Whitemans Creek Tier Three Local Area Water Budget and Risk Assessment

Model Development and Calibration Report

Prepared for:

Grand River Conservation Authority
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Cambridge, Ontario, N1R 5W6

On behalf of:

Lake Erie Source Protection Region

Prepared by:

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March 2018

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Earth Science Information Systems

March 27, 2018

Stephanie Shifflett, P.Eng.
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RE: Whitemans Creek Tier 3 – Model Development and Calibration Report

Dear Ms. Shifflett:

We are pleased to provide a copy of our final report titled: *Whitemans Tier 3 Model Development and Calibration Report*. This report describes the physical setting, the conceptual hydrogeologic model, and the numerical model developed to simulate the surface water and groundwater systems in the Whitemans Creek subwatershed. The model is calibrated and has been used for the Tier 3 Water Budget and Risk Assessment of the Bright and Bethel wellfields. In addition, we have developed and validated an irrigation demand module for the subwatershed which should prove useful in future drought and water management studies.

The report presents the data and methods as applied to the entire model area, which extends beyond the Whitemans Creek subwatershed. The main body of the report focusses on the subwatershed, with details related to municipal water use outside the subwatershed moved to an appendix.

We trust this work report meets with your satisfaction, and we look forward to discussing it with you. If you have any questions, please call.

Yours truly,
Earthfx Incorporated

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- Sonja Strynatka P.Geo., Senior Hydrogeologist
- Martin Keller, Lake Erie Source Protection Program Manager
- Hajnal Kovacs (now with Conservation Sudbury)
- Zoë Green, Geomatics Applications Development Specialist

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- Scott Bates, Water Budget Program Analyst, OMNRF
- Kathryn Baker, Water Budget Program Analyst, OMOE
- Lynne Milford, Water Budget Program Analyst, OMOE

The depth and quality of this study has been greatly enhanced by the comments provided by members of the project Peer Review Team:

- Roger Freymond, P.Eng., Stantec (representing the County of Brant)
- Tony Lotimer, P.Geo., (representing the County of Oxford)
- Chris Neville, P.Eng., S.S. Papadopulous & Associates
- Dr. David L. Rudolph, P.Eng., Waterloo Hydrogeology Advisors Inc.
- Dr. Rob Schincariol, P.Geo., University of Western Ontario
- Dr. Hugh R. Whiteley, P.Eng.

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This work benefited enormously from detailed field observations of crop cover collected by Dr. Stewart J. Sweeney, Senior Soil Scientist Ontario Soil Survey, OMAFRA and his staff. We thank Melisa Kopan, OMAFRA for her assistance in preparing and interpreting the data. Nicholas Fitzpatrick P.Eng. (GHD Canada) freely shared his extensive dataset collected at KPM's Reid's property. These data were applied to characterize the geologic and hydrogeologic conditions in the vicinity of the Bethel Road wellfield. Thanks go to Tom Arsenault, Data Control Lead and Melanie Taylor of the Water Survey Division, Environment Canada for their assistance in conducting a data review of historical streamflow observations in the Whitemans Creek subwatershed. We also thank Tecia White, Senior Hydrogeologist, Whitewater Hydrogeology Limited for her efforts in the field data collection phase of this study.

The Grand River Conservation Authority (GRCA) hosted a workshop on February 12th, 2015 at the GRCA Administrative Centre in Cambridge, Ontario. We wish to thank the speakers:

- David Dilks (Lura Consulting)
- Dr. Andy Bajc (Ontario Geological Survey)
- Dr. John Spoelstra (Environment Canada)
- Dr. Laura Timms (Credit Valley Conservation Authority)
- Larry Halyk (Trout Unlimited Canada Middle Grand Chapter)
- Rebecca Shortt (OMAFRA)

We also wish to acknowledge the many attendees who provided comments and feedback during project start-up.

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1 Introduction

1.1 *Background*

The Ontario government passed the Clean Water Act in October 2006 to protect drinking water at the source as part of an overall commitment to human health and the environment. Conservation Authorities have been charged with coordinating the Source Water Protection (SWP) process, including the provision of technical expertise to determine the best ways to protect the quality and quantity of sources of drinking water within a watershed. This is considered to be the first step in a multi-barrier approach to ensuring safe drinking water. SWP studies are funded by the Province of Ontario.

Source Water Protection Plans are being prepared by the Conservation Authorities, with the support of the Regional Municipalities, for each Source Protection Region. An important element of the SWP plan is the technical assessment of potential risks to municipal water supplies from both a water quantity and water quality perspective. A three-tiered approach has been defined under the Clean Water Act for the purpose of assessing the risks to municipal water supplies with respect to water quantity.

According to the SWP assessment process, municipal supplies within subwatersheds that are identified as being potentially stressed are required to undergo a Tier 3 Local Area Water Budget and Risk Assessment (Tier 3 Assessment). The Tier 2 Water Quantity Stress Assessment completed for the Grand River watershed in 2009 (AquaResource, 2009a and 2009b) reported that:

> *The Whiteman's Creek Assessment area was classified as having a Moderate potential for stress based on drought impacts simulated to occur at the Bright #4 well, and supplemental information provided by County of Oxford hydrogeological support staff. Based on this classification, the Bright system meets the requirement under the Technical Rules for the completion of a* [Tier 3] *local water budget and risk assessment."*

Therefore, this Tier 3 Assessment is being undertaken for the groundwater municipal supplies operated by the County of Oxford in the Village of Bright and for the Bethel Road wellfield servicing the Town of Paris, both situated within the Whitemans Creek subwatershed.

Previous studies have shown that the Whitemans Creek subwatershed is drought sensitive and has been subject to frequent Low Water Response declarations. The surface water and groundwater resources of the subwatershed play a critical role in sustaining high-value agricultural activities and supporting an environmentally sensitive cold water fishery. Further to the Tier 3 Assessment objectives, the OMNRF Surface Water Monitoring Centre is funding additional work through this study to improve the understanding of the long-term sustainability of the subwatershed and investigate drought response, agricultural water use, and low-water mitigation strategies within the Whitemans Creek subwatershed.

1.2 *Project Objectives and Scope*

The first objective of this project was to complete a Tier 3 Assessment for the area surrounding the Village of Bright and the Paris Bethel Municipal wellfields. According to the Technical Rules for Assessment Reports (MOE, 2009), the Tier 3 assessment includes:

- defining a "local area" around each municipal wellfield;
- conducting detailed water budget assessments for each local area;
- delineating vulnerable areas around each well or wellfields with respect to water quantity (WHPA-Q1/WHPA-Q2); and
- quantifying the level of risk of failure to provide adequate supply for existing and planned municipal water demand after accounting for other water use in the area under current and proposed land use and under average climate and drought conditions.

The work program for the Tier 3 Assessment was designed in accordance with the Technical Rules for Assessment Reports (under the Clean Water Act, 2006)) and the updated Water Budget and Water Quantity Risk Assessment Guide (referred to herein as the Water Budget Guide) developed for the Ontario Ministry of Natural Resources and Ontario Ministry of the Environment (MNR, 2011).

The objective of a Tier 3 Assessment, as defined in the Water Budget Guide, is to:

> *"…estimate the likelihood that a municipality's drinking water wells will be able to supply their allocated pumping rates considering increased municipal water demand, projected land development, drought conditions, and other water uses".*

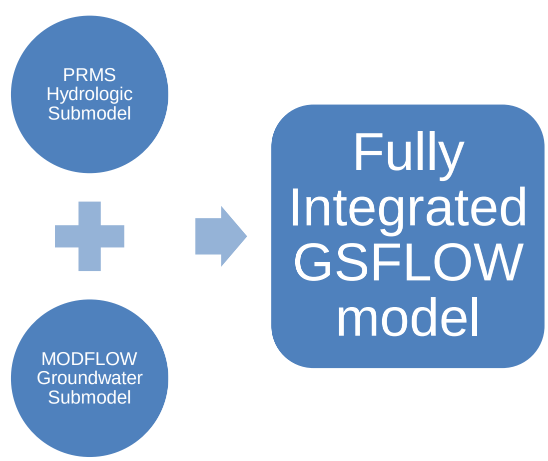
Specifically, the Tier 3 Assessment includes the development of refined surface water and groundwater flow models and the application of the models to evaluate groundwater or surface water supply sources in the local area surrounding the municipal supply well. Various scenarios (related to future land-use practices, future water demand, and drought conditions) are evaluated with the models to assess the response of the groundwater and the surface water systems and evaluate the risk that a community may not be able to meet its current or planned water demands from the municipal water source.

While the first objective of this study addresses municipal well supply issues, a second objective was to improve the overall understanding of the watershed function under low water response conditions. Groundwater resources play an important role during drought periods because water stored in aquifers can help to sustain streamflows and supply farms with water for crop irrigation. The Whitemans Creek subwatershed has a high density of agricultural water users; therefore, understanding the effects of drought and increased irrigation demand on the groundwater system is of critical importance when it comes to balancing hydrologic, ecological and agricultural interests within the subwatershed. Additional studies are planned to use the model developed as part of the Tier 3 Assessment to investigate drought response, evaluate the effects of agricultural water use, and help identify low-water mitigation strategies.

1.3 *Technical Approach*

The hydrologic and hydrogeologic conditions in the Whitemans Creek subwatershed are highly variable and previous studies indicate that there is a significant interaction between the groundwater and surface water systems. The interactions are complex, non-linear, and highly transient in nature. Characterizing the response of streams, wetlands, and aquifer levels to changing climate and water use is essential to the understanding the overall water budget and function of the subwatershed.

To address this complexity and system interaction a fully integrated surface and groundwater modelling approach was selected for this study. The project objectives can best be addressed with a modelling tool that represents the complexity and dynamic feedback between the systems in a consistent and detailed manner. The integrated model represents both the daily interactions and longer-term seasonal and inter-annual changes in subsurface storage under a wide range of climatic and water use conditions.



The U.S. Geological Survey GSFLOW integrated model computer code (Markstrom *et al*., 2008) was selected for use in this study. GSFLOW is constructed from two proven USGS submodels: MODFLOW and PRMS. The components and linkage of these models is described in detail in Section 7. The integrated model represents all surface water bodies (streams, wetlands, lakes, and ponds) as well as the subsurface geologic and hydrogeologic features in the study area.

1.4 *Study Area Extents and Model Boundary*

The dual objectives of this integrated modelling study include the analysis of both the municipal supply wells and the broader function and behavior of the Whitemans Creek subwatershed (referred herein as the *study subwatershed*). To address the wellfield issues the model has been developed and refined to a level of detail needed to assess the Tier 3 Assessment objectives. To assess the subwatershed-scale objectives, the study area and model boundaries have been extended beyond the limits of the subwatershed to capture the regional hydrologic and hydrogeologic processes which influence the subwatershed. Lateral groundwater inflows and outflows across the boundaries of the subwatershed can represent significant components of the overall water balance and may influence the sub-regional and local groundwater and surface water flow systems. Accordingly, the model boundary encompasses a 1,400 km^2 area (referred to as the *model area*) as shown in Figure 1.1. The boundaries of the model area were selected to correspond to natural physical boundaries such as watershed divides and/or significant surface water or groundwater features. The rationale for the selection of model boundaries is discussed further on in Section 9.2.

1.5 *Report Scope and Structure*

The objective of this report is to present the development and calibration of the integrated model. The application of the integrated model for the Tier 3 Assessment will be presented in a subsequent document. This report will serve as the detailed foundation for that work.

Please note that the documentation of an integrated model is both highly technical and very detailed, because the broad range of scientific disciplines within the scope of the work. This report broadly consists of three sections. The first, in Sections 1 through 6, present a detailed discussion of the groundwater and surface water resources of the model area. Section 7 introduces the GSFLOW model code and provides an overview of the model behavior. Sections 8 through 11 present the model representation of the study area and the calibration of the model to field observations.

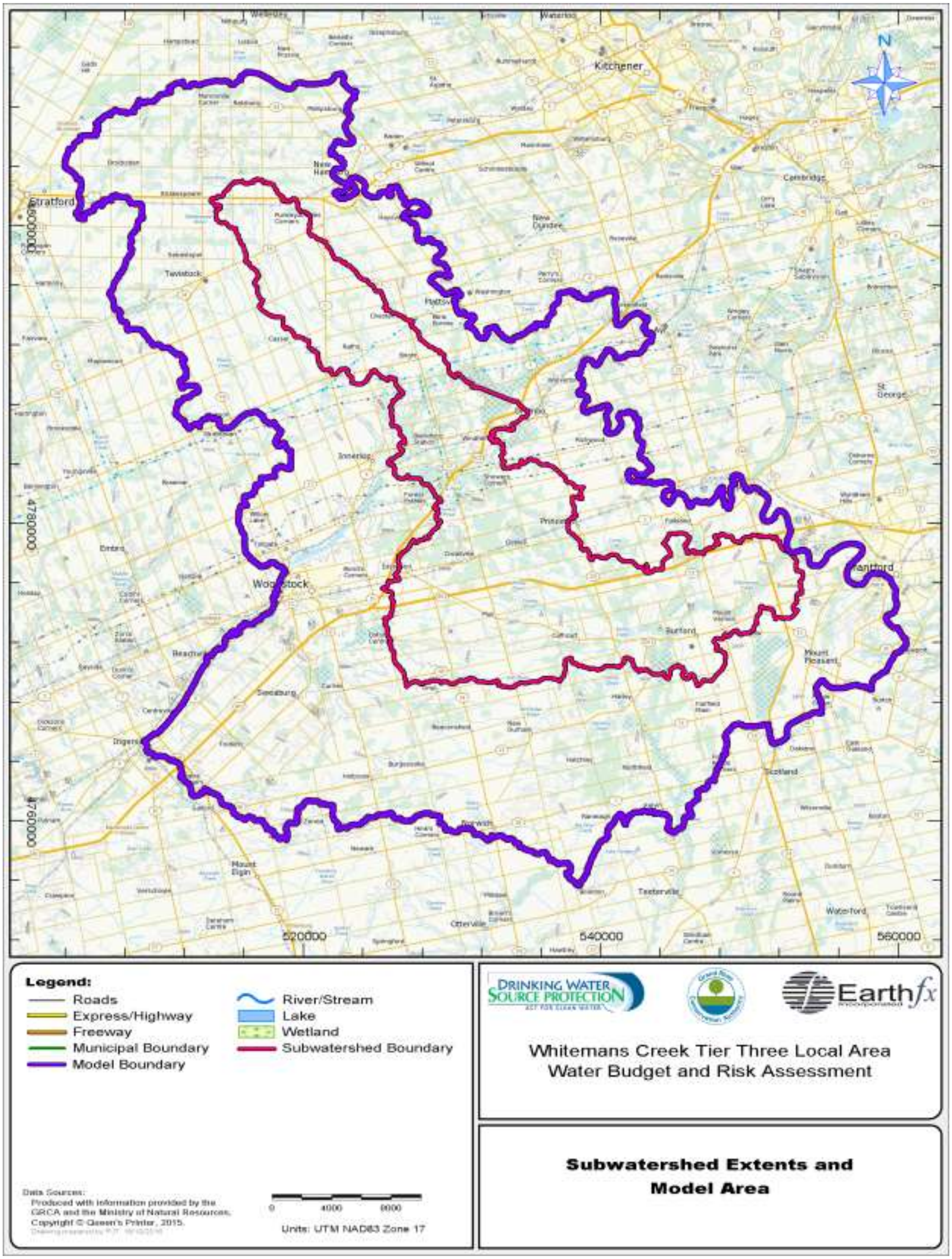


Figure 1.1: Whitemans Creek Tier 3 study subwatershed and model boundaries.

2 Watershed Overview

The Whitemans Creek subwatershed is located in southwestern Ontario between the City of Brantford to the west and City of Woodstock to the east (Figure 1.1). The subwatershed drains an area of approximately 400 km² from headwaters in the northwest to an outfall into the main branch of the Grand River to the southeast. From the Whitemans outfall, the Grand River discharges into Lake Erie at Port Maitland and onwards into the St. Lawrence River.

The subwatershed covers nine historic geographic townships: Brantford, Burford, Blenheim, Oxford (on Thames), Blandford, Bright, Zorra, Wilmont, and North and South Easthope (Figure 2.2) (Geographic township boundaries were obtained from OMNR (2015a)). The majority of the watershed is now part of Brantford and Oxford Counties, with a small portion overlapping with Perth County and the Regional Municipality of Waterloo. The natural resources of the subwatershed are managed by the Grand River Conservation Authority (GRCA).

