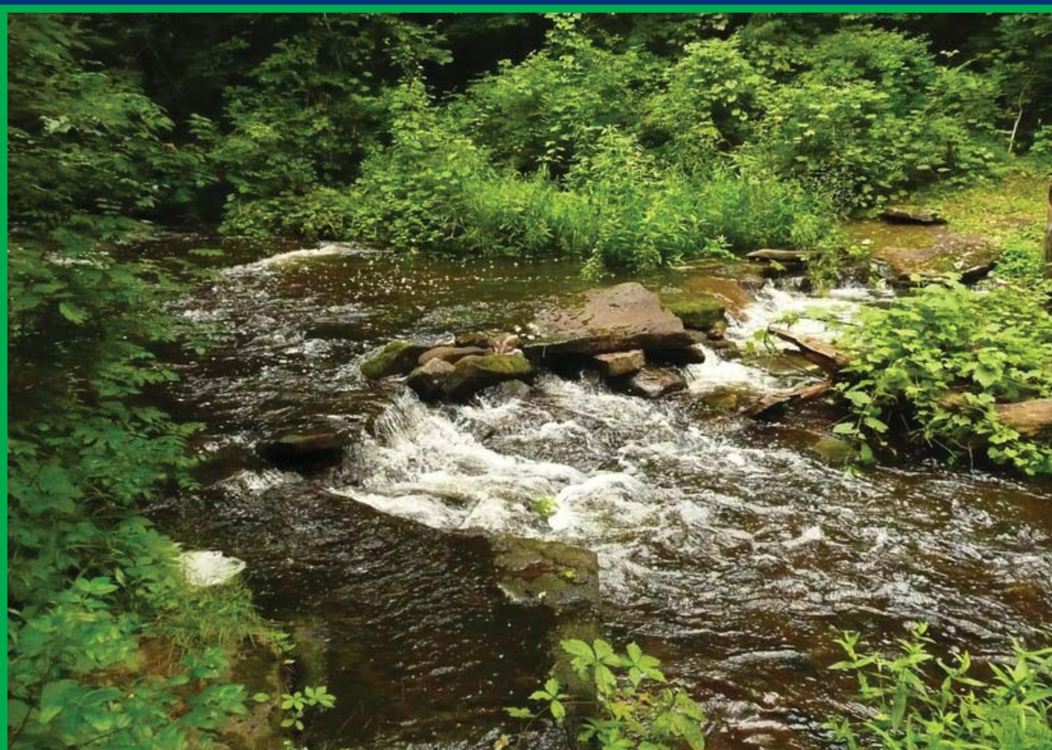
FINAL DRAFT
Tier 2 Water Budget
Village of Madoc
Quinte Source Protection Region



Prepared March 2010

Quinte Region

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1.0 Introduction

As part of the Source Water Protection Program, Quinte Conservation has completed Conceptual and Tier 1 water budget activities. This work has been subject to the Peer Review process and is summarised in the following reports:

1.) Conceptual Water Budget – Quinte Conservation – Final Draft Report - December 8, 2006.
2.) Tier 1 Water Budget (Final Draft) Quinte Conservation April 14, 2009.

From the conceptual work the potential for ground water stress at the annual and watershed scale was evaluated as minimal. Refinement of scale (time and spatial) at the Tier 1 level also indicated minimal potential for groundwater stress throughout the watershed. However, two of the subwatersheds, the Picton and Camden catchments as located by Figure 1, were assessed as having a moderate level of stress on an annual time scale. Since neither of these catchments contain municipal drinking water wells, further water budget activities were not required in accordance with the Ministry of the Environment (MOE) Technical Rules (2006). Through this process the municipal groundwater system supplying the Village of Madoc was identified as having water supply problems during the summer of 2007. Because of this occurrence and requirements of the MOE Technical Rules (2006) the subwatershed (Tweed Catchment on Figure 1) containing these wells was assigned a moderate level of stress. Due to this occurrence further water budget activities for this area to assess potential for water quantity stress and supply problems.

A Tier 2 water budget entails the development of a computer based three dimensional groundwater flow model to assess groundwater flows and levels in the subwatershed. To assist in this work and development of a ground water flow model, Quinte Conservation engaged the services of Schlumberger Water Services (SWS) formerly Waterloo Hydrogeologic Inc. A copy of the report prepared by Schlumberger Water Services is provided in Appendix A and a general overview of the Tier 2 process and work completed by Quinte Conservation is provided below.

2.0 Work Plan

The Tier 2 work plan has been developed in reference to the following documents:

- Ministry of the Environment Guidance Module 7: Water Budget & Water Quantity Risk Assessment (March 30, 2007),
- Ministry of the Environment: Technical Rules: Assessment Report, Clean Water Act, 2006 (August 24, 2009),
- Ministries of the Environment & Natural Resources, Technical Bulletin Water Budget & Water Quantity Risk Assessment Tier 2 Subwatershed Stress Assessment Groundwater Drought Scenarios (July, 2009).

The objective of the Tier 2 water budget work may be described as follows:

- Evaluate the percent water demand (monthly and annual) for the subwatershed and ability of the municipal wells to meet demand under drought conditions,
- Based on the results of assessment assign the subwatershed a groundwater stress level of significant, moderate or low.

In respect of the MOE Technical Rules (2006) the assessment required evaluation of the water budget for the subwatershed containing the Village of Madoc wells through the use of a three dimensional groundwater flow model to assess groundwater flows and levels. This entailed completion of the following activities:

- Review existing groundwater flow model and establish a suitable study area for the Tier 2 work.
- Develop a new groundwater flow model to cover the study area through incorporation of variables from the existing model and other available information about the municipal water supply and subwatershed.
- Review water use in the subwatershed and project future rates of water use at the municipal wells,
- Apply the model to assess the % water demand (current and future) in the subwatershed and ability of the municipal wells to meet demand under drought conditions (2 and 10 year scenarios),
- Assign the subwatershed a stress level of significant, moderate or low in accordance with the MOE Technical Rules.
- Assess the degree of uncertainty associated with the model used to assess the water budget,
- Document all work in support of source protection, as directed by the source protection guidance documents.

Work relating to the ground water flow model and results of assessment are described in the SWS Report contained in Appendix A. A discussion of information prepared by Quinte Conservation is provided below followed by overview of the results of the Tier 2 assessment.

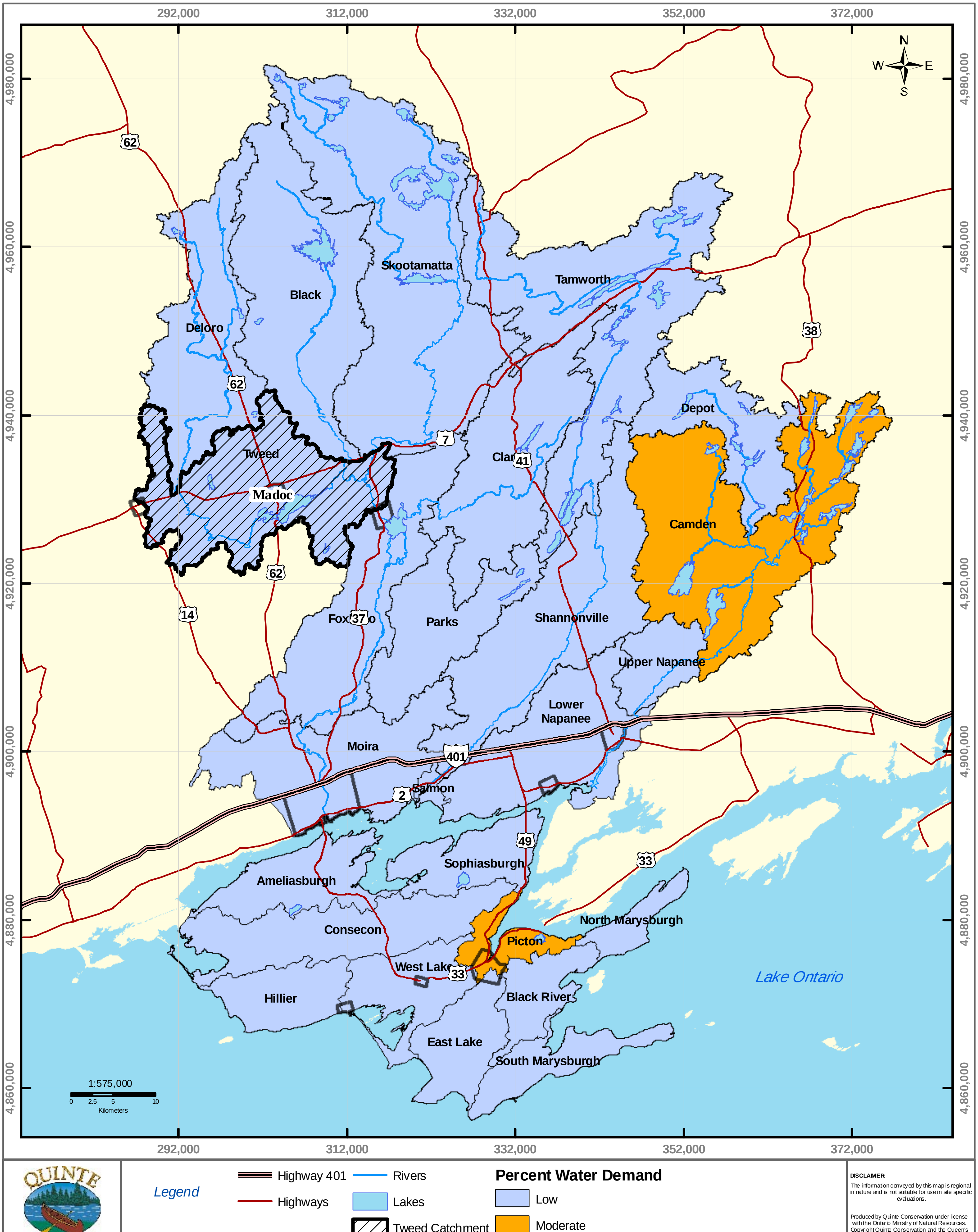

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Figure 1 Subwatershed Groundwater Stress Levels

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Data is projected in NAD 83 UTM Zone 18N.

DIGITAL MAPPING SOURCES:

Base Map - Ontario Ministry of Natural Resources
Stress - Calculated by WHI

3.0 Water Budget

The Water budget equation for the subwatershed may be represented as below and as listed in Table 1 as determined using an existing Watershed Hydrology Model (Gawser).

P = ET + Runoff + Infiltration + Losses (net storage)

Where:

P = Precipitation

ET = Evapotranspiration

Infiltration = Baseflow to Stream

Runoff = Surface Runoff

Losses = Change in storage

The long term water budget for the subwatershed is as presented in Table 1. This analysis indicates average annual precipitation to be in the order of 947 mm with 557 mm or 58% lost to evapotranspiration and the balance to runoff. The total runoff may be further subdivided into surface runoff and infiltration (groundwater recharge) at 58% and 42 % respectively. The changes in storage are also reported to reflect the fluxes of water in an out of storage such as lakes, wetlands and aquifers.

Table 1: Long Term Monthly Water Budget for Madoc Subwatershed (1950-2005)

Mean Monthly Flow Volume Summary for Deer Creek u/s Madoc (1950-2005)								
Month	**Rainfall**	**Snowfall**	**Precip**	**Actual ET**	**Total Flow**	**Runoff**	**Baseflow**	**NetStor**
JAN	25	45	70	9	23	6	17	38
FEB	21	42	63	8	17	5	13	38
MAR	40	34	75	8	62	44	18	4
APR	66	11	76	30	127	103	24	-81
MAY	76	1	77	77	44	21	23	-44
JUN	84	0	84	103	19	6	13	-38
JUL	63	0	63	105	10	3	7	-52
AUG	81	0	81	83	7	4	4	-9
SEP	93	0	93	62	9	5	3	22
OCT	74	2	76	45	12	6	6	20
NOV	74	21	95	20	24	11	13	52
DEC	40	55	95	9	34	13	21	52
Total	737	210	947	557	388	227	162	2

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4.0 Quinte Conservation Data

To assist in the modelling process the following information was developed and/or provided to SWS for review:

- Existing ground water flow model,
- Climate data for assessing average and drought conditions,
- Annual and monthly groundwater recharge rates,
- Characteristics and demand of the municipal wells (current and future),
- Water demand in the subwatershed &
- Information regarding the stream flow in Madoc & Deer Creeks,

4.1 Existing and New Groundwater Flow Model

An existing three dimensional numeric groundwater flow model was available for the area around the Village of Madoc. This model was developed by Dillon Consulting to delineate the well head protection area capture zones (zones of horizontal time of travel) around the Village water well system. The work was originally completed as part of the Quinte Regional Municipal Groundwater Study in October, 2004 and further updated in 2007. The update included the incorporation of new hydrogeologic field data which included calibration wells, mapping of bedrock faults/fractures and better estimates of aquifer hydraulic parameters. The steady state model was developed in Modflo for an area of approximately 168 square kilometers as illustrated by Figure 2.

Based on review of the existing groundwater flow model, and requirements for the Tier 2 water budget it was determined that a new model would be required to represent the larger subwatershed area containing the Municipal Wells. The larger study area, as illustrated by Figure 2, covers approximately 278 square kilometers and follows the boundaries of the subwatershed located primarily around and up gradient of the Village of Madoc Municipal Wells. This area was modeled through the use of Modflo in both the steady state and transient modes. Detailed information is provided in the SWS Report including discussion of the results of the Tier 2 assessment.

4.2 Climate

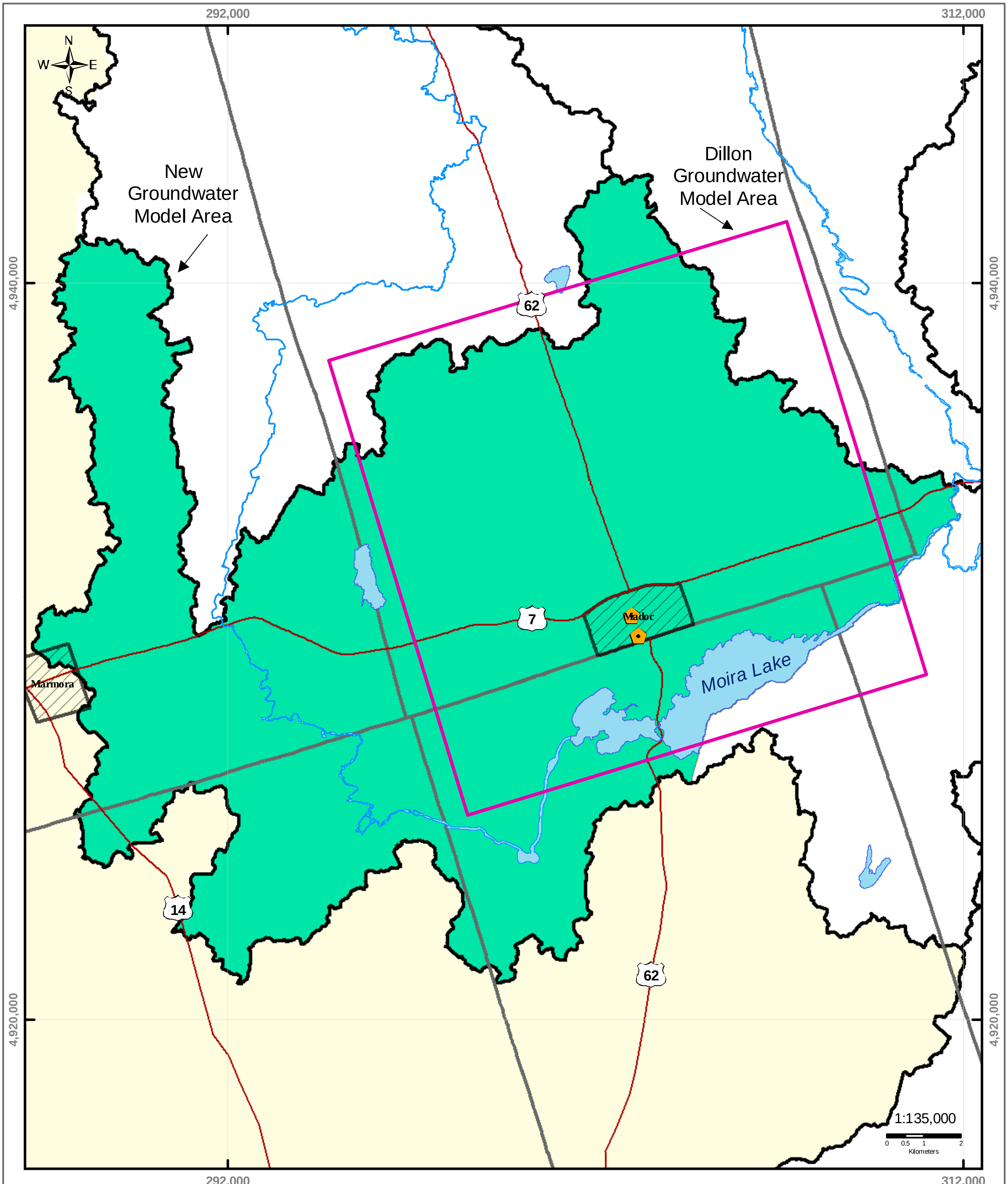
For the Tier 2 exercise consideration of the following climate conditions was required:

- Average Climate - assessed for the period of 1971-2000,
- Two Year Drought - a simulated period with no groundwater recharge,
- Ten Year Drought - continuous ten year period for which precipitation record exists with the lowest mean annual precipitation.

Climate data (precipitation and temperature) for the area was evaluated using Environment Canada climate station data as interpreted and modeled spatially by Natural Resources Canada – Great Lakes Forestry Services (McKenney et al, 2006). This data set has been previously used and discussed in both the Conceptual and Tier 1 water budget reports (Quinte Conservation, 2006 & 2009). From this data a GIS model used to assess the distribution of precipitation and evapotranspiration across the watershed under average climate conditions for the 1971-2000 period.

For the two year drought period no climate data was required. For the 10 year drought period, climate station data was reviewed for a total of 36 climate stations (at the locations illustrated by Figure 3) to determine the period with the lowest 10 year mean annual precipitation. The period of record for these stations collectively ranged from 1895 to 2008, however, only 17 stations had continuous enough record to allow determination of a 10 year average. From this review the Stirling climate station was chosen as exhibiting the lowest mean annual precipitation of 718 mm for the period of 1956-1965. In addition stream flow data for the Foxboro stream gauge (Environment Canada) located on the Moira River (see Figure 3) was reviewed. Data for this station is available from 1915 to present and the 10 year period with the lowest mean annual flow was also 1956 to 1965; at 23 cubic metres/second.

A review of climate station records was also completed by Dr. Harold Schroeter using climate station data around the Quinte Region. Through this work a similar 10 year drought period was identified as extending from November 1956 to November 1966. A summary of this work can be found in the Quinte Conservation, Tier 2 Water Budget for Ameliasburgh Subcatchment Prince Edward County, Draft Report, February 2010, Spec. Ref., Appendix C, Quinte Conservation Watershed Hydrology Model by Schroeter and Associates



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Legend

- Madoc Wells
- Rivers
- Dillon Groundwater Model Area
- Highways
- Lakes
- New Groundwater Model Area
- Highway 401
- Gauge Catchments

Figure 2 Groundwater Model Study Area

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Data is projected in NAD 83 UTM Zone 18N.

DIGITAL MAPPING SOURCES:

Base Map - Ontario Ministry of Natural Resources
Subcatchments - Derived using ArcHydro
Gauge Locations - Water Survey of Canada

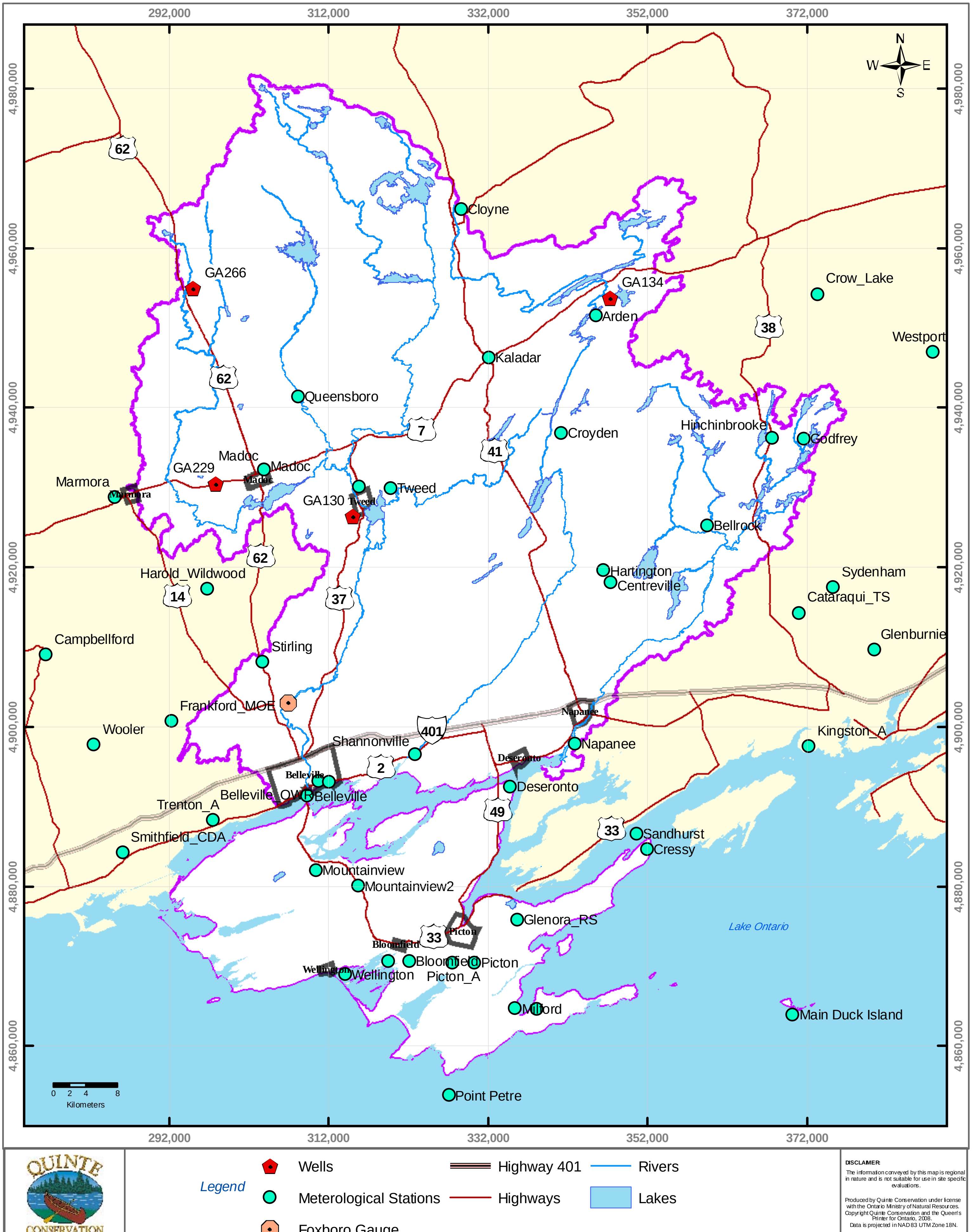

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Figure 3 Select Quinte Area Monitoring Stations

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Base Map - Ontario Ministry of Natural Resources
Subcatchments - Derived using ArcHydro
Gauge Locations - Water Survey of Canada

4.3 Groundwater Recharge

The Tier 2 water budget work requires the development of both steady state and transient groundwater flow models. In terms of the steady state model, annual rates of groundwater recharge were applied; however the transient model required refinement of the recharge rates to a monthly time scale.

A method and the results for calculating groundwater recharge in the Quinte Watershed are outlined in the Quinte Conservation Conceptual and Tier 1 Water Budget Reports. This method entailed the use of a GIS water budget model to asses the distribution of precipitation and evapotranspiration across the watershed. After determination of the natural water budget the model was used to assess infiltration based on slope, land cover and soil permeability. The rate of recharge was further calibrated in reference to water level data from a network of ground water monitor wells and stream flow gauges. Data from these stations was used to calculate specific yield and annual rates of recharge for the regional aquifers.

To permit use of this data for transient groundwater modelling further work was completed to determine the monthly distribution of recharge. This was completed by evaluating the distribution of recharge throughout the course of the year for 4 monitor wells located on the Precambrian shield (well numbers 130, 134, 229, & 266 at the locations illustrated by Figure 3). From analysis of recharge data and hydrographs the distribution of recharge between 2003 and 2007 was determined as illustrated by Figure 4 and summarised in Table 2. Groundwater recharge for the study area was then calculated using the GIS water budget model from climate data and infiltration factors for the average climate and 10 year drought period. As expected the distribution of recharge is with high recharge in the spring and fall and low in the winter and summer. Following calculation of annual recharge the monthly distribution was determined by applying the apportionments as listed in Table 2.

The rates of recharge as determined from the GIS model were then used in development of the Tier 2 steady state and transient ground water flow models. This assessment did not provide any new information that would change delineation of the significant groundwater recharge areas as originally reported in the Tier 1 Water Budget Report.

Figure 4: Average Monthly Distribution of Recharge (2003/07)

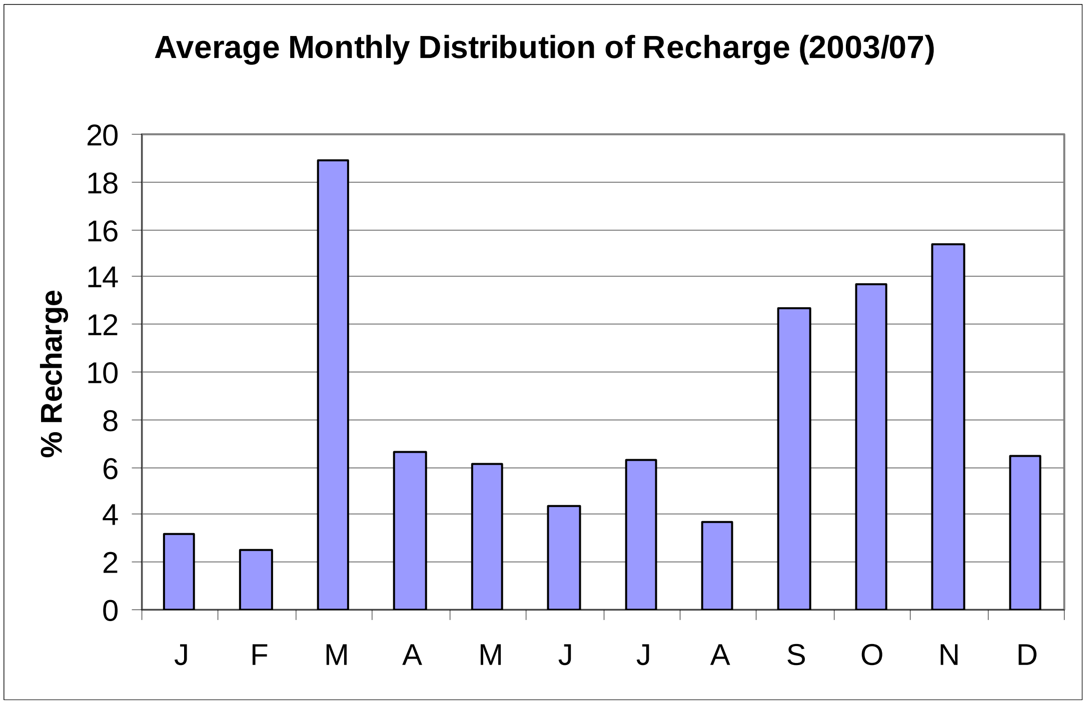


Table 2: Average Distribution of Recharge in %- (2003/07)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
3	2	19	7	6	4	6	4	13	14	15	6

4.4 Municipal Wells & Pumping Rates

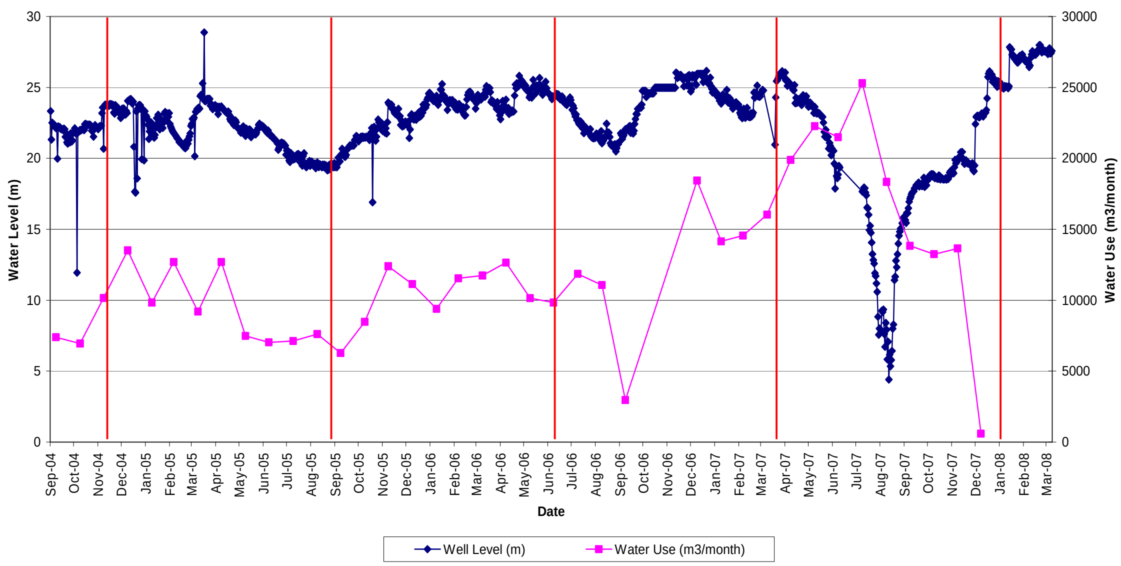
The Village of Madoc obtains supply from 2 wells referred to as the Whytock and Rollins wells. The supply wells are located on the west side of the Village one at the north (Whytock Well) and the Rollins Well at 600 metres to the south, as illustrated by Figure 2. Deer Creek is located at approximately 150 metres to the east of both wells, flowing from the north through the middle of the Village into Moira Lake. Given the close proximity of the wells to the Creek, both are classified as GUDI (Groundwater Under the Direct Influence of Surface Water) with necessary water treatment including physical filtration, ultraviolet and chlorine disinfection.

