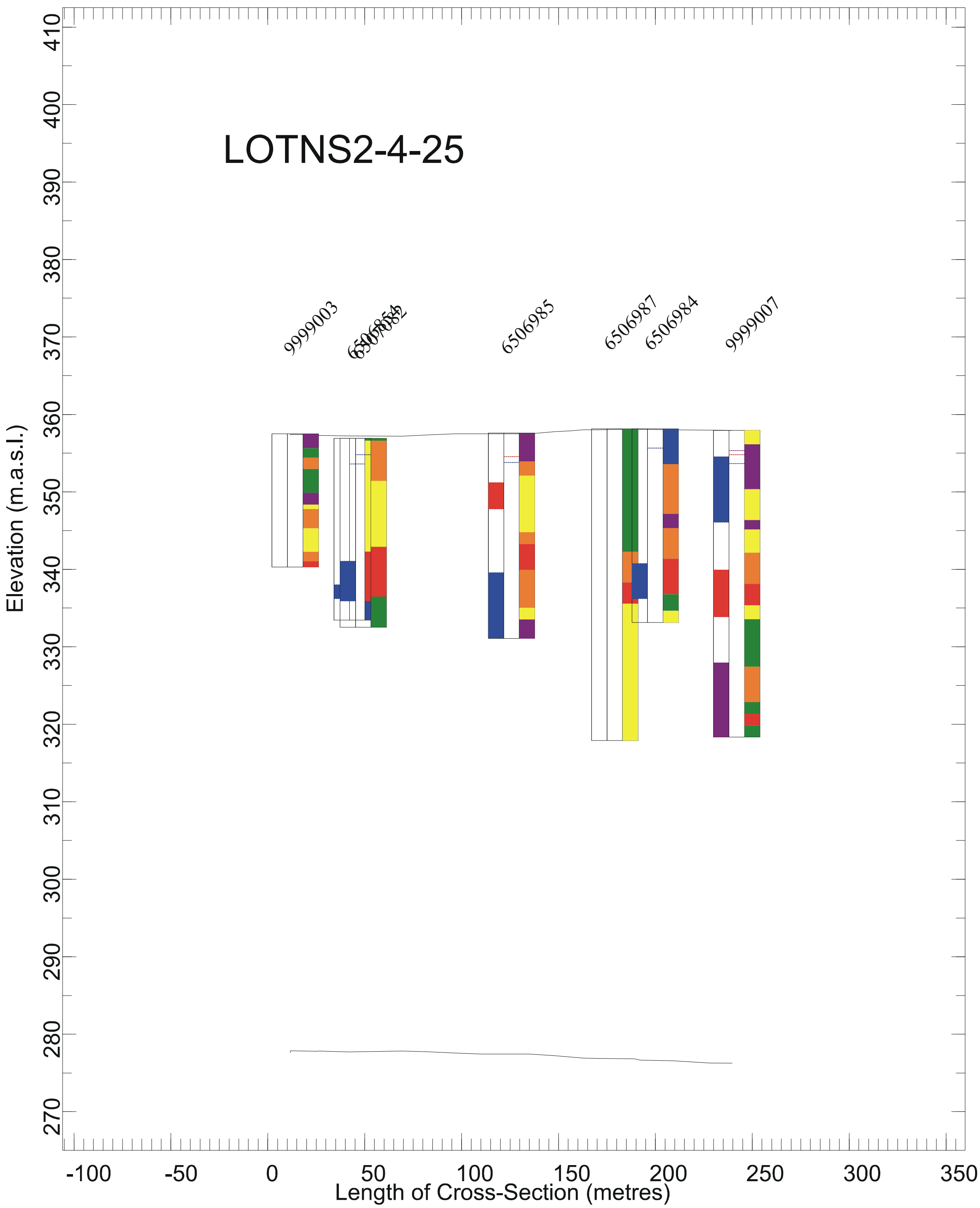
Elevation (m.a.s.l)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6506984
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Length of Cross-Section (metres)
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390
380
370
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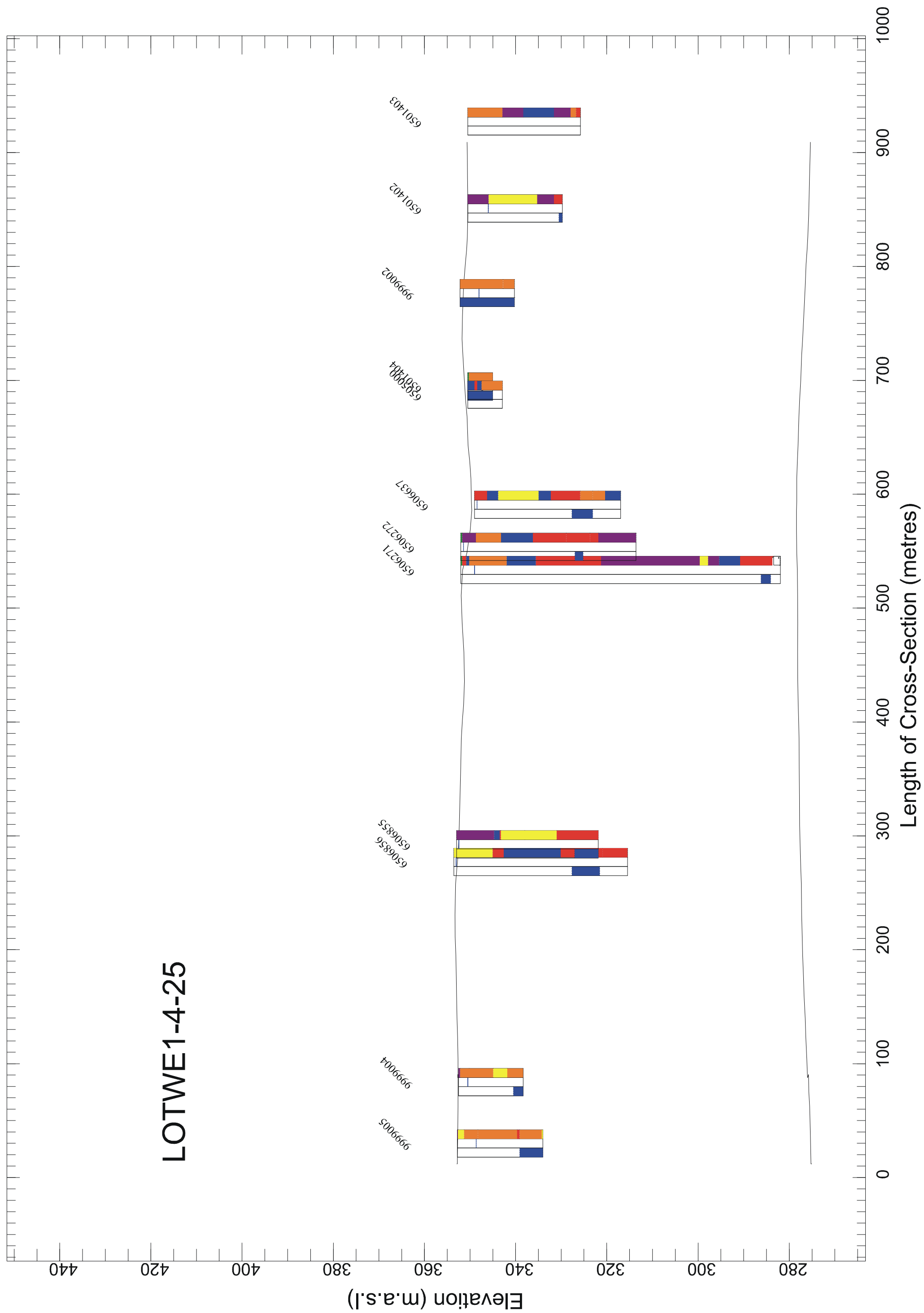
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Elevation (m.a.s.l)
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6506271
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6506856
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9999005
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