The western and southern extent of the Whitemans Creek subwatershed defines the watershed divide between the Grand River and the Thames River to the west, and Big Creek to the south. Whitemans Creek is shown in relation to its neighbouring catchments on Figure 2.3. The subwatershed is home to three main tributaries; Whitemans, Horner, and Kenny Creeks, which have a combined stream length of 369 km. Whitemans Creek transitions into Horner Creek upstream of the town of Princeton, while the tributary of Kenny Creek joins Whitemans Creek from the west near Burford. The central portion of the watershed is home to a number of Provincially Significant Wetlands (PSW's) as shown on Figure 2.4; primary Benwall Swamp, Pine Pond, and Chesney Bog. Black Creek Swamp straddles both the Whitemans Creek and Nith subwatersheds west of Drumbo

Land surface topography for the study area, based on a 10-m digital elevation model (DEM), is shown in Figure 2.5. Relief in the study area is generally low, with some local topographic variation occurring where creeks and streams have incised through the Tillsonburg, Paris, and Galt Moraines that traverse the central and southeastern portions of the study watershed (the physiography of the study area is discussed in Section 3.1). Minimum elevation is 210 metres above sea level (masl) at the Grand River confluence, rising to 385 masl in the northwest portion of the watershed (Figure 2.6). Elevation profiles of Whitemans Creek from its headwaters in Horner and Kenny Creeks to its confluence with the Grand River are presented in Figure 2.7 and Figure 2.8, respectively.

2.1 *Historical Settlement and Land Use*

The original inhabitants of the subwatershed were the Attiwandaronk First Nations, numbering approximately 5,000 in the Brant County area prior to European contact. The tribe was historically known as the Neutral Indians as they remained passive in the wars between the Huron and Iroquois tribes. The Attiwandaronk were obliterated by the Iroquois in 1653 after sheltering French Jesuit refugees from Fort Ste. Marie (Sainte-Marie among the Hurons) and a nearby Huron tribe (Dunham, 1945). The sub-watershed remained largely uninhabited for the next 130 years (Reville, 1920).

European resettlement of the watershed began in the late 1790s, delayed by the swampy nature of the area, which posed a barrier to transportation. Several mills were constructed along the Creek in the early phases of resettlement. The first was built by Abraham Dayton in 1793 at the mouth of Whitemans Creek. Shortly after, Thomas Hornor settled the lower banks of the now Horner Creek and constructed several grist and saw mills on the Whitemans Creek at Princeton (Warner, Beers & Co., 1883). Warner, Beers & Co. suggest that Whitemans Creek was named for Thomas Horner, the first white man to settle in the subwatershed (see http://www.ingersolltimes.com/2010/07/14/how-horner-creek-got-its-name).

Burford Township reached full settlement by the late 1820s, however, the water resources in the area continued to attract investment. N.A. Fraser purchased the land in 1841 where the Apps' Mill Conservation Area sits today (McKean, 1976). Fraser dug out the mill pond at the site, and created the dyke which runs along the southern border of the pond, adjacent the river, from scab of the pond (Figure 2.9). The early mill was primarily used to grist flour and required very little head; a small upstream diversion channel provided adequate volume to fill the mill pond. William and Charles Apps immigrated from Battle, East Sussex, England in 1854 and purchased the mill and a partially constructed home from Mr. Fraser in 1858.

Early settlers to the subwatershed found an untamed wilderness; describing streams abundant with brook trout and beaver. Less welcome neighbours such as bears, wolves, and Mississauga rattlesnakes were quickly eliminated. Settlers into the interior found “oak openings” or “oak islands” on the swampy interior plains which boasted some of the most fertile soil in Upper Canada, prompting widespread land clearing across the subwatershed. When referring to the creeks of Burford Township, Warner, Beers & Co. offer a description of the hydrologic effects of this early settlement:

> *“Big Creek,” rising in Oxford, flows into Burford at the southern part of the west boundary, and flows with an exceedingly tortuous and sluggish course east into Wyndham. “King’s” and “Landon’s” Creeks, with several minor tributaries, intersect the township, adding beauty and verdure to the land through which they flow. But every year since the destruction of the forests which fed and secured them, the streams grow less; the brook trout and other fish, thirty years ago so abundant in these creeks, have disappeared, poisoned, it is thought by the sawdust from the mills.* (Warner, Beers & Co., 1883)

With changing land use in the area and increasing irrigation to support local tobacco farming, the flow was further reduced in Whitemans Creek. By the 1900’s, summer low flow was reduced to “a mere trickle” during the months when grain farmers needed their produce ground at the Apps’ Mill. A series of structures, ranging from temporary brush and gravel weirs to a concrete wing dam, were constructed at Apps’ Mill from the 1910s into the 1950s to divert sufficient flow into the mill pond during the summer months. Evidence of these water taking structures are still visible at Apps’ Mill today (Figure 2.10). With Albert Apps death in 1956, the mill was closed, leaving the site unused for over 20 years.

By the late-1950s, 78% of the Whitemans Creek subwatershed was dedicated to agriculture (Latornell, 1962). A survey of 195 famers in the subwatershed found that 184 were irrigating croplands an average of six times per year. The survey reported that 36% were diverting flow from streams, with a further 56% taking water from online or offline ponds. Irrigation demand was reportedly so large that many small streams were pumped completely dry. In response to the water demands in the watershed, a series of dams were proposed to hold back the spring freshet for use later in the growing season. Several schemes were proposed which included dams on Kenny Creek at Vandecar, Horner Creek at Princeton, and Whitemans Creek at Apps Mill. These plans were advanced in the 1960s through a series of engineering feasibility studies (Kilborn, 1969) and management programs.

The Grand River Conservation Authority acquired 258 acres in the Whitemans Creek valley, including the former Apps’ Mill, in the mid-1960’s for use as part of a future reservoir project. These water control projects never came to pass, either due to economic factors or increasing annual precipitation trends. During the mid-1970’s, the Kiwanis Club of Brantford leased an 11 acre parcel of land to north of the mill site for development as a meeting place and summer camp. In turn, the Club paid $100,000 to aid in the preservation of the Apps’ Mill. Also during this period, the GRCA began a tree plantation program with an aim to restore native species. In the early 1980’s, the GRCA, with a grant from SC Johnson and Son Limited, developed the Apps’ Mill and adjacent lands as an interpretive recreational area. A one-story nature center was built at Rest Acres Park to provide environmental education programs to the general public and nearby school boards year round.

2.2 *Modern Land Use*

Current land use and coverage within the Whitemans Subwatershed were evaluated with the Southern Ontario Land Resource Information System (SOLRIS v2) mapping compiled by MNR (2014). The coverage is provided on Figure 2.11 and clearly shows the significance of the agricultural land use over the region. Actively cultivated agricultural fields comprise 60% of the watershed, with “undifferentiated uses” encompassing an additional 16%. Within the Whitemans Creek watershed, the undifferentiated classification includes some agricultural features not included in tilled classification such as orchards, fallow lands, and undeveloped pastures. This brings the total estimated agricultural coverage to 76%

(304 km²) of the subwatershed. Natural areas, including forests and wetlands, cover 19% of this relatively rural area. Developed or settled areas (i.e., rural residential, transportation, parks, industrial, commercial, etc.) cover the remaining 5% of the subwatershed area. A detailed breakdown of the SOLRIS land coverage for the subwatershed is provided in Table 2.1 and illustrated on Figure 2.1.

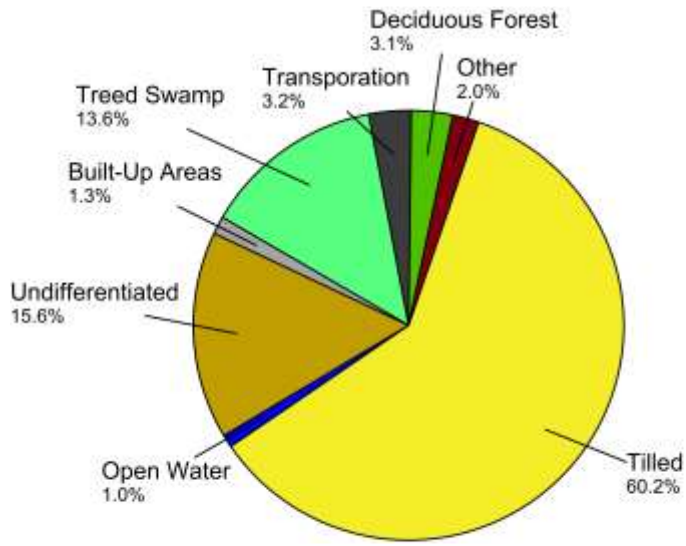


Figure 2.1: Summary of land use within the within the Whitemans Creek watershed (MNR SOLRIS v2, 2014).

Given the large percentage of the subwatershed dedicated to agricultural activity and the swampy nature of the Kenny and Horner headwater, a significant portion of the subwatershed has been tile drained as shown on Figure 4.5. The distribution of tile drainage around the subwatershed likely has a significant effect on the hydrologic behavior of the watershed and is further discussed in Section 4.3. Irrigation of croplands, the principal water use in the Whitemans Creek subwatershed, is discussed in Section 6.

2.3 *Agricultural Land Use*

Agricultural land usage within the study area is documented in crop inventories available from Ontario Ministry of Agriculture, Farming and Rural Affairs (OMAFRA) and Agriculture and Agri-Food Canada (AAFC). Agriculture resource inventory (AgRI) mapping is available for 1983 (Figure 2.12), 2013 (Figure 2.13), and 2016 (Figure 2.14) from OMAFRA and are derived from air photo analysis combined with windshield surveys. The recent AgRI products cover only the Whitemans Creek subwatershed, while the 1983 mapping covers much of southwestern Ontario. Annual crop inventory mapping has been produced by AAFC for southern Ontario since 2011, and the 2013 mapping is presented on Figure 2.15. The AAFC dataset is primarily derived from RADARSAT-2 radar imagery with Landsat-8 optical imagery and is provided as a 30x30 m raster (AAFC, nd.).

The recent AgRI 2013 and 2016 mapping products (Figure 2.13 and Figure 2.14, respectively) were analyzed to determine the crop types grown within the Whitemans Creek subwatershed (Table 2.2). The primary crops are corn and other field crops such as soybeans, wheat, forages (e.g., hay and alfalfa) and cereals (e.g., barley and rye). When combined, these represent the majority of the land coverage. The 2013 dataset had approximately 5800 acres classified as “field” with the specific crop type information left blank. These parcels were assumed to be agricultural, but with an unknown crop type or land usage and were subsequently re-classified as “unknown”. Approximately 12% of the agricultural area within the subwatershed is classified as “unknown”, because fields without road access could not be positively identified in the windshield survey. The 2016 data appear to be more complete, with only 9% of the subwatershed area remaining unclassified.

The historical 1983 AgRI mapping (Figure 2.12) provides some insight into the changing crop patterns within the study area. Total agricultural coverage appears to have remained consistent over the last 30 years (79% compared with 77% agricultural land currently). The agricultural landscape however, has changed since the previous 1983 ARI survey as shown in Table 2.3. While the different crop classes used in each survey make the two datasets difficult to compare directly, tobacco appears to have played a much larger role in 1983, covering over 5,600 ha of the 40,000 ha watershed, compared to current estimates of tobacco coverage at approximately 700 ha. The total subwatershed area dedicated to tobacco has dropped from 14% to 2%. Many of the tobacco farms have been repurposed for corn, wheat and other crops. Some of the parcels that have been classified as unknown in the 2013 and 2016 data correspond to tobacco farms from the 1983 data; therefore, it is possible that some of these unknown farms are still growing tobacco. This assumption is only relevant in the southeastern and central regions of the subwatershed where tobacco growth has historically been abundant.

The remotely-sensed AAFC crop inventory mapping was also analyzed to estimate agricultural land practices within the Whitemans Creek subwatershed. The AAFC mapping covers the entire study area with no gaps or unclassified areas. While not field-verified to the same extent as the AgRI data, the AAFC mapping offers a more complete coverage over a wider area. Table 2.5 presents a breakdown of the crop and land coverage in the subwatershed for 2011 through 2015. As noted in the AgRI dataset, the crop types within the subwatershed appear to be dominated by corn and other field crops such as soybeans, wheat, forages and cereals which, in 2013, represented 70.6% of the subwatershed area, or 94% of the identified agricultural area. The methods used to derive the AAFC crop inventories have improved over the period of record, with a noted improvement in accuracy of over 10% for 2013 and onwards when Landsat-8 imagery was introduced to the classification methodology (AAFC, nd.).

A limited comparison of the relative quality of the remotely-sensed AAFC crop inventories relative to the field-verified OMAFRA AgRI mapping was undertaken. The comparison is based on the percentage of each crop type identified by the AAFC data that match the ARI crop description. Some minor crop types from both ARI and AAFC were combined for ease of comparison (e.g., edible beans were combined with other vegetables). No comparison could be made for instances where AAFC data corresponded to areas classified as unknown by the ARI survey. The results of the comparison are summarized in Table 2.4. On an area-weighted basis, there is a 69% match between the 2013 AgRI and the 2013 AAFC crop inventory. Good accuracy is found on the majority crop types of corn and soybeans, with a generally good match also found for crop types associated with irrigation (tobacco, sod, vegetables, and ginseng.) Overall accuracy of the 2013 AAFC crop inventory was estimated at 87.0% for the province of Ontario (AAFC, nd). While the suggested accuracy is lower within the Whitemans Creek subwatershed, the overall agreement is good. Based on this assessment, the AAFC rasters can reliably be used to augment and infill the recent OMAFRA AgRI products, where necessary, should parameterization of the numerical model require detailed agricultural mapping.

2.4 *Aquatic and Terrestrial Habitat*

Whitemans Creek cold water fisheries support three salmonid species; Brown, Brook, and Rainbow Trout (refer to thermal mapping provided on Figure 2.16). The creek is also home to Rock Bass, Brook Lamprey, and several families of Perch Darters and Suckers. The lower reach of Whitemans Creek provides habitat for the Wavyrayed Lampmussel, a species of special concern (DFO, 2015). The Silver Lamprey, also a species of concern, is found within the several tributaries of Whitemans Creek above Kenny Creek (DFO, 2015). These species combine to form a diverse and complex aquatic environment, unique in the surrounding region.

Several sources reference the historically poor condition of the aquatic habitat in Whitemans Creek. In 1953, it was observed that there is “remarkably” little Speckled or Brown trout in the watershed. A 1953 survey found Brown Trout at only two locations in the watershed, and no Brook or Rainbow trout were spotted (GRCA, 1954). At the time, this was attributed to the high temperature fluctuations in the watershed, a result of heavy irrigation. The 1962 subwatershed conservation report states that “*Whiteman Creek and its tributaries have little value as fishing waters*” (Latornell, 1962). While Brown Trout have been stocked in Whitemans Creek as early as 1914 (Lasenby and Kerr, 2001), a concerted effort has been made by the GRCA and local volunteers to restore salmonids to the subwatershed over the past 40 years. Whitemans Creek is now considered prime salmonid spawning habitat with a portion of Horner Creek and the entirety of Whitemans Creek designated a fish sanctuary by the Ministry of Natural Resources (OMNR). Catch limits on Brown and Rainbow trout exist between Cleaver and Robinson roads, and fishing on the creek is prohibited during spawning periods. This restriction was originally initiated in 1990 to control the harvest of young trout.

There is little remaining representation of the indigenous Carolinian forest that inhabited the area before European colonization. The majority of forested conservation lands are first-stage successional species. These include Cottonwood, Trembling Aspen, Balsam Poplar, Willow, and shrubbery. Secondary species include Poplar, Sugar Maple, and several varieties of oak. Forested areas make up 3.5% of the land cover in Whitemans Creek. However, Whitemans Creek, in combination with the Horner and Kenny branches, serves as a continuous terrestrial habitat corridor from the Grand River Valley into Oxford and Norwich counties.

2.5 *Tables and Figures*

Table 2.1: Land use within the Whitemans Creek watershed (MNR SOLRIS v2, 2014).