The Rollins well was drilled in 2006 to replace a well located inside of the pump house building. This new well was drilled approximately 6 metres to the east of the old well and constructed with a greater depth of casing in attempt to protect water quality through sealing off shallow fractures which potentially contribute shallow water containing contaminants. The well was advanced to a depth of 49 metres, constructed with 10 metres of steel casing, to intercept water in a fractured Precambrian bedrock aquifer at depths of 11, 15, and 27 metres. Please note that in terms of water taking there was no change to the taking as permitted for the original well; however the permit was amended to reflect the replacement well.

The Whytock Well was drilled in 1978 to a depth of 90 metres in an unconfined Precambrian bedrock aquifer. The well was reported as intercepting a main water bearing fracture at a depth of 64 metres and was constructed with 7 metres of water tight casing.

The existing, future and permitted water use of the two wells is reported in Table 3. Please note the actual or existing water use was determined based on records of use provided by the municipality for 2002 to 2006. The study year of 2007 was an abnormal year for the Municipality given problems experienced with the water system and thus pumping rates were not considered to be representative. These problems are illustrated by Figure 5 which is a hydrograph of water levels for the Rollins well with water use also graphed. This figure illustrates an increase in water use for 2007 together with a decrease in water levels.

Figure 5: Hydrograph and Water Use of Rollins Well (data as provided by the Ontario Clean Water Agency)



The future pumping rates for the municipal wells were determined in respect of the County of Hastings Official Plan for the area which projects growth over the next 25 years to be in the order of 18%. To account for this growth the pumping rates were increased proportionally. Please note that in all cases the actual and future pumping rates are significantly lower than the Permit to Take Water Rate. From this data the committed demand for the system is considered to be the future pumping rates.

Table 3: Village of Madoc Water Use (cubic metres)

Demand	Whytock	Rollins	Total
Actual	257	325	582
Future	303	384	687
Permitted	818	1469	2287

4.5 Water Demand

The water demand for the subwatershed was determined based on information taken from the Tier 1 water budget report. The details of this data are provided in the Quinte Conservation Tier 1 Water budget Final draft Report dated April 14, 2009. This demand was determined for monthly and annual time periods and generally included the following:

- Domestic & Commercial Water Use as determined using water well records and population census data with a consumptive use of 105 litres/well/day.

- Permit to take water data for 9 individual takings within the subwatershed. Request to the Ministry of the Environment did not result in obtaining actual use data, however consumptive factors were applied to each use.

- Agricultural Water Use: Water use for the subwatershed as prepared by Rob DeLoe (2002) was assigned to the agricultural wells after applying consumptive factors.

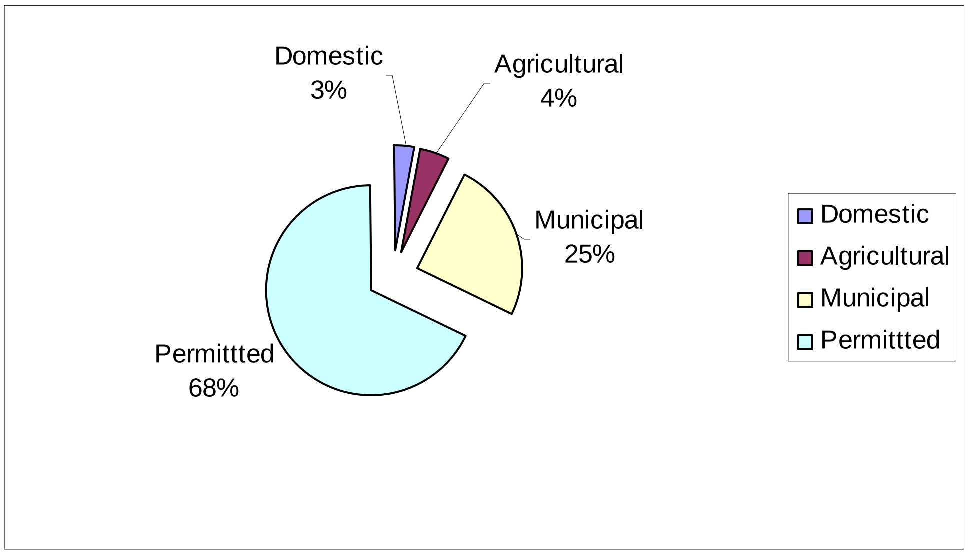
Municipal Water Use: Water use for the Village of Madoc wells was applied based on actual numbers and projection of growth over 25 years based on Ministry of Finance Projections.

A summary of the water use in the subwatershed is provided by Table 4 and Figure 6. For future pumping only the rates for the municipal wells were increased.

Table 4: Subwatershed Water Use with Consumptive Factors

Water Use Category	# of Wells	Consumptive Factor	Total (m3/day)
Domestic Wells	701	0.2	73.6
Agricultural Wells	68	0.8	103.6
Municipal Wells	2	1	582
Permit to Take Water	9	0.25-1	1606

Figure 6: Distribution of Water Use



4.6 Surface Water Flow Model

An existing surface water flow model was reviewed to assist in interpretation of the hydrology of the subwatershed (specifically Madoc and Deer Creeks). This model was developed for Quinte Conservation for watershed management purposes and is referred to as the Quinte Conservation Watershed Hydrology Model (QCWHM); formulated using the GAWSER (Guelph All-Weather Sequential-Events Runoff model) program (Version 6.9.11). The development and overall results are described in the Quinte Conservation Report Draft Tier 2 Water Budget – Ameliasburgh Subcatchment, Quinte Source Protection Region (February, 2010). The catchments covering the study area are as illustrated by Figure 7 with those high lighted in red used specifically in the Tier 2 process for comparison with the groundwater flow model. Please note that the estimate of baseflow from the surface water model was compared with that of the groundwater flow model as an approximation only. The surface water model predicts baseflow in the Creek from a mixture of sources such as lakes, wetlands and groundwater. The groundwater model predicts baseflow as the component of flow coming from the groundwater. Therefore this comparison can only be used as an approximation (i.e. to establish if the groundwater model overestimates baseflow in the Creek).

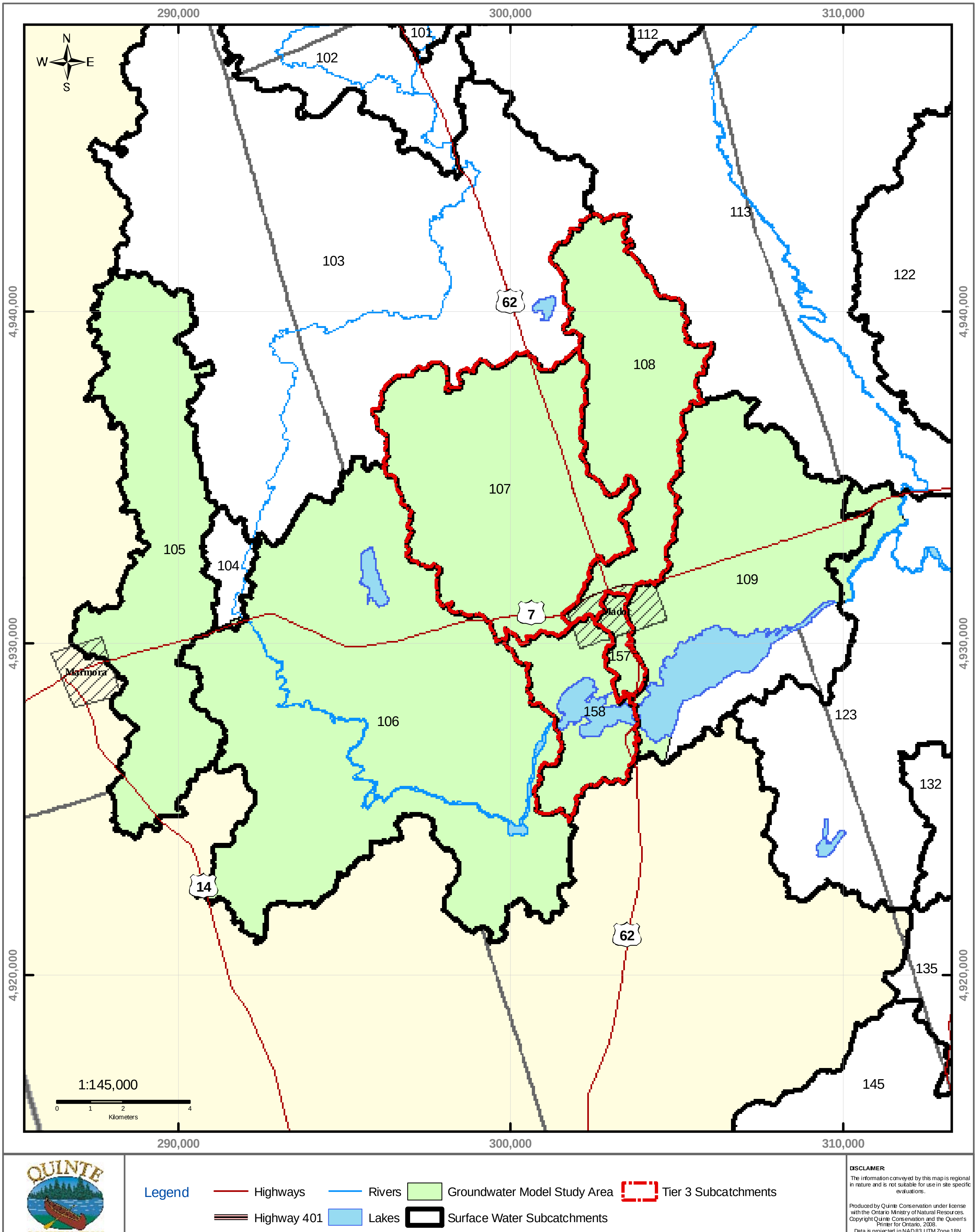


Figure 7 Madoc Study Area with Subcatchments

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DIGITAL MAPPING SOURCES:

Base Map - Ontario Ministry of Natural Resources
Subcatchments - Derived using ArcHydro
Gauge Locations - Water Survey of Canada

5.0 Groundwater Model Results

For the Tier 2 water budget exercise the MOE Technical Rules prescribe a number of scenarios which require completion prior to assigning a hydrologic stress of significant, moderate or low to the subwatershed. These scenarios are summarised as follows:

Scenario A: Current water demand under average climate conditions.

Scenario B: Future water demand under average climate conditions.

Scenario D: Current water demand under 2 year drought climate conditions.

Scenario E: Future water demand under 2 year drought climate conditions.

Scenario G: Current water demand under 10 year drought climate conditions

Scenario H: Future water demand under 10 year drought climate conditions.

Please note that in accordance with the Rules completion of the above scenarios requires percent water demand calculations for the subwatershed under scenarios A and B. Completion of scenarios D, E, G, & H require assessment of the ability of the Municipal Wells at the Village to meet water demands. For scenarios A and B the percent water demand is calculated using the following equation:

$$\text{\% Water Demand (Stress)} = \frac{Q_{Demand}}{Q_{Supply} - Q_{\mathrm{Re}\,serve}} \text{ X } 100$$

Where:

Q_{Demand} = Monthly & annual demand calculated as consumptive takings for both current and future projections (monthly & annual).

Q_{Supply} = Ground water supply calculated as the average annual recharge and monthly rate (monthly = annual divided equally by 12)

$Q_{\mathrm{Re}\,serve}$ = Ground water reserve is estimated as 10% of the average annual groundwater discharge rate or 10 % of supply if discharge is not available.

Subject to the percent water demand calculations for Scenarios A and B the subwatershed is assigned a stress level of significant, moderate or low in accordance with the thresholds listed in Table 5. In addition to these thresholds the subwatershed may be assigned a moderate level of stress should the municipal wells not be able to meet demand under scenarios D, E, G, and H or if there is historic evidence that the a municipal well was pumped dry and was not able to meet demand. Another possibility where the subwatershed may be assigned a moderate level of stress is when the annual percent water is between 8 -10%, or monthly between 23 -25%, the uncertainty of the groundwater model is high and a sensitivity analysis indicates that the stress could be moderate.

Table 5: Groundwater Stress Thresholds (% water demand)

Ground water Quantity Stress Assignment	Average Annual	Monthly Maximum
Significant	> 50%	>25%
Moderate	>25-50%	>10-25%
Low	0-25%	0-10%

5.1 Results

The result of the percent water demand calculations for scenario A or B are listed in Tables 6 & 7. From this assessment the maximum monthly % water demand was determined to be 4.6% and the annual was 4.2%. In accordance with the threshold values this level of demand correlates to a low level of subwatershed stress. As regards to scenarios D, E, G & H, (2 and 10 year droughts) scenarios E and H were completed and indicated the wells were able to meet demand, thus signifying a low level of stress. However, scenarios D and E (2 year drought) were not completed as per reference to the Ministries of the Environment & Natural Resources, Technical Bulletin Water Budget & Water Quantity Risk Assessment Tier 2 Subwatershed Stress Assessment Groundwater Drought Scenarios (July, 2009). This bulletin indicates that if the ten year drought scenario is completed first and the stress level is assigned as low then the 2 year drought scenario does not need to be completed.

In spite of assignment of a low level of stress to the subwatershed under scenarios A, B, G & H, the fact remains that one of the municipal wells was pumped dry in 2007. This circumstance triggers a moderate level of stress. However, further assessment of the circumstance has indicated that it was due to an operational issue and not an issue with the source water supply. This was attributed to increased demand on the Rollins Wells as a result of taking the other well (Whytock well) offline due to a water quality problem, and a problem with the water treatment system (at the Rollins Well) which allowed significant volumes of water to be pumped to waste. An illustration of the increased water use and decrease in water levels at the Rollins Well is provided by Figure 5. Discussion with the municipality about this situation has indicated that the problems have been rectified and they have not experienced any water shortages since then.

5.2. Uncertainty

The other potential situation where a moderate level of stress could be assigned is when there is a high level of uncertainty associated with the groundwater model, and a sensitivity analysis indicates the % water demand could be increased to the moderate threshold value. The uncertainty associated with models used to represent natural systems can often be considered as high and a discussion of the uncertainty of the model is provided in the SWS report of Appendix A. Based on a combination of factors the uncertainty with the model was assigned as high. In spite of this assignment the actual uncertainty is considered low given that under realistic conditions the wells have been shown to meet the water demands of the community and previous assessment of the percent water demand at the Tier 1 level also provided a low stress assessment. However, when the wells are pumped at rates higher than the committed demand it has been shown that they are not capable. During 2007 the Rollins well was being pumped at approximately 800 m^3/day versus a committed demand rate of 384 m^3/day.

Table 6: Percent Water Demand, Average Climate, Current Conditions

	Recharge	Pumping	Baseflow	Water Demand
	m3/d	m3/d	m3/d	%
January	56,933	1,993	62,286	3.9
February	56,933	1,935	62,286	3.8
March	56,933	2,099	62,286	4.1
April	56,933	1,983	62,286	3.9
May	56,933	2,021	62,286	4.0
June	56,933	1,918	62,286	3.8
July	56,933	2,141	62,286	4.2
August	56,933	2,210	62,286	4.4
September	56,933	2,219	62,286	4.4
October	56,933	1,733	62,286	3.4
November	56,933	1,911	62,286	3.8
December	56,933	1,876	62,286	3.7
Average	56,933	2,003	62,286	4.0

Table 7: Percent Water Demand, Average Climate, Future Demand

Month	Recharge	Pumping	Baseflow	Water Demand
	m3/d	m3/d	m3/d	%
January	56,933	2,116	62,181	4.2
February	56,933	2,048	62,181	4.0
March	56,933	2,240	62,181	4.4
April	56,933	2,093	62,181	4.1
May	56,933	2,138	62,181	4.2
June	56,933	2,017	62,181	4.0
July	56,933	2,229	62,181	4.4
August	56,933	2,311	62,181	4.6
September	56,933	2,322	62,181	4.6
October	56,933	1,798	62,181	3.5
November	56,933	2,009	62,181	4.0
December	56,933	1,978	62,181	3.9
Average	56,933	2,108	62,181	4.2

5.4 Ground/Surface Water Interactions

Although the groundwater model indicated the wells were able to meet the water demands of the Village under the 10 year drought conditions, it was determined that drawdown in the wells increased with additional demand. Under such conditions more leakage of water from the nearby Creek was assessed as assisting in supply to the aquifer. At this level of work insufficient information is available to confirm with confidence the volumes of water being contributed by the Creek and if this contribution would result in impact to water levels in the Creek. Further work to assess these volumes and changes in stage levels of the Creek would be required to assess impact.

6.0 Conclusions & Recommendations

Following development and calibration of a three dimensional groundwater flow model various scenarios of current and future water demand were assessed. The results of assessment as outlined above and in the Schlumberger Water Services of Appendix A indicated the subwatershed to exhibit a low level of stress. Through use of this model the ability of the wells to meet demands of the community for current and future demand under average and drought climate conditions was assessed. The model demonstrated that the wells were capable of meeting the demand, however it was found that under drought conditions more flow from the Creek provided recharge to the aquifer. Further work would be required to evaluate the volume of water reaching the wells from the Creek and to assess if this taking would result in stress conditions on the Creek.

In spite of assignment of a low stress, the MOE Technical Rules 35 (2) (e) indicates that if a municipal well was pumped dry after January 1, 1990 then the subwatershed is assigned a moderate level of stress. In spite of the Municipal well being pumped dry in 2007, it is important to note that this occurred when the well was pumped at rates that were much higher than the committed demand as listed in Table 3 (384 m3). Assessment of the circumstances as to why this happened resulted in the conclusion that this was due to an operational problem, whereby increased demand was placed on this well and much water was being pumped to waste over an extended period of time.

Efforts to implement water conservation in the community would assist in minimizing water use and potential stress under dry conditions. Regular monitoring and periodic review of the water takings as well as landuse should be completed to ensure the status of the water budget work has not changed significantly.

References

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QUINTE Tier 2
Numerical Groundwater Flow Modelling for Water Budget Assessment

7295

DRAFT REPORT

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1 Introduction

1.1 Background

In the Technical Rules, Assessment Report, Clean Water Act, 2006 (Technical Rules) (December, 2008), "Tier Two" is described as a procedure where a water budget is developed using computer-based three-dimensional groundwater flow models and computer-based continuous surface water flow models to assess groundwater flows and levels, surface water flows and levels, and the interactions between them. This work allows more refined estimation of the water budget components to improve reliability and refine the estimate of potential water quantity stress

From the Quinte Conservation water budget activities, the Village of Madoc subwatershed has not been identified as exhibiting a high level (significant or moderate) of stress. However in recent past (2007) one of the wells was reported as being pumped dry on several occasions. In accordance with the Ministry of the Environment (MOE) Technical Rules (2008) such systems that have experienced this problem are to be assigned a moderate level of stress and are to proceed onto more detailed water budget work. In this case, Quinte Conservation Authority (Quinte) has determined that a Tier Two water budget will be required. Schlumberger Water Services has been retained to construct a three-dimensional groundwater flow model that will adequately fulfill the requirements as outlined in the Technical Rules (MOE, 2008).

1.2 Study Area

It is important for the ground water model study area to encompass the subwatershed containing the Municipal wells supplying the Village of Madoc. Therefore, the study area was chosen as the complete domain comprising the Madoc 1 and Madoc 2 subwatersheds to the west of Madoc and Deer Creeks, and a portion of the Tweed subwatershed to the east of the creeks, for a total area of 278 km^2. This area is based on the original subwatershed (Tweed) as used at the tier 1 level but has been refined to be more representative of the aquifer system containing the Village of Madoc wells. The local study area is presented in Figure 1. This domain satisfies the requirements of the Tier Two, and is a useful tool for simulating groundwater flow near Madoc.

1.3 Objectives

The objectives of this modelling investigation are to:

- Develop a steady-state three-dimensional groundwater flow model that will satisfy the requirements of the Technical Rules
- Calibrate the model to existing steady state pumping conditions at Madoc
- Verify and if required adjust the model under transient conditions
- Assess the volumes of available groundwater to allow calculation of percent water demand for the subwatershed under current and future demand average climate,
- Assess the ability of the municipal wells to meet demand under drought conditions, (2 and 10 year drought scenarios)
- Identify knowledge gaps and uncertainty in the model

This report describes the data and methodology used to construct and calibrate the groundwater flow model, and discusses the results of the steady-state and transient flow models.

2 Development of the Steady-State Numerical Groundwater Flow Model

Once the study area and domain were established, a conceptual model of the system was developed. The hydrostratigraphy of the region (e.g. hydraulic conductivity, porosity, and storativity), recharge to the groundwater system, and the stresses placed on the system have been included. Observation head values are also required to calibrate the model to current conditions. The data gathered include:

- Digital Elevation Model (DEM) from Quinte CA at a 10-metre resolution
- 2007 MNR/OGS Bedrock Geology shape files
- Natural Resources and Values Information System (NRVIS) dataset to locate the rivers and wetlands within the domain
- Local monitoring wells and MOE Water Wells Records
- Previous three-dimensional groundwater model obtained from Dillon Consulting
- Water Budget ArcGIS model

2.1 Model Domain

The conceptual and numerical flow models were built using the Schlumberger Water Services software packages Visual MODFLOW 3D-Builder 2008.1 (SWS, 2008) and Visual MODFLOW 2009.1 (SWS, 2009). Visual MODFLOW 3D-Builder (3D-Builder) is an add-on module for the Visual MODFLOW numerical modeling software package. Visual MODFLOW VMOD is the graphical user interface for the program USGS MODFLOW (MacDonald and Harbaugh, 1988), a three-dimensional modular finite-difference groundwater flow model that solves the groundwater flow equation:

$$\underbrace{\frac{\partial}{\partial x}\left(K_{xx}\,\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\,\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\,\frac{\partial h}{\partial z}\right)}_{\text{Groundwater Flux in 3-D}}\;\underbrace{+\,W}_{\text{Sink/Source term}}\;=\;\underbrace{S_s\,\frac{\partial h}{\partial t}}_{\text{Change in Storage}}$$

Figure 2 presents a plan view of the model grid. The regional grid spacing is approximately 125 m by 125 m. Near the municipal wells, the grid has been refined to approximately 15 m by 15 m. There are five active layers, with elevations in active cells ranging from approximately 280 metres above sea level (masl) to 40 masl.

The top layer of the model grid is based on the DEM provided by Quinte, and was obtained from the Ontario Geological Survey. Figure 3 presents the DEM elevations across the model domain. The elevations in the lower layers are based on bedrock mapping of the region and the interpolations of borehole records obtained from the MOE Water Wells Database. The unit depths have been normalized to the DEM. Figure 4 presents the bedrock surface elevations.

To minimize numerical dispersion in a model, it is a best practice in modelling to align the x-axis and y-axis with the predominant direction of groundwater flow. Prevailing regional groundwater flow within the model domain, which is based on interpolations of water levels obtained from the MOE WWIS database, is from the northwest to the southeast, as presented in Figure 5. The model grid has been rotated five degrees counter-clockwise to align the general flow direction parallel to the Y axis.

2.2 Model Properties

2.2.1 Hydrostratigraphy and Hydraulic Conductivity

The regional geology and hydrogeology was interpreted by Dillon (2007). Lithologic units in the Madoc region consist of sandy till overburden, fractured Paleozoic limestone, fractured Precambrian metamorphic and granitic undifferentiated rock. The report indicates that the main aquifer near Madoc Village is a confined-to-unconfined fractured Precambrian rock aquifer. The productivity of the aquifer varies according to the number of fractures and their interconnections. Therefore, the amount of water a well will produce also varies significantly across the region. Dillon’s study concluded that areas of low permeability were still able to produce, due to the presence of the fracture network. However, the fractures are heterogeneous and very difficult to characterize or map. As a result, definitive flow patterns around the wells are difficult to predict.

In this model, average flow through the unit is being simulated rather than including specific faults in the model. To account for the presence of faults within the various bedrocks, and therefore potentially different transmissivities, fourteen hydraulic conductivity zones have been incorporated into the model. Vertical hydraulic conductivity (K_z) is set to an order of magnitude lower than the horizontal hydraulic conductivity (K_x and K_y). Hydraulic conductivities used in the model are estimates and based on a combination of data obtained from the Dillon model and report, the general hydrogeological literature, and the parameter estimation software PEST that was used to calibrate the model.

The overburden, which is represented only in layer 1 of the model, has a significantly varied thickness across the domain (between 0 and approximately 20 metres) (Dillon, 2007). In this model, representing the overburden units as discrete hydraulic conductivity zones resulted in layer 1 being very thin. As a consequence, many of the model cells were disconnected, which led to convergence problems with the model solution. Therefore, the first layer is combined with the second layer and many of the hydraulic conductivity zones assigned in layer 1 are representative of a combination of the overburden and bedrock units directly underneath. Generally, in layer 1, the combined overburden/fractured rock hydraulic conductivity zones have lower values than the exposed fractured rock conductivity zones, as it is expected that infiltration would be lower in the presence of overburden. The hydraulic conductivity of the combined layer was calculated as the harmonic average of both layers, assuming that most of the groundwater flow is vertically directed near the top of the aquifer. The rest of the active layers (2 through 5) are defined based on the thicknesses of the known bedrock units, which were calculated using data obtained from the MOE Water Wells Database.

Figure 6 presents the distribution of hydraulic conductivity zones in the active model layers. Layer 1 represents a mixture of sandy till overburden materials, and exposed outcrops of fractured limestone and fractured Precambrian metamorphic and granitic rocks. Layers 2 and 3 represent the deeper fractured limestone and fractured Precambrian rocks. Layers 4 and 5 represent the Precambrian basement rock that still has sufficient flow to be included in the active region of the model. The values used were based initially on the values provided in the Dillon model and report (2007), and for horizontal hydraulic conductivity (K_x and K_y), range between 2 x 10^{-5} and 3 x 10^{-8} m/s. The model assumes an equivalent porous medium; the fractures are included as part of the average hydraulic conductivity. When representing a fractured system with the equivalent porous medium approach, the effect of fractures on the flow can be reproduced by introducing anisotropy for the hydraulic conductivities, increasing the hydraulic conductivity parallel to the fracture planes. Dillon, 2007 has analyzed fractured, but only measured the strike of faults visible on aerial images. In the absence of information on the three dimensional orientation of the faults, it was assumed that within this generally flat lying rocks, the majority of the fractures would be parallel to the bedding plane and there the vertical conductivity was set to one tenth of vertical conductivity. K_x and K_y have been set as equivalent. Table 2-1 lists the specific hydraulic conductivity zones used in the model, and presented in Figure 6.