SOLRIS ID	Name	ELC Code	Area (km²)	Percentage of Watershed
193	Tilled	--	241	60.20%
250	Undifferentiated	UN	62.6	15.60%
131	Treed Swamp	SWC/SWM/SWD	54.6	13.60%
201	Transportation	COT	12.7	3.20%
93	Deciduous Forest	FOD	12.4	3.10%
160	Marsh	MA	3.2	0.80%
202	Built-Up Area - Pervious	COP	3	0.70%
135	Thicket Swamp	SWT	2.2	0.60%
191	Plantations –Tree Cultivated	CUP	2.3	0.60%
203	Built-Up Area - Impervious	COI	2.4	0.60%
192	Hedge Rows	CUH	1.6	0.40%
204	Extraction - Aggregate	COE	1	0.30%
90	Forest	FO	0.7	0.20%
91	Coniferous Forest	FOC	0.4	0.10%
92	Mixed Forest	FOM	0.5	0.10%
140	Fen	FE	0.2	0.10%
170	Open Water	OA	0.3	0.10%

Table 2.2: 2013 and 2016 ARI breakdown of the Whitemans Creek subwatershed.

Description		2013			2016		
		Number of Field Parcels	Area (ha)	Percentage of Whitemans Subwatershed	Number of Field Parcels	Area (ha)	Percentage of Whitemans Subwatershed
AGRICULTURAL	Corn	911	9636	23.7%	966	9423	23.2%
	Soybeans	601	5965	14.7%	716	6147	15.1%
	Unknown	1246	4935	12.1%	954	3703	9.12%
	Winter Wheat	180	2294	5.65%	300	2546	6.27%
	Other - Agricultural	2523	1842	4.53%	2583	2474	6.09%
	Alfalfa/Grass/Hay	255	1753	4.31%	297	1776	4.37%
	Roughland	2495	1725	4.25%	2207	1291	3.18%
	Grain	92	762	1.88%	146	881	2.17%
	Tobacco	68	542	1.34%	27	257	0.63%
	Vegetable	50	528	1.30%	84	677	1.67%
	Pasture	153	491	1.21%	264	657	1.62%
	Edible Beans	18	191	0.47%	78	907	2.23%
	Ginseng	26	138	0.34%	21	98.6	0.24%
	Sod	4	60.9	0.15%	5	93.3	0.23%
	Sugar Beet	4	57.8	0.14%	1	17.7	0.04%
	Fruit	8	23.4	0.06%	5	7.95	0.02%
	Specialty Crop Land	26	21.4	0.05%	90	452	1.11%
	Greenhouse	45	19.7	0.05%	51	15.9	0.04%
	Lettuce	4	13.7	0.03%	2	5.7	0.01%
	Blueberries	1	0.98	0.00%	1	0.98	0.00%
	Sub-Total	***8710***	***30999***	***76.3%***	***8798***	***31431***	***77.6%***
NON-AGRICULTURAL	Natural Areas	1778	7689	18.9%	1776	7625	18.8%
	Built Up	529	1003	2.47%	521	586	1.44%
	Infrastructure	256	884	2.18%	255	879	2.16%
	Other	5	44.3	0.11%	1	6.1	0.01%
	Sub-Total	***2568***	***9621***	***23.7%***	***2553***	***9095***	***22.4%***
Grand Total		**11278**	**40620**	**100.0%**	**11351**	**40527**	**99.8%**

Table 2.3: 1983 ARI breakdown of the Whitemans Creek subwatershed.

1983 ARI Description	Number of Field Parcels	Area (ha)	Percentage of Whitemans Subwatershed
Corn System	140	8919	22.2%
Mixed System	91	7617	19.0%
Continuous Row Crop	121	6295	15.7%
Tobacco System	55	5611	14.0%
Grain System	66	1096	2.73%
Hay System	50	874	2.18%
Extensive Field Vegetables	33	489	1.22%
Grazing System	33	489	1.22%
Pasture System	12	147	0.37%
Mkt. Gardens / Truck Farms	7	62	0.15%
Orchard	3	32	0.08%
Nursery	3	10	0.02%
Non Agricultural	403	8461	21.1%
Total	***1017***	***40100***	***100%***

Table 2.4: Comparison of ARI and AAFC crop inventory mapping within the Whitemans Creek subwatershed.

2013 ARI Crop Type	Area of Crop Identified by AAFC (ha)	Area of ARI and AAFC Matches (ha)	Percent Matching
Corn	9268	8315	89.7
Soybeans	5883	4950	84.1
Cereals	4556	2454	53.9
Wheat	2694	1824	67.7
Pasture/Forages	2279	1430	62.8
Vegetables	424	280	66.0
Tobacco	366	299	81.7
Sod/Turf	60.8	34.92	57.5
Ginseng	43.8	38.8	88.5
Fruit	32.7	7.11	21.8
Nursery	24.5	1.26	5.15
Total	***16,364***	***11,319***	***69.2%***

Table 2.5: Subwatershed land coverage (2011-2015), as determined from AAFC crop mapping.

	Description	Index Code	2011	2012	2013	2014	2015
AGRICULTURAL	Corn	147	32.0%	30.4%	29.2%	31.7%	27.9%
	Soybeans	158	13.9%	22.3%	19.5%	21.4%	26.4%
	Pasture / Forages	122	15.6%	10.4%	11.8%	12.2%	12.5%
	Wheat	140	--	--	9.3%	5.9%	4.2%
	Rye	137	--	--	0.9%	0.7%	1.2%
	Tobacco	148	--	--	2.0%	0.4%	0.9%
	Potatoes	177	--	0.0%	0.8%	0.1%	0.5%
	Other Vegetables	179	--	0.8%	0.7%	0.1%	0.4%
	Ginseng	149	--	--	0.2%	0.3%	0.4%
	Oats	136	--	--	0.2%	0.1%	0.3%
	Sod	192	--	--	0.2%	0.1%	0.1%
	Orchards	188	--	0.6%	0.1%	0.0%	0.1%
	Nursery	194	0.1%	0.1%	0.2%	0.2%	0.1%
	Barley	133	--	--	0.4%	0.1%	0.1%
	Vineyards	190	--	--	--	--	0.1%
	Peas	162	--	--	--	0.2%	0.0%
	Beans	167	1.9%	0.5%	--	0.3%	0.0%
	Other Crops	199	1.1%	2.7%	--	--	0.0%
	Fallow	131	0.1%	0.5%	--	0.0%	--
	Cereals	132	12.1%	6.2%	--	--	--
	Canola / Rapeseed	153	0.1%	--	0.0%	--	--
	Vegetables	175	1.5%	--	--	--	--
	Berries	181	--	0.2%	0.0%	0.0%	--
	Other Fruits	189	--	--	0.0%	0.1%	--
	Herbs	193	0.4%	0.1%	--	--	--
	Buckwheat	195	--	0.1%	0.1%	--	--
		Sub-Total	***78.8%***	***74.7%***	***75.5%***	***73.9%***	***75.1%***
NON-AGRICULTURAL	Broadleaf	220	16.9%	17.3%	17.8%	15.5%	14.9%
	Urban / Developed	34	2.5%	2.0%	2.4%	4.8%	4.7%
	Shrubland	50	0.5%	2.5%	1.1%	2.8%	2.5%
	Mixedwood	230	0.8%	1.5%	1.5%	1.3%	1.4%
	Wetland	80	0.3%	0.8%	0.6%	1.0%	0.9%
	Water	20	0.1%	0.1%	0.2%	0.3%	0.2%
	Exposed Land / Barren	30	0.1%	0.9%	0.8%	0.2%	0.1%
	Grassland	110	0.0%	0.0%	--	0.1%	0.0%
		Sub-Total	***21.2%***	***25.2%***	***24.4%***	***26.0%***	***24.8%***
		Grand Total	***100%***	***100%***	***100%***	***100%***	***100%***

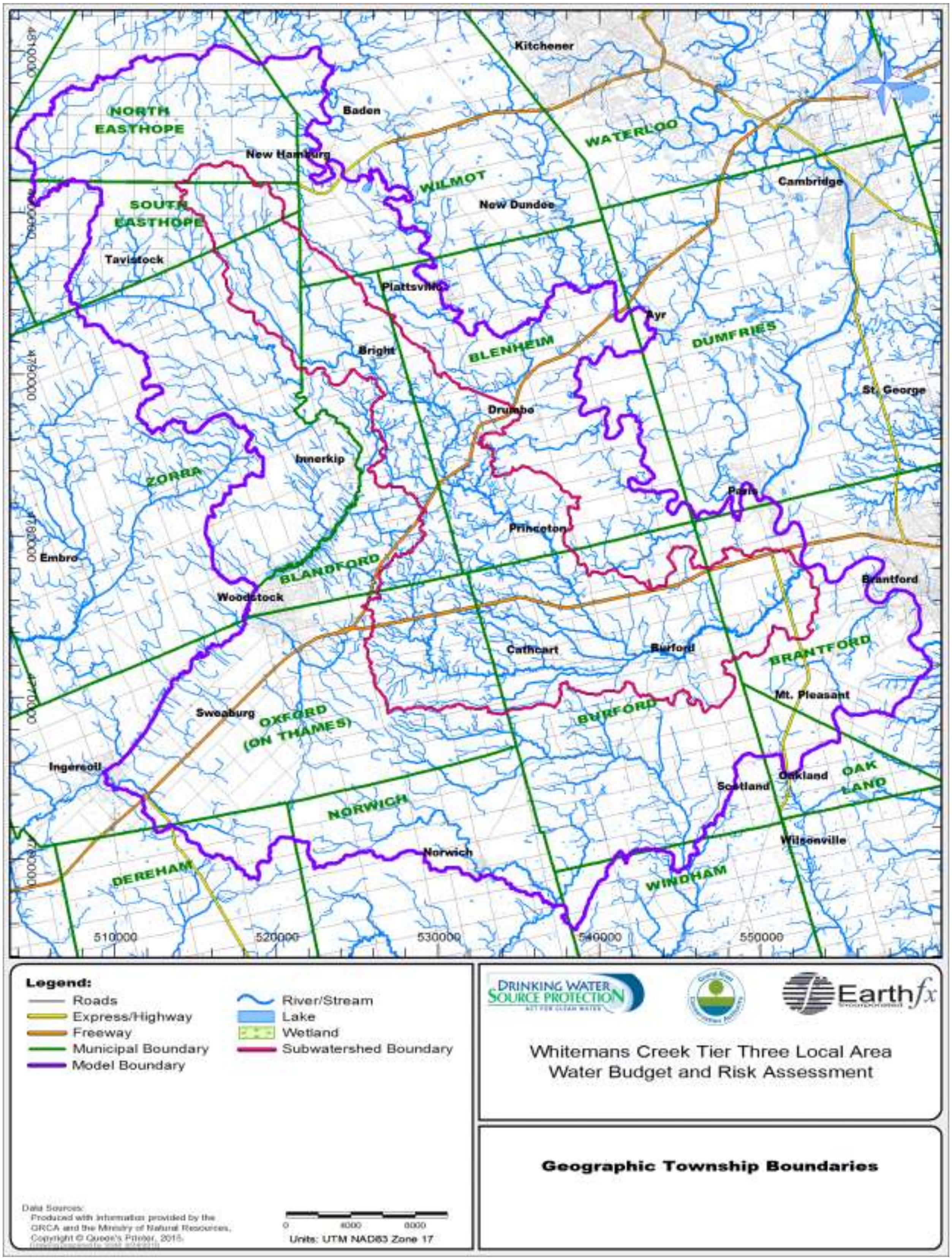


Figure 2.2: Geographic township boundaries (OMNRF, 2013).

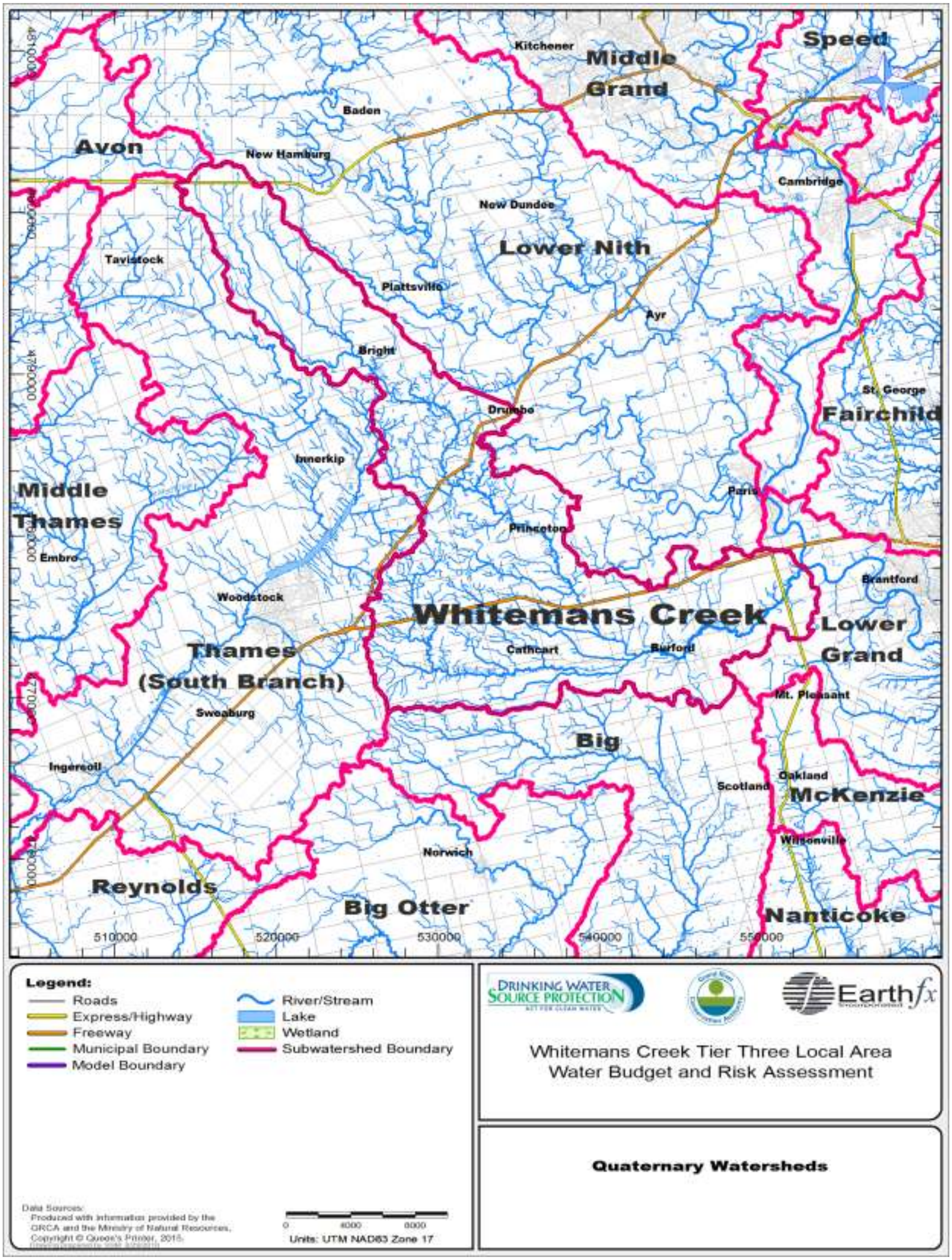


Figure 2.3: Quaternary watersheds.