The porosity of the fractured Precambrian rock and used in the original Dillon model is based on field data collected by Dillon (2007), at a value of 1.2% (0.012). The updated model also incorporates fractured limestone and overburden materials. To allow for differences in some of the other materials, an average value of 2% (0.02) was used for the total porosity across the model domain.

Table 2-1: Hydraulic Conductivity Zones in Model

Zone – Colour – Location in Model	Material	Horizontal K_x (m/s)	Vertical K_z (m/s)
1 – White – Layer 1	Fractured Precambrian Rock	6 x 10^{-5}	6 x 10^{-6}
2 – Navy – Layer 1	Fractured Limestone	2.3 x 10^{-5}	2.3 x 10^{-6}
3 – Green – Layers 1 to 3	Fractured Precambrian Rock	2.8 x 10^{-5}	2.8 x 10^{-6}
4 – Teal – Layer 2	Fractured Precambrian Rock	3 x 10^{-5}	3 x 10^{-6}
5 – Maroon – Layer 1	Fractured Precambrian Rock	4.1 x 10^{-6}	4.1 x 10^{-7}
6 – Purple – Layer 1	Overburden and Fractured Precambrian Rock	4.0 x 10^{-7}	4.0 x 10^{-8}
7 – Dark Grey – Layers 2 to 4	Fractured Precambrian Rock	2.5 x 10^{-6}	2.5 x 10^{-7}
8 – Blue – Layer 1	Overburden and Fractured Limestone	1.3 x 10^{-7}	1.3 x 10^{-8}
9 – Light Blue – Layers 2 to 3	Fractured Precambrian Rock	3.0 x 10^{-8}	3.0 x 10^{-9}
10 – Fuschia – Layers 1 to 3	Fractured Limestone	8.8 x 10^{-6}	8.8 x 10^{-7}
11 – Yellow – Layer 1	Overburden	1.9 x 10^{-6}	1.9 x 10^{-7}
12 – Blue Hatched – Layers 2 to 3	Fractured Limestone and Precambrian Rock	2.2 x 10^{-6}	2.2 x 10^{-7}
13 – Maroon Hatched – Layers 1 to 3	Fractured Precambrian Rock	1.3 x 10^{-6}	1.3 x 10^{-7}
14 – Light Grey – Layer 5	Fractured Precambrian Rock	2.0 x 10^{-7}	2.0 x 10^{-8}

2.3 Model Boundary Conditions

The boundary conditions in a numerical flow model define the flow conditions at the interface between the model domain and the outer world. The boundary conditions applied in the numerical model, and presented in Figure 7 and consist of:

- River boundaries to simulate Madoc Creek and Deer Creek in the vicinity of Madoc
- Drain boundaries to simulate wetland areas and other small creeks that represent areas of discharge further from Madoc
- Constant head boundaries to represent Moira Lake and Jarvis Lake
- Recharge boundaries to simulate precipitation and evapotranspiration across the domain
- No-flow boundaries at the edge of the model domain to represent the borders of the subwatersheds
- At the bottom of the model, flow was assumed to be horizontal and a no-flow boundary condition was assigned

2.4 Lakes, Creeks and Wetlands

Dillon's conceptual model (2007) indicates that the bedrock fracture storativity is very low, and that the fracture system is likely connected hydraulically to surface water sources. Madoc is considered to be in an area of converging groundwater flow which originates from the upland areas to the north, west and east.

The locations of the lakes and rivers in the model are based on GIS data from the NRVIS dataset. The region represented in the model domain is covered by numerous wetlands and small creeks and tributaries, most of which are unlikely to be significant with respect to the regional model. The majority of the creeks and wetlands in the model are designated by drain boundaries, to represent the areas of discharge throughout the model domain. Madoc Creek and Deer Creek, which are located near the municipal pumping wells, have been designated by river boundaries. It is possible that the proximity of the pumping wells to these creeks result in a hydraulic connection, and that a portion of the water being pumped at the wells is being drawn from the creeks. Figure 7 presents the locations of the drain and river boundaries used to represent the wetlands and creeks across the model domain. MODFLOW uses the drain boundaries to simulate the effects of hydrologic features which remove water from the aquifer at a rate proportional to a head, while rivers may add or remove water from the aquifer depending on the head difference between river stage and the water table. The creek stages are initially set to the elevation of the DEM; to improve the model calibration, some of the stages were reduced to a maximum of 0.4 metres below the DEM.

2.5 Constant Head

Constant head boundaries are used to represent Moira Lake and Jarvis Lake, a smaller lake further north in the study area and within the model domain (Figure 7). The locations of the lakes are based on the same GIS data from the NRVIS dataset. During construction of the model, it was noted that the DEM in the region of the two lakes had not been hydro-corrected to the lake level; consequently, the layer 1 model surface representing the lakes (Moira Lake and Jarvis Lake) was manually adjusted to coincide with the DEM in Google™ Earth (2009). Moira Lake was adjusted to an elevation of 155 masl, and Jarvis Lake was adjusted to 212 masl.

2.6 Recharge

Groundwater recharge from infiltrating precipitation is estimated to be between 90 and 125 mm per year, which is approximately 10% to 15% of the total yearly precipitation. The lands that are designated as recharge areas generally consist of elevated lands where the net direction of groundwater flow is downward. Recharge tends to increase where the overburden is less thick and the fractured bedrock network is closer to the surface (Dillon, 2007). There are seven zones of recharge delineated in the model, shown in Figure 8, which are based on the type of soil or rock observed at ground surface. The initial values are based on zonal statistic calculations from the water budget model to obtain average recharge for the year, and have been modified within a small margin during calibration to achieve a better statistical fit. Table 2-2 gives the values used in each zone. The average recharge in the model for the overall domain is approximately 90 mm/yr.

Table 2-2: Recharge Zones

Zone	Material	Recharge (mm/yr)
A	Fractured Limestone	105
B	Fractured Precambrian Rock	88
C	Fractured Precambrian Rock	89
D	Fractured Precambrian Rock	80
E	Fractured Precambrian Rock	85
F	Overburden	96
G	Fractured Precambrian Rock	100
H	Impervious Zones due to current land development	0
I	Projected Impervious Zones due to anticipated land development	40*

* The Zone I recharge rate is only used when simulating future conditions. For models simulating current pumping conditions, the recharge rate applied in this zone is the same as the background recharge rate in the Madoc area, specifically 80 mm/yr.

2.7 Pumping Wells

There are twelve pumping wells included in the updated numerical model, as presented in Figure 9. Rollins and Whytock are the municipal wells and are located near the town of Madoc. Rollins is the primary well; Whytock is secondary. Conley Shaft, Henderson Shaft, Quarry Spring, E&W Pits and the IKO wells are industrial pumping wells. The NPW well represents water pumped from non-permitted domestic and agricultural wells, within the subwatershed containing the Village of Madoc.

Table 2-3 presents the casing depth, the bottom of the open borehole, the number of months each well is operating and the pumping rate allocated in the numerical model. Conley Shaft and Henderson Shaft are very deep open boreholes (i.e. greater than 250 m bgs); however, the operators have indicated that the majority of the water is taken from the upper more transmissive units; in this model, the bottoms of the screens for these two wells are placed at the bottom of the lowest active model layer.

Table 2-3: Pumping Wells

Well Name	Casing Depth (m bgs)	Depth to Bottom of Well (m bgs)	Months of Operation per year	Model Pumping Rate (m^3/day)
Whytock Well	7	91.4	Year round	257
Rollins Well	10.7	48.8	Year round	325
NPW Well	17	26	Year round	10
Conley Shaft	2	112.9	Year round	285.7
Henderson Shaft	2	114	Year round	95.2
E&W Pits	2	25	July to September	40.2*
Quarry Spring	2	12	May	344.7
IKO-TW4	6	31	Year round	22.2
IKO-TW5	6	79	Year round	7.2
IKO-TW6	6.5	31	Year round	724.3
IKO-Pond1	N/A	N/A	April to November	40*
IKO-Pond2	N/A	N/A	June to September	37.3*

* Pro-rated to a yearly rate for the steady state model

The pumping rates used in the model for the municipal wells are based on the monthly measured pumping rates supplied by Quinte. They are calculated based on the percentage of groundwater pumped and the amount of time per year that the wells are pumped. The rates used are 325 and 257 m^3/day for Rollins and Whytock, respectively, and are representative of an average five-year withdrawal rate.

For the industrial wells, the values used in the model are based on the Permit-to-take-water (PTTW) rates multiplied by the percentage of groundwater pumped, the consumptive factor and the amount of time the well is pumped per year. For example, the E&W Pits well operates July-Sept (25%), pumps 50% groundwater, and has a consumptive factor of 50%. The PTTW rate is 655 m^3/day; when multiplied by the consumptive factor, the percent groundwater factor and pro-rated to the yearly rate, this results in a model pumping rate of 41 m^3/day. The rate calculations for all pumping wells in the model are given in Appendix A.

The non-permitted water (NPW) pumping well represents the pumping rates for both the domestic and agricultural non-permitted wells/water-takings. The agricultural water-taking estimates are based on the type of farming conducted with a consumption factor of 80% applied. The private water-taking estimates are based on the number of wells, the population and a consumptive factor of 20%. The combined rate for the NPW well is calculated at 10 m^3/day for the area in the vicinity of the municipal wells. This volume is extracted in the model using a single well placed centrally in the subwatershed zone. Appendix B provides a discussion of the methodology used to calculate the rate for the NPW well in the model.

Based on the low pumping rate in the NPW well, it is unlikely that this pumping rate will strongly affect the modelling results. However, to confirm this, two steady-state scenarios have been run, one with the NPW well on and one with the NPW well off. This is discussed further in Section 3, Steady State Modelling Results.

2.8 Model Calibration

A good calibration is essential to be able to defend and have confidence in a numerical model. One of the primary indicators of calibration is the statistical comparison of predicted heads to those observed in monitoring wells. To calibrate a regional model, one of the goals is to arrive at a normalized root mean square error (NRMS) of less than 10%. The root mean square (RMS) is a statistical measure of the magnitude of the residual heads. The residual head, R, is the difference between calculated and observed heads in the model. For the number of calibration targets in the model, *n*, the RMS is represented by the following equation:

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n} R_i^2}$$

The NRMS is calculated by dividing the RMS by the maximum difference in the observed head values:

$$NRMS = [RMS / \{X_{obs\text{-}max} - X_{obs\text{-}min})]$$

While the NRMS is convenient as it allows expressing the average quality of the calibration in a single value, it is equally important to assess a calibration by reviewing the spatial distribution of residuals. The mapping allows distinguishing local differences of the calibration results. A map of the residual head distribution is presented in Figure 13. Calibration of a numerical flow model is completed by adjusting values in the boundary zones or model properties such as hydraulic conductivity zones to match as best as possible the observed head elevations with those calculated in the simulation. For this model, a combination of manual and automated calibration methods was used.

Based on best estimate input data, calibration was optimized using WinPEST (PEST), a parameter estimation program incorporated into Visual MODFLOW 2009.1. WinPEST will adjust model parameters until the fit between model calculations and field observations is optimized. It performs this function using a Gauss-Marquardt-Levenberg nonlinear estimation technique. The mathematics of the software is fully described in the PEST manual (Doherty, 2002). The limitation of PEST is that it does not have the capability to differentiate a reasonable parameter from an unreasonable one. Therefore, it is also important to assess and potentially modify the calibration manually during the process, to ensure that the final parameters established for the model are realistic with respect to the physical hydrogeological system.

In addition to comparing the calculated heads with observed heads, the baseflows of four of the subwatershed regions used in the water budget analysis were compared with the model results for baseflow. Figure 10 presents the locations in the model of the four subwatershed regions, specifically zones 107 and 108 to the north, and 157 and 158 to the south. Madoc and the municipal pumping wells are located in Zone 157.

2.9 Calibration Targets

The target data used to calibrate a numerical flow model should ideally be from a single date or limited time period of sampling. Most of the calibration targets used to calibrate the updated Quinte model have been obtained from the MOE Water Wells Records database;

these wells were installed between 1947 and 1982. The observed heads were recorded at the time of installation and thus, are not from a single sampling event. It is likely that the conditions have varied significantly over that period of time. These wells are, therefore, not as reliable for calibration but still useful for a general regional calibration. Appendix C gives the location, observation elevation and water elevation of the 389 observation targets used for model calibration. The target elevations have been normalized to the ground surface DEM in the model. Figure 11 presents the distribution of the observation head targets across the model domain.

To mitigate the unreliability of the older wells, and provide some more reliable high quality data, a private survey was conducted by Quinte during July 2006 (Dillon, 2007). The survey included:

- reconnaissance survey of the area around the Madoc Village to determine areas where wells may exist (privately serviced residential and commercial developments)
- attendance at residences and businesses selected at random to obtain information about the water supply and inspection of the well,
- inspection of the well construction, measurement of static water level, and well depth
- locations of all wells, determined by GPS (selected wells in close proximity to the municipal wells were also surveyed by an Ontario Land Surveyor P.A. Miller Surveying Ltd. to determine accurate elevations in reference to geodetic bench marks, and by overlaying the coordinates on a high-quality DEM
- collecting water quality samples at selected wells, and submitted to Caduceon Laboratories in Kingston, Ontario for analysis of general chemistry and metals
- making general notes about construction and status of the wells to assist in evaluation of constructed preferential pathways of flow

Eleven local monitoring wells were re-surveyed; their coordinates, type of use, depths, model target elevations and water elevations are given in Table 2-4. Because the data from these wells is much more reliable, these targets have been given a weight of a factor of two greater than the MOE well targets when performing the WinPEST calibration. The local monitoring wells near Madoc are shown in Figure 11 in the inset.

Table 2-4: High Quality Observation Targets

Well Name	UTM NAD83, Zone 18N X,Y Coordinates	Use	Depth (bgs)	Screen Elevation (masl)	Water Elevation (masl)
1	302774, 4932490	Residential	43	136.96	176.82
2	302636, 4932302	Commercial	26.5	156.49	178.05
3	303658, 4932107	Arena	11.1	173.83	182.55
4	303870, 4932105	Commercial	25.46	158.03	181.6
5	302978, 4931435	Commercial, not used	16.26	154.36	169.58
6	303111, 4931472	Residential	25	154.09	167.92
7	302459, 4930674	Institutional	25	149.93	170.31
8	302587, 4930146	Commercial	19.4	147.85	162.7
9	302959, 4930239	Residential	48.3	119.47	164.01
10	303678, 4931018	Municipal, not used	51.5	149.29	166.88
11	303285, 4930293	Residential	29	135.78	158.16

3 Steady State Modelling Results

Figure 12 presents the simulated water table elevation map. The blue contours represent the equipotentials. The olive green zones represent the regions in layer 1 where the cells have become dry. Generally, groundwater flow is towards Moira Lake. For the entire domain, flow is dominantly from the north to the south and generally in agreement with the mapped water table presented in Figure 5. Groundwater particle tracking simulations indicate that the majority of the flow to both of the municipal pumping wells derives from the subsurface aquifers to the north of the village. However, some of the water is also being taken from the Deer Creek.

Figure 13 presents a map of the distribution of residuals across the model domain. Blue dots indicate wells where the calculated head is greater than the observed head, while red dots indicate the reverse. The larger the dot on the map is, the greater the residual. Ideally, the distribution of residuals in a model should be scattered, and show no specific pattern. If a significant number of residuals of the same colour exist in one area of the model, it indicates that the model is not adequately simulating the hydrogeological conditions.

For the most part, the scatter of residuals is very good. Given that the regional data is not of the highest quality, it is expected that higher residuals would be observed, as the data for the regional targets were gathered over such a long period of time, and likely under widely varying conditions. Figure 13 shows that, with one exception, the residuals are scattered randomly across the model domain. The exception is in the northeastern section of the domain, where there is a tendency for the model to be dry. The majority of the high residuals, or targets where the observed head is much greater than the calculated head, occur in this region. The area around Madoc does not show any problems with significant residual heads.

Given the extent of this model and data available, the calibration may be considered good, with few problem areas.

3.1 Statistical Calibration of the Steady State Model

Of the 389 target wells listed in Appendix C, only six targets (all located in model layer 1) are located in dry cells. A model cell will become dry when the highest calculated head elevation is below the base of that cell. At that point, MODFLOW stops calculating heads in that cell, and any observation targets associated with that cell are not included in the calibration statistics.

Figure 14 presents a scatter plot of the calculated heads versus observed heads for the entire domain and the local monitoring wells at Madoc. The further away a point lies from the diagonal solid blue line indicates a larger residual. Points above the line represent targets where the calculated heads exceed the observed head. Points below the line represent the reverse. The regional dataset NRMS on 383 active points is 5.5%. The NRMS for the 11 local monitoring wells is 8.6%. Both figures indicate that generally, the points are scattered generally along the diagonal line. This indicates that the simulated gradient is reasonable with respect to the entire model domain, and also for the local area near Madoc.

Appendix C lists the calculated head values and residuals for all the observation targets in the model. The maximum residual for the local wells dataset occurs at MW11, at a value of 3.3 metres. For the regional dataset, however, there are two points with residuals greater than 20 metres. These targets are located in the extreme northeast section of the model, (i.e. highlighted as the largest red dots in Figure 13). The maximum residual observed in this region of the model is 23 metres at MOE well 2909923. If this area is discounted, given that it is likely not representing that region adequately, then the highest residual in the model becomes 17 metres at MOE well 2901087 (located at the central north end of the model domain). The NRMS for the regional model in this case is 5.3%.

Statistically, with the exception of the targets located in the northeast region, the model is considered to be well calibrated, both locally and regionally.

3.2 Baseflow Calibration

Baseflow is defined as “that part of the stream discharge that is not attributable to direct runoff from precipitation or melting snow and is usually sustained by groundwater” (American Meteorology Society, 2000). Zone Budget is a program developed by the U.S. Geological Survey to calculate water budgets for user-defined zones in a model, and incorporated into Visual MODFLOW as an add-on module.

The water budgets calculated for the four subwatershed regions (Figure 10) are compared with the water budget analysis results of the GAWSER model (Quinte Conservation, 2009) in Table 3-1. Appendix D presents the exported results from the model from the Zone Budget module. When comparing the GAWSER model and the numerical groundwater flow model, there are significant discrepancies observed in northern zones 107 and 108. Zone 108, with a 90% discrepancy, however, contains the northeastern section of the model domain where it has already been established that there are very high residuals and dry cells. Zone 107 also shows a percent difference greater than 50%. This region also contains several targets with high residuals (as high as 15 or 16 metres at wells 2908082 and 2909647, respectively).

Table 3-1: Comparison of Baseflow Zone Budget in Model with GAWSER

GAWSER				Zone Budget Net Discharge (m^3/day)	Percent Difference (%)
Zone	Subwatershed Area (km^2)	Baseflow (mm/yr)	Baseflow over Area (m^3/day)		
107	45.2	182.6	22,612	10,131	55
108	29.6	167.2	13,559	1,336	90
157	2.53	192.4	1,333	864	35
158	13.2	143.8	5,200	3,031	42

The southern zones, 157 and 158, with percent discrepancies of 35% and 42%, respectively, show greater agreement between the GAWSER and groundwater flow model. Madoc is located in zone 157 and has the best agreement with the GAWSER results.

All the zones in the numerical groundwater model show less baseflow than in the GAWSER model. This was expected since the baseflow of the GAWSER model is not directly comparable to the baseflow as defined in MODFLOW. Dillon (2007), in their conceptual model, describes the Madoc region as an area where the bedrock fracture storativity is low, and the fracture system is likely hydraulically connected to surface water sources or to an overlying overburden reservoir to sustain continuous large withdrawals such as GAWSER reports for those subwatersheds. It is considered, therefore, that there is significant water being drawn from the wetlands storage in the northern region of the domain (Zones 107 and 108) (Personal Communication with M. Boone, Quinte). In that case, the amount of baseflow reported by the zone budget analysis in the numerical groundwater model for those regions would be expected to be significantly less than what is shown in the GAWSER model.

3.3 Sensitivity in the Model

A sensitivity analysis was completed on the model by increasing and decreasing hydraulic conductivity by 50% and recharge zones by 20%. In general, the model appears to be less sensitive at the regional scale and more sensitive at the local scale. Further, the model appears to be more sensitive to changes in hydraulic conductivity than to changes in recharge. Table 3-2 presents the NRMS calibrations for the analysis. In one case, i.e. decreasing the recharge by 20%, the local and regional NRMS values have not changed (Scenario 4). However, when comparing the average recharge amounts for the three scenarios, as given in Table 3-2, the annual recharge for Scenario 4 is significantly lower than measured conditions. The model seems to be more sensitive to changes in hydraulic conductivity, expressed by a deterioration of the calibration statistics. Changes in recharge impact the model to a lesser degree or may even improve the calibration results.

This sensitivity analysis results should be considered preliminary, and not a definitive explanation of the sensitivity of the calibrated model.

Table 3-2: Comparison of NRMS values from Sensitivity Analysis

	Original	Scenario 1 K_{xyx} increased by 50%	Scenario 2 K_{xyx} decreased by 50%	Scenario 3 Recharge increased by 20%	Scenario 4 Recharge decreased by 20%
Average Recharge for Model Domain (mm/year)	90.4	N/A	N/A	108.4	75.3
Regional NRMS (%)	5.5	5.8	6.8	5.6	5.5
Local NRMS (%)	8.6	9.1	10.9	9.3	8.7

4 Development of the Transient Numerical Groundwater Flow Model

4.1 Objectives and Approach

According to the Technical Rules (Table 1 – Subwatershed Stress Level Scenarios) (2008), six scenarios are required to evaluate the subwatershed stress levels using the numerical groundwater flow model. The objective of the modelling is to be able to evaluate the volume of ground water supply available for comparison with the volume of ground water being used to assess the % water demand for the subwatershed. In addition drought scenarios are to be run in the model to determine whether the Village of Madoc Municipal pumping wells are able to meet demand under drought conditions. Subject to the % water demand calculations and the reliability of the municipal wells under drought conditions, a subwatershed stress level is assigned as significant, moderate or low in accordance with thresholds provided in the Technical Rules Number 35. Table 4-1 presents the transient modelling scenarios completed for the Tier 2 Madoc study.

Table 4-1: Transient Modelling Scenarios

Scenario	Technical Rules Description
1	Average Climate – Current Demand (% water demand)
2	Average Climate – Future Demand (% water demand)
3	2 year Drought – Current Demand (Municipal Well Reliability)
4	2 year Drought – Future Demand (Municipal Well Reliability)
5	10-year Drought – Current Demand (Municipal Well Reliability)
6	10-year Drought - Future Demand (Municipal Well Reliability)

To convert the steady state model to transient, several modifications are required:

- Addition of properties for simulating time-varying conditions, specific storage and specific yield
- Time-varying recharge amounts for average climate conditions
- Time-varying recharge amounts for 10-year drought conditions
- Time-varying pumping rates for current conditions
- Time-varying pumping rates for future use (25-year pumping rates projected)
- Update observation data to use in comparing calibration of steady-state model with transient model (Scenario 1)
- Time-varying conditions at constant head boundaries (discussed in section 4.2.2)

4.2 Modifications to the Model

This section documents the changes made to the model parameters, boundary conditions, pumping wells and observations, to convert the steady state model to transient flow conditions.

4.2.1 Specific Storage and Specific Yield

Specific Storage (S_s) is defined as the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head due to aquifer compaction and water expansion. Specific Yield (S_y) is known as the storage term for an unconfined aquifer. It is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area per unit decline in the water table. For sand and gravel aquifers, specific yield is often equal to the porosity.

The Dillon report (2007) indicates that the main aquifer near Madoc Village is a confined-to-unconfined fractured Precambrian rock aquifer, and that the bedrock fracture storativity is low. Therefore, in the model, a value of 1×10^{-5} m^{-1} was assigned for specific storage, and 0.01 for specific yield.

4.2.2 Boundary Conditions

The drain, constant head and river boundaries used in the steady-state model have not been modified at this time as no measured data on stream stages and lake levels was available as input for the model. As more information becomes available for the region, these parameters should be re-examined and upgraded in the model. The current levels are considered to be in accord with the average conditions. Therefore, under drought conditions, it is expected that the levels would likely decline.

4.2.3 Recharge

Transient recharge estimates for the zones in the steady state model have been provided by Quinte. The estimated monthly recharge rates for the average climate conditions and 10-year drought conditions are given in Table 4-2. The values used to simulate the 10-year drought conditions are based on the Tier 1 GIS water budget model for the time period between 1956 and 1965. Appendix E gives the exported water budget values from the Tier 1 GIS model for the model domain.

The monthly recharge rates for each zone in the model (Figure 8) are given in Table 4-3 (average monthly climate conditions) and Table 4-4 (10-year drought conditions). The amounts for each zone are calculated by applying the monthly apportion of recharge given in Table 4-2 to the recharge value assigned to each model zone in the steady state model, as shown in Table 2-2. The recharge during the 10-year drought conditions is calculated as approximately 50% of the amount observed during average conditions.

Table 4-2: Monthly Distribution of Recharge

Month	Average Climate Recharge (mm/month)	10-year Drought Recharge (mm/month)
January	3	1
February	2	1
March	17	9
April	6	3
May	5	3
June	4	2
July	6	3
August	3	2
September	11	6
October	12	6
November	14	7
December	6	3
Totals	89 mm/year	46 mm/year

Table 4-3: Monthly Recharge (mm/month) - Average Climate Conditions

Month	Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G
January	3.36	2.82	2.85	2.56	2.72	3.07	3.20
February	2.62	2.19	2.22	1.99	2.12	2.39	2.49
March	19.81	16.60	16.79	15.09	16.04	18.11	18.87
April	7.00	5.87	5.93	5.33	5.67	6.40	6.67
May	6.40	5.36	5.42	4.88	5.18	5.85	6.10
June	4.60	3.86	3.90	3.51	3.72	4.21	4.38
July	6.66	5.58	5.64	5.07	5.39	6.09	6.34
August	3.87	3.25	3.28	2.95	3.13	3.54	3.69
September	13.31	11.15	11.28	10.14	10.77	12.17	12.67
October	14.40	12.07	12.21	10.97	11.66	13.17	13.72
November	16.16	13.54	13.69	12.31	13.08	14.77	15.39
December	6.79	5.69	5.76	5.17	5.50	6.21	6.47

Table 4-4: Monthly Recharge (mm/month) - 10-Year Drought Conditions

Month	Zone A	Zone B	Zone C	Zone D	Zone E	Zone F	Zone G
January	1.74	1.46	1.47	1.32	1.41	1.59	1.65
February	1.35	1.13	1.15	1.03	1.09	1.24	1.29
March	10.24	8.58	8.68	7.80	8.29	9.36	9.75
April	3.62	3.03	3.07	2.76	2.93	3.31	3.45
May	3.31	2.77	2.80	2.52	2.68	3.02	3.15
June	2.38	1.99	2.02	1.81	1.92	2.17	2.26
July	3.44	2.88	2.92	2.62	2.79	3.15	3.28
August	2.00	1.68	1.70	1.52	1.62	1.83	1.91
September	6.88	5.76	5.83	5.24	5.57	6.29	6.55
October	7.44	6.24	6.31	5.67	6.03	6.81	7.09
November	8.35	7.00	7.08	6.36	6.76	7.63	7.95
December	3.51	2.94	2.98	2.67	2.84	3.21	3.34

4.2.4 Pumping Wells

Current monthly average pumping rates (Scenarios 1 and 2) and projected 25-year pumping rates (Scenarios 3 and 4) for the Rollins and Whytock municipal wells have been provided by Quinte, and listed in Table 4-5. The current rates are based on average monthly pumping rates between 2002 and 2006, which are considered to be the most representative of the actual current rates. Future pumping rates were determined according to the Hastings official plan population projections, foreseeing a growth of 18%. The water demand and hence the pumping rates were considered to increase in the same proportion.

Several of the industrial wells (i.e. E&W Pits, Quarry Spring, Pond2 and IKO-Pond) do not operate for the full year. In the steady state model, these wells were pro-rated to a yearly amount to account for the time the wells are off. In the transient model, these wells have been set to turn on and off according to the times they are active. Appendix A gives the transient pumping rates allocated for these wells. Because these rates are based on the maximum pumping rate allowed according to their PTTW, the rates are not modified for the 25-year future projections.

Table 4-5: Transient Pumping Rates for Current and 25-Year Projections

Month	Model Days	Current Pumping Rates		25-Year Projected Rates	
		Rollins (m^3/day)	**Whytock (m^3/day)**	**Rollins (m^3/day)**	**Whytock (m^3/day)**
January	31	397.5	284.3	469.1	335.5
February	59	343.4	280.5	405.2	331.0
March	90	391.0	395.7	461.4	466.9
April	120	348.9	262.4	411.7	309.6
May	151	408.6	240.0	482.1	283.2
June	181	293.8	252.3	346.7	297.7
July	212	271.9	221.1	320.8	260.9
August	243	306.0	256.3	361.1	302.4
September	273	311.6	259.8	367.7	306.6
October	304	149.3	211.8	176.2	249.9
November	334	282.5	256.5	333.4	302.7
December	365	398.0	166.1	469.6	196.0
	Yearly Averages	**325**	**257**	**384**	**303**

4.2.5 Observation Targets

Several targets containing transient data are added to the model for this phase of the study. Water levels (averaged monthly) over a period of time have been collected from the Rollins and Whytock municipal wells using data provided by the Ontario Clean Water Agency. PGMN well 229, which has a record of monthly water levels, is also included. Water levels have also been collected twice from six of the eleven local wells in July and September of 2007. Table 4-6 (on the following page) contains the coordinate locations, screen midpoint elevations, time steps and water levels for the transient wells.

Table 4-6: Transient Modelling Observation Targets

Well Name	X,Y Coordinates*	Screen Elevation (masl)	Model Time days /Month	Water Elevation (masl)
Rollins	303181, 4930412	136.82	31 / January	163.66
			59 / February	163.91
			90 / March	163.07
			120 / April	162.72
			151 / May	163.41
			181 / June	162.89
			212 / July	159.01
			243 / August	160.42
			273 / September	159.16
			304 / October	159.58
			334 / November	161.55
			365 / December	162.76
Whytock	302980, 4930976	119.10	31 / January	147.71
			59 / February	147.90
			90 / March	142.90
			120 / April	150.77
			151 / May	148.43
			181 / June	146.28
			212 / July	139.64
			243 / August	142.99
			273 / September	140.80
			304 / October	144.80
			334 / November	146.13
			365 / December	148.36
PGMN 229	297896, 4930485	184.86	31 / January	224.36
			59 / February	223.82
			90 / March	224.15
			120 / April	224.96
			151 / May	224.33
			181 / June	224.02
			212 / July	223.65
			243 / August	223.34
			273 / September	223.12
			304 / October	223.51
			334 / November	224.17
			365 / December	224.44
5	302978, 4931435	154.36	212 / July	169.58
			273 / September	168.32
6	303111, 4931472	154.09	212 / July	167.92
			273 / September	166.7
7	302459, 4930674	149.93	212 / July	170.31
			273 / September	165.41
8	302587, 4930146	147.85	212 / July	162.7
			273 / September	158.9
9	302959, 4930239	119.47	212 / July	164.01
			273 / September	160.07
11	303285, 4930293	135.78	212 / July	158.16
			273 / September	151.21

* UTM NAD83, Zone 18N

5 Uncertainty in the Model

A numerical groundwater flow model is a representation of hydrogeological and physical conditions based on a set of assumptions and available data used to construct the hydrogeological conceptual model. Therefore, a model must be recognized as having limitations and uncertainty. According to Rule 36, uncertainty of the modeling results must be classified as high or low.

The main limitations contributing to uncertainty are listed here:

- Calibration targets for the regional model. The majority of the well targets used for regional calibration are MOE wells, which were installed between the 1940s and 1980s. Observation head data from these wells is suspect as there is no consistency of obtaining the measurements (i.e. no quality control) and the measurements were not obtained within a reasonably small time period.
- The 11 monitoring wells located near the municipal pumping wells, and which were resurveyed, are adequate for calibrating the Madoc area of the model; however, this was completed very recently. Currently, only two time periods of sampling are available for six of these wells.
- The model parameters porosity and storativity, which are required for the transient model, are estimated; only a single value is applied for the entire model domain. More data on individual units should be incorporated into the model if possible.
- Hydraulic conductivities used in the model are estimates based on previous modelling studies, the parameter estimation software and judgement based on the physical and hydrogeological system. MODFLOW is a finite difference equivalent porous medium simulator and does not easily model fracture systems. It is possible to represent fractures using hydraulic conductivity zones, but they must be designated individually. In the Madoc region, although it is believed that connective fractures to the wells exist, these pathways are not explicitly known. The current model does not include any specific fractures. Any new data concerning these parameters should be incorporated into the model.
- Boundary conditions such as river stage for Deer Creek and Madoc Creek, and lake levels for Moira Lake and Jarvis Lake were not available for the transient modelling. Along with changes in recharge, it is expected that lake levels and streams would also be affected by seasonal or drought conditions. These levels should be included in the simulation
- The sensitivity analysis conducted on the model was minimal. There is insufficient data available to conduct a validation of the model. To validate a groundwater flow model, there should be a second complete and reliable dataset that is measured at a different stress period (i.e. season) from the initial dataset used to calibrate.

Uncertainty in a numerical flow model is generally reflective of the quality of the data used to develop the model, the amount of data available, the complexity of the physical system and the complexity of the numerical model. There is a great deal of regional data available; however, it is not of the highest quality. The data available for Madoc is of much higher quality; therefore, in this region of the numerical model, there is greater certainty about the simulation results. Results for the rest of the domain are not as certain. The model indicates that the projected pumping rates at Rollins and Whytock would be sustainable. However, for the 10-year drought conditions, the certainty of the model results is lower. Under these conditions, it is likely that not only would the amount of recharge be affected but the levels in the many creeks, ponds and lakes proximal to Madoc would also be reduced. At this time, the model does not include this information, due to the lack of availability of the data. Therefore, it would be prudent to recognize that although the simulations indicate that pumping at current and future demand would be sustainable, there is the possibility that one or both of the wells might run dry under lengthy drought conditions, especially considering that the Rollins well did run dry in the summer of 2007 (albeit under much higher pumping rates). Overall the uncertainty of model results in respect to the subwatershed stress calculations is considered to be high.

6 Analysis of Subwatershed Stress Level

6.1 Introduction

The decision criteria for Rule 35 to define the subwatershed stress levels in a Tier Two Water Budget are summarized in Table 1. The modeling scenarios that are required to determine the stress level are summarized in the table below

Table 6-1: Summary of Criteria for the Tier 2 Subwatershed Stress Assessment

	Required information	**Climate**	**Water demand**
Significant	% water demand	Average	Existing/Future
Moderate	% water demand	Average	Existing/Future
	Model output: Did municipal well go dry in the past?	NA	NA
	Model output: Did municipal well go dry during these scenarios?	2-year drought	Existing/Future
	Model output: Did municipal well go dry during these scenarios?	10-year drought	Existing/Future
Low	All information above	All	All

6.2 Stress Level Calculation

Part I.1 of the Technical Rules defines that the following rule is to be used to calculate the percent of water demand in relation to groundwater:

$$\%\,WaterDemand = \frac{Demand}{Supply - \mathrm{Re}serve} * 100\% \quad (1)$$

Where

Demand = Total groundwater extraction in watershed by pumping

Supply = Recharge + groundwater inflow-groundwater outflow (annual divided by 12 months)

Reserve = 10% of annual base flow

The water demand thresholds are defined as maximum monthly percentages. For the purpose of evaluating whether there is a significant stress level, the various components of the percentage water demand equation were simulated using the transient model. Each element used in equation (1) is discussed below.

Total Pumping:

The pump rates summing municipal and private groundwater extraction is summarized in Tables 6.2 and 6.3 for average and future conditions. To simulate 25 years planned pump rates, the current rates were increased by 18%.

It should also be noted that during all model runs, the industrial Conley-Shaft, TW6 and Pond2 went dry. The volume pumped by the wells in the water budget of the model output is, therefore, significantly lower than the sum of all pump rates. The dry cells for the industrial wells pumping large volumes show that the high volumes used in the model are likely unsustainable and the actual pumped rates are much lower. The rates used in the model are based on the permits to take water in absence of more accurate information. In addition, a significant percentage of the pumped water may consist of surface water, so that the amount of pumped groundwater is much lower. However, the total pump rates as shown below were considered to be more conservative than the lower water budget pump rates and were, therefore, used in the stress level calculation.

Table 6-2: Total Pumping by Well Category. Average Climate, Current Demand

	Municipal	Industrial	Agricultural	Domestic	Total
	m^3/d	m^3/d	m^3/d	m^3/d	m^3/d
Jan	681	1,134	104	74	1,993
Feb	624	1,134	104	74	1,935
Mar	787	1,134	104	74	2,099
Apr	611	1,194	104	74	1,983
May	649	1,194	104	74	2,021
Jun	546	1,194	104	74	1,918
Jul	493	1,470	104	74	2,141
Aug	562	1,470	104	74	2,210
Sept	572	1,470	104	74	2,219
Oct	361	1,194	104	74	1,733
Nov	540	1,194	104	74	1,911
Dec	564	1,134	104	74	1,876
Total Year	582	1,244	104	74	2,004

Table 6-3: Total Pumping by Well Category. Average Climate, Future Demand

	Municipal	Industrial	Agricultural	Domestic	Total
	m^3/d	m^3/d	m^3/d	m^3/d	m^3/d
Jan	804	1,134	104	74	2,116
Feb	736	1,134	104	74	2,048
Mar	928	1,134	104	74	2,240
Apr	721	1,194	104	74	2,093
May	766	1,194	104	74	2,138
Jun	645	1,194	104	74	2,017
Jul	582	1,470	104	74	2,229
Aug	663	1,470	104	74	2,311
Sept	675	1,470	104	74	2,322
Oct	426	1,194	104	74	1,798
Nov	637	1,194	104	74	2,009
Dec	666	1,134	104	74	1,978
Total Year	687	1,244	104	74	2,109

Recharge:

To remain consistent with the flow model, recharge was calculated as the area weighted mean of model recharge rates. The average monthly rates were extracted from the model water budget results. Then, the monthly average was calculated as the yearly total recharge divided by 12 resulting in an average value of 53,930m^3/d (89mm/yr). The 10 year drought scenario used 51% of this recharge rate.

Baseflow:

Baseflow information was extracted from the transient model run for average climate conditions and current and future demand. Baseflow was calculated as the net inflow into rivers and lakes by calculating the difference between river leakage, constant head and drain boundaries in and out of the system. The transient model provided an average of 62,286m^3/d for the current demand scenario and 62,181 m^3/d for the future demand scenario.

Groundwater Inflow/Outflow:

Groundwater inflow and outflow term can be ignored for this model, since all boundaries around the study area are either no flow boundaries (border of watershed) or river leakage (Tweed River on the east boundary).

6.3 Scenarios

6.3.1 Current climate, Current Water Demand

Under these conditions, referred to in the Rules as scenario A, the municipal wells are sustainable. A maximum percent water demand of 4.4% is reached from July to September. The yearly average is 4.0%. The small differences between the monthly values can be explained by the constraint in the methodology to use monthly average recharge values rather than the actual monthly values. This procedure attenuates the stress level in months with low recharge.

6.3.2 Current Climate, Future Water Demand

Under these conditions, referred to in the Rules as scenario B, the municipal wells can be pumped sustainably at the projected rate. A maximum percent water demand of 4.6% is reached from July to September and the yearly average is 4.2%, slightly higher than in scenario A.

6.3.3 10 Year Drought, Current Water Demand

This scenario, referred to in the Rules as scenario G, retains the current pumping rates (Table 4-5). The recharge schedule has been modified to simulate drought conditions as observed over a 10-year time period, given in Table 4-4.

The Rollins and Whytock wells both appear to be sustainable under the 10-year drought and current pumping conditions. However, the model results show that a significant portion of the pumped water originates from the Deer Creek.

6.3.4 10 Year Drought, Future Water Demand

This scenario, referred to in the Rules as scenario H, combines the higher pumping rates projected for the municipal wells with the estimated 10-year drought reductions in recharge.

Similar to the results of Scenario 2, the Rollins and Whytock wells both appear to be sustainable under the 10-year drought and 25-year projected pumping conditions. The model results show that the portion of water originating from Deer Creek increases under these conditions.

6.3.5 Two Year Drought Scenarios

The two year drought scenarios are referred to in the Rules as Scenarios D and E and investigate the stress level under a period of two years with no groundwater recharge. The MNR technical Bulletin on Water Budget and Water Quantity Risk Assessment states that: *"If the ten year drought scenario has been completed and neither of the scenarios G and H triggered a circumstance in Rule 35(2)(e), then the stress level is assigned as low according to Rule 35(3) and therefore the two year drought scenario does not need to be run. in MNR, 2009, the two year drought scenario is not required if the 10 year simulation reveals that the municipal wells do not go dry."* Since, for both 10 year drought scenarios, the municipal wells could be pumped sustainably, the 2 Year drought scenarios were not completed for this study.

6.4 Stress Level Results

6.4.1 Test for Significant Stress Level

A significant subwatershed stress level is reached if the maximum monthly water demand percentage in scenarios A and B is equal or greater to 50% and if the annual water demand exceeds 25%. As summarized in Table 6-4 the maximum monthly percentage water demand based on the flow model predictions is only 4.6% and the annual demand is 4.2%. The subwatershed does therefore not present a significant stress level.

6.4.2 Test for Moderate Stress Level

The predicted average yearly water demand percentages are less than 10% for scenarios A and B and the maximum monthly demand percentage is also smaller than 25%. However, circumstance 35 (e) can be considered to have occurred in 2007, when the Rollins well went dry during a hot and dry summer. Due to the warm weather, the pump rate was increased to an unsustainable rate in respect to the normal pump rate.

Circumstance 2 (f) is considered to be matched if the circumstances of rule 35 (e) incur during the modelled two and 10-year drought scenarios for the existing systems. The model runs under drought conditions for current and future pump rates did not lead to dry conditions at the municipal wells during the scenarios G and H. As discussed in section 6.3.5, the 2 year drought scenarios do not have to be completed in this case.

Rule 35(2)(e) states that a moderate water stress level is also reached if one of the investigated wells went dry or could not be pumped at its operational rate after January 1990. As mentioned in section 1.1, this was indeed the case for the Rollins well, which went dry in summer 2007. While the low recharge preceding the event may have contributed to the problem, we consider that the main origin was the very high pump rate of 833 m^3/d as opposed to the normal rate of 325 m^3/d and is also significantly higher than the projected 25 years future pump rate of 383 m^3/d for this well. The pump rate was increased to meet higher water demands due to an operational requirement of the water treatment system and to compensate temporarily for the Whytock well, which had been taken offline. It is therefore considered, that the incident was due to an operational issue and that therefore the conditions for Rule 35(2)(e) are not met.

Since none of the conditions for a significant or moderate water stress level were met, the resulting stress level of the subwatershed is low.

Table 6-4: Water Budget for Study Area, Average Climate, Current Conditions

	Recharge	Pumping	Baseflow	Water Demand
	m3/d	m3/d	m3/d	%
January	56,933	1,993	62,286	3.9
February	56,933	1,935	62,286	3.8
March	56,933	2,099	62,286	4.1
April	56,933	1,983	62,286	3.9
May	56,933	2,021	62,286	4.0
June	56,933	1,918	62,286	3.8
July	56,933	2,141	62,286	4.2
August	56,933	2,210	62,286	4.4
September	56,933	2,219	62,286	4.4
October	56,933	1,733	62,286	3.4
November	56,933	1,911	62,286	3.8
December	56,933	1,876	62,286	3.7
Average	56,933	2,003	62,286	4.0

Table 6-5: Water Budget for Study Area, Average Climate, Future Demand

Month	Recharge	Pumping	Baseflow	Water Demand
	m3/d	m3/d	m3/d	%
January	56,933	2,116	62,181	4.2
February	56,933	2,048	62,181	4.0
March	56,933	2,240	62,181	4.4
April	56,933	2,093	62,181	4.1
May	56,933	2,138	62,181	4.2
June	56,933	2,017	62,181	4.0
July	56,933	2,229	62,181	4.4
August	56,933	2,311	62,181	4.6
September	56,933	2,322	62,181	4.6
October	56,933	1,798	62,181	3.5
November	56,933	2,009	62,181	4.0
December	56,933	1,978	62,181	3.9
Average	56,933	2,108	62,181	4.2

Table 6-6: Assessment of Circumstances of Rule 35 in Subwatershed of Madoc 1+2 and Tweed River

Stress	#	Condition	Criteria Met
Significant	(a)	During scenario A or B in Table 1, the annual percent water demand for groundwater for the subwatershed would be greater than or equal to 25%.	No
	(b)	Where there is a planned type I, II or III system proposed to be located within the subwatershed, during scenario C in Table 1, the annual percent water demand for groundwater for the subwatershed would be greater than or equal to 25%.	N/A
	(c)	During scenario A or B in Table 1, the maximum monthly percent water demand for groundwater for the subwatershed would be greater than or equal to 50%.	No
	(d)	Where there is a planned type I, II or III system proposed to be located within the subwatershed, during scenario C in Table 1, the maximum monthly percent water demand for groundwater for the subwatershed would be greater than or equal to 50%.	N/A
Moderate	(a)	During scenario A or B in Table 1, the annual percent water demand for groundwater for the subwatershed would be less than 25% but greater than 10%.	No
	(b)	Where there is a planned type I, II or III system proposed to be located within the subwatershed, during scenario C in Table 1, the annual percent water demand for groundwater for the subwatershed would be less than 25% but greater than 10%.	N/A
	(c)	During scenario A or B in Table 1, the maximum monthly percent water demand for groundwater for the subwatershed would be less than 50% but greater than 25%.	No

	(d)	Where there is a planned type I, II or III system proposed to be located within the subwatershed, during scenario C in Table 1, the maximum monthly percent water demand for groundwater for the subwatershed would be less than 50% but greater than 25%.	N/A
	(e)	At any time after January 1, 1990, in relation to a type I, II or III system within the subwatershed, either of the following circumstances occurred: (i) the groundwater level in the vicinity of the well was not at a level sufficient for the normal operation of the well; or (ii) the operation of a well pump was terminated because of an insufficient quantity of water being supplied to the well.	No
	(f)	In relation to a type I, II or III system within the subwatershed, either of the circumstances described in clause (e) would occur: (i) during either or both of scenarios D and E*; and (ii) during either or both of scenarios G and H.	No
	(g)	In relation to a planned type I, II or III system proposed to be located within the subwatershed, either of the circumstances described in clause (e) would occur: (i) during any or all of scenarios D, E and F; and (ii) during any or all of scenarios G, H and I.	N/A
	(h)	All of the following are true: (i) the result of one or more annual percent water demand calculations made in accordance with sub-clause (a) or (b) of sub-rule (2) is between 8% and 10%, inclusive; (ii) the uncertainty associated with the percent demand calculations required by this rule, when evaluated to be high or low considering the factors set out in rule 36, is high; (iii) a sensitivity analysis of the data used to prepare the Tier 2 Water Budget suggests that the stress level for the subwatershed could be moderate.	No
	(i)	All of the following are true: (i) the result of one or more maximum monthly percent water demand calculations made in accordance with clause (c) or (d) of sub-rule (2) is between 23% and 25%, inclusive; (ii) the uncertainty associated with the percent demand calculations required by this rule, when evaluated to be high or low considering the factors set out in rule 36, is high; (iii) a sensitivity analysis of the data used to prepare the Tier 2 Water Budget suggests that the stress level for the subwatershed could be moderate.	No
Low		Neither a stress level of Significant nor Moderate was assigned in the circumstances listed above.	Yes

* according to the MNR technical Bulletin on Water Budget and Water Quantity Risk Assessment, the 2 year drought scenarios do not need to be completed if the 10 year drought scenario did not indicate problems meeting water demands at the system.

7 Summary and Recommendations

7.1 Summary

Schlumberger Water Services has built a steady state and a transient model for Quinte, to accommodate an area comprising several subwatersheds in the Quinte region. The study involved building upon a previous model constructed by Dillon Consulting (2007), and incorporating new field information that had become available since the time of the 2007 study. These models were used to assess % water demand and for additional assessment.

The main conclusions of the study are:

1. The steady state model is adequately calibrated for the Village of Madoc. The regional model has been developed using MOE water well records. The steady state statistical calibration of the regional model is satisfactory. Improvement of the calibration would require additional high quality data consisting in recent water level measurement from surveyed wells
2. Data for the regional model is minimal. Uncertainty is high especially in the northeastern and northwestern regions of the model
3. The numerical model uses an equivalent porous medium approach. Hence, specific fractures are not incorporated into the current model. The subsurface aquifer is composed of a Precambrian fractured rock, and therefore, greater transmissivity around the wellfield may exist than is currently modelled. However, the results show that both current pumping and future demand pumping should be sustainable under average climate conditions and more than likely under moderate drought conditions.
4. With respect to the subwatershed stress level a level of low was determined.

7.2 Recommendations

Further work should be completed to improve the model regionally. Specifically, a greater understanding of the porosity and storage in different hydrogeologic units should be incorporated into the model. Hydraulic conductivity zones used in the model should be reassessed, as more information about the fracture network in the vicinity of the wellfield is gathered. Where possible, more information regarding the transmissivity of the units near the wellfield should also be gathered.

A verification of the calibration targets should be conducted. This includes upgrading the regional calibration target data, as well as verifying the water level logger data used to measure heads in the Whytock and Rollins pumping wells.

A validation simulation should be completed. To do this, a second reliable regional dataset is required, for example from a pumping test. Higher quality data should be acquired for regions further away from the Village of Madoc, to ensure that the entire model domain is adequately represented.

The model indicates that significant portions of the groundwater pumped by the municipal wells may originate from nearby surface water features. Scenario analysis and field data collection is also recommended to investigate the effects of changes in surface water levels associated with the municipal pumping wells. Specifically, more data on the water stages of Deer Creek, Madoc Creek and Moira Lake would be a valuable addition to the current model.

A sensitivity analysis should be completed according to ASTM guidelines. In addition, due to the heterogeneities known to exist within the flow system, a sensitivity analysis examining these effects in the model is also recommended.

8 References

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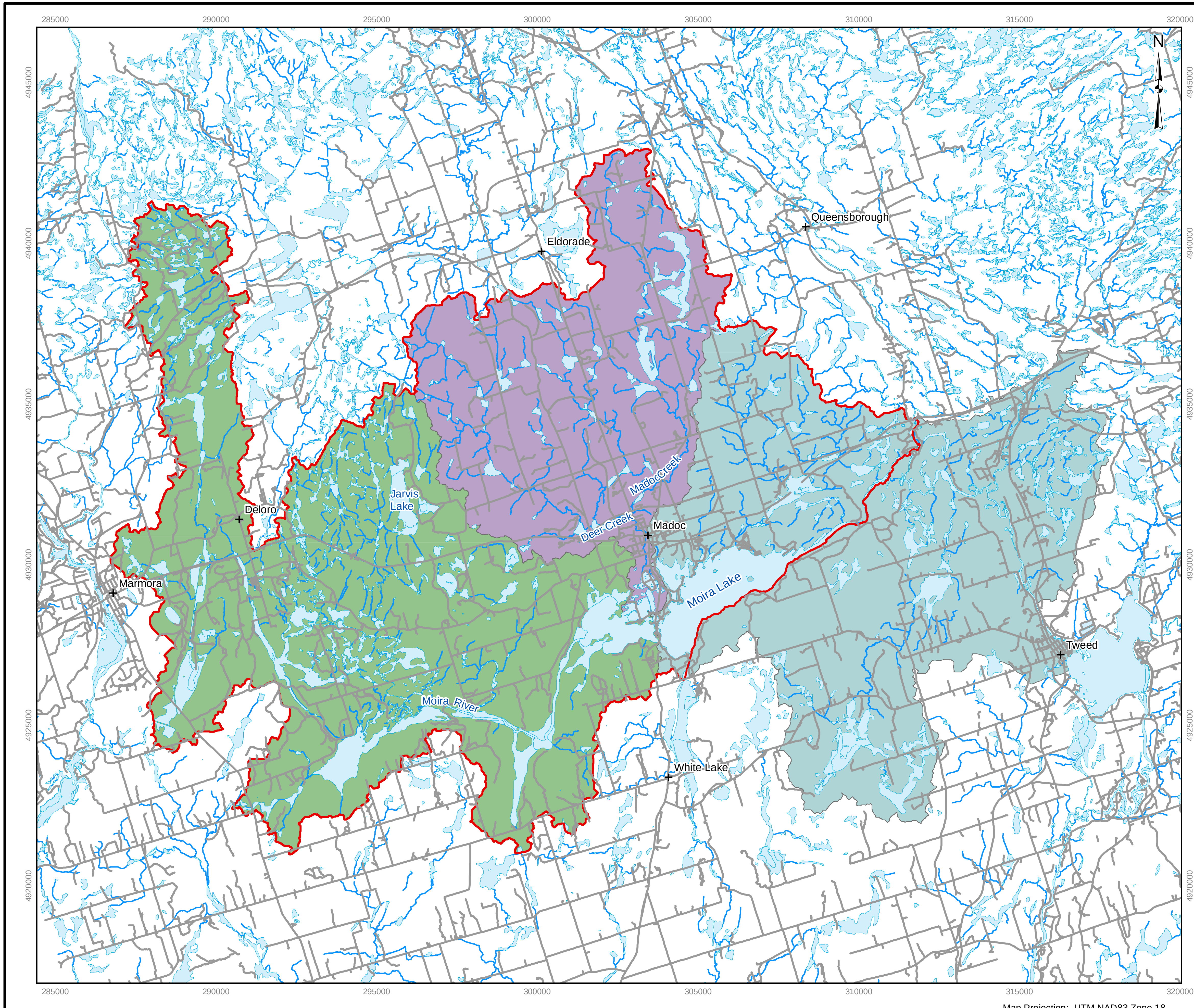
Schlumberger Water Services (SWS), 2008. Visual MODFLOW 2008.1 3D-Builder User's Manual. Schlumberger Water Services, Waterloo, Ontario, Canada



Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

- + Towns
- Roads
- Rivers/Streams
- Lakes
- Study Area

Subwatersheds

- Madoc 1
- Madoc 2
- Tweed

1:120,000

0 0.5 1 2 3 4
Kilometers

Note - Map must be printed at paper size 11 X 17 for the representative fraction to be correct