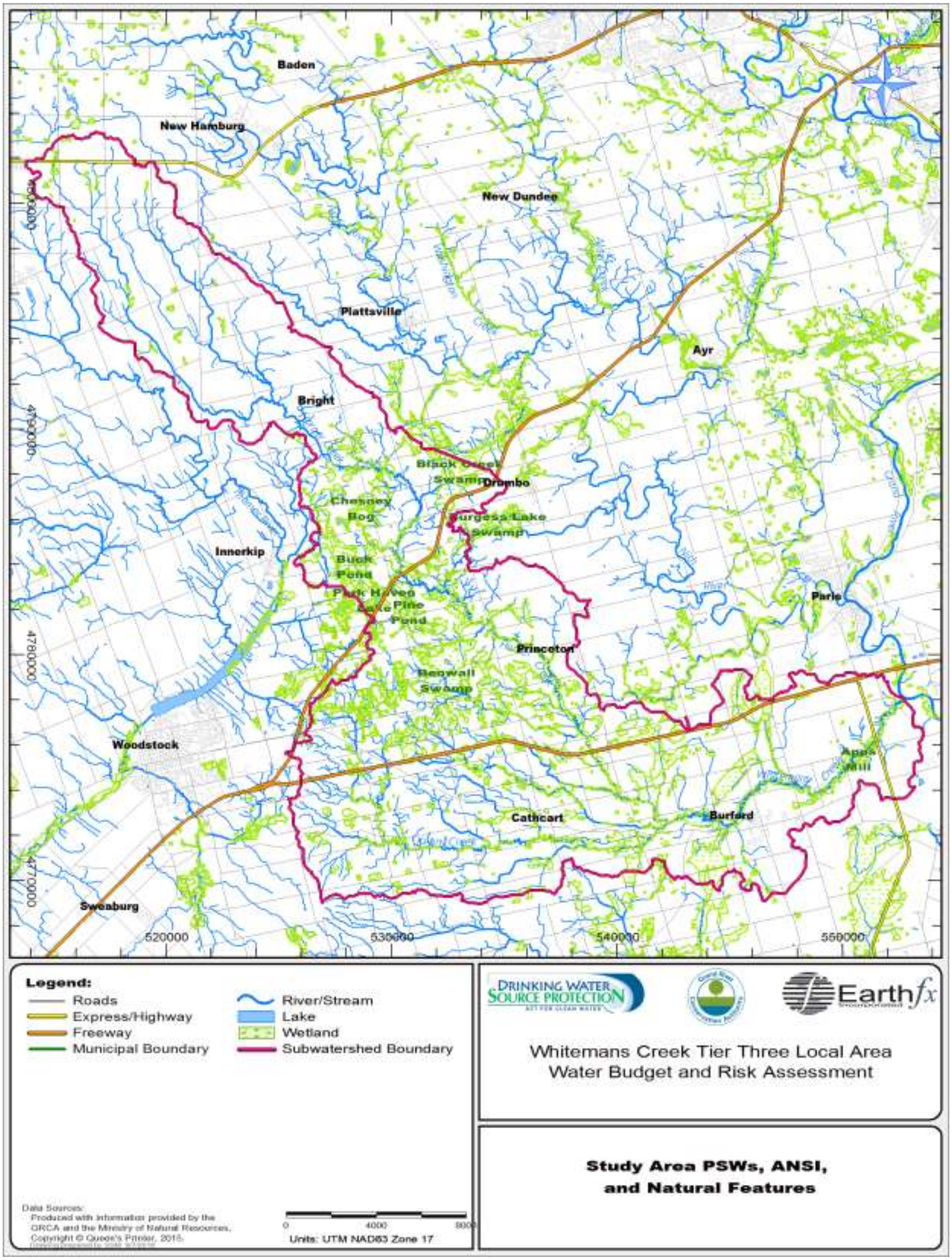


Figure 2.4: Study area Provincially Significant Wetlands (PSW), Areas of Natural and Scientific Interest (ANSI), and other natural features

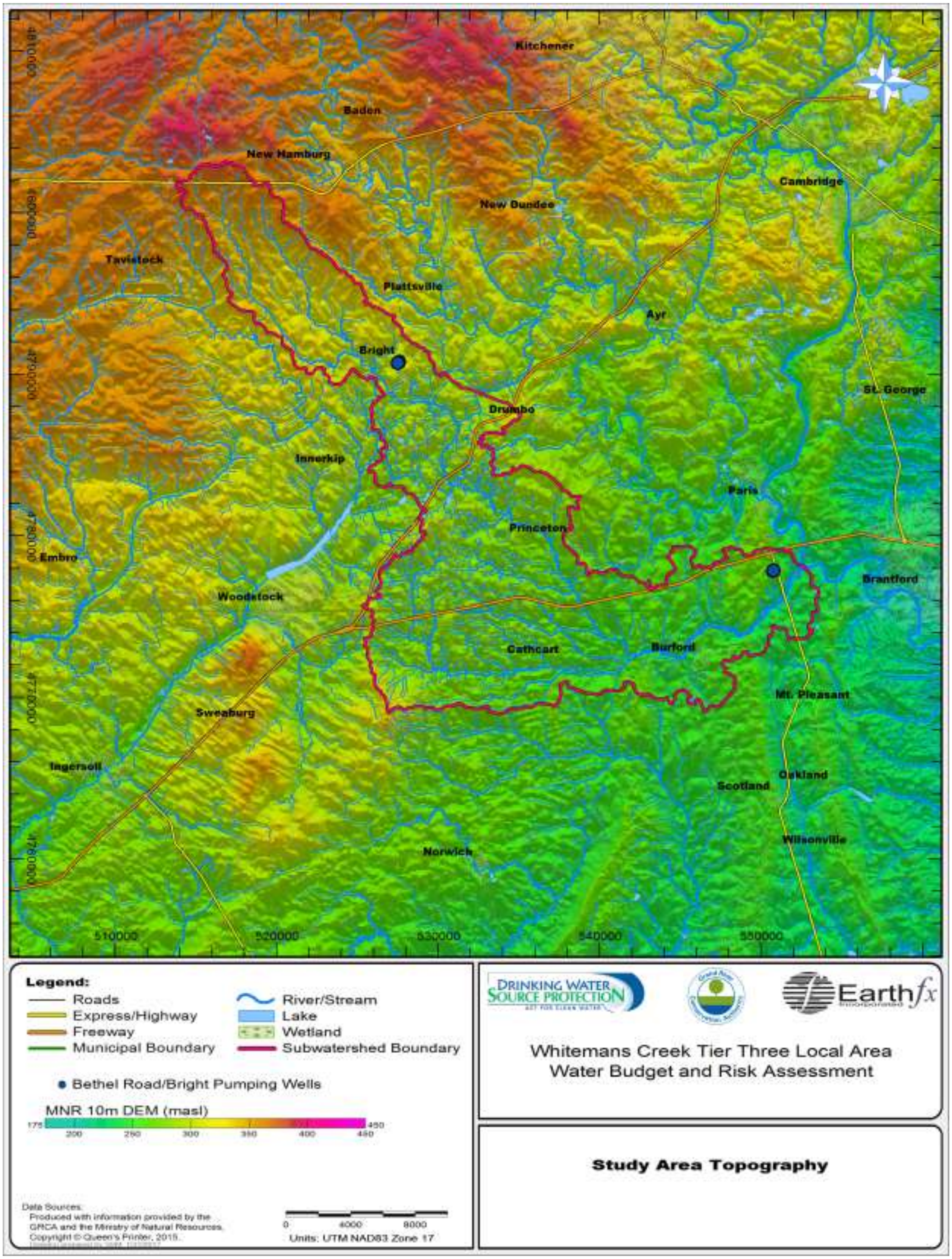


Figure 2.5: Study area topography.

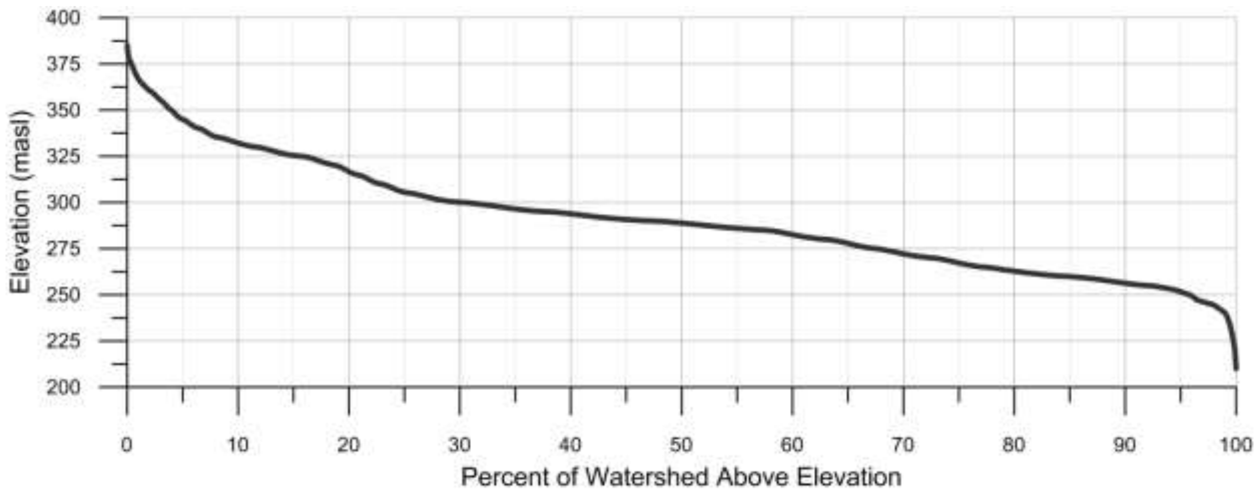


Figure 2.6: Hypsometric profile of the Whitemans Creek subwatershed.

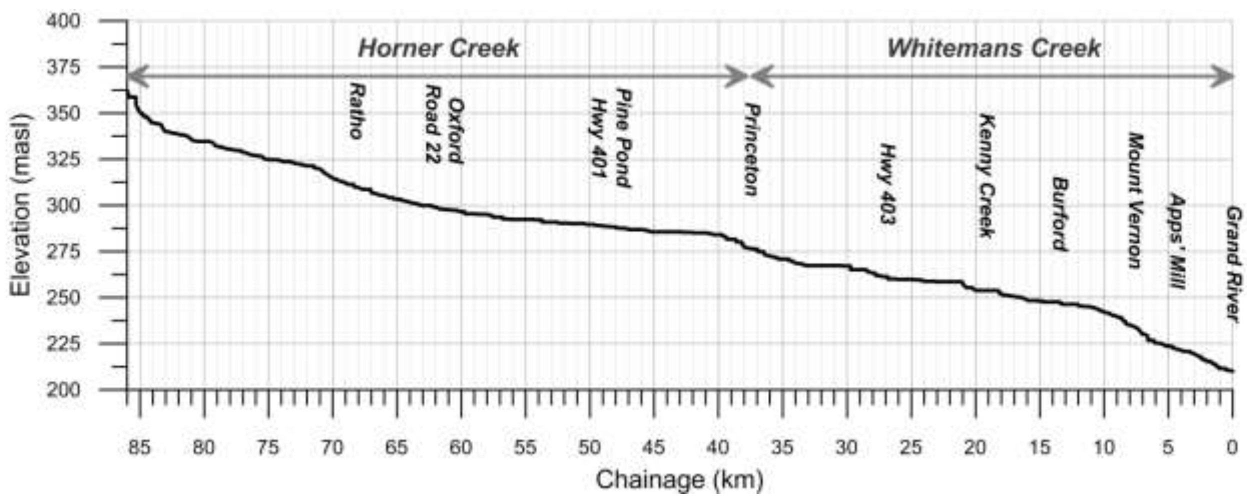


Figure 2.7: Elevation profile of Whitemans and Horner Creeks.

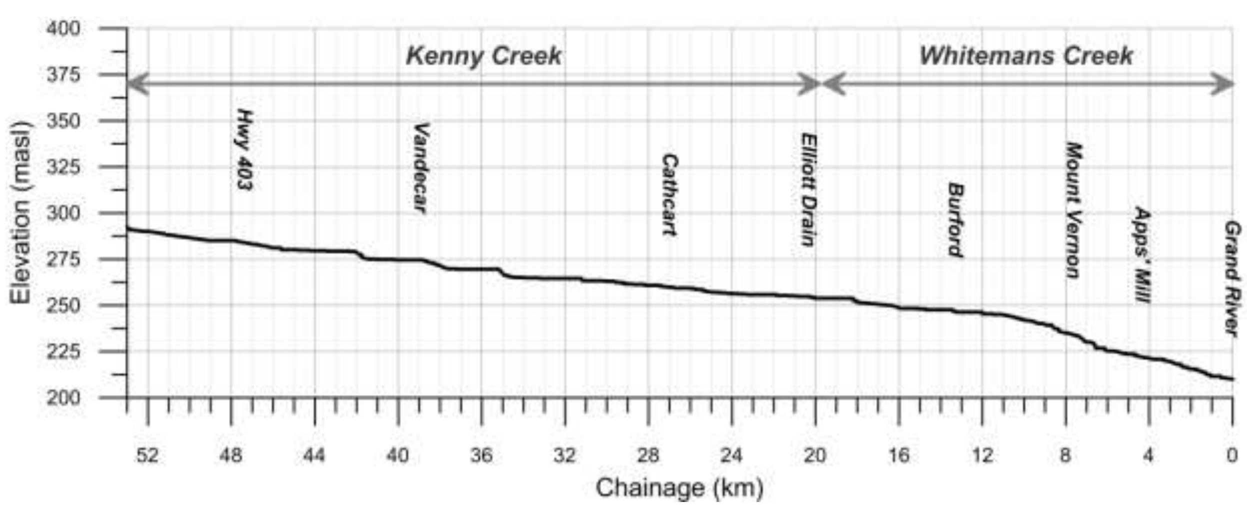


Figure 2.8: Elevation profile of Whitemans and Kenny Creeks.

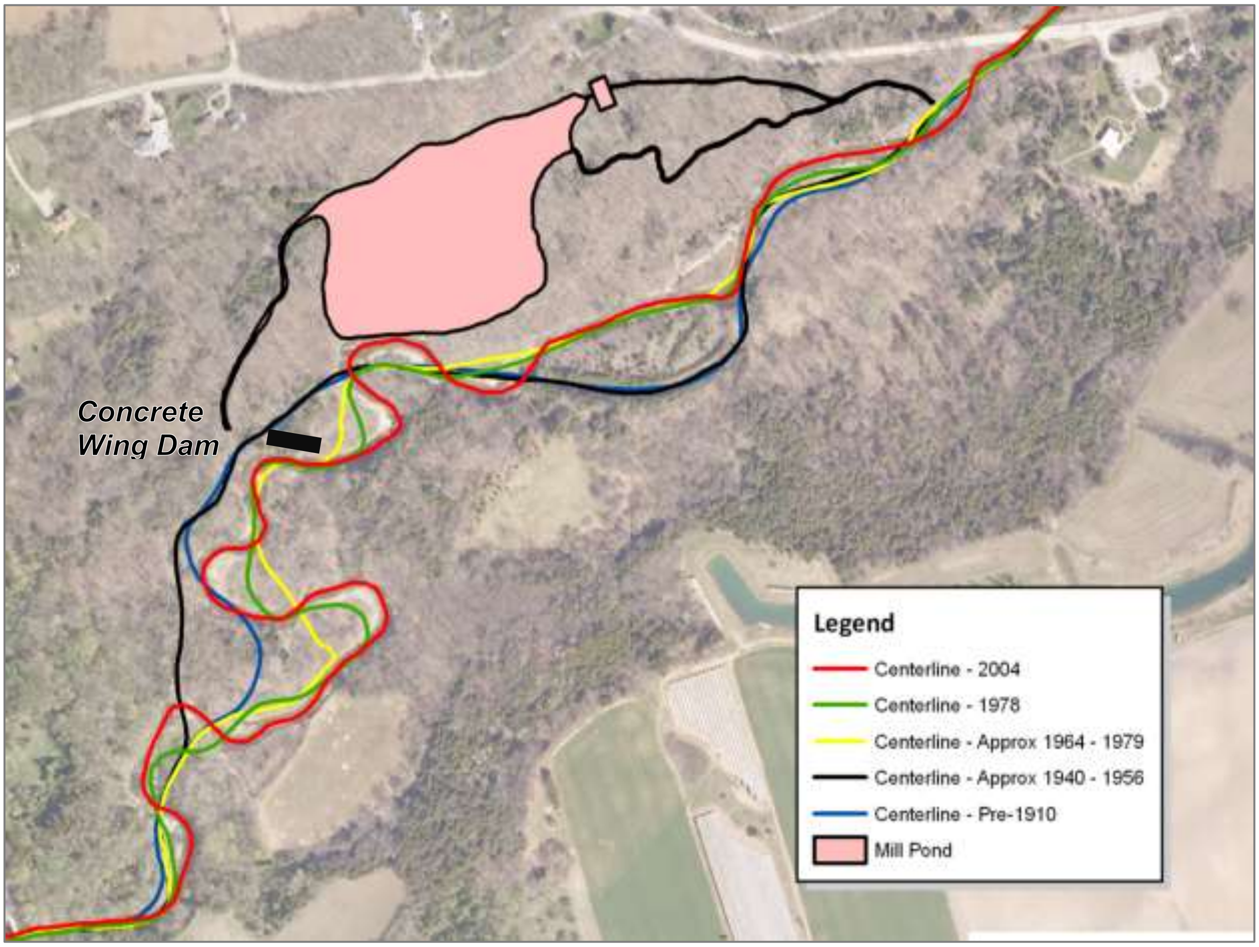


Figure 2.9: Historical channel alignment of Whitemans Creek at Apps' Mill showing the location of the Mill pond and remnant structures (Lounder and Thompson, 2009).