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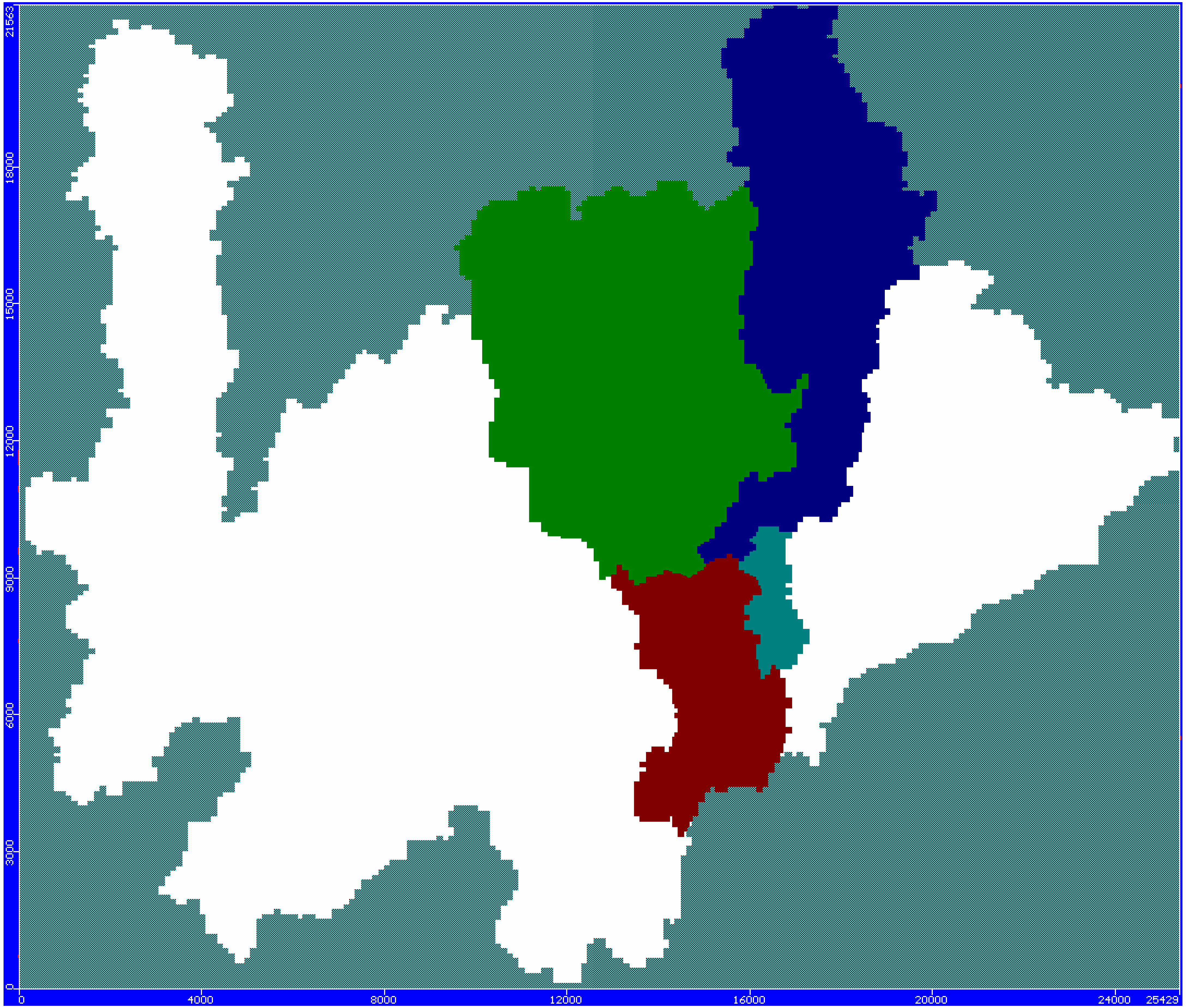
Figure 1: Study Area



Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

- Zone Budget – 107
- Zone Budget – 108
- Zone Budget – 158
- Zone Budget – 157

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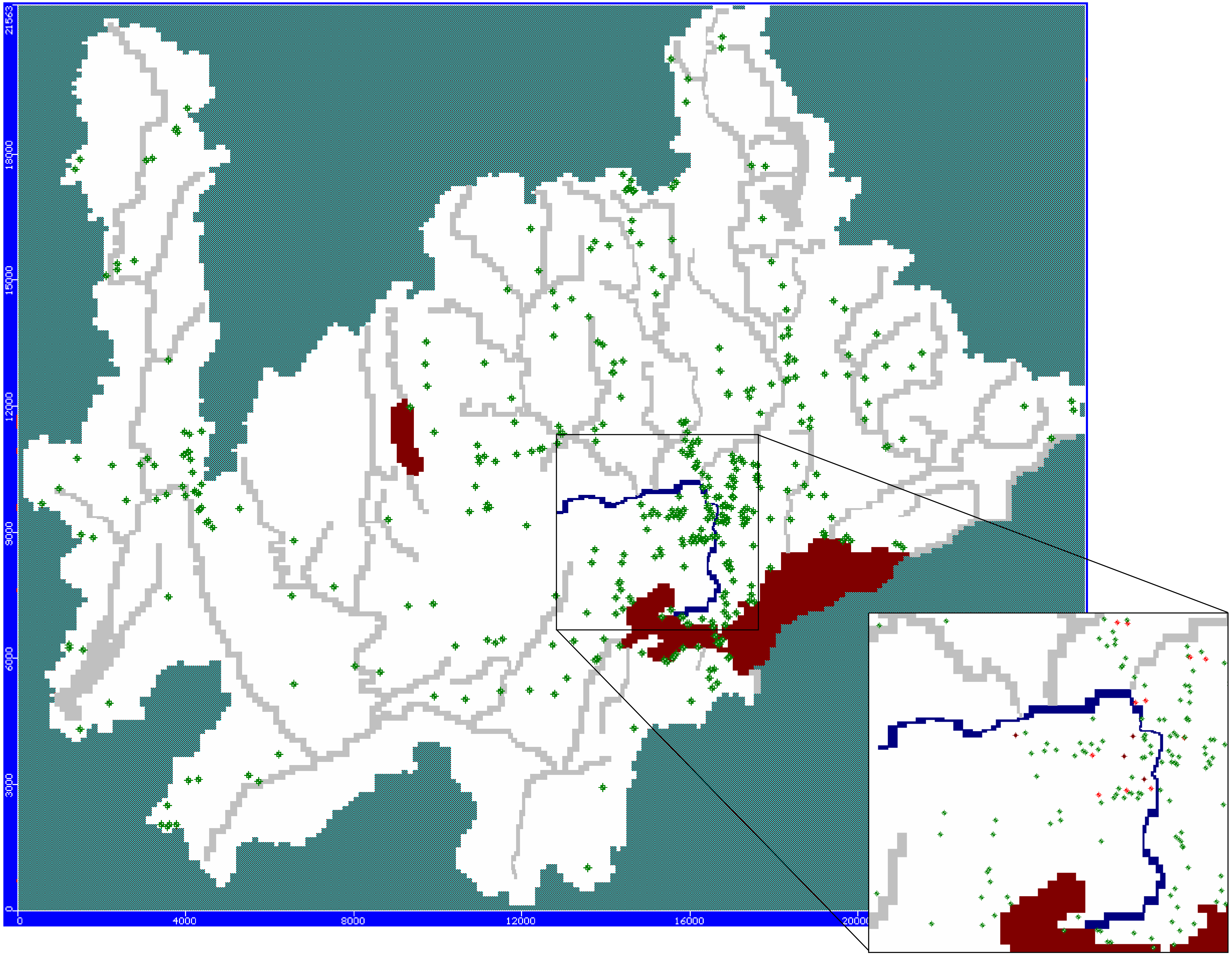
Figure 10: Zone Budget Subwatershed Regions

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

- Pumping Wells
- MOE Water Well
- Monitory Wells resurveyed by Quinte CA
- River Boundary
- Constant Head Boundary
- Drain Boundary

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Figure 11: Observation Head Targets

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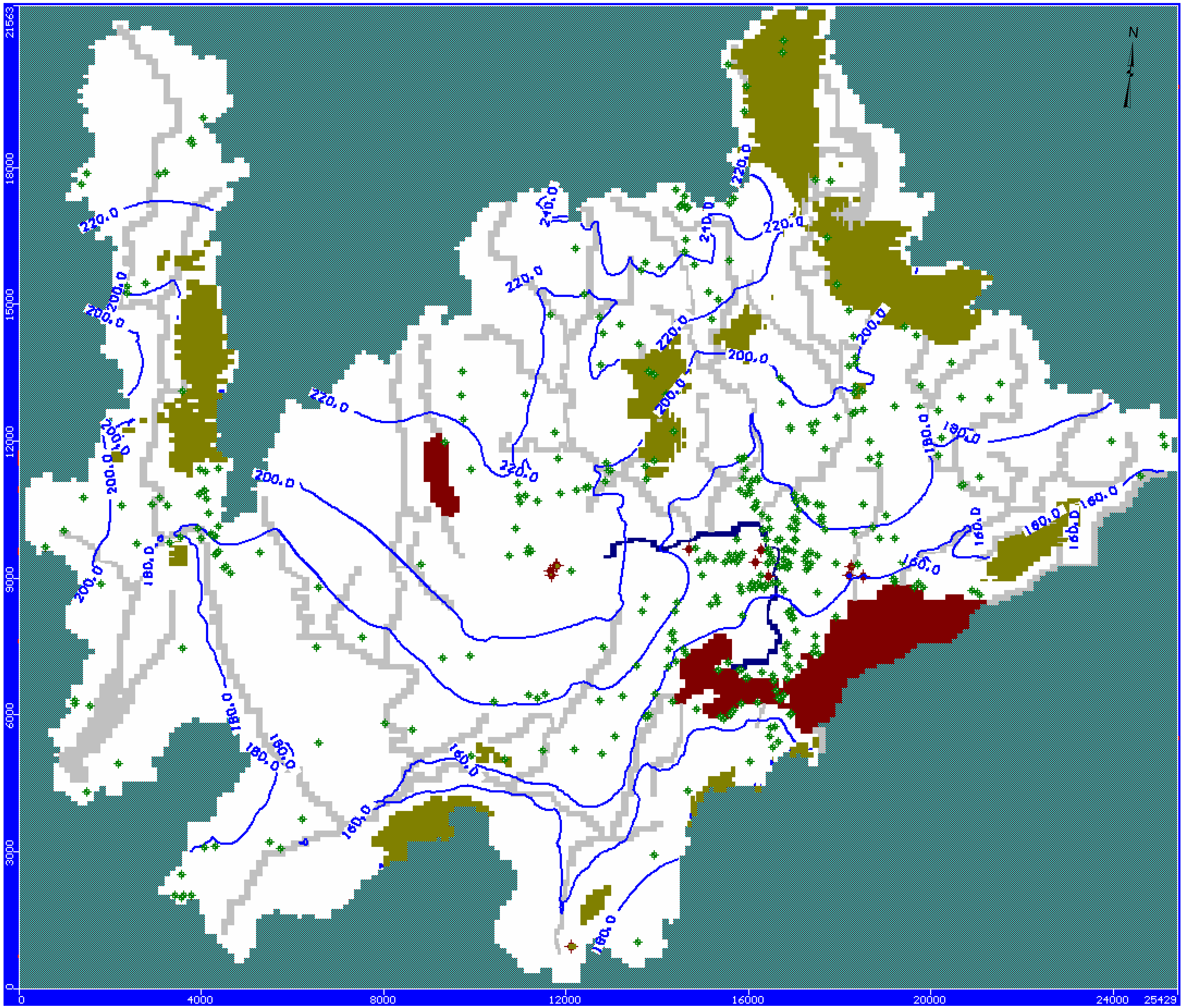

Legend

- Groundwater Equipotentials (m)
- Pumping Wells
- Observation Wells
- River Boundary
- Constant Head Boundary
- Drain Boundary
- Dry Cell

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Figure 12: Groundwater flow in Numerical Model

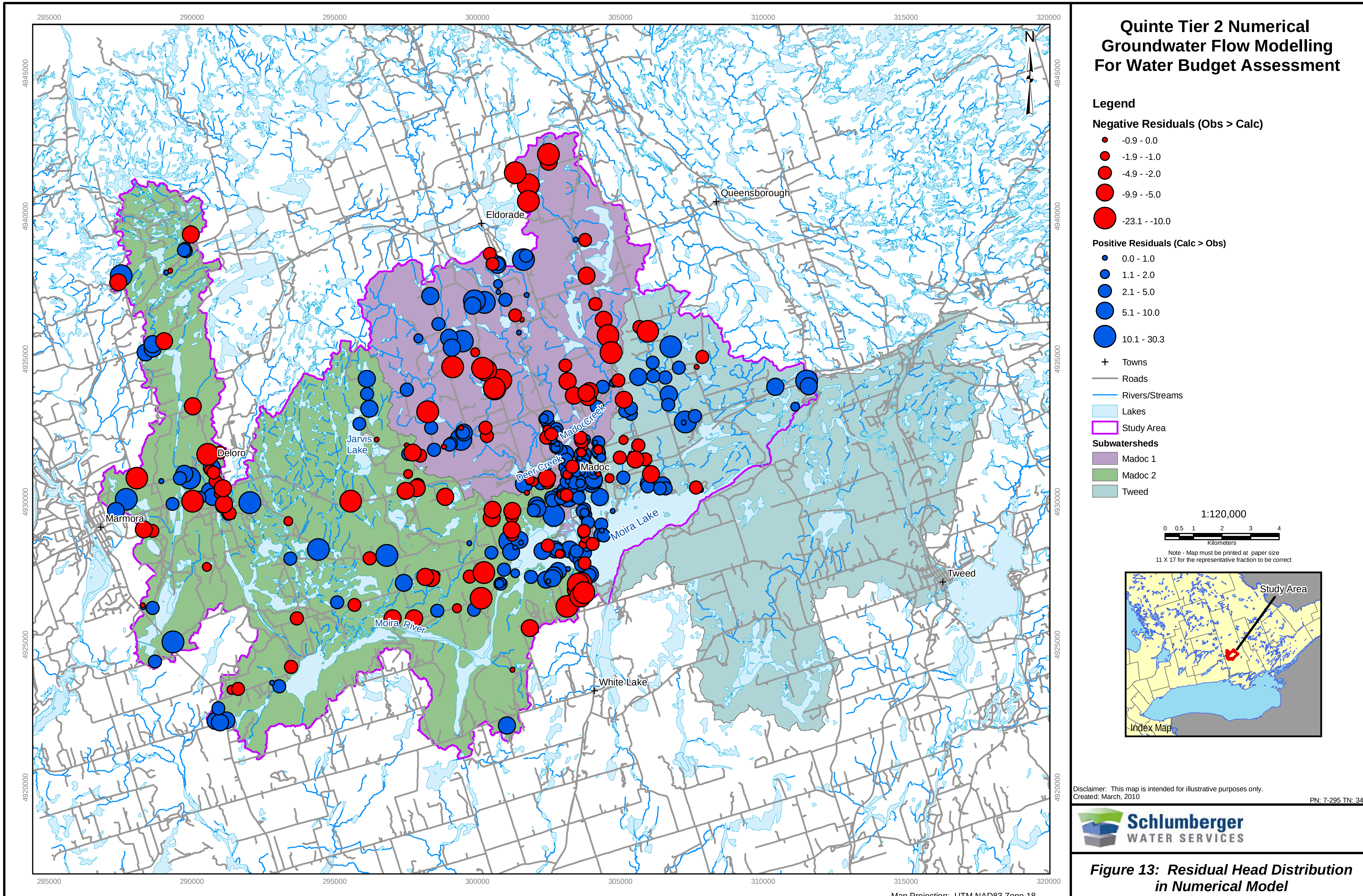
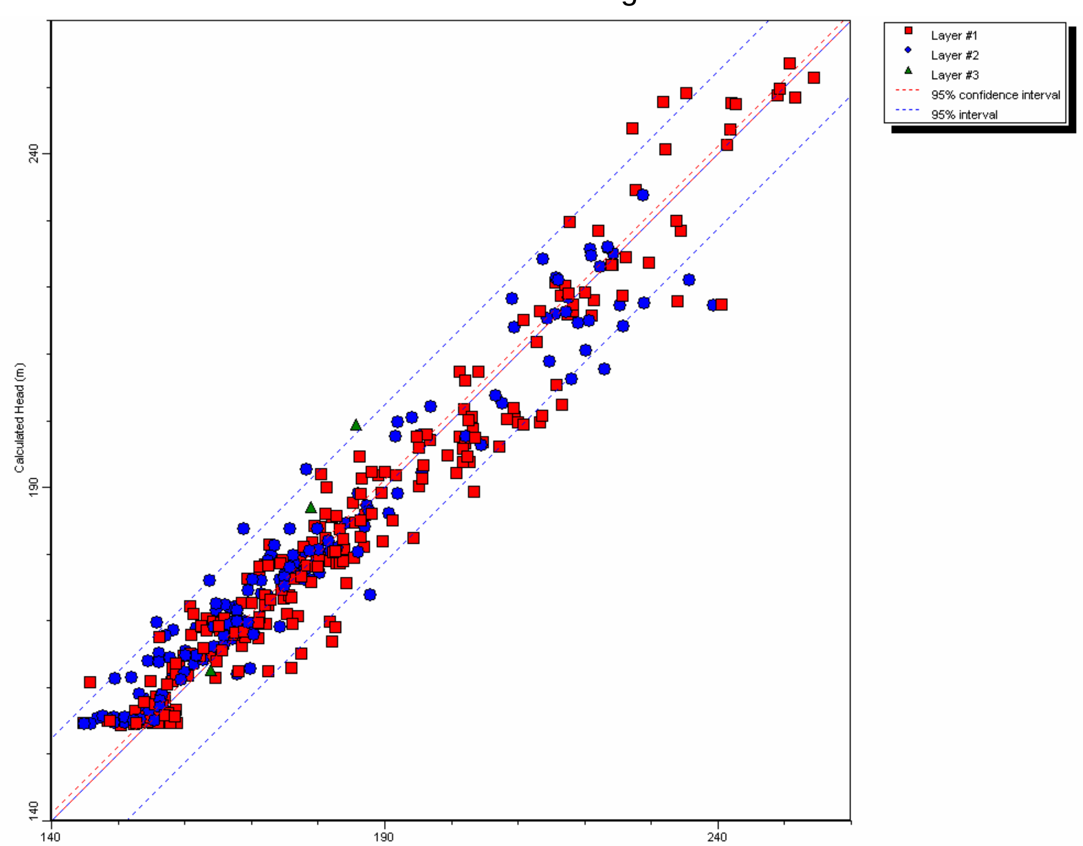


Figure 13: Residual Head Distribution in Numerical Model

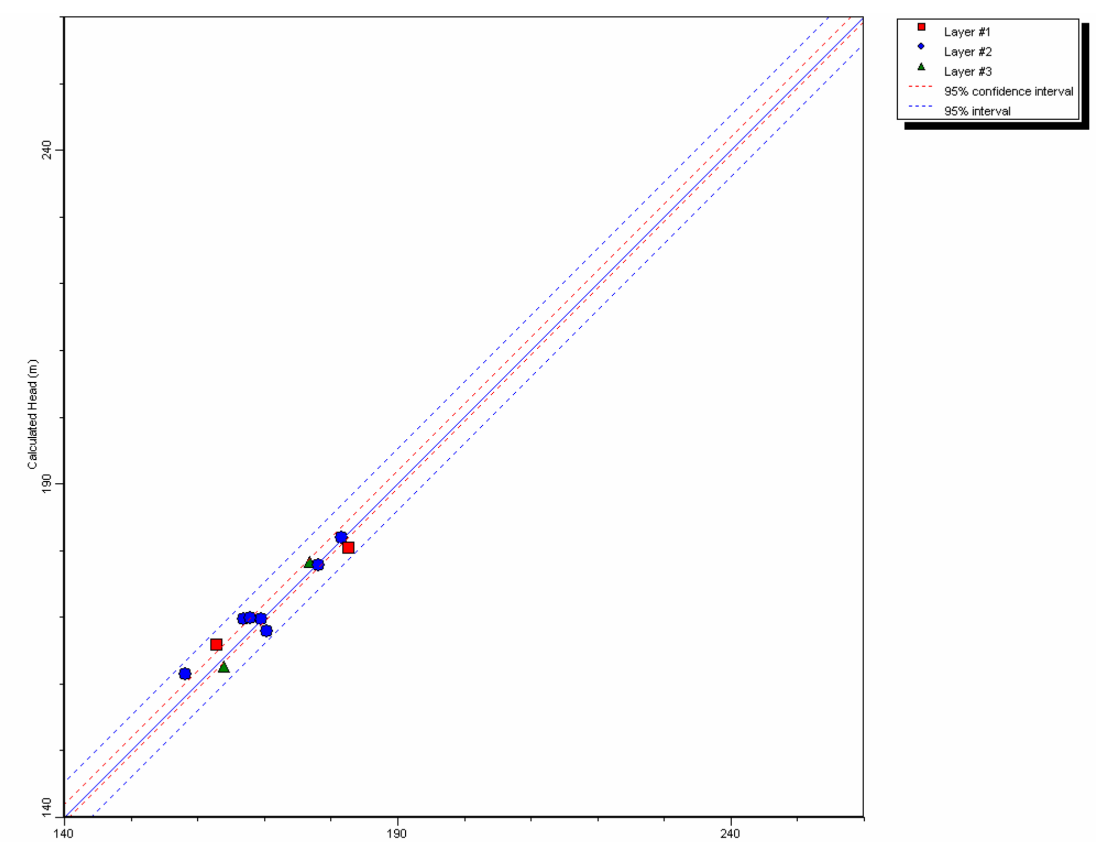
A. Observed vs. Calculated Heads Regional



Max. Residual: -23.057 (m) at 2909923/1
Min. Residual: 0.007 (m) at 2905156/1
Residual Mean : 0.635 (m)
Abs. Residual Mean : 4.593 (m)

Num. of Data Points : 383
Standard Error of the Estimate : 0.307 (m)
Root Mean Squared : 6.041 (m)
Normalized RMS : 5.512 (%)
Correlation Coefficient : 0.971

B. Observed vs. Calculated Heads Local



Max. Residual: 3.28 (m) at 11/1
Min. Residual: 0.104 (m) at 5/1
Residual Mean : 0.648 (m)
Abs. Residual Mean : 1.777 (m)

Num. of Data Points : 11
Standard Error of the Estimate : 0.627 (m)
Root Mean Squared : 2.086 (m)
Normalized RMS : 8.553 (%)
Correlation Coefficient : 0.969

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

- Layer #1
- Layer #2
- Layer #3
- 95% confidence interval
- 95% interval

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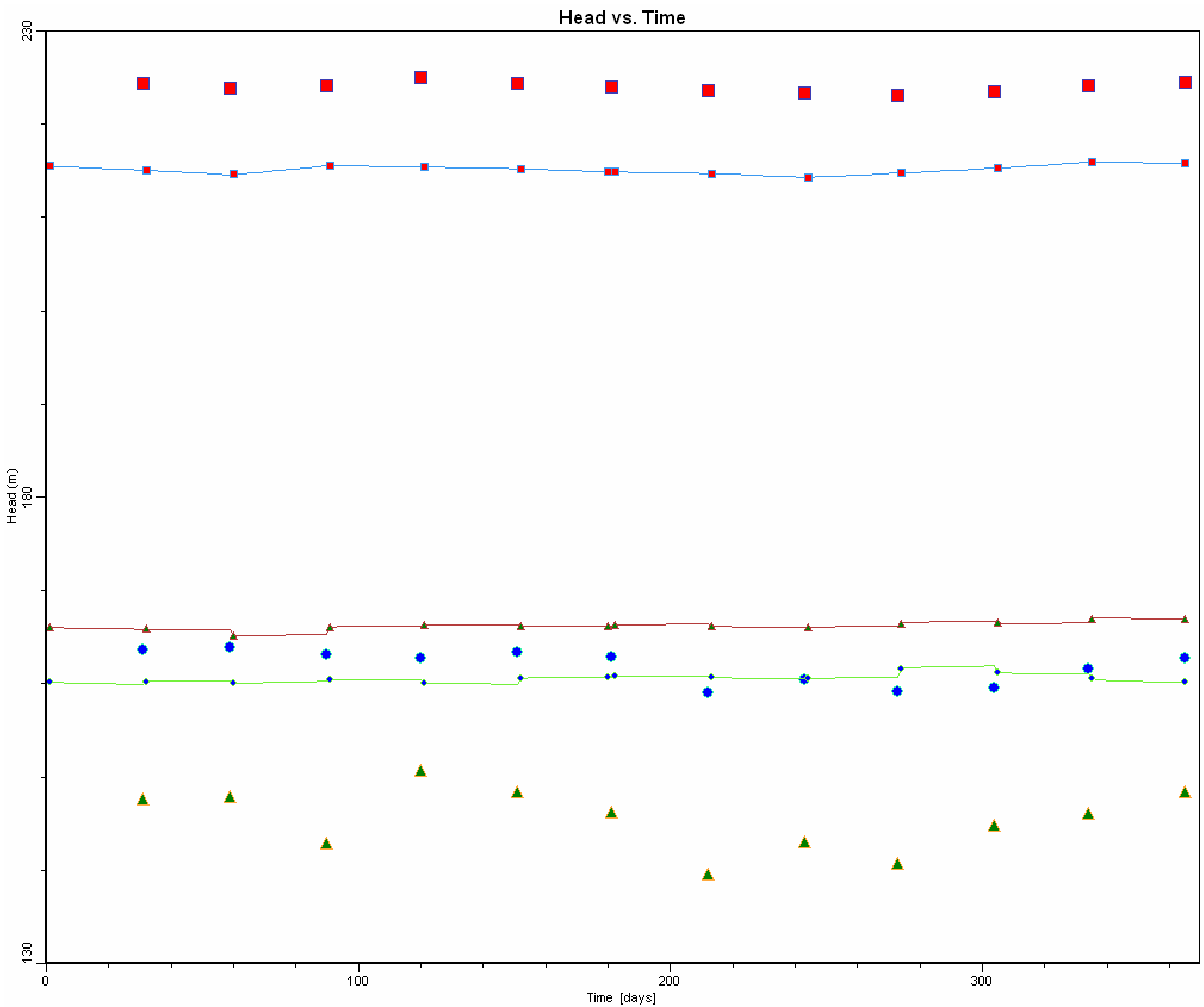
Figure 14: Regional and Local Model Calculated Heads vs. Observed Heads

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

PGMN229_OBS/1 (Observed)
PGMN229_OBS/1 Interpolated
ROLLINS_OBS/1 (Observed)
ROLLINS_OBS/1 Interpolated
WHYTOCK_OBS/1 (Observed)
WHYTOCK_OBS/1 Interpolated

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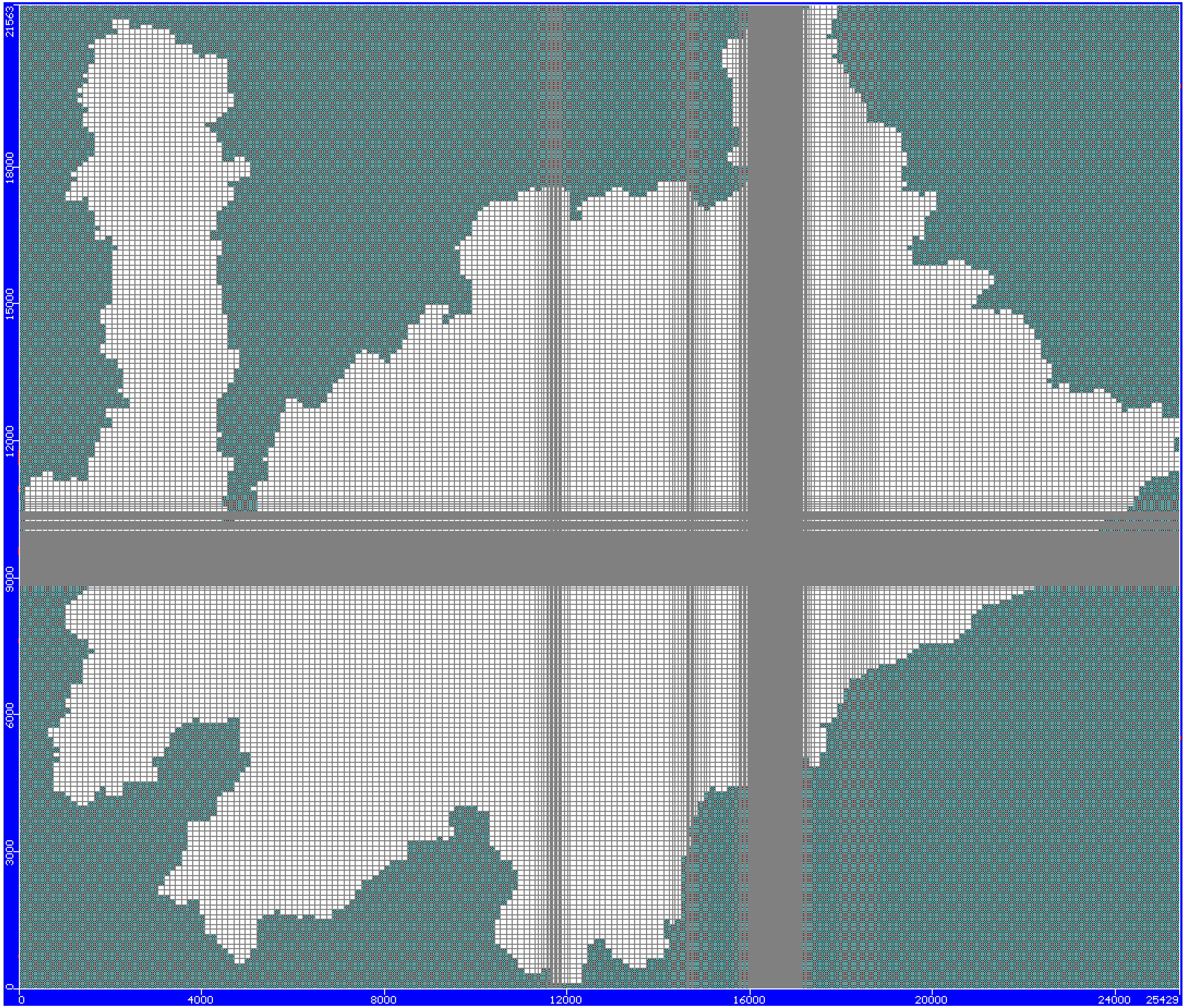
Figure 15: Transient Model Scenario 1 Heads vs. Time