Figure 2.10: Remains of the concrete wing dam at Apps' Mill on the main branch of Whitemans Creek which catastrophically failed during a flash flood on 27 April 1936.

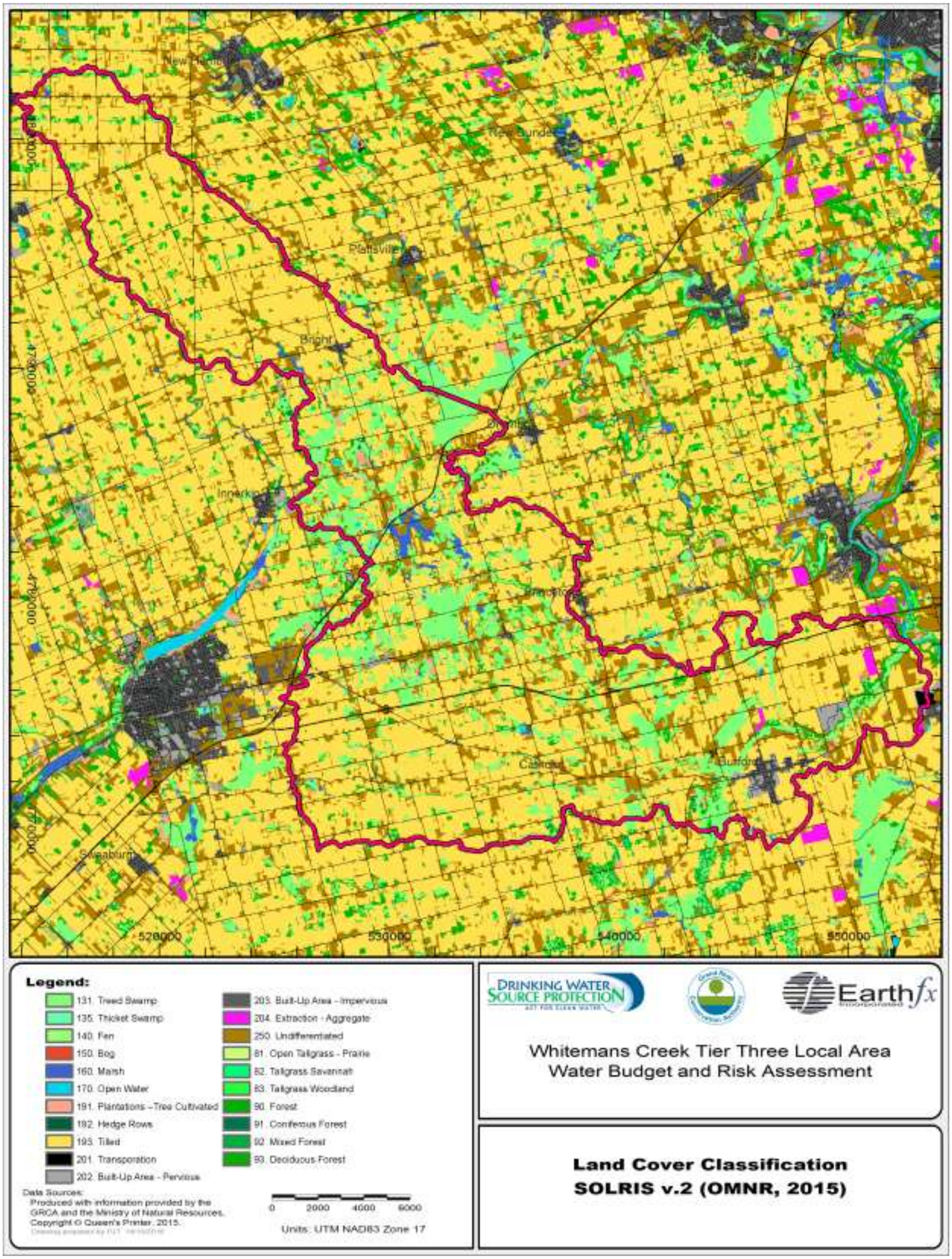


Figure 2.11: Subwatershed land coverage (from OMNR SOLRIS v2, 2014).

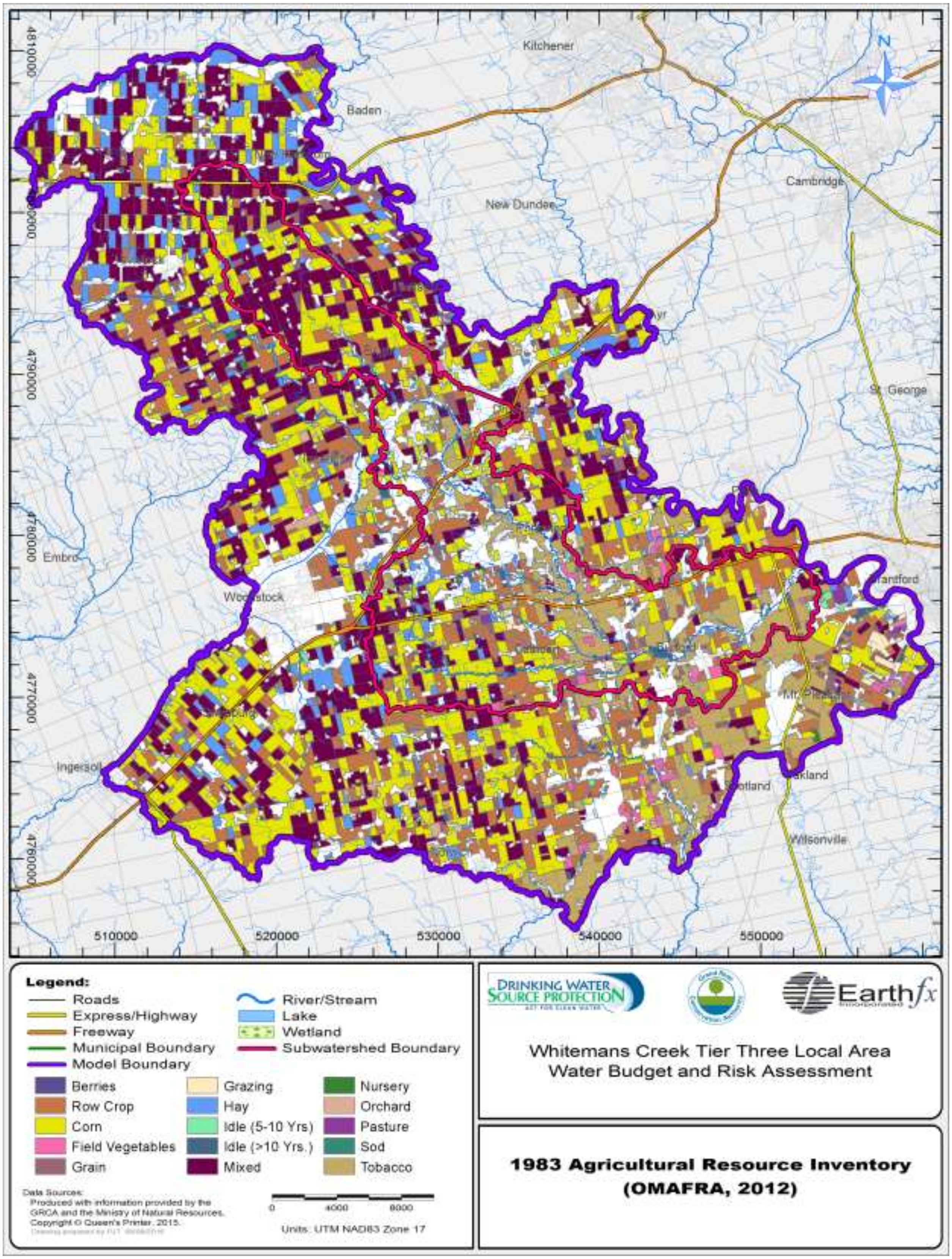


Figure 2.12: 1983 Agricultural Resource Inventory (from OMAFRA, 2012).

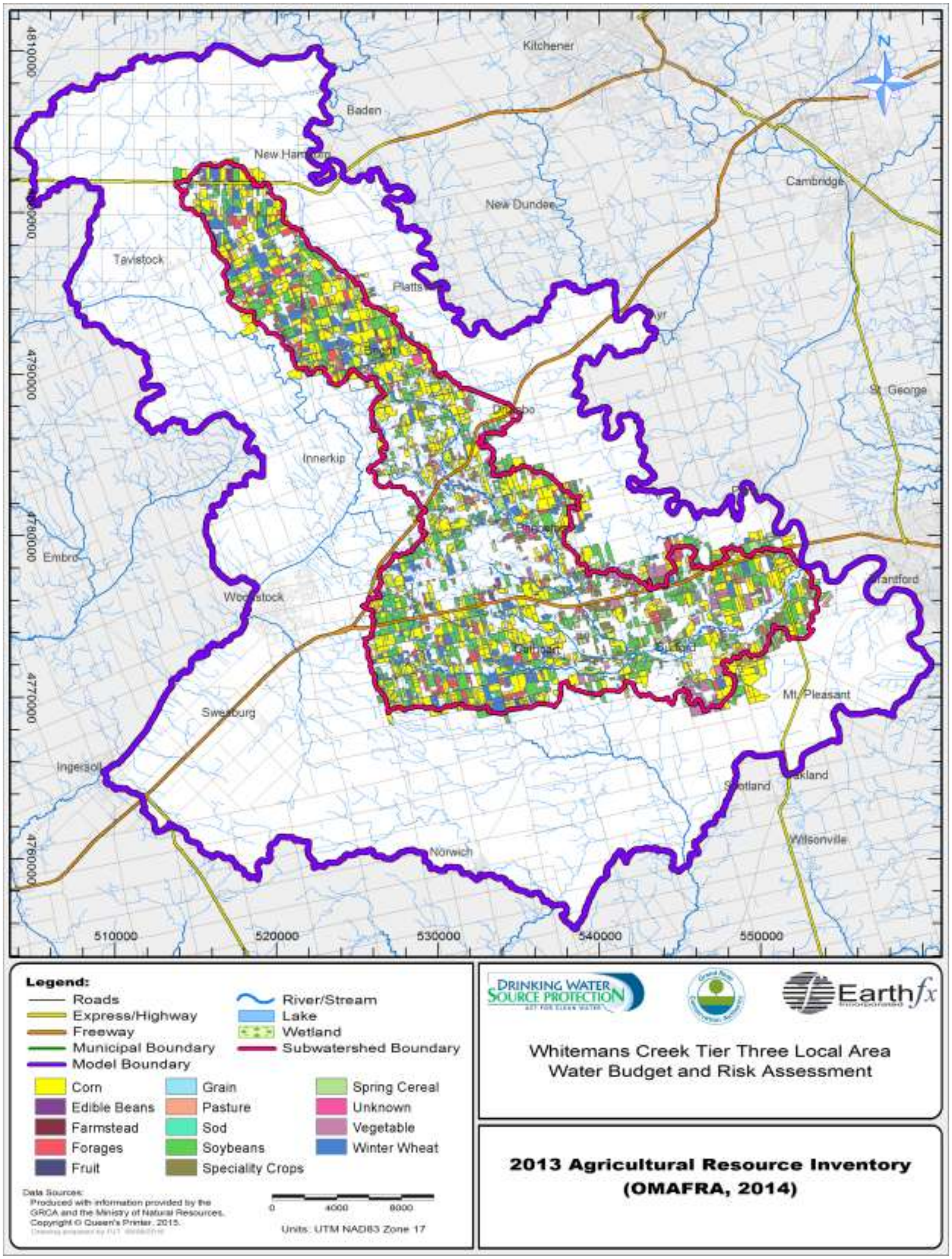


Figure 2.13: 2013 Agricultural Resource Inventory (from OMAFRA, 2014).

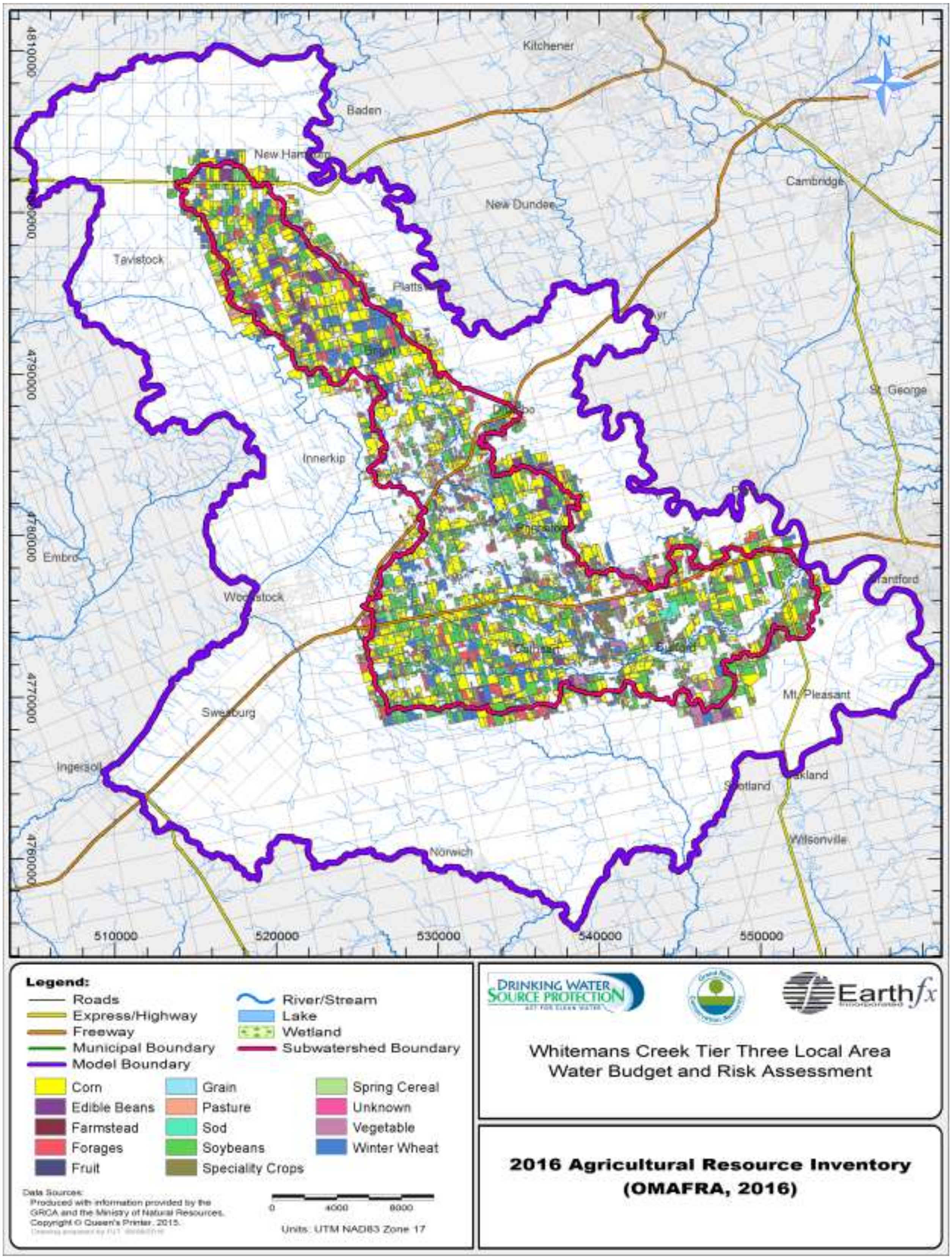


Figure 2.14: 2016 Agricultural Resource Inventory (from OMAFRA, 2016).