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

- Inactive Cells
- Active Cells

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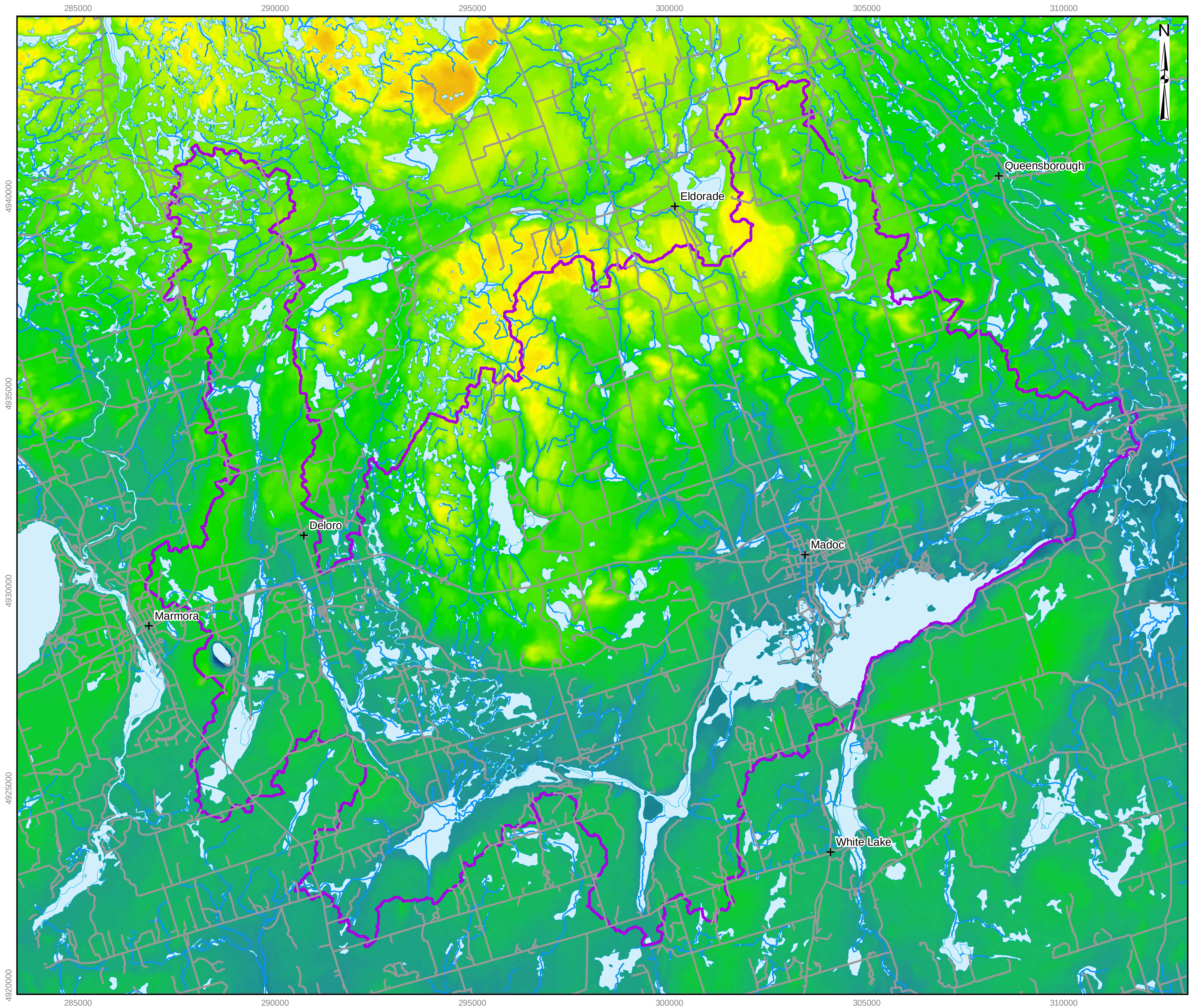
Figure 2: Numerical Flow Model Grid

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

Ground Surface Elevation (masl)

- High : 361
- Low : 118
- Towns
- Roads
- Study Area
- Rivers/Streams
- Lakes

1:100,000

0 0.5 1 2 3 4
Kilometers

Note - Map must be printed at paper size 11 X 17 for the representative fraction to be correct

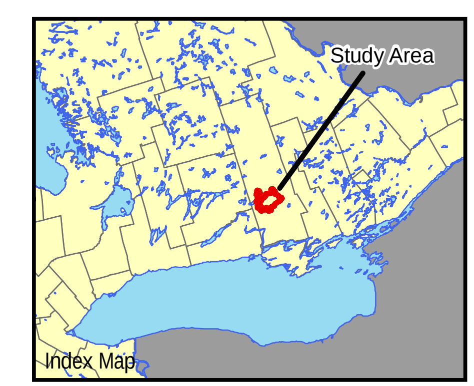


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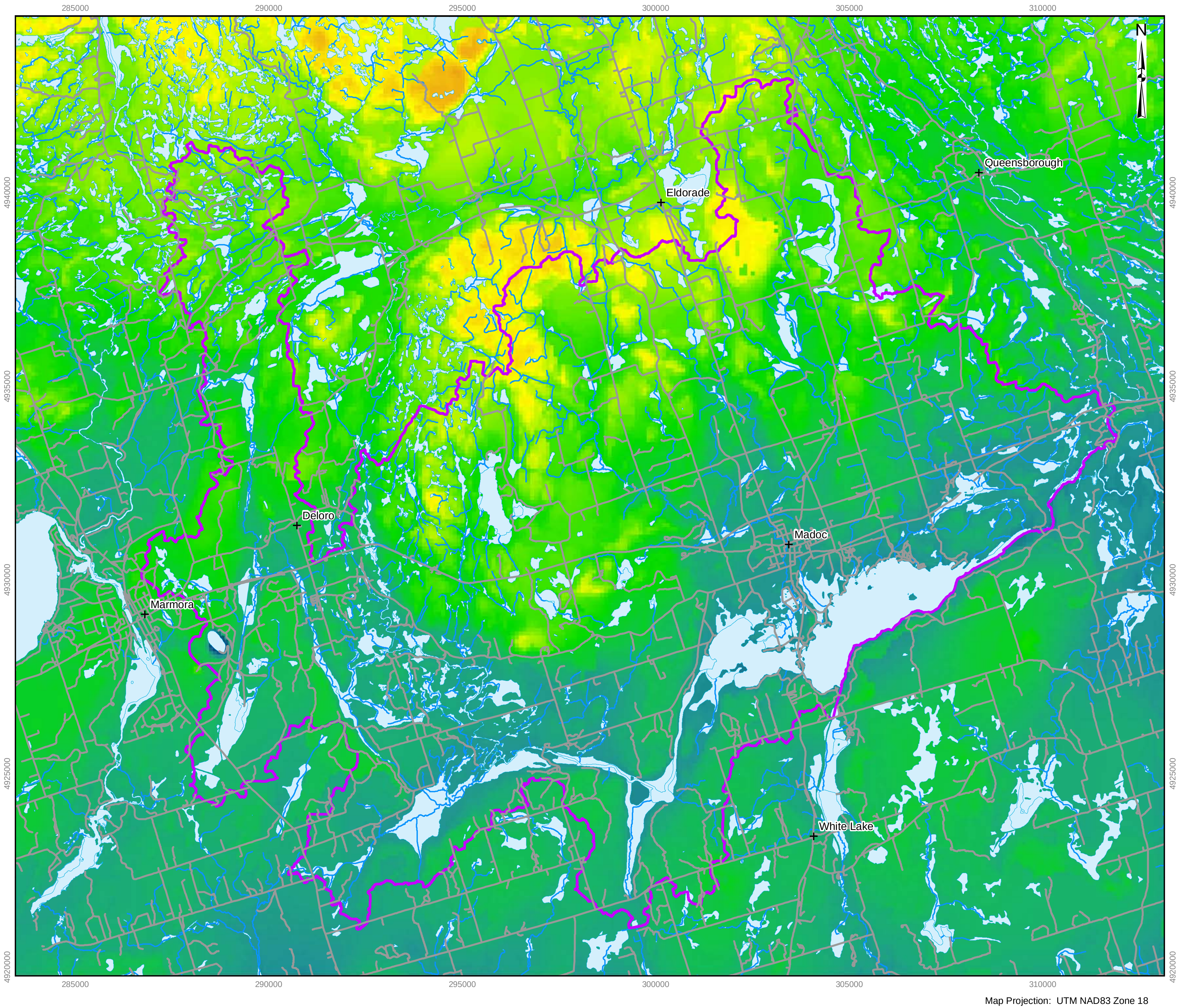
Figure 3: Ground Surface Digital Elevation Model



Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

Bedrock Elevation (masl)

High : 361

Low : 114

+ Towns

Roads

Study Area

Rivers/Streams

Lakes

1:100,000

0 0.5 1 2 3 4

Kilometers

Note - Map must be printed at paper size 11 X 17 for the representative fraction to be correct

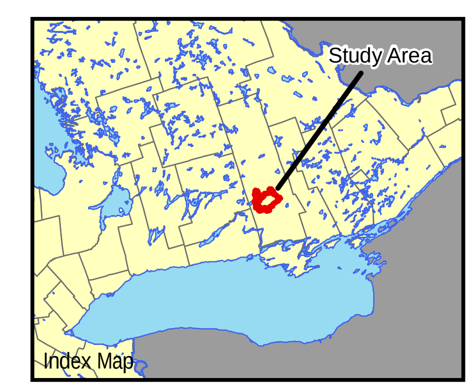


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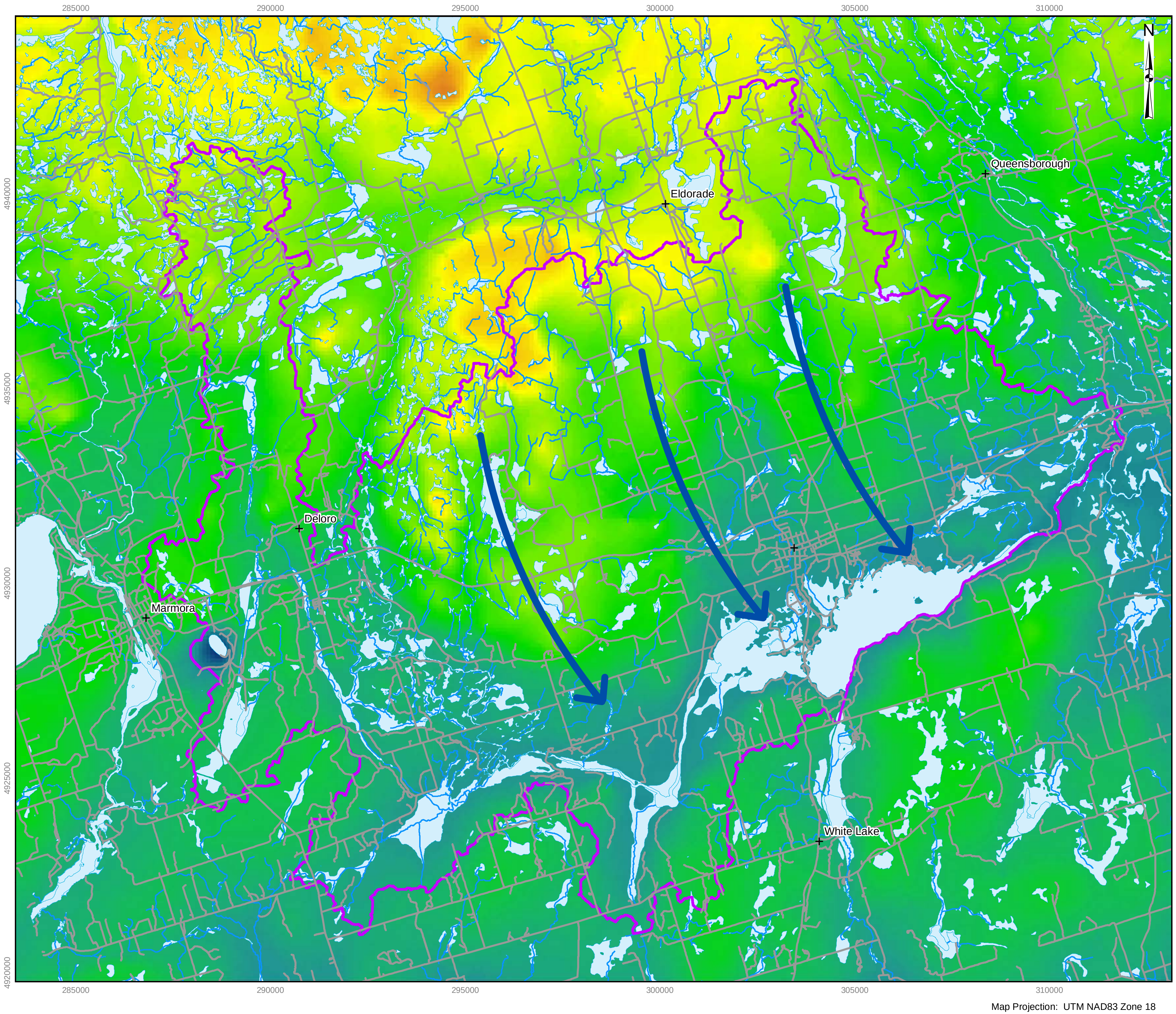
Figure 4: Bedrock Surface Elevation



Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

Water Table (masl)

High : 332

Low : 118

Towns

Roads

Study Area

Rivers/Streams

Lakes

Groundwater Flow Direction

1:100,000

0 0.5 1 2 3 4

Kilometers

Note - Map must be printed at paper size 11 X 17 for the representative fraction to be correct

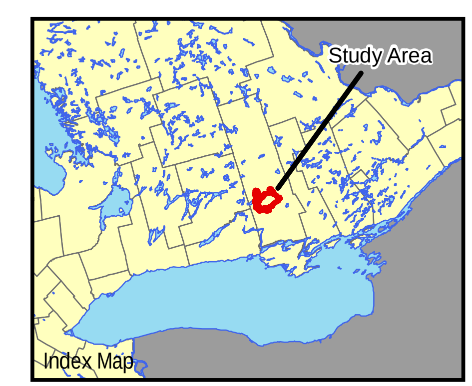


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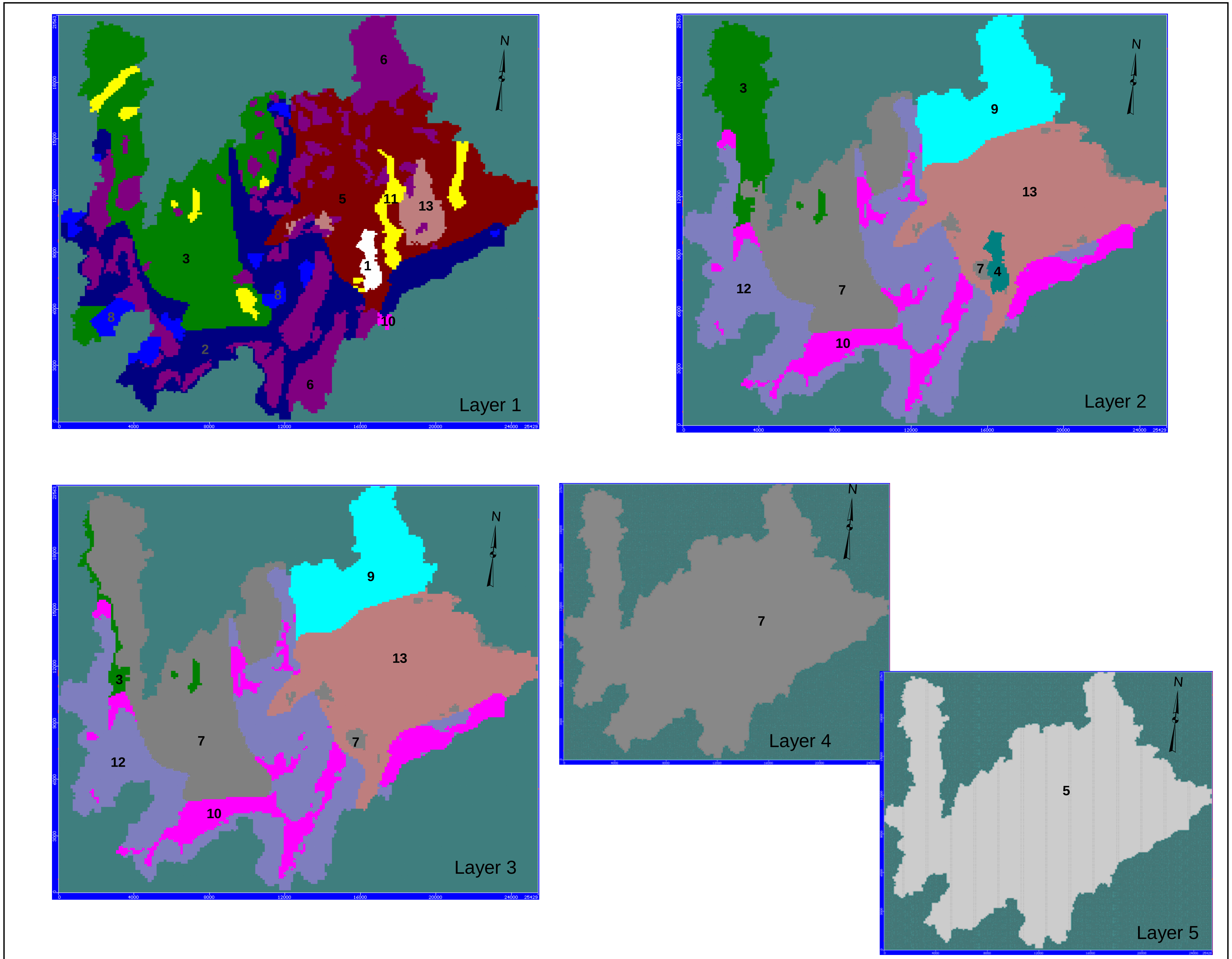
Figure 5: Regional Groundwater Flow

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Conductivity Zones Kx (m/s):

6.0×10^{-5}	Zone 1
2.3×10^{-5}	Zone 2
2.8×10^{-5}	Zone 3
3.0×10^{-5}	Zone 4
4.1×10^{-6}	Zone 5
4.0×10^{-7}	Zone 6
2.5×10^{-6}	Zone 7
1.3×10^{-7}	Zone 8
3.0×10^{-8}	Zone 9
8.8×10^{-6}	Zone 10
1.9×10^{-6}	Zone 11
2.2×10^{-6}	Zone 12
1.3×10^{-6}	Zone 13
2.0×10^{-7}	Zone 14

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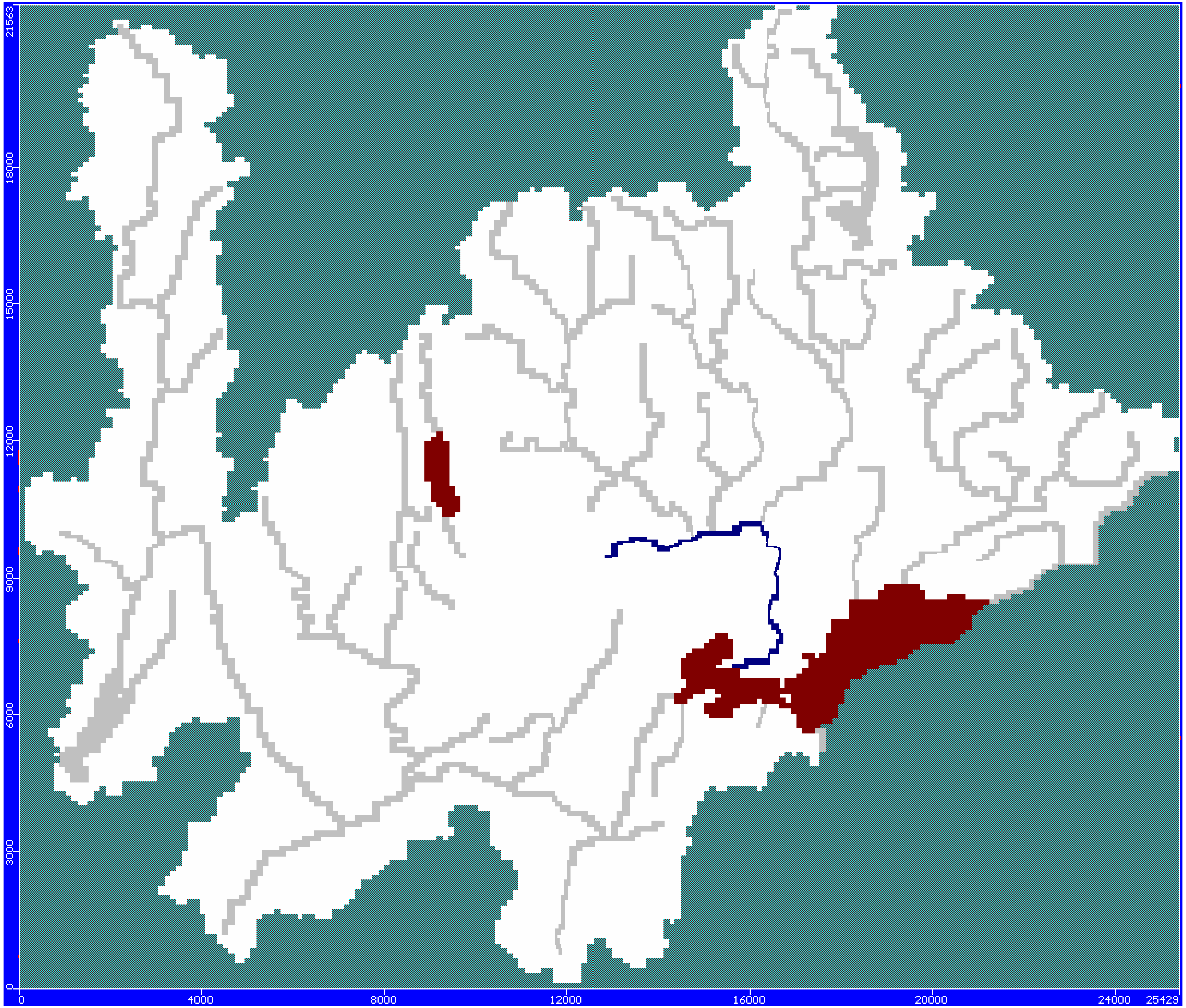
Figure 6 : Hydraulic Conductivity Zones



Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment

Legend

River Boundary

Constant Head Boundary

Drain Boundary

Date: January, 2010

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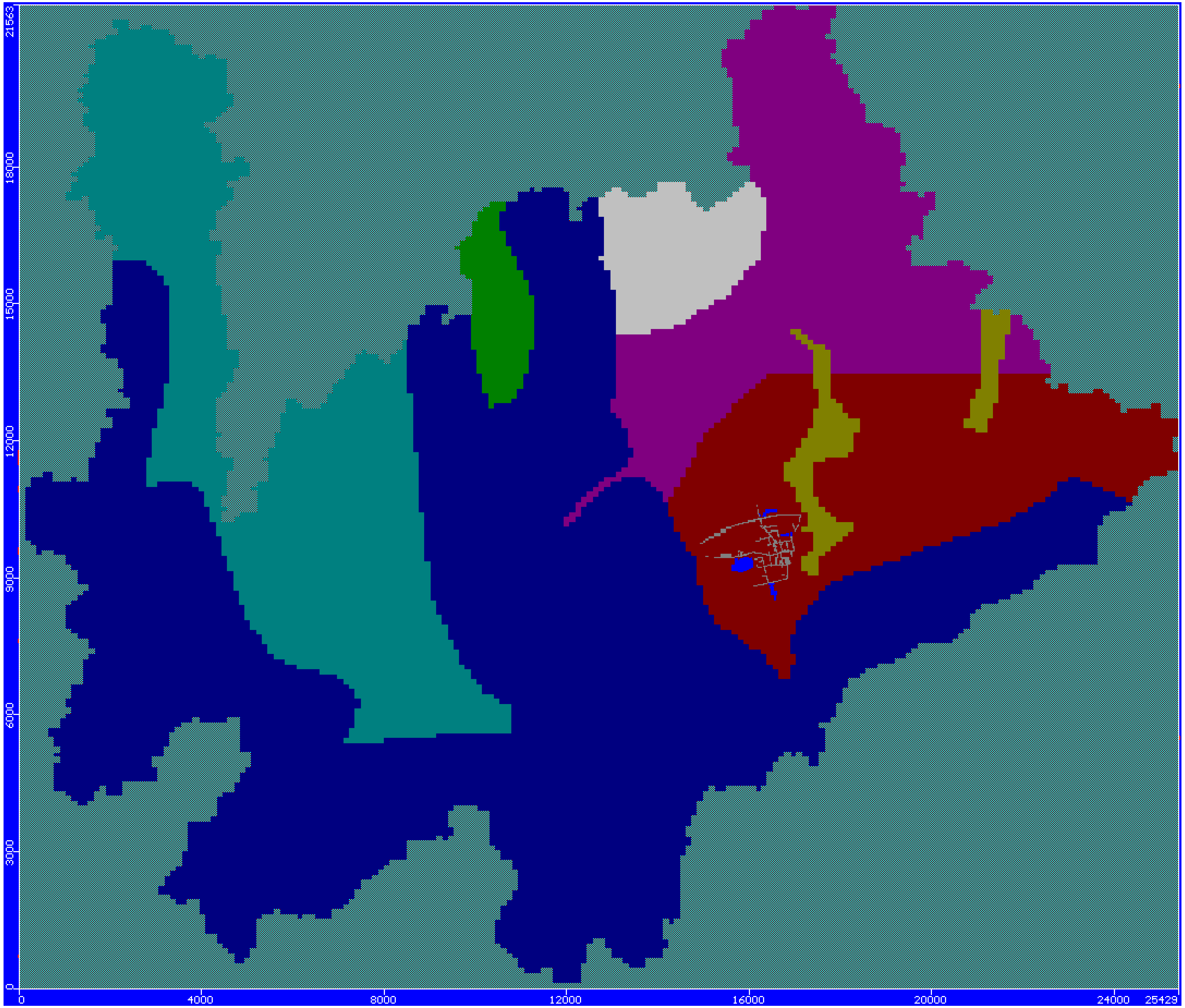
Figure 7: Numerical Model Flow Boundaries

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

- Recharge Zone A
- Recharge Zone B
- Recharge Zone C
- Recharge Zone D
- Recharge Zone E
- Recharge Zone F
- Recharge Zone G
- Recharge Zone H
- Recharge Zone I

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PN: 7-295 TN: 3254

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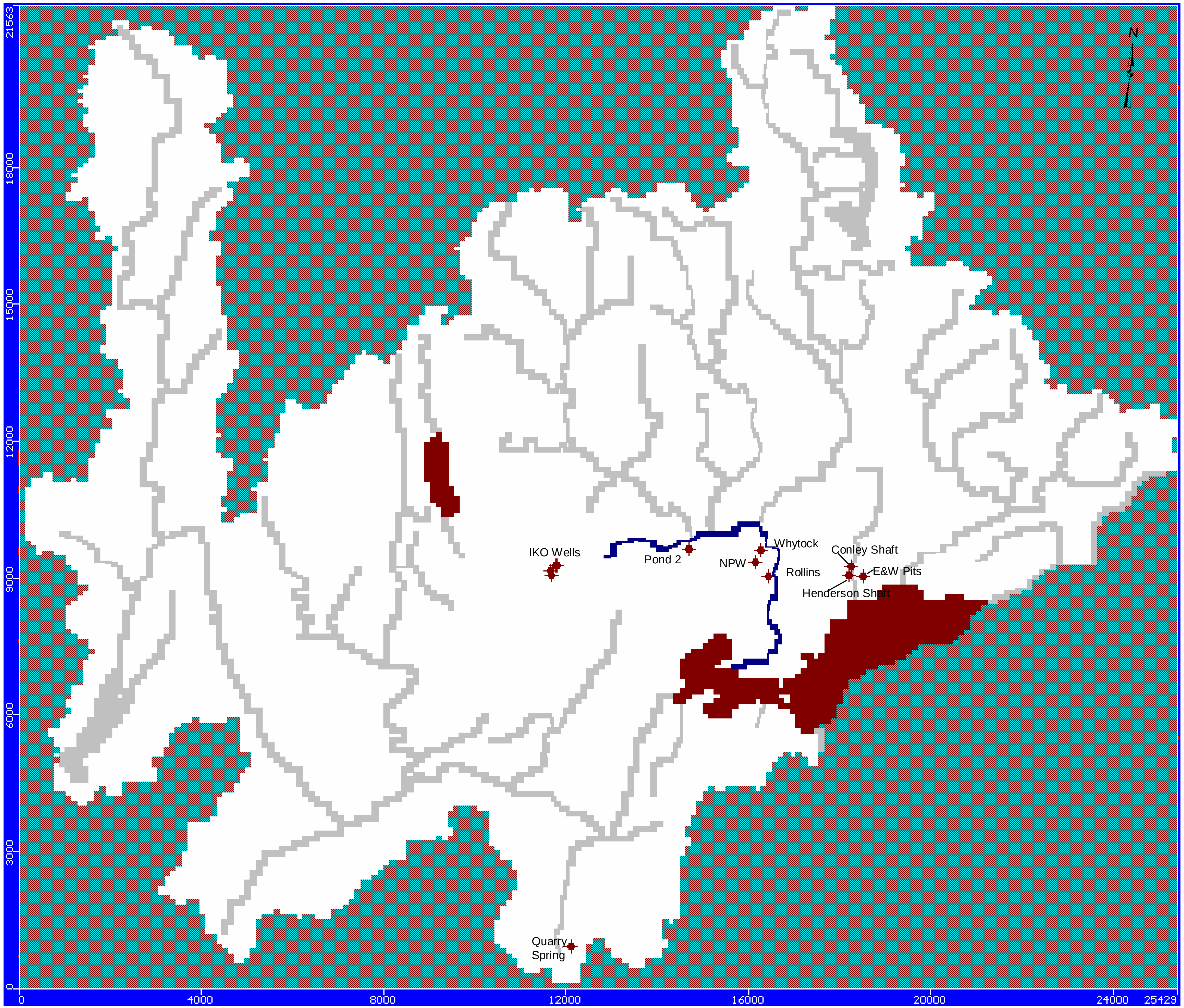
Figure 8: Numerical Model Recharge Zones

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



Legend

- Pumping Well
- River Boundary
- Constant Head Boundary
- Drain Boundary

Date: January, 2010

PN: 7-295 TN: 3255

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Figure 9: Location of Pumping Wells

Pumping Rates for Steady State Model

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
Whytock	303181.16	4930411.21	--	100	100%	91.4	All year	7	166.04	159.04	74.64	257+
Rollins	302979.24	4930975.21	--	100	100%	48.8	All year	10.7	173.27	162.57	124.50	325+

Industrial Wells

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
Conley Shaft	304979	4930794	3927.7	50	25%	260	All year	2	164.88	162.88	52.00**	286*
Henderson Shaft	304956	4930594	654.6	50	50%	260	All year	2	164.6	162.60	50.6**	95*
E&W Pits	305259	4930595	654.6	50	50%	25	July to September	2	159.32	157.32	134.32	41
Quarry Spring	299600	4921950	16546.2	50	50%	12	May	2	178.68	176.68	166.68	345
Pond2	301400	4930850	320.0	50	70%	4	June to September	2	173.99	171.99	169.99	37

IKO Wells

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
TW4	298537.56	4930250.41	110.9	100	20%	30.8	All year	6	219.64	213.64	188.84	22
TW5	298422.75	4930132.88	28.8	100	25%	79.3	All year	6	235.41	229.41	156.11	7
TW6	298554.805	4930244.71	724.3	100	100%	30.8	All year	6	219.64	213.64	188.84	724
IKO-Pond	298453	4930040	480.0	50	25%	2.5	April to November	2	225.07	223.07	222.57	40

+ Rates provided by Mark Boone of Quinte

* Rates for Conley Shaft and Henderson Shaft are based on personal communication with Mark Boone of Quinte

** Bottom of borehole is much deeper but personal communication from well operators indicates that flow is observed near the top of the shaft. Screen was adjusted to reflect this.

Municipal Well Pumping Rates for Transient Models - Current Conditions

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
Whytock	303181.16	4930411.21	--	100	100%	91.4	January	7	166.04	159.04	74.64	284
							February					281
							March					396
							April					262
							May					240
							June					252
							July					221
							August					256
							September					260
							October					212
							November					257
							December					166
Rollins	302979.24	4930975.21	--	100	100%	48.8	January	10.7	173.27	162.57	124.50	397
							February					343
							March					391
							April					349
							May					409
							June					294
							July					272
							August					306
							September					312
							October					149
							November					283
							December					398

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Municipal Well Pumping Rates for Transient Models - 25-Year Projections

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
Whytock	303181.16	4930411.21	--	100	100%	91.4	January	7	166.04	159.04	74.64	364
							February					359
							March					506
							April					336
							May					307
							June					323
							July					283
							August					328
							September					333
							October					271
							November					328
							December					213
Rollins	302979.24	4930975.21	--	100	100%	48.8	January	10.7	173.27	162.57	124.50	509
							February					439
							March					501
							April					447
							May					523
							June					376
							July					348
							August					392
							September					399
							October					191
							November					362
							December					509

Schlumberger WATER SERVICES

Industrial Well Pumping Rates for Transient Models

WellName	World X	World Y	Maximum Pumping Rate (m3/day)	Percentage Groundwater	Consumptive Factor	Well Depth (m bgs)	Time Pumped	Depth to Casing (m bgs)	Ground Surface in Model (masl)	Top of Screen Elevation (masl)	Bottom of Screen Elevation (masl)	Calculated Rate (m3/day)
Conley Shaft	304979	4930794	3927.7	50	25%	260	All year	2	164.88	162.88	52.00**	286*
Henderson Shaft	304956	4930594	654.6	50	50%	260	All year	2	164.6	162.60	50.6**	95*
E&W Pits	305259	4930595	654.6	50	50%	25	January to June	2	159.32	157.32	134.32	0
							July to September					164
							October to December					0
Quarry Spring	299600	4921950	16546.2	50	50%	12	January to April	2	178.68	176.68	166.68	0
							May					164
							June to December					0
Pond2	301400	4930850	320.0	50	70%	4	January to April	2	173.99	171.99	169.99	0
							May					112
							June to December					0
IKO Wells												
TW4	298537.56	4930250.41	110.9	100	20%	30.8	All year	6	219.64	213.64	188.84	22
TW5	298422.75	4930132.88	28.8	100	25%	79.3	All year	6	235.41	229.41	156.11	7
TW6	298554.805	4930244.71	724.3	100	100%	30.8	All year	6	219.64	213.64	188.84	724
IKO-Pond	298453	4930040	480.0	50	25%	2.5	January to April	2	225.07	223.07	222.57	0
							May					60
							June to December					0

Appendix B: Application of Non-Permitted Wells in Model

Non-permitted water demand for non-permitted agricultural use (livestock watering) and non-serviced residential use is estimated using GIS methods, and by applying the methodology provided in the Ontario Ministry of Natural Resources report *Agricultural Water Use in Ontario by Watershed: Estimates for 2001*. The report provides a monthly estimate for each stock well within the given watershed. The complete document is included with this appendix.

Non-serviced residential water use is calculated by multiplying the number of non-serviced private and commercial wells by typical per capita water use rates. A consumptive factor is applied to the total pumping rate, as designated in the attached OMNR report, which gives the consumptive pumping rate for the entire area.

The MOE WWIS database was queried to locate the total wells within the study area (i.e. model domain). The annual rates for agricultural use and private use are 1.905 and 0.525 m^3/day, respectively. The consumptive factors for the agricultural and private wells are 80% and 20%, respectively. Therefore, the non-permitted water uses within the complete study area are shown in Table 1 below.

Table 1: Non-Permitted Water Use for Study Area

Type of Non-Permitted Well	Number of Wells	Annual Rate per Well (m3/day)	Total Pumping (m3/day)	Consumptive Rate	Consumptive Pumping Rate (m3/day)
Agricultural	68	1.905	129.5	80%	103.6
Private	701	0.525	368.0	20%	73.6
Total			497.6		177.2

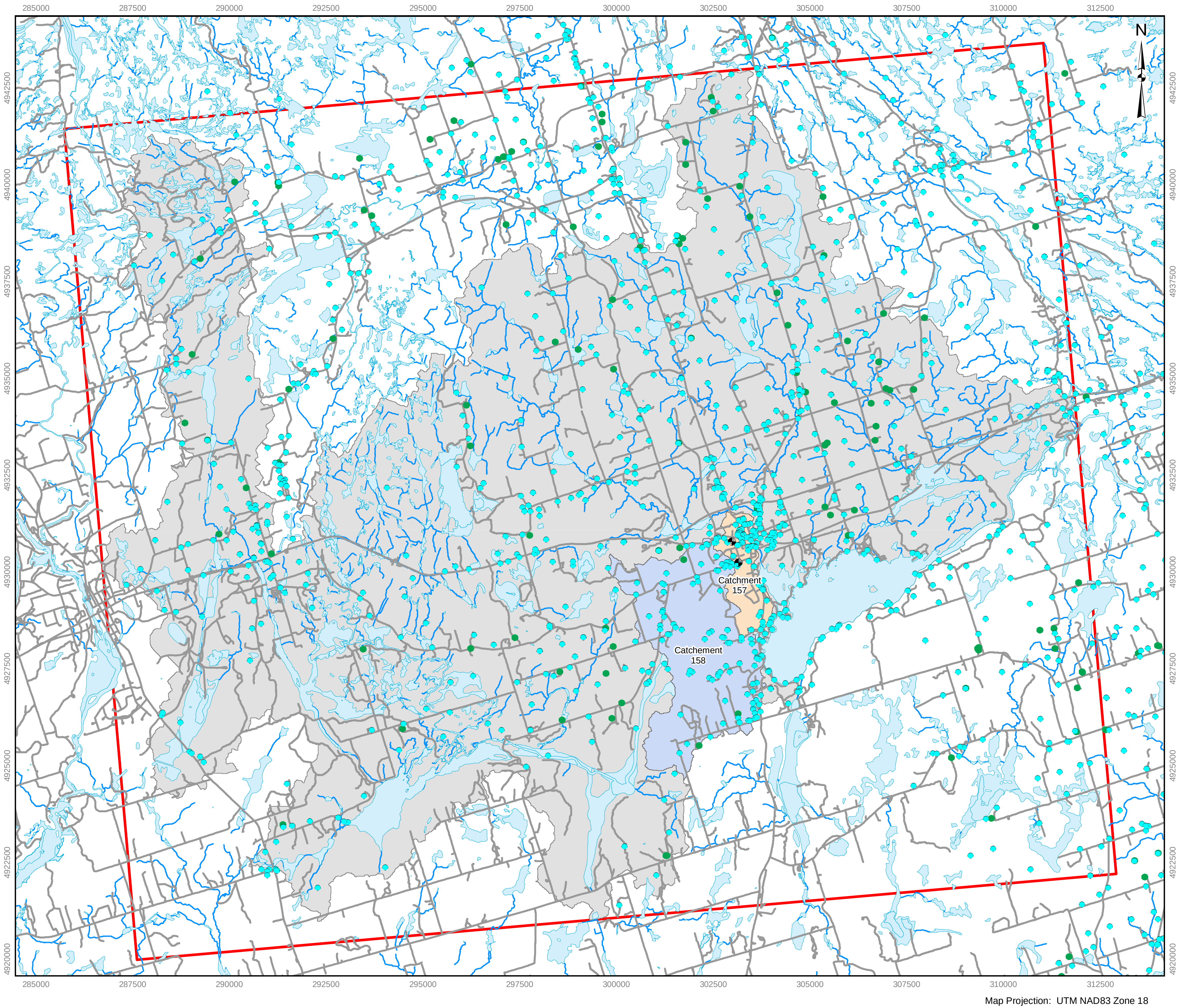
In the numerical model, the non-permitted pumping is only applied in the area directly impacted by municipal pumping. The impacted area is described by the GAWSER model catchments 157 & 158, as presented in Figure 1. Table 2 gives the amounts that were applied to the model. A ratio of 5.7% of the total non-permitted pumping within the study area was applied to a single location within the GAWSER catchments 157 and 158. The 5.7% was calculated by dividing the total area of the domain by the combined GAWSER catchments within the study area.

Table 2: Non-permitted pumping within Areas 157 & 158

Non-Permitted	Total Pumping (m3/day)	Consumptive Rate	Applied to Model (m3/day)
Agricultural	7.4	80%	5.9
Private	20.9	20%	4.2
Total	28.3		10.1

Schlumberger WATER SERVICES

Quinte Tier 2 Numerical Groundwater Flow Modelling For Water Budget Assessment



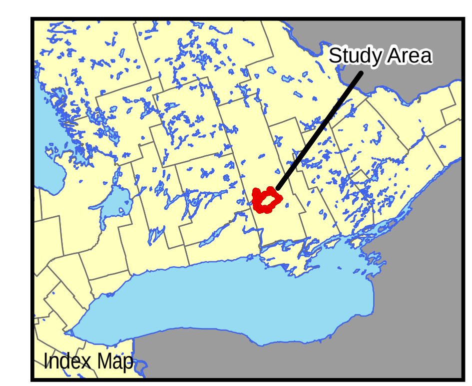
Legend

- Municipal Wells
- Non-Permitted Private Wells
- Non-Permitted Agricultural Wells
- Roads
- Catchment 157
- Catchment 158
- Lakes
- Rivers/Streams
- Study Area
- Model Extent

1:100,000

0 0.5 1 2 3 4
Kilometers

Note - Map must be printed at paper size 11 X 17 for the representative fraction to be correct



Disclaimer: This map is intended for illustrative purposes only.
Created: January, 2010

PN: 7-295 TN: 3236

Schlumberger WATER SERVICES

Figure 1: Non-Permitted Wells within the Study Area

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
1	16208.67	11137.4	302774	4932490	136.96	176.82	179.47	2.65
2	16071.19	11149.43	302636	4932490	156.49	178.05	178.84	0.79
3	17055.93	10678.81	303658	4932107	173.83	182.55	180.57	-1.98
4	17266.94	10658.34	303870	4932105	158.03	181.60	181.77	0.17
5	16319.94	10068.63	302978	4931435	154.36	169.58	169.72	0.14
6	16455.66	10093.9	303111	4931472	154.09	167.92	169.98	2.06
7	15736.59	9355.764	302459	4930674	149.93	170.31	168.05	-2.26
8	15818.09	8818.618	302587	4930146	147.85	162.70	165.90	3.20
9	16196.78	8878.842	302959	4930239	119.47	164.01	162.97	-1.04
10	16980.94	9592.212	303678	4931018	149.29	166.88	169.83	2.95
11	16526.24	8904.224	303285	4930293	135.78	158.16	161.50	3.34
2900860	16032.94	4975.267	303136	4926336	175.29	181.70	167.68	-14.02
2900863	15385.67	5965.448	302404.9	4927266	137.86	149.02	155.35	6.33
2900869	16933.83	6024.743	303942	4927460	145.20	150.16	155.39	5.23
2900870	16779.11	6424.75	303753	4927845	155.09	158.79	154.78	-4.01
2900885	16710.49	6340.409	303692	4927755	145.13	155.24	154.64	-0.60
2900886	16917.91	6979.765	303842.9	4928410	157.21	154.09	155.75	1.66
2900891	17411.47	7366.219	304300.9	4928838	137.66	152.71	155.41	2.70
2900892	17411.47	7366.219	304300.9	4928838	141.01	152.71	155.41	2.70
2900893	17478.21	7520.991	304353.9	4928998	152.25	154.82	155.64	0.82
2900904	12819.98	7480.829	299716.9	4928552	187.09	191.64	188.93	-2.71
2900909	16027.09	8776.241	302798.9	4930122	154.68	159.20	163.74	4.54
2900910	16933.18	8187.027	303752.9	4929614	154.14	156.99	158.59	1.60
2900911	16960.52	8109.349	303786.9	4929539	153.18	153.90	158.37	4.47
2900912	16910.11	8210.126	303727.9	4929635	154.14	155.73	158.65	2.92
2900913	17509.93	8686.662	304283.9	4930162	149.50	154.48	164.10	9.62
2900915	19207.25	8914.598	305954.9	4930537	147.89	153.00	155.71	2.71
2900916	19836.34	8796.319	306591.9	4930474	149.27	152.88	155.58	2.70
2900917	19645.54	8806.989	306400.9	4930468	151.37	152.89	154.95	2.06
2900918	21076.7	8631.588	307841.9	4930418	149.92	153.98	154.80	0.82
2900919	20900.28	8726.324	307657.9	4930497	145.90	157.93	155.49	-2.44
2900920	20895.3	8726.76	307652.9	4930497	146.36	157.32	155.57	-1.75
2900992	17015.8	9854.171	303689.9	4931282	145.24	167.87	172.22	4.35
2901013	16519.04	9477.031	303227.9	4930863	159.38	165.88	166.23	0.35
2901014	16529.69	9380.737	303246.9	4930768	147.46	156.20	165.07	8.87
2901015	16441.86	9329.195	303163.9	4930709	164.78	163.85	164.82	0.97
2901017	15814.54	9433.265	302529.9	4930758	148.39	167.18	167.43	0.25
2901018	16704.23	9838.265	303380.9	4931239	170.84	171.22	169.64	-1.58
2901019	16447	9628.888	303142.9	4931008	163.66	165.28	168.59	3.31
2901020	17013.67	9841.307	303688.9	4931269	141.09	166.81	172.11	5.30
2901021	16443.59	9566.949	303144.9	4930946	170.29	168.66	167.62	-1.04
2901022	16639.69	9834.878	303316.9	4931230	168.98	172.24	169.54	-2.70
2901023	17040.69	9828.905	303716.9	4931259	139.80	166.09	172.30	6.21
2901024	16875.73	9618.482	303570.9	4931035	135.72	161.73	169.07	7.34
2901025	16903.04	9334.019	303622.9	4930754	152.21	164.35	166.26	1.91
2901026	16675.59	9258.555	303402.9	4930659	142.29	161.41	163.49	2.08
2901033	9355.856	11968.83	295874.8	4932721	209.72	209.52	213.85	4.33
2901034	9742.922	12468.99	296216.8	4933253	220.14	215.60	219.71	4.11
2901035	9737.717	13522.46	296119.8	4934302	222.78	222.03	226.16	4.13
2901041	11225.59	9576.765	297945.9	4930501	220.10	217.38	212.91	-4.47
2901047	12886.66	11524.4	299430.9	4932586	199.49	201.85	202.12	0.27
2901051	12214.42	16220.87	298351.9	4937206	219.63	227.62	232.35	4.72
2901061	13761.43	11173.83	300332.9	4932313	185.32	195.61	192.87	-2.74
2901062	13933.56	13462.54	300304.9	4934608	184.46	218.15	206.41	-11.74
2901064	13604.93	14123.69	299919.9	4935238	220.80	226.11	224.43	-1.68
2901065	12802.82	14352.47	299100.9	4935396	204.67	215.84	221.04	5.20
2901071	16091.57	8905.111	302851.9	4930256	158.77	164.70	164.05	-0.65
2901072	15494.79	9346.805	302218.9	4930644	156.05	167.96	171.14	3.18
2901074	15247.64	9424.642	301965.9	4930700	165.52	174.90	173.51	-1.39
2901075	15640.57	9395.284	302359.9	4930705	158.46	170.99	169.71	-1.28
2901076	15741.61	9850.209	302420.9	4931167	148.01	168.00	170.00	2.00
2901078	15935.18	10835.09	302527.9	4932165	164.23	174.27	177.20	2.93

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2901079	16125.31	10541.4	302742.9	4931889	159.47	172.48	174.52	2.04
2901080	16147.85	10569.54	302762.9	4931919	148.19	171.47	174.77	3.30
2901082	16043.9	10918.93	302628.9	4932258	166.05	177.01	177.94	0.93
2901083	15919.53	11631.48	302442.9	4932957	161.73	177.57	181.29	3.72
2901087	14082.6	15831.56	300246.9	4936981	224.80	227.10	242.83	15.73
2901088	14605.8	16155.19	300739.9	4937349	230.93	241.30	241.05	-0.25
2901089	13739.29	15911.79	299897.9	4937031	224.36	235.32	247.90	12.58
2901091	14566.03	17203.65	300608.9	4938390	240.23	248.89	247.84	-1.05
2901112	17363.38	9317.836	304082.9	4930778	161.81	164.27	170.31	6.04
2901113	17326.12	9224.729	304053.9	4930682	151.16	158.37	168.74	10.37
2901114	17267.06	9180.709	303998.9	4930633	154.06	160.92	168.19	7.27
2901120	17676.29	10060.39	304329.9	4931545	183.78	177.31	179.19	1.88
2901121	17055.23	10213.1	303697.9	4931643	177.41	169.31	176.25	6.94
2901122	16186.88	10671.53	302792.9	4932024	136.95	174.47	175.79	1.32
2901125	17099.91	10494.28	303717.9	4931927	177.06	180.43	179.53	-0.90
2901126	16206.86	11186.75	302767.9	4932539	151.42	176.40	179.78	3.38
2901129	15335.8	15113.61	301557.9	4936375	216.85	224.16	223.03	-1.13
2901130	15578.2	15956.69	301725.9	4937236	215.04	224.30	223.55	-0.75
2901149	18736.14	10104.18	305381.9	4931681	175.46	179.70	179.01	-0.69
2901151	18513.86	10615.5	305115.9	4932171	185.15	187.00	185.00	-2.00
2901154	17361.39	12358.58	303815.9	4933807	206.24	204.71	196.19	-8.52
2901155	18282.57	12607.24	304711.9	4934135	194.56	196.79	196.78	-0.01
2901159	15676.3	17330.37	301703.9	4938613	249.58	250.74	250.81	0.07
2901160	17458.74	17739.57	303443.9	4939176	210.60	215.64	210.39	-5.25
2901164	15968.24	19795.3	301779.9	4941094	215.70	229.01	211.47	-17.54
2901166	16750.59	20533.92	302494.9	4941898	203.53	225.38	211.23	-14.15
2901170	19753.31	12746.59	306164.9	4934402	182.96	185.19	187.95	2.76
2901176	20722.54	11054.68	307277.9	4932801	153.19	157.16	168.08	10.92
2901177	20175.77	11700.79	306676.9	4933397	166.31	174.64	179.43	4.79
2901178	20158.47	12661.95	306575.9	4934353	175.48	182.01	185.73	3.72
2901181	19696.62	14324.53	305970.9	4935969	199.59	207.16	195.26	-11.90
2901190	21283.67	12924.89	307673.9	4934713	183.48	189.57	188.96	-0.61
2901340	1509.296	8943.185	288321.8	4929023	196.71	209.46	197.14	-12.32
2901468	1575.412	6187.938	288627.8	4926284	176.54	180.32	184.06	3.74
2901469	1237.627	6239.575	288286.8	4926306	163.91	184.21	184.53	0.32
2901483	589.0287	9680.196	287340.8	4929677	202.56	201.18	203.17	1.99
2901491	1795.653	8865.933	288613.8	4928971	196.16	201.19	194.99	-6.20
2901498	1372.296	17646.24	287426.8	4937681	230.42	229.64	223.32	-6.32
2901506	4226.453	9962.247	290939.8	4930275	167.88	182.24	180.46	-1.78
2901507	3538.88	9893.913	290260.8	4930147	175.58	178.21	180.27	2.06
2901508	4321.851	9916.759	291038.8	4930238	172.68	181.95	180.49	-1.46
2901509	4315.144	9518.83	291066.8	4929841	180.53	181.83	179.03	-2.80
2901512	3931.976	10084.38	290635.8	4930371	167.72	172.95	179.93	6.98
2901514	4081.981	10915.47	290712.8	4931212	168.02	187.41	186.70	-0.71
2901515	3963.211	10831.5	290601.8	4931118	170.36	187.69	185.98	-1.71
2901517	3083.236	10766.95	289730.8	4930977	153.59	175.83	183.81	7.98
2901518	4070.152	10906.46	290701.8	4931202	142.62	178.99	186.49	7.50
2901520	3966.791	11377.26	290557.8	4931662	201.92	203.42	189.14	-14.28
2901522	3595.802	13103.16	290037.8	4933349	179.63	204.50	195.90	-8.60
2901531	4390.509	11401.43	290977.8	4931723	197.22	195.08	189.36	-5.72
2901535	3221.839	17892.98	289247.8	4938088	223.11	223.95	223.04	-0.91
2901536	3068.002	17844.21	289098.8	4938026	213.06	222.36	222.77	0.41
2901537	3756.227	18574	289720.8	4938813	219.25	223.58	225.58	2.00
2901538	3792.413	18608.98	289753.8	4938851	218.63	223.55	225.70	2.15
2901539	4046.064	19098.74	289963.8	4939361	227.41	234.41	228.17	-6.24
2901540	6531.137	7482.946	293451.8	4928006	173.15	168.57	172.70	4.13
2901701	3796.522	2030.535	291202.8	4922336	163.36	171.16	175.89	4.73
2901708	6224.252	3711.341	293474.8	4924222	166.46	168.54	166.15	-2.39
2901710	4080.837	3088.783	291393.8	4923415	174.70	180.15	177.28	-2.87
2901717	3420.82	2050.355	290826.8	4922323	165.64	172.09	177.01	4.92
2901737	1495.152	4306.775	288711.8	4924403	178.26	182.81	185.60	2.79
2903928	25136.25	11914.27	311599.9	4934042	158.69	163.30	170.60	7.30