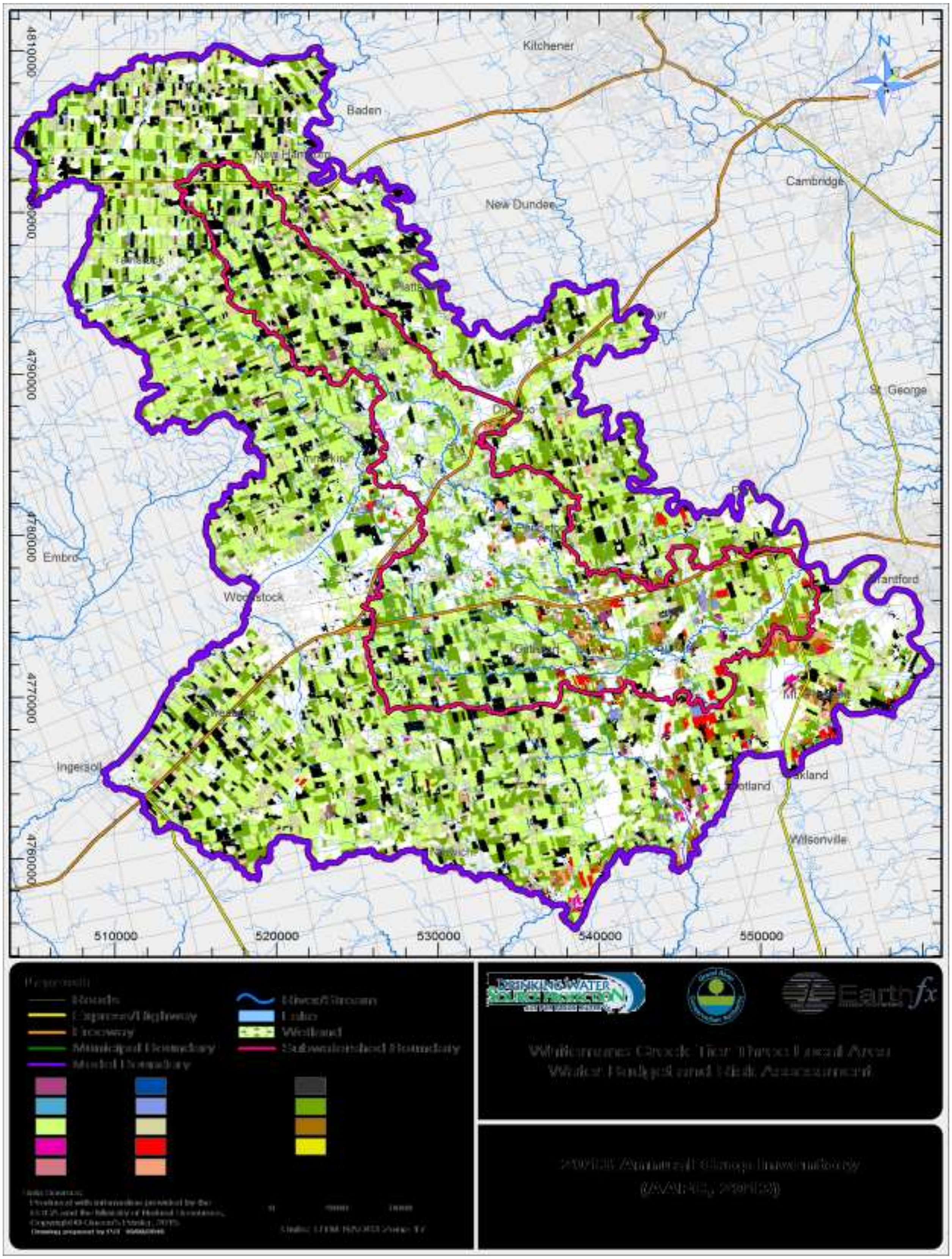


Figure 2.15: 2013 Annual Crop Inventory (from AAFC, 2013).

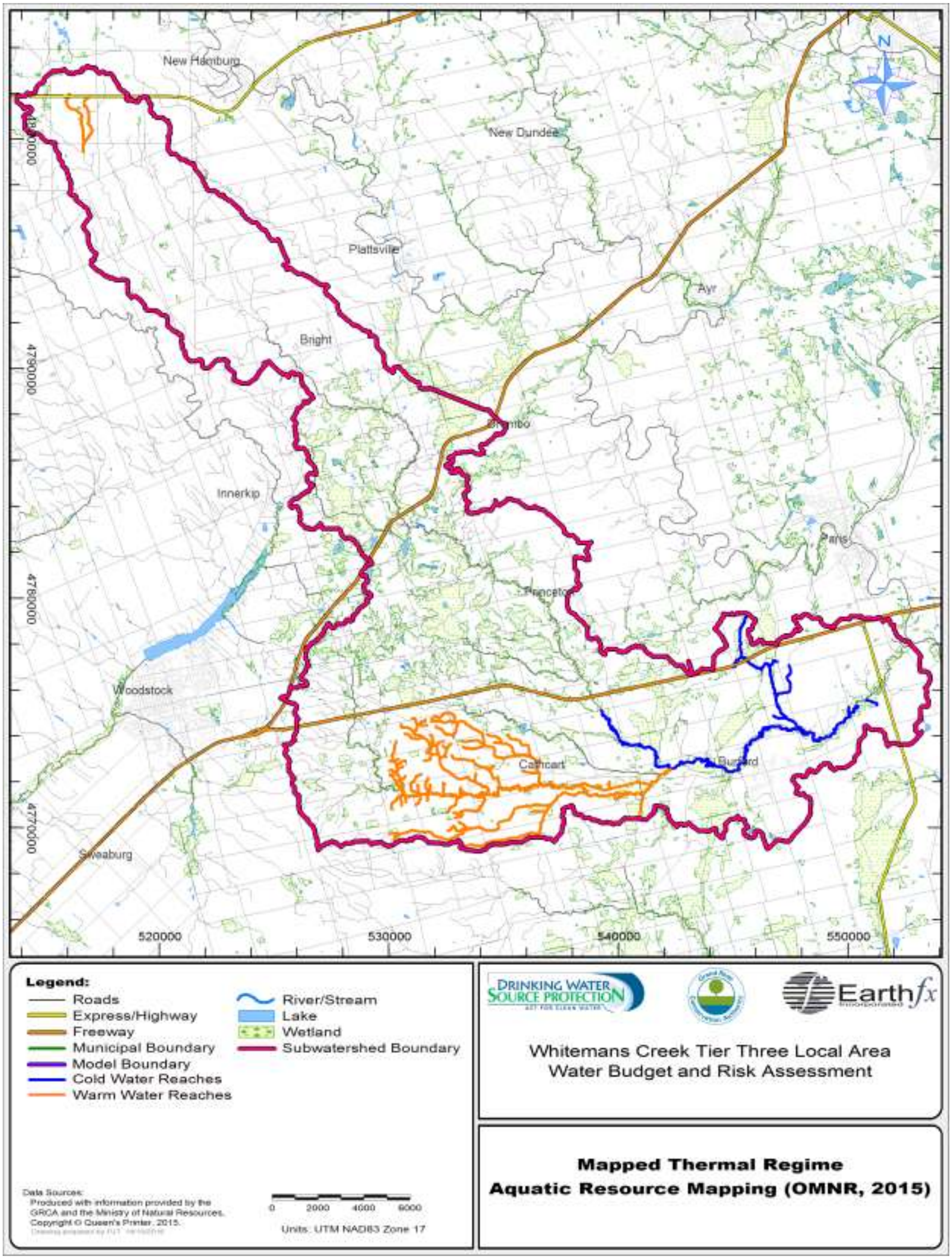


Figure 2.16: Thermal regime of mapped study area streams (from OMNR, 2015e).

3 Physiography and Geological Setting

The development of a three-dimensional integrated model requires the compilation and synthesis of physiographic, geologic, hydrologic and hydrogeologic information. This section introduces and summarizes the physiography and geologic setting, and provides the reader with an introduction to the physical geography and geologic (natural) history of the study area.

The physiographic discussion broadly describes how the underlying geologic structure, terrain, and topography are reflected in stream and wetland patterns. These patterns are discussed in more detail in Section 4. Similarly, the geologic setting introduced in this chapter provides a foundation and stratigraphic framework for the detailed presentation of the three-dimensional (3D) hydrogeologic layering, aquifer properties, and water level patterns presented in Section 5.

3.1 *Physiography*

The Tier 3 Assessment area encompasses six physiographic regions described by Chapman and Putnam (1984). The four main regions include the Norfolk Sand Plain, Horseshoe Moraines, Mount Elgin Ridges, and Oxford Till Plain (Figure 3.6). The Stratford Till Plain and, farther to the north, the Waterloo Hills occur only to a limited extent within the study area.

3.1.1 **Southeast Watershed Physiographic Features**

The southeastern portion of the Whitemans Creek subwatershed consists of the Horseshoe Moraines and the Norfolk Sand Plain. The meltwater stream deposits and spillways of the Horseshoe Moraines give the region two chief landform components: (1) irregular, stony knobs and ridges that are composed mostly of till with some sand and gravel deposits (kames); and (2) sand and gravel terraces and outwash deposits (Figure 3.7). Significant sand and gravel outwash deposits and associated gravel pit operations are found near the Town of Paris, Ontario. South of Paris, the moraines tend to flatten and disappear under the Norfolk Sands, and the high-energy coarse sand and gravel outwash deposits transition into the finer deltaic sand of the Norfolk Sand Plains.

The Norfolk Sand Plain is one of two major deltas of glacial Lakes Whittlesey and Warren. In a manner typical of deltaic deposits, the soil within the Norfolk Sand Plain is composed predominantly of medium to coarse sand; however, the unit lacks the gradation from coarse to fine sand that might be expected of a delta environment. As deposition of these sands proceeded from west to east, it resulted in the partial burial of the Galt, Paris and Tillsonburg moraines. The physiographic setting within the southern portion of the study area is therefore a reflection of the interrelationship between the upland morainic structures of the Horseshoe Moraines, dissecting to varying degrees the flat lowlands of the Norfolk Sand Plains. Extensive wetland formation within the intermorainal sections of the Norfolk Sand Plain near the Town of Burford and further west toward Carthart attest to the influence of the moraines on local drainage within the sand plains. As Whitemans Creek flows from west to east across these two physiographic regions, it cuts through the Tillsonburg and Galt moraines and forms incised valleys as it passes through deltaic and outwash sand deposits between Burford and the Grand River.

3.1.2 **Central Watershed Physiographic Features**

The central portion of the Whitemans Creek subwatershed is part of the Mount Elgin Ridges physiographic region. Within the study area, the western edge of the Mount Elgin Ridges region is bounded by the Ingersoll and St. Thomas moraines, while the eastern edge loosely conforms to the Norwich Moraine. These ridge moraines are typically composed of pale brown calcareous clay or silty clay till. The vales present a starkly contrasting soil profile - commonly containing gravel, sand or silt alluvium. While the ridges are generally well drained, the vales are imperfectly or even poorly drained by virtue of their low topographic relief, resulting in the underdeveloped stream systems within the Kenny Creek catchment. Extensive construction of tile drain systems has occurred during the last century to improve drainage in the vales. The Mount Elgin region is one of the most prosperous dairy and livestock regions of Ontario as the ridges are typically cultivated while the vales are used for pasture.

3.1.3 Northwest Watershed Physiographic Features

The Oxford Till Plain and the Stratford Till Plain regions occur in the northwestern portion of the study area and represent the regional uplands of the Whitemans Creek subwatershed. The Oxford Till Plain lies to the west of the Ingersoll Moraine, and includes the Town of Woodstock and the Community of Bright. The surface is dominated throughout much of the region by pale brown calcareous loam till that becomes increasingly drumlinized to the south of Innerkip. Two exceptional features to the extensive loam tills of the Oxford Till Plains are a clay plain to the southeast of Tavistock and three well-marked glacial meltwater valleys, the most notable being occupied by what is presently the Thames River. The ancient meltwater valleys originate north of the Town of Drumbo, and then cross the Whitemans Creek subwatershed in a southwesterly direction towards the Town of Woodstock. At Innerkip, the valleys have cut down through overburden to bedrock.

The northern end of the Whitemans Creek subwatershed falls within the Stratford Till Plain physiographic region. Within the study area, the region is characterized by fairly level (undrumlinized) plains composed of brown calcareous silty clay till. As a result of the natural soil's poor drainage, municipal ditches and tile drains are common. Shallow glacial ridges (referred to by Bajc and Dodge (2011) as the Gads Hill Moraines) provide some local relief to this region between Tavistock and Stratford. The small portion of the Waterloo Hills physiographic region that extends within the study area (though outside of the Whitemans Creek subwatershed) includes the Easthope Kame Moraine – a large sand and gravel moraine extending up to 45 m above the surrounding plains (Karrow, 1986).

3.2 *Geologic Setting*

The geology in the Whitemans Creek subwatershed and the surrounding area consists of a complex assemblage of Quaternary age unlithified clastic sediments (primarily tills and intervening sand and gravel units), that unconformably overlie Silurian and Devonian marine sedimentary bedrock units (Figure 3.8).

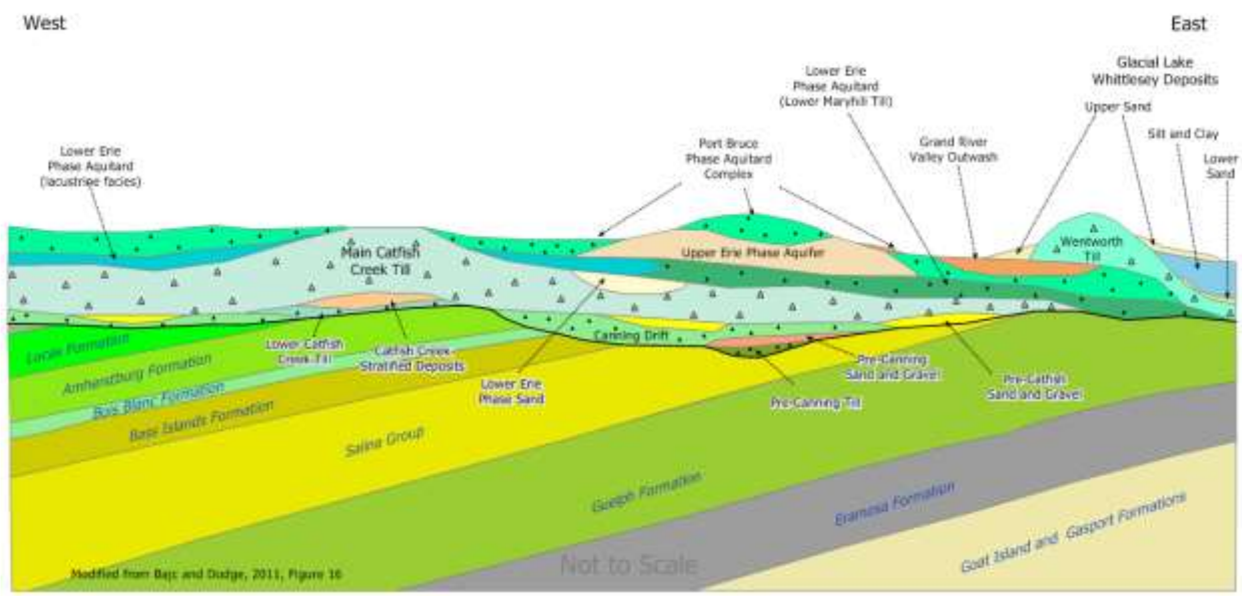


Figure 3.1: Schematic representation of Stratigraphic Framework

3.2.1 Geologic Map Sources

The interpreted subcrop of the dipping Paleozoic rocks appear on the digital compilation map of Armstrong and Dodge (2007; see Figure 12) which references earlier work, such as Sanford (1969). Mapping of Quaternary sediments in the study area has been carried out by Cowan (1972, 1975), Barnett

(1978, 1982) and Karrow (1987, 1993). These maps have been incorporated into a digital compilation map of the Quaternary geology of southern Ontario by the Ontario Geological Survey (OGS, 2010; see Figure 13). There are useful summaries of both the Paleozoic geology (Johnson *et al.*, 1992) and Quaternary (surficial) geology (Barnett, 1992) in the Geology of Ontario volume published by the OGS.

Most recently, A.J. Bajc of the OGS has carried out drilling in the study area (Bajc and Shirota, 2007) and in the Brantford-Woodstock area (Bajc and Dodge, 2011). This program and the three-dimensional geologic models developed by the OGS helped form the foundation of the conceptual stratigraphic and hydrostratigraphic models of the study area.