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2903947	16190.59	6272.463	303180	4927642	147.90	154.36	154.85	0.49
2903953	13784.19	5961.009	300809.9	4927122	143.02	154.00	156.76	2.76
2903957	14979.59	9068.649	301729.9	4930322	172.86	176.55	176.08	-0.47
2903959	20230.49	12062.39	306699.9	4933762	175.09	172.66	181.76	9.10
2903962	17596.45	10295.24	304229.9	4931772	176.14	179.06	181.19	2.13
2903965	17305.7	9266.669	304029.9	4930722	153.72	162.45	169.51	7.06
2903966	14413.16	17510.14	300429.9	4938682	247.17	254.33	250.16	-4.17
2903968	16853.05	9256.079	303579.9	4930672	153.34	157.82	164.49	6.67
2903969	15851.98	11582.18	302379.9	4932902	170.29	176.35	181.21	4.86
2904070	10420.44	6295.452	297429.8	4927162	160.03	173.45	179.20	5.75
2904236	17610.27	10223.77	304249.9	4931702	176.28	177.75	180.59	2.84
2904267	17921.48	8158.784	304739.9	4929672	148.96	154.63	155.56	0.93
2904268	14337.43	7809.827	301199.9	4929012	177.85	176.92	170.22	-6.70
2904297	16264.18	8835.803	303029.9	4930202	159.59	160.50	161.85	1.35
2904301	15289.04	8589.857	302079.9	4929872	164.50	164.21	169.45	5.24
2904335	16536.16	5288.601	303610	4926692	176.70	182.08	165.71	-16.37
2904395	16865.52	8251.169	303679.9	4929672	150.18	156.57	158.78	2.21
2904552	16766.51	9414.224	303479.9	4930822	142.93	160.20	165.41	5.21
2904557	16014.11	11025.93	302589.9	4932362	160.84	180.21	178.29	-1.92
2904565	16919.44	5997.895	303930	4927432	156.09	153.07	155.62	2.55
2904569	15850.41	6974.784	302779.9	4928312	147.85	150.37	154.38	4.01
2904601	16595.3	5735.145	303630	4927142	165.50	172.58	162.00	-10.58
2904603	16795.79	7454.213	303679.9	4928872	153.43	158.00	156.37	-1.63
2904648	9913.889	5095.033	297029.8	4925922	155.72	167.92	162.19	-5.73
2904650	13731.86	8575.519	300529.9	4929722	195.83	202.65	191.19	-11.46
2904661	16803.24	9260.437	303529.9	4930672	153.61	156.17	163.89	7.72
2904691	16811.09	9350.094	303529.9	4930762	156.48	160.86	165.23	4.37
2904692	8816.784	9306.679	295569.8	4930022	206.34	216.65	200.98	-15.67
2904707	16768.62	20797.36	302489.9	4942162	222.17	239.29	211.22	-28.07
2904745	14162.05	12804.12	300589.9	4933972	210.33	213.30	200.48	-12.82
2904747	16854.32	7549.475	303729.9	4928972	149.25	158.68	156.70	-1.98
2904748	16615.22	6536.459	303580	4927942	137.89	151.05	154.70	3.65
2904751	18387.5	9297.501	305104.9	4930847	158.45	159.79	166.74	6.95
2904822	12737.78	14710.5	299004.9	4935747	200.90	209.16	218.04	8.88
2904850	16983.18	9596.032	303679.9	4931022	134.06	168.72	169.89	1.17
2904908	3811.429	18528.01	289779.8	4938772	215.06	220.95	225.39	4.44
2904986	15545.57	7162.065	302459.9	4928472	150.40	157.80	154.77	-3.03
2904987	16442.11	10295.85	303079.9	4931672	149.84	164.68	171.88	7.20
2905043	15612.17	9414.834	302329.9	4930722	153.68	169.03	170.09	1.06
2905051	17471.65	7721.325	304329.9	4929197	152.56	152.53	156.58	4.05
2905053	16875.78	9228.995	303604.9	4930647	151.68	162.71	164.21	1.50
2905080	16216.12	8860.085	302979.9	4930222	160.54	158.62	162.33	3.71
2905081	14250.83	7049.481	301179.9	4928247	156.55	154.93	160.99	6.06
2905084	4107.262	10722.53	290754.8	4931022	178.79	190.71	185.65	-5.06
2905085	11158.18	9563.59	297879.9	4930482	220.22	221.11	212.89	-8.22
2905086	14830.46	9658.892	301529.9	4930897	162.18	172.09	174.00	1.91
2905087	12405.6	15216.38	298629.9	4936222	214.64	217.03	220.02	2.99
2905088	14174.81	12777.91	300604.9	4933947	206.72	209.94	200.30	-9.64
2905089	4545.915	9253.708	291319.8	4929597	180.13	183.05	178.70	-4.35
2905156	5512.976	3211.43	292809.8	4923662	162.03	165.64	165.55	-0.09
2905203	16402.89	9847.564	303079.9	4931222	151.60	165.81	169.66	3.85
2905204	16782.39	8735.256	303554.9	4930147	156.70	158.20	160.97	2.77
2905205	17381.66	9561.169	304079.9	4931022	163.22	170.06	172.73	2.67
2905206	14352.5	7637.859	301229.9	4928842	163.46	171.05	167.22	-3.83
2905209	14314.02	7771.722	301179.9	4928972	169.86	175.32	170.50	-4.82
2905210	14425.71	8474.662	301229.9	4929682	179.95	186.95	179.98	-6.97
2905211	16430.91	9594.158	303129.9	4930972	164.08	167.07	168.05	0.98
2905229	16837.99	6788	303780	4928212	144.96	152.70	155.09	2.39
2905234	15851.76	8711.274	302629.9	4930042	157.38	162.30	164.65	2.35
2905235	16954.68	8122.91	303779.9	4929552	152.15	153.90	158.41	4.51
2905290	16273.4	9055.838	303019.9	4930422	160.74	158.09	163.02	4.93
2905321	14481.4	17142.79	300529.9	4938322	249.99	251.61	247.71	-3.90

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2905322	15193.71	14671.31	301454.9	4935922	208.13	214.47	214.71	0.24
2905326	13680.81	8278.84	300504.9	4929422	193.25	200.75	189.27	-11.48
2905384	25083.08	12109.64	311529.9	4934232	172.04	160.87	171.94	11.07
2905433	16739.07	12829.61	303154.9	4934222	200.14	202.03	196.63	-5.40
2905478	12970.99	11352.4	299529.9	4932422	186.60	191.73	198.09	6.36
2905533	17622.6	10594.1	304229.9	4932072	173.39	179.51	183.68	4.17
2905549	12730.96	6314.148	299729.9	4927382	160.14	178.60	175.12	-3.48
2905634	16915.28	12262.09	303379.9	4933672	202.48	195.80	193.36	-2.44
2905639	18494.1154	13097.6696	304879.9	4934642	215.28	215.28	Dry Cell	N/A
2905641	15118.43	9508.221	301829.9	4930772	163.67	175.73	174.18	-1.55
2905642	15934.17	11374.23	302479.9	4932702	157.39	171.59	176.66	5.07
2905667	17526.73	9498.286	304229.9	4930972	159.47	172.57	172.59	0.02
2905671	17020.65	10827.45	303609.9	4932252	174.61	183.88	180.83	-3.05
2905673	20670.18	12957.48	307059.9	4934692	172.71	186.00	189.03	3.03
2905799	16538.02	6871.462	303473.9	4928269	144.74	152.99	155.31	2.32
2905806	12435.85	10972.6	299029.9	4931997	196.67	204.00	206.93	2.93
2905807	13733.39	11461.37	300279.9	4932597	196.90	199.49	195.55	-3.94
2905989	12941.1	11355.02	299499.9	4932422	170.43	195.30	198.20	2.90
2905992	11197.66	9670.557	297909.9	4930592	209.65	218.32	213.53	-4.79
2905993	14649.01	17108.05	300699.9	4938302	238.90	242.05	246.89	4.84
2905994	17257.51	9461.611	303964.9	4930912	158.09	161.34	171.14	9.80
2905995	15619.15	6051.426	302630	4927372	123.15	146.96	155.30	8.34
2906027	2177.177	4942.753	289335.8	4925096	176.79	180.52	191.00	10.48
2906030	2919.302	10625.7	289579.8	4930822	174.96	180.02	183.72	3.70
2906120	5752.475	3069.015	293060.8	4923541	155.88	158.60	161.98	3.38
2906122	11493.61	5216.814	298592.9	4926181	144.00	161.82	164.88	3.06
2906128	18338.5853	13041.0093	304729.9	4934572	205.71	205.71	Dry Cell	N/A
2906154	15825.21	10932.04	302409.9	4932252	159.40	178.83	177.23	-1.60
2906157	4639.534	9119.036	291424.8	4929471	162.31	178.23	178.42	0.19
2906289	15169.53	8428.659	301974.9	4929701	164.03	165.41	169.32	3.91
2906293	21075.34	11220.56	307614.9	4932997	163.40	165.90	171.27	5.37
2906302	15893.57	11197.09	302454.9	4932522	155.51	178.02	177.00	-1.02
2906307	6574.108	8800.214	293379.8	4929322	167.17	179.57	178.00	-1.57
2906308	4503.888	9232.289	291279.8	4929572	168.27	182.76	178.65	-4.11
2906327	4315.091	3104.426	291625.8	4923451	175.80	183.32	176.82	-6.50
2906361	16164.96	8780.239	302935.9	4930138	146.93	159.97	162.41	2.44
2906371	16347.06	8773.343	303117.9	4930147	145.74	159.48	161.18	1.70
2906373	4266.039	9955.772	290979.8	4930272	176.20	180.06	180.57	0.51
2906384	17049.48	10067.05	303704.9	4931497	158.74	169.51	174.38	4.87
2906509	16406.95	9320.204	303129.9	4930697	144.22	160.14	164.84	4.70
2906525	8025.31	5813.367	295085.8	4926473	159.61	166.68	169.24	2.56
2906604	16655.86	8883.849	303415.9	4930284	135.70	152.08	161.53	9.45
2906623	16399.02	8828.022	303164.9	4930206	137.26	149.53	161.35	11.82
2906642	15307.08	8474.847	302107.9	4929759	159.46	163.31	168.05	4.74
2906643	11840.62	11626.96	298379.9	4932597	203.32	210.85	214.58	3.73
2906650	19774.35	13216.54	306144.9	4934872	171.90	186.46	188.97	2.51
2906651	14365.9609	12209.0806	300844.9	4933397	209.29	209.29	Dry Cell	N/A
2906652	14205.6891	13016.1202	300614.9	4934187	207.31	207.31	Dry Cell	N/A
2906676	19215.33	9867.52	305879.9	4931487	172.93	175.97	173.44	-2.53
2906677	18509.5	12699.81	304929.9	4934247	207.72	203.18	198.33	-4.85
2906716	14411.03	13068.42	300814.9	4934257	218.41	210.78	200.25	-10.53
2906749	11764.03	12185.77	298254.9	4933147	203.50	225.85	214.02	-11.83
2906800	8627.872	5667.295	295698.8	4926380	158.24	170.41	168.04	-2.37
2906801	15084.81	9410.781	301804.9	4930672	159.79	174.42	174.81	0.39
2906802	15937.83	6826.601	302879.9	4928172	157.37	155.99	154.64	-1.35
2906817	14585.86	7436.755	301479.9	4928662	148.12	153.19	159.20	6.01
2906965	12489.15	11008.09	299079.9	4932037	197.59	202.12	205.79	3.67
2906966	12230.07	10915.31	298829.9	4931922	202.01	212.76	210.87	-1.89
2906969	15614.8	6001.616	302630	4927322	131.01	149.40	155.51	6.11
2906970	15456.55	5915.079	302479.9	4927222	142.50	155.95	155.80	-0.15
2906974	16650.21	6362.748	303630	4927772	140.47	152.30	154.52	2.22
2906979	4008.275	9877.942	290729.8	4930172	172.61	172.47	179.00	6.53

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2906982	13819.52	6009.113	300840.9	4927173	130.54	154.75	156.67	1.92
2907106	16938.75	8308.003	303747.9	4929735	144.29	156.73	159.08	2.35
2907154	18353.53	12638.17	304779.9	4934172	194.05	196.25	197.48	1.23
2907159	15575.35	17197.66	301614.9	4938472	231.49	231.72	245.98	14.26
2907206	18358.5	13842.32	304679.9	4935372	204.04	208.31	199.13	-9.18
2907209	3267.97	10595.19	289929.8	4930822	165.69	168.93	183.83	14.90
2907212	18323.55	10000.75	304979.9	4931542	172.13	179.93	177.73	-2.20
2907213	18216.54	13653.98	304554.9	4935172	202.50	203.09	199.59	-3.50
2907215	14391.61	8279.894	301212.9	4929485	173.64	183.73	177.81	-5.92
2907216	17210.11	10755.67	303804.9	4932197	174.92	181.03	182.43	1.40
2907227	19420.06	14502.31	305679.9	4936122	188.53	202.28	196.49	-5.79
2907228	19217.73	12763.33	305629.9	4934372	174.29	186.27	194.64	8.37
2907261	16558.27	6747.224	303504.9	4928147	138.66	149.44	154.81	5.37
2907279	15571.07	9518.811	302279.9	4930822	168.44	171.13	170.87	-0.26
2907288	13200.08	14544.58	299479.9	4935622	214.31	217.80	229.52	11.72
2907295	14413.34	7185.837	301329.9	4928397	152.75	156.73	157.55	0.82
2907298	16476.51	5524.698	303530	4926922	168.67	177.39	164.03	-13.36
2907301	14334.9	6289.261	301329.9	4927497	145.74	153.29	155.25	1.96
2907308	17733.98	16456.7	303829.9	4937922	205.04	220.16	207.03	-13.13
2907415	10760.95	9497.961	297489.9	4930382	200.85	220.78	211.99	-8.79
2907439	17480.62	12413.4	303929.9	4933872	199.04	203.60	196.95	-6.65
2907440	14680.64	17125.36	300729.9	4938322	241.50	242.60	246.76	4.16
2907441	16919.64	12311.9	303379.9	4933722	203.51	201.76	193.75	-8.01
2907442	17044.19	10293.37	303679.9	4931722	160.26	175.03	176.86	1.83
2907542	3562.561	2488.67	290929.8	4922772	170.77	174.29	177.05	2.76
2907569	15673.32	6096.878	302680	4927422	121.92	148.44	155.27	6.83
2907575	10963.04	10775.21	297579.9	4931672	212.77	216.49	216.67	0.18
2907597	1236.406	6305.933	288279.8	4926372	178.44	185.50	184.67	-0.83
2907600	15673.32	6096.878	302680	4927422	131.98	148.44	154.90	6.46
2907601	3622.96	2031.667	291029.8	4922322	167.33	171.16	176.68	5.52
2907602	17331.85	9565.527	304029.9	4931022	167.84	171.94	172.45	0.51
2907605	17681.73	11843.7	304179.9	4933322	181.16	189.08	191.69	2.61
2907606	17029.24	10696.2	303629.9	4932122	176.27	182.18	180.40	-1.78
2907608	19008.56	10372.46	305629.9	4931972	180.04	186.38	181.64	-4.74
2907649	1495.909	17877.35	287529.8	4937922	204.23	213.76	223.68	9.92
2907652	12127.36	9167.614	298879.9	4930172	191.80	214.70	206.00	-8.70
2907685	15856.25	8188.895	302679.9	4929522	135.30	145.77	160.96	15.19
2907690	14871.91	6116.801	301879.9	4927372	144.73	151.08	155.53	4.45
2907719	18855.38	11490.07	305379.9	4933072	185.56	186.62	190.65	4.03
2907720	16927.14	10102.84	303579.9	4931522	163.11	172.80	173.25	0.45
2907855	19733.3	8903.708	306479.9	4930572	139.72	147.83	155.87	8.04
2907856	17413.38	12218.52	303879.9	4933672	206.27	201.78	195.35	-6.43
2907870	17522.98	10602.82	304129.9	4932072	179.95	183.22	183.35	0.13
2907884	13943.5197	11568.461	300479.9	4932722	204.61	204.61	Dry Cell	N/A
2907902	11377.09	10688.79	297999.9	4931622	222.24	221.32	215.85	-5.47
2907911	15874.29	9542.474	302579.9	4930872	161.67	169.05	167.74	-1.31
2907912	16039.15	10853.09	302629.9	4932192	152.29	174.93	177.53	2.60
2907941	17538.58	7339.037	304429.9	4928822	142.37	152.41	155.01	2.60
2907942	19369.69	9337.048	306079.9	4930972	154.44	168.08	162.39	-5.69
2908014	13560.41	7074.751	300489.9	4928212	169.88	175.77	175.72	-0.05
2908016	11185.99	6439.278	298179.9	4927372	173.76	191.11	183.05	-8.06
2908063	4383.089	10146.3	291079.8	4930472	181.38	189.61	181.82	-7.79
2908078	4084.841	11326.78	290679.8	4931622	185.49	192.01	188.50	-3.51
2908080	15918.39	19225.48	301779.9	4940522	240.69	233.97	211.70	-22.27
2908082	13814.61	13537.19	300179.9	4934672	209.02	223.10	207.69	-15.41
2908143	2369.476	15241.18	288629.8	4935372	184.89	194.22	200.43	6.21
2908282	13657.69	15759.32	299829.9	4936872	221.26	232.15	240.01	7.86
2908285	3568.793	1986.215	290979.8	4922272	167.94	172.52	176.80	4.28
2908320	13571.93	1010.671	301029.9	4922172	175.36	181.28	182.37	1.09
2908321	6576.637	5387.005	293679.8	4925922	168.67	178.90	174.92	-3.98
2908337	12185.93	5247.592	299279.9	4926272	174.03	171.02	169.06	-1.96
2908338	13754.31	5963.624	300779.9	4927122	142.03	155.79	157.44	1.65

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2908343	14665.22	4328.009	301829.9	4925572	172.22	176.15	167.22	-8.93
2908344	18298.1	14299.33	304579.9	4935822	211.52	213.69	199.66	-14.03
2908352	14602.81	17383.13	300629.9	4938572	245.29	249.32	248.76	-0.56
2908353	14820.74	15858.33	300979.9	4937072	214.09	228.79	231.96	3.17
2908403	17029.89	7835.26	303879.9	4929272	154.80	155.49	157.56	2.07
2908404	16783.94	9613.463	303479.9	4931022	154.40	165.99	167.88	1.89
2908421	11872.69	10846.2	298479.9	4931822	210.68	213.33	214.57	1.24
2908423	16062.33	8823.349	302829.9	4930172	153.59	158.58	163.80	5.22
2908428	13947.31	6448.648	300929.9	4927622	153.87	157.30	160.32	3.02
2908437	11109.33	13021	297529.9	4933922	208.76	216.17	220.14	3.97
2908477	23968.96	11996.31	310429.9	4934022	154.28	164.71	172.31	7.60
2908492	16882.34	7296.068	303779.9	4928722	148.93	157.51	156.20	-1.31
2908617	24605.29	11237.97	311129.9	4933322	140.57	156.42	158.94	2.52
2908652	4384.964	9594.031	291129.8	4929922	184.62	185.43	179.48	-5.95
2908682	10661.13	5029.658	297779.9	4925922	161.18	169.81	163.11	-6.70
2908690	10939.38	11078.42	297529.9	4931972	225.02	219.98	217.40	-2.58
2908693	16712.3	13384.06	303079.9	4934772	200.43	202.57	199.90	-2.67
2908699	14627.83	7342.74	301529.9	4928572	146.78	156.35	157.14	0.79
2908725	2107.354	15113.54	288379.8	4935222	183.65	191.94	199.74	7.80
2908727	18649.91	12009.95	305129.9	4933572	197.85	202.35	194.19	-8.16
2908740	18664.85	11607.12	305179.9	4933172	182.85	188.11	191.71	3.60
2908746	18196.61	14860.31	304429.9	4936372	204.00	209.40	Dry Cell	N/A
2908813	16838.11	9658.915	303529.9	4931072	133.34	164.41	169.11	4.70
2908815	11539.01	6458.583	298529.9	4927422	157.60	182.86	179.45	-3.41
2908816	11380.87	6372.037	298379.9	4927322	155.16	186.11	178.74	-7.37
2908843	18872.81	11689.3	305379.9	4933272	186.54	190.06	191.72	1.66
2908864	14232.62	7426.503	301128.9	4928621	166.29	156.11	167.13	11.02
2908867	10902.03	10077.87	297579.9	4930972	214.15	218.31	214.83	-3.48
2908868	17264.61	9370.646	303979.9	4930822	132.11	155.87	169.88	14.01
2908871	9299.961	7256.767	296229.8	4928022	185.84	188.09	184.03	-4.06
2908893	20672.19	11029.97	307229.9	4932772	159.00	167.54	168.39	0.85
2908913	16298.49	6944.617	303228.9	4928321	144.59	148.71	155.11	6.40
2908962	19189.75	9001.453	305929.9	4930622	142.68	153.91	157.93	4.02
2908963	15348.83	6978.514	302279.9	4928272	138.59	145.86	154.58	8.72
2908964	15987.64	6822.244	302929.9	4928172	147.20	152.69	154.67	1.98
2908967	16301.4	10408.54	302929.9	4931772	150.63	167.93	171.93	4.00
2908986	13063.2	5522.178	300129.9	4926622	169.68	182.63	168.06	-14.57
2908988	14906.12	9376.223	301629.9	4930622	145.08	170.26	176.15	5.89
2908989	15720.5	9505.737	302429.9	4930822	157.56	174.33	169.31	-5.02
2909014	21520.18	13264.57	307879.9	4935072	191.12	195.59	190.69	-4.90
2909016	1425.01	10756.43	288079.8	4930822	199.53	215.77	201.39	-14.38
2909026	12849.58	11112.07	299429.9	4932172	154.64	185.80	200.31	14.51
2909115	17941.98	12523.61	304379.9	4934022	190.75	194.79	197.17	2.38
2909116	11116.83	10811.94	297729.9	4931722	220.63	225.65	216.62	-9.03
2909117	18351.6587	13190.4385	304729.9	4934722	210.36	210.36	Dry Cell	N/A
2909118	11004.14	10671.23	297629.9	4931572	202.19	217.61	216.22	-1.39
2909124	15835.82	6233.234	302830	4927572	133.10	144.72	154.66	9.94
2909309	13941.13	2935.82	301229.9	4924122	164.56	175.02	171.05	-3.97
2909311	21019.64	8690.786	307779.9	4930472	135.57	155.49	155.14	-0.35
2909381	2789.742	15455.37	289029.8	4935622	195.76	207.64	202.58	-5.06
2909382	2263.06	10582.73	288929.8	4930722	198.50	195.16	193.87	-1.29
2909383	9701.487	12993.6	296129.8	4933772	199.59	220.98	222.95	1.97
2909401	16814.01	7100.278	303728.9	4928521	140.08	156.97	155.93	-1.04
2909402	15800.39	6988.195	302728.9	4928321	127.28	144.88	154.59	9.71
2909403	16492.86	5723.028	303529	4927121	164.54	176.06	162.34	-13.72
2909421	9910.706	11369.19	296479.8	4932172	182.24	217.17	215.62	-1.55
2909424	18865.36	9883.081	305529.9	4931472	175.18	184.29	175.52	-8.77
2909467	17793.12	17706.3	303779.9	4939172	207.08	219.01	209.48	-9.53
2909516	12779.29	5145.489	299879.9	4926222	170.32	165.17	168.19	3.02
2909594	17599.73	10344.14	304228.9	4931821	183.86	183.82	181.65	-2.17
2909596	4155.83	10417.13	290829.8	4930722	162.20	187.12	183.72	-3.40
2909600	2590.73	9750.002	289328.8	4929921	180.24	181.08	185.39	4.30

Appendix C: Observation Targets, Calculated Heads and Residuals

Well	X-Model	Y-Model	X-World	Y-World	Screen Elevation (masl)	Observed Head (masl)	Calculated Head (masl)	Calculated - Observed (m)
2909601	3296.782	9788.613	290028.8	4930021	192.54	194.38	182.43	-11.95
2909603	3594.421	7453.787	290528.8	4927721	163.85	186.31	184.56	-1.75
2909608	9905.31	7303.184	296828.8	4928121	166.23	178.30	189.51	11.21
2909647	12771.88	13677.6	299128.9	4934721	211.70	235.76	220.80	-14.96
2909693	13240.18	6409.129	300228.9	4927521	159.91	187.82	172.28	-15.54
2909701	11663.61	14778.38	297928.9	4935721	209.39	217.63	219.06	1.43
2909874	17112.87	7074.131	304028.9	4928521	157.53	158.47	155.68	-2.79
2909923	15556.17	20259.98	301328.9	4941521	223.57	240.51	211.39	-29.12
2909925	16993.29	10296.82	303628.9	4931721	171.43	177.51	176.66	-0.85
2909950	15120.39	15279.01	301328.9	4936521	222.40	233.80	229.63	-4.17
2909971	17911.05	9313.086	304628.9	4930821	169.89	168.84	169.57	0.73
2909974	16364.46	8846.103	303128.9	4930221	163.63	164.63	161.55	-3.08
2909985	17944.6	15433.45	304128.9	4936921	200.88	206.62	202.46	-4.16
2909987	15802.83	11605.55	302328.9	4932921	155.04	178.72	181.98	3.26
2910062	2381.466	15389.7	288628.8	4935521	178.76	197.02	202.07	5.05
2910063	7531.874	7711.596	294428.8	4928321	152.28	163.77	175.92	12.15
2910104	14618.55	16427.12	300728.9	4937621	236.09	241.92	243.44	1.52

Appendix D:
Zone Budget Analysis Results

	Zone 1		Zone 2		Zone 3		Zone 4		Zone 5		
			Region 108		Region 107		Region 157		Region 158		
INPUT											
Storage		0		0		0		0		0	m^3/day
Constant Head		270.6		0		0		0		1.8916	m^3/day
Wells		0		0		0		0		0	m^3/day
Drains		0		0		0		0		0	m^3/day
MNW		0		0		0		0		0	m^3/day
Recharge		48559		1721.7		9986.4		594.53		3173.2	m^3/day
ET		0		0		0		0		0	m^3/day
River Leakage		0		53.52		664.99		1548.3		45.418	m^3/day
Stream Leakage		0		0		0		0		0	m^3/day
Surface Leakage		0		0		0		0		0	m^3/day
General-Head		0		0		0		0		0	m^3/day
From Zone # to #	2 to 1	1068.1	1 to 2	662.77	1 to 3	4770.3	1 to 4	1195.9	1 to 5	2128	m^3/day
From Zone # to #	3 to 1	4546.3	3 to 2	139.41	2 to 3	98.536	2 to 4	98.77	2 to 5	12.016	m^3/day
From Zone # to #	4 to 1	1023.6	4 to 2	77.109	5 to 3	184.86	5 to 4	215.58	3 to 5	185.03	m^3/day
From Zone # to #	5 to 1	2084	5 to 2	12.446		0		0	4 to 5	29.901	m^3/day
Total IN		**57552**		**2667**		**15705**		**3653**		**5575**	**m^3/day**
OUTPUT											
Storage		0		0		0		0		0	m^3/day
Constant Head		2865.7		0		0		0		2488.4	m^3/day
Wells		860.29		0		37.333		110.21		0	m^3/day
Drains		45070		989.8		9311.9		0		474.54	m^3/day
MNW		0		0		0		0		0	m^3/day
Recharge		0		0		0		0		0	m^3/day
ET		0		0		0		0		0	m^3/day
River Leakage		0		399.71		1484.4		2412.3		115.65	m^3/day
Stream Leakage		0		0		0		0		0	m^3/day
Surface Leakage		0		0		0		0		0	m^3/day
General-Head		0		0		0		0		0	m^3/day
From Zone # to #	1 to 2	662.77	2 to 1	1068.1	3 to 1	4546.3	4 to 1	1023.6	5 to 1	2084	m^3/day
From Zone # to #	1 to 3	4770.3	2 to 3	98.536	3 to 2	139.41	4 to 2	77.109	5 to 2	12.446	m^3/day
From Zone # to #	1 to 4	1195.9	2 to 4	98.77	3 to 5	185.03	4 to 5	29.901	5 to 3	184.86	m^3/day
From Zone # to #	1 to 5	2128	2 to 5	12.016					5 to 4	215.58	m^3/day
Total OUT		**57553**		**2667**		**15704**		**3653**		**5575**	**m^3/day**
IN - OUT		**-1.49**		**-0.07**		**0.73**		**-0.01**		**0.01**	**m^3/day**
Percent Discrepancy		**0.00**		**0.00**		**0.00**		**0.00**		**0.00**	**%**

Appendix E: Water Budget, 1956 to 1965

Subwatershed: Madoc **Area of Capture Zone (m^2):** 228255300

Month	Precipitation (mm)	Actual Evapotranspiration (mm)	Infiltration (mm)	Adjusted Recharge (mm)	Total Water Use (mm)	Average Water Use over Subwatershed (mm)
Jan	59.29	0.00	16.75	6.95	36085.90	0.10
Feb	67.63	0.00	28.96	12.02	32929.10	0.09
Mar	44.76	0.00	32.75	13.61	42242.70	0.12
Apr	72.22	28.80	26.58	11.04	35524.30	0.10
May	74.00	75.18	0.00	0.00	166661.90	0.46
Jun	56.41	108.18	0.00	0.00	33952.48	0.09
Jul	64.56	113.07	0.00	0.00	33346.08	0.09
Aug	76.22	99.71	0.00	0.00	33957.28	0.09
Sep	65.48	68.77	0.00	0.00	33981.28	0.09
Oct	56.67	40.40	0.00	0.00	28173.90	0.08
Nov	74.48	8.87	2.28	0.77	30543.50	0.08
Dec	68.18	0.00	4.46	1.52	33034.70	0.09

all depths in mm over the capture zone

Schlumberger WATER SERVICES