3.2.2 Bedrock Topography and Overburden Deposits

The bedrock surface in the study area exhibits an irregular topography that is typical of the southern Ontario Paleozoic surface (Figure 3.8). The Onondaga Escarpment is regionally mapped along the western edge of the Whitemans Creek subwatershed where the subcrop of the Silurian-age Bass Islands Formation meets that of the overlying Bois Blanc Formation (Figure 3.9). Data from the Ontario Oil, Gas and Salt Resources Library (OGSR) suggest that the Bass Island Formation forms a plateau that corresponds closely with the western and southern portion the Whitemans Creek subwatershed.

The total overburden thickness in the study area is presented in Figure 3.10. The thick sediments of the Waterloo Moraine are evident in the north, while the overburden thins considerably to the west and south of the Whitemans Creek subwatershed. The areas of thinner overburden likely allow increased recharge to the upper bedrock units of the Onondaga Escarpment.

3.2.3 Paleozoic Geology

The study area lies in a transitional zone between two major Paleozoic sedimentary basins – the Appalachian basin to the southeast and the Michigan basin to west (Armstrong and Carter, 2010). The Paleozoic sedimentary rocks that underlie the area dip gently to the south or southwest and get progressively younger in that direction (presented schematically in cross section in Figure 3.1, and in plan view in Figure 3.9). Bedrock outcropping in the region is generally poor, with the exception of deeply incised river valleys of the Thames River near Woodstock, and the Grand River along the eastern edge of the study area. Regional knowledge of the distribution and lithologic character of the rocks is mainly a product of subsurface studies using OGSR data from oil and gas wells.

The oldest unit subcropping in the model area is the Silurian Guelph Formation, which comprises thinly-to thickly-bedded fossiliferous dolostones, typically fine- to medium-crystalline in texture, deposited in both open marine and lagoonal environments (Brunton, 2009). This formation subcrops in the northeast part of the model area (Armstrong and Dodge, 2007). It is overlain by the Salina Group (formerly the Salina Formation), a thick, complex package of shales, carbonate rocks, and evaporites - anhydrite, gypsum and halite (Figure 3.2). Within the Salina Group, eight units of formational rank have been recognized in the subsurface in Ontario (Armstrong and Carter, 2010), with the lower two members exhibiting an increase in shale content. The Salina Group directly underlies most of the Whitemans Creek subwatershed (Figure 3.9). It is conformably overlain by the dark brown to light greyish tan, finely crystalline dolostones of the Bass Islands Formation, which is the uppermost Silurian unit in the area (Johnson *et al*., 1992; Armstrong and Carter, 2010). The top of the Bass Islands Formation is an erosional surface that represents a significant regional unconformity (Johnson *et al*., 1992).

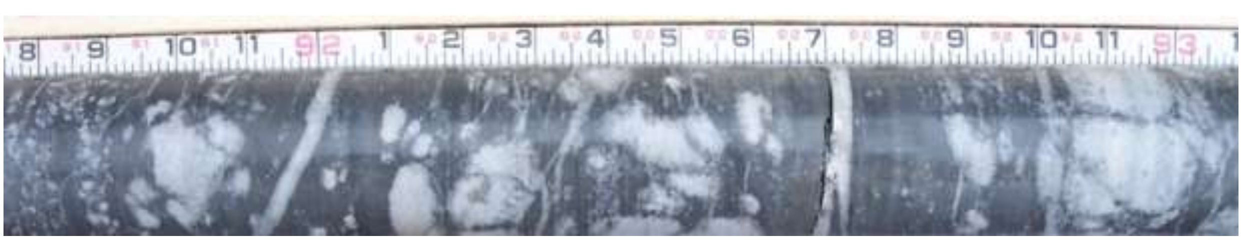


Figure 3.2: Core sample of the Salina Formation showing gypsum veins and nodules (Earthfx, 2005).

The Early Devonian Bois Blanc Formation forms the base of the next sedimentary sequence in the region. It consists mainly of fine- to medium-grained, cherty limestone and dolostone (Figure 3.3) but has a basal sandstone member in the Appalachian basin (Johnson *et al*., 1992). Together with the underlying Bass Islands Formation, the Bois Blanc Formation helps to define the Onondaga Escarpment - an easterly- to northerly-facing bedrock cuesta that is buried by Quaternary sediments in the region. The Amherstburg Formation of the Detroit River Group, which overlies the Bois Blanc in the study area, is a relatively thick unit consisting of fine- to coarse-grained limestones and dolostones that are generally bituminous and bioclastic (Johnson *et al.*, 1992; Armstrong and Carter, 2010). This unit transitions eastward into the cherty, fossiliferous limestones of the Middle Devonian Onondaga Formation (Armstrong and Carter, 2010). The Lucas Formation is the next unit in the sequence and conformably overlies the Amherstburg Formation of the Detroit River Group. At the margins of the Michigan basin, it consists of high-purity limestones and bituminous and cherty dolostones and may contain blebs and thin beds of anhydrite-gypsum (Johnson *et al.*, 1992). The contact of the Middle Devonian Dundee Formation with the underlying Detroit River Group is sharp and erosional (Johnson *et al*., 1992). The Dundee Formation consists of fossiliferous, medium- to thick-bedded limestones and minor dolostones; oil staining is common in porous beds and along fractures (Armstrong and Carter, 2010). This is the youngest Paleozoic unit present in the study area and subcrops in the southwest part of the model area.

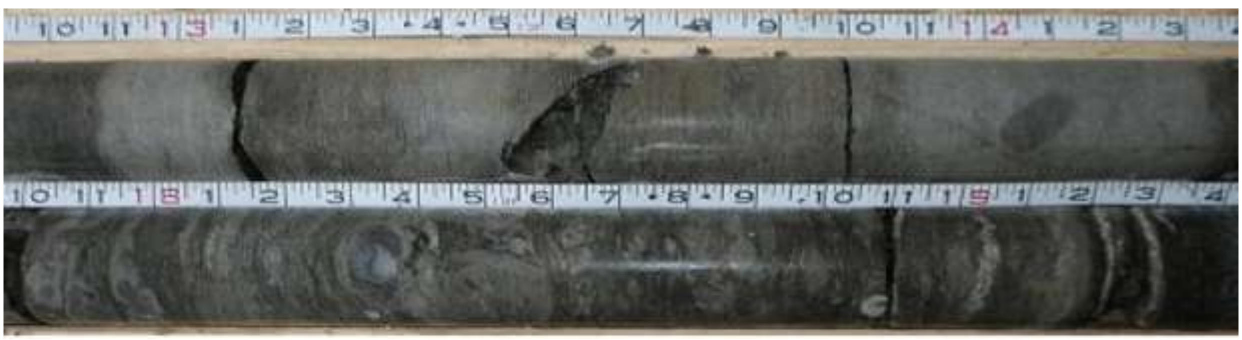


Figure 3.3: Core samples from the Bois Blanc Formation (Earthfx, 2005)

3.2.4 **Quaternary Geology**

Like all of southern Ontario, the Whitemans Creek area was repeatedly glaciated during the Pleistocene Epoch, although locally there is only clear evidence for glacial activity during the Wisconsinan glacial, the final major glacial episode (see Barnett, 1992). Most of the Pleistocene sediments were deposited either directly from glacier ice, in meltwater streams, or in ice-marginal or ice-dammed lakes (Figure 3.4). The pattern of glaciation in the Great Lakes region is typically lobate, with glacial ice flowing from the north filling the lake basins and then spreading out radially as the local ice masses became thicker. With increasing ice thickness and coalescence of ice lobes, an overriding regional south to southwesterly flow was established near the time of the glacial maximum during the Nissouri Phase of the Late Wisconsinan (the Late Wisconsinan is now called the Michigan Subepisode, see Karrow *et al*., 2000). Bajc and Dodge (2011) note that this pattern of glacial lobation has probably occurred repeatedly during the Pleistocene. The present study area was in a zone of glacial convergence with ice flowing out of the Lake Huron and Georgian Bay basins meeting ice from the Lake Ontario-Lake Erie basins (Barnett, 1992; Karrow, 1993). Episodes of glacial recession in the area were marked by interlobate glaciofluvial and glaciolacustrine sedimentation and the formation of a number of major moraines (Barnett, 1992). The surficial exposure of the tills is shown in Figure 3.11.

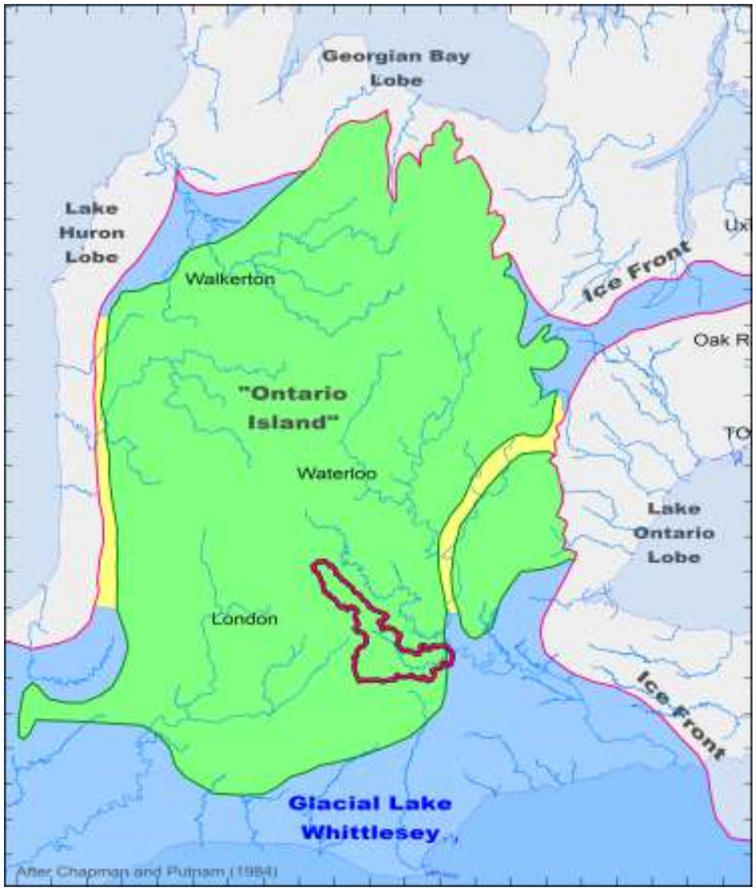


Figure 3.4: Glacial Lake Whittlesey, following separation of the Ontario-Erie lobe.

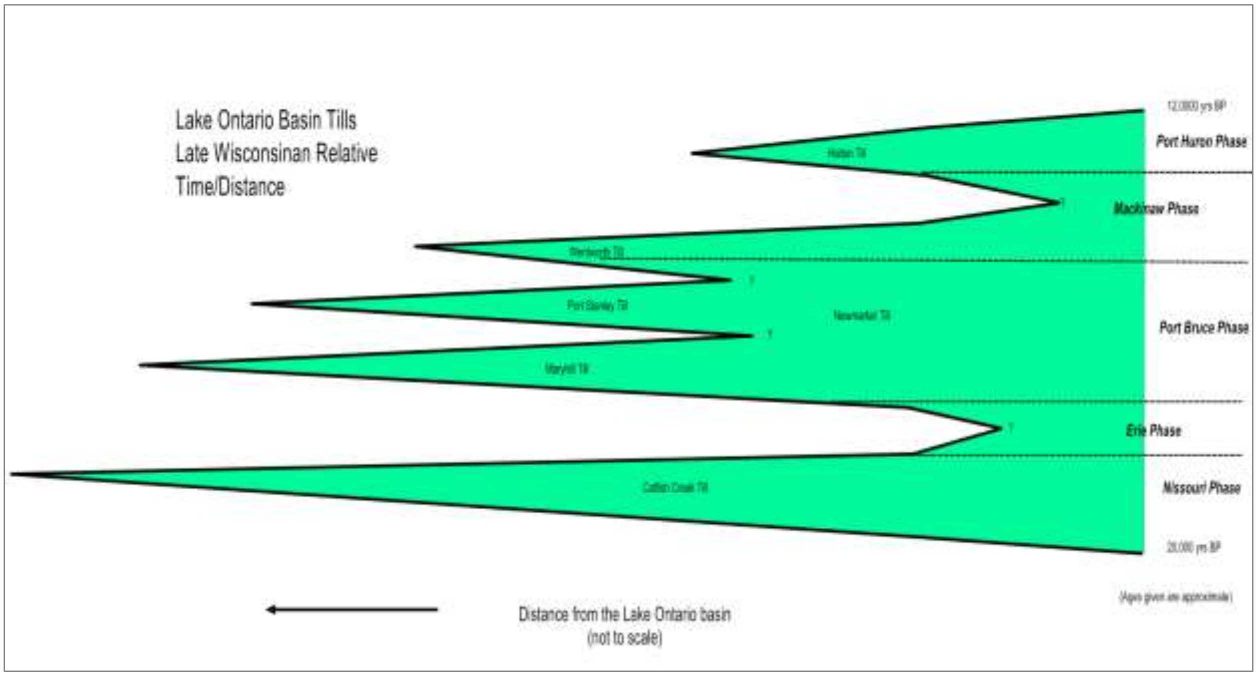
3.2.4.1 Early Wisconsin Age Units

The oldest known sediments in the region are the 'lower beds' of Karrow (1963, 1987), which are considered Early Wisconsinan in age. These deposits include a coarse-textured 'pre-Canning' unit overlain by interbedded diamictons and glaciolacustrine sediments (Bajc and Dodge, 2011). These sediments are discontinuous and sporadic in their distribution (Bajc and Dodge, 2011) and are only exposed in sections along the Nith River (Karrow, 1963) and at the Lafarge Zorra quarry (Cowan, 1975; Bajc and Dodge, 2011). The next major unit is the Canning Till, a very stiff, clayey silt diamicton containing very few pebbles and cobbles (Karrow 1963; Cowan, 1972). The Canning Till is associated with fine-grained glaciolacustrine deposits and, in a few boreholes, overlies water-bearing sands (the 'pre-Canning aquifer' of Bajc and Dodge, 2011).

3.2.4.2 Nissouri Phase (Late Wisconsinan)

Following the recession of the Lake Erie lobe ice that deposited the Canning Till, the area was subjected to a period of erosion and lacustrine sedimentation. The Catfish Creek Till was deposited during the Nissouri phase (Figure 3.5) of the Michigan subepisode (formerly known as the Late Wisconsinan) when glacial ice extended as far south as southern Ohio (Bajc and Dodge, 2011). Typically, the Catfish Creek Till is a stony, overconsolidated, sandy silt to silty sand diamicton with colour ranging from greyish brown to light olive brown (Cowan, 1975; Barnett, 1982; Bajc and Dodge, 2011). This unit is extensive in the subsurface throughout southwestern Ontario and is commonly referred to as 'hardpan' by water well drillers because of its stiffness. The till was deposited mainly by southerly-flowing ice and is commonly associated with glaciofluvial sand and gravel deposits (Cowan, 1975).

As glacial ice withdrew from the region during the Erie phase, much of the area was affected by glacial lakes and local pondings, with deposition of sediments ranging from fine sands to laminated silt and clay (Cowan, 1975; Bajc and Dodge, 2011). Thin, fine-grained diamictons may be interbedded with these sediments (Bajc and Dodge, 2011). In the northern part of the study area, interlobate glaciofluvial and glaciolacustrine sedimentation produced much of the complex Waterloo Moraine (Bajc and Shirota, 2007) and possibly the Easthope Moraine (Karrow, 1993). These features have cores of fine sand or sand and gravel and are capped by fine-grained tills deposited during the Port Bruce phase (Karrow, 1993).



(Karrow, P.F., 2005)

Figure 3.5: Late Wisconsin (Michigan Subepisode) till relative time-distance diagram

3.2.4.3 Port Bruce Phase

As many as five till sheets were deposited with the return of glacial ice to the region during the Port Bruce phase (Figure 3.5), reflecting the complex interaction of ice flowing out of the Georgian Bay and Lake Huron basins meeting ice from the southeast coming out of the Lake Erie and Lake Ontario basins (Barnett, 1992). Bajc and Dodge (2011) and other authors refer to the areas where the ice lobes meet as the interlobate zone. Many of the till units are relatively thin with limited areal extent and probably represent fairly local ice margin fluctuations (Karrow, 1993; Bajc and Dodge, 2011). Within the region, the oldest of these tills is probably the Stirton Till, a massive, blocky, clay-rich diamicton, deposited by the Lake Huron-Georgian Bay lobe, which has not been found east of Conestoga Lake and may not extend south of the Nith River (Karrow, 1993). The Erie-Ontario lobe Maryhill Till is possibly slightly younger than the Stirton Till, and has been interpreted to extend across much of the study area. It is a very fine-grained diamicton that commonly is interbedded with laminated silt and clay and caps parts of the eastern flank of the Waterloo Moraine (Karrow, 1993).

The Tavistock Till is a Lake Huron-Georgian Bay lobe till that is a major stratigraphic unit within the region, with extensive areas of mapped outcrop (Karrow, 1993; Bajc and Dodge, 2011). The Tavistock Till overlies the Maryhill Till within the study area. Texturally, this till is a pebbly, gritty, clayey silt diamicton (Bajc and Dodge, 2011). Other Lake Huron-Georgian Bay lobe tills in the region include the Mornington and Stratford tills, which were probably deposited during minor ice re-advances during overall retreat from the glacial maximum represented by the Tavistock Till (Karrow 1993; Bajc and Dodge, 2011). The relatively thin Stratford Till, which outcrops extensively in the northwestern part of the area, is a fairly stony, sandy silt diamicton that is usually soft and friable (Karrow, 1993).

The major Port Bruce-age Erie-Ontario lobe till in the region is the Port Stanley Till (or Port Stanley Drift), which is quite extensive at surface or in the shallow subsurface in the eastern half of the study area (OGS, 2010; Bajc and Dodge, 2011). Cowan (1975) describes this till as a stiff to very stiff clayey silt to silt till, typically ranging in thickness from 1.3 to 6 metres but may be up to 41 metres thick in the Tillsonburg Moraine (Barnett, 1982). In the northern part of the area, it has a much sandier texture due to incorporation of material from overridden glaciofluvial deposits (Karrow, 1993). Barnett (1982) has identified "at least four major and several minor till layers" within the Port Stanley Till in the Tillsonburg area, but Cowan (1975) observed only a single till unit in the Port Stanley in the Woodstock and Brantford map areas. This till is associated with fine-grained glaciolacustrine sediments that contain diamictons (Bajc and Dodge, 2011) and is approximately contemporaneous with the Tavistock Till (Cowan, 1975). There are patches of Port Stanley Till directly overlying either granular sediments or Maryhill Till in the southeastern part of the Waterloo Moraine (see OGS, 2010).

3.2.4.4 Mackinaw Phase

The Mackinaw phase was mainly a time of ice recession from the area with active glaciofluvial and glaciolacustrine sedimentation. The extensive Grand River outwash was deposited at this time (Bajc and Dodge, 2011). During the final phases of the Wisconsinan, a series of major glacial lakes in southwestern Ontario were centred on the Lake Erie basin but only appear to have affected part of the area (Barnett, 1992). The Erie-Ontario ice lobe re-advanced in the eastern part of the area as far as the Paris Moraine, overriding areas of outwash and depositing the Wentworth Till, a very silty, often stony, sand diamicton (Karrow, 1993; Bajc and Dodge, 2011). Both the advance and retreat of the Wentworth ice was accompanied by deposition of extensive proglacial outwash in the north and central parts of the study area (Karrow, 1993) and glaciolacustrine sedimentation in Glacial Lake Whittlesey in the south (Cowan, 1975; Barnett, 1978), including the fine sands that make up the Norfolk sand plain (Chapman and Putnam, 1984).

There are a number of moraines in the region associated with the various ice lobes and till units. Most of these moraines are products of minor glacial re-advances or 'standstills' during ice margin recession (Barnett, 1992). The major Erie-Ontario lobe moraines include the Ingersoll, St. Thomas, Norwich, and Tillsonburg moraines, which are associated with the Port Stanley Till, and the Paris, Galt, and Moffat moraines, associated with the Wentworth Till (Cowan, 1972, 1975; Barnett, 1978, 1982). Moraines deposited by Huron-Georgian Bay ice include the Chesterfield and Lakeside moraines, both associated with the Tavistock Till, and the Gads Hill moraine, which comprises several low, northeast-trending ridges and is possibly associated with both the Tavistock and Stratford Tills (Karrow, 1993). The Macton Moraine, which extends into the extreme northern part of the area, in made of silty clay Mornington Till (Karrow, 1993).

3.3 *Conclusions*

The complex geologic history of the study area has resulted in a highly variable set of geologic conditions across the watershed. The low permeability tills in the northwest transition to the highly permeable Norfolk sand plan in the southeast. No single large feature (such as the Waterloo Moraine) dominates the study area, although the close correlation between the subwatershed boundary and the buried Onondaga Escarpment suggests that the deeper subsurface structure may directly influence the hydrologic processes in the study area. The hydrology and hydrogeology are discussed in detail in subsequent sections of this report.

3.4 Figures

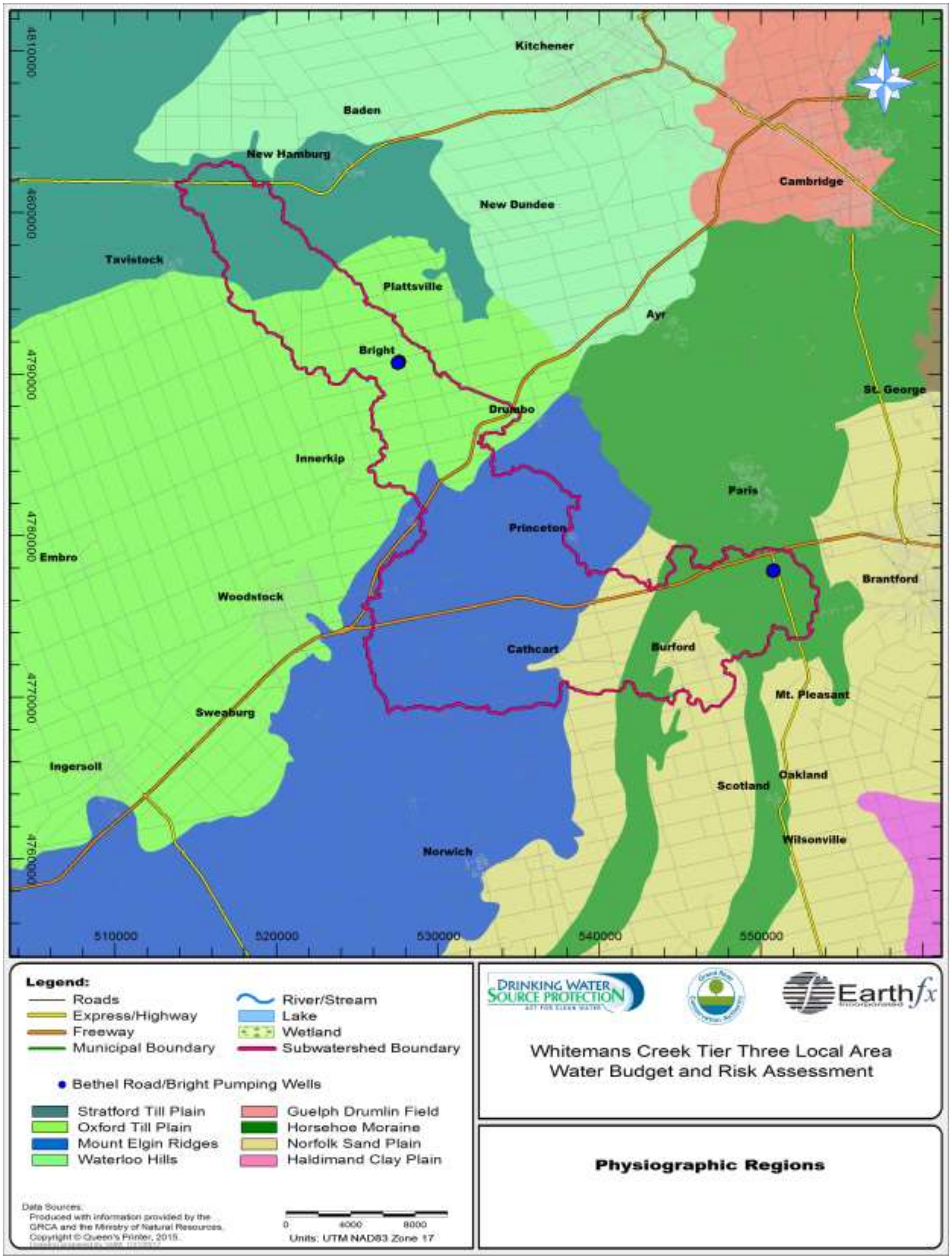


Figure 3.6: Physiographic regions (from OMNDM, 2007).

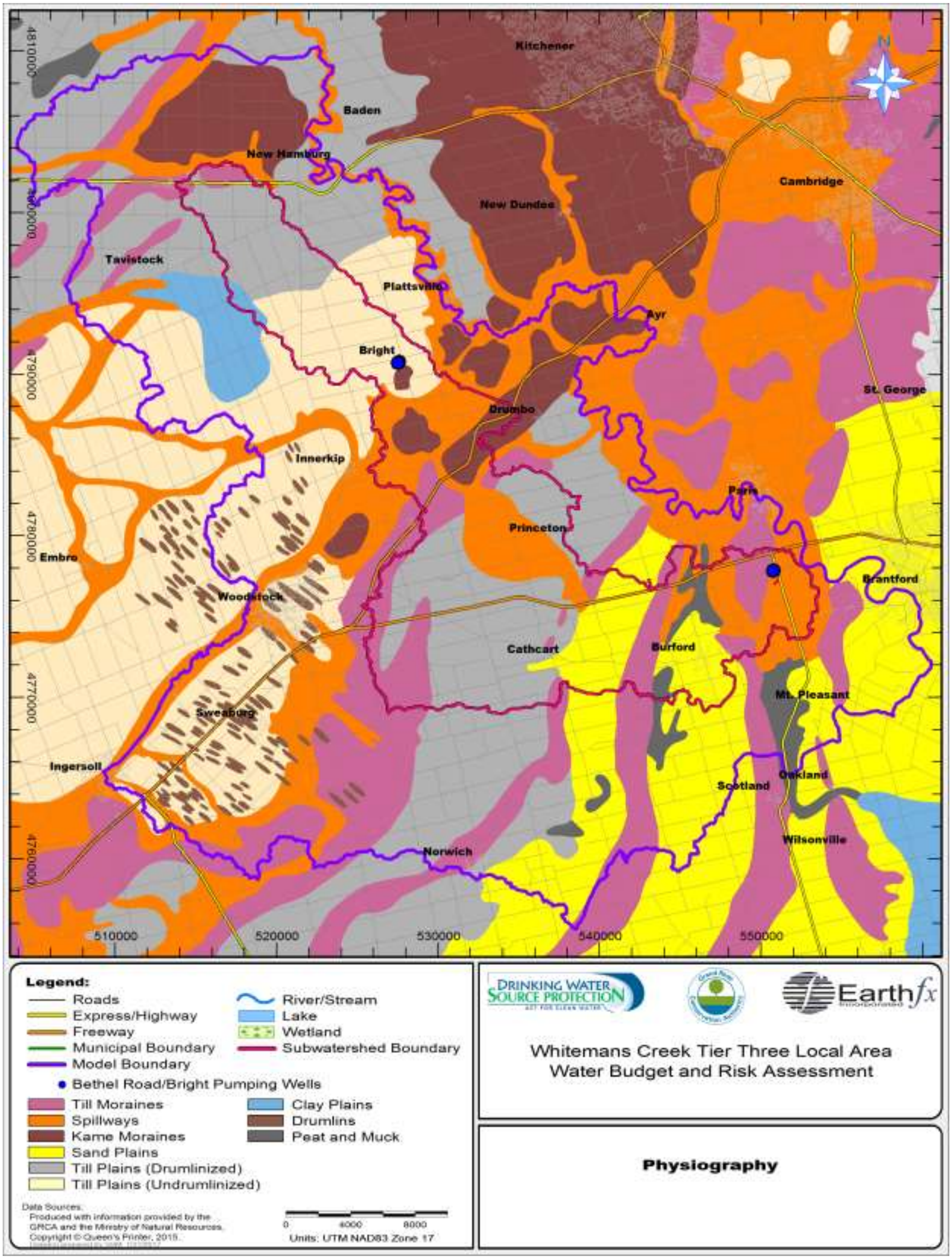


Figure 3.7: Physiographic features (from Chapman and Putnam (1984)).

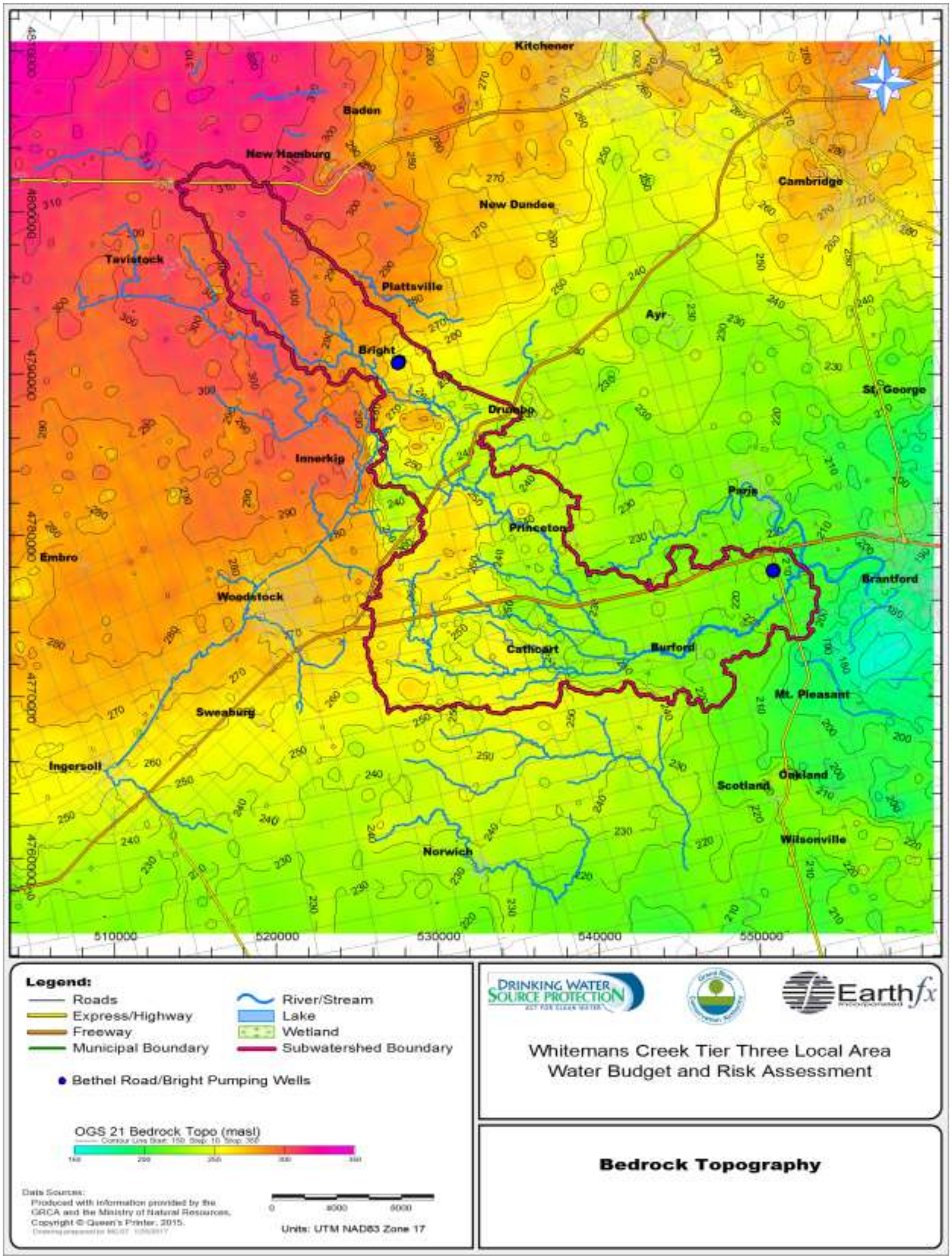


Figure 3.8: Bedrock topography, as interpolated from borehole data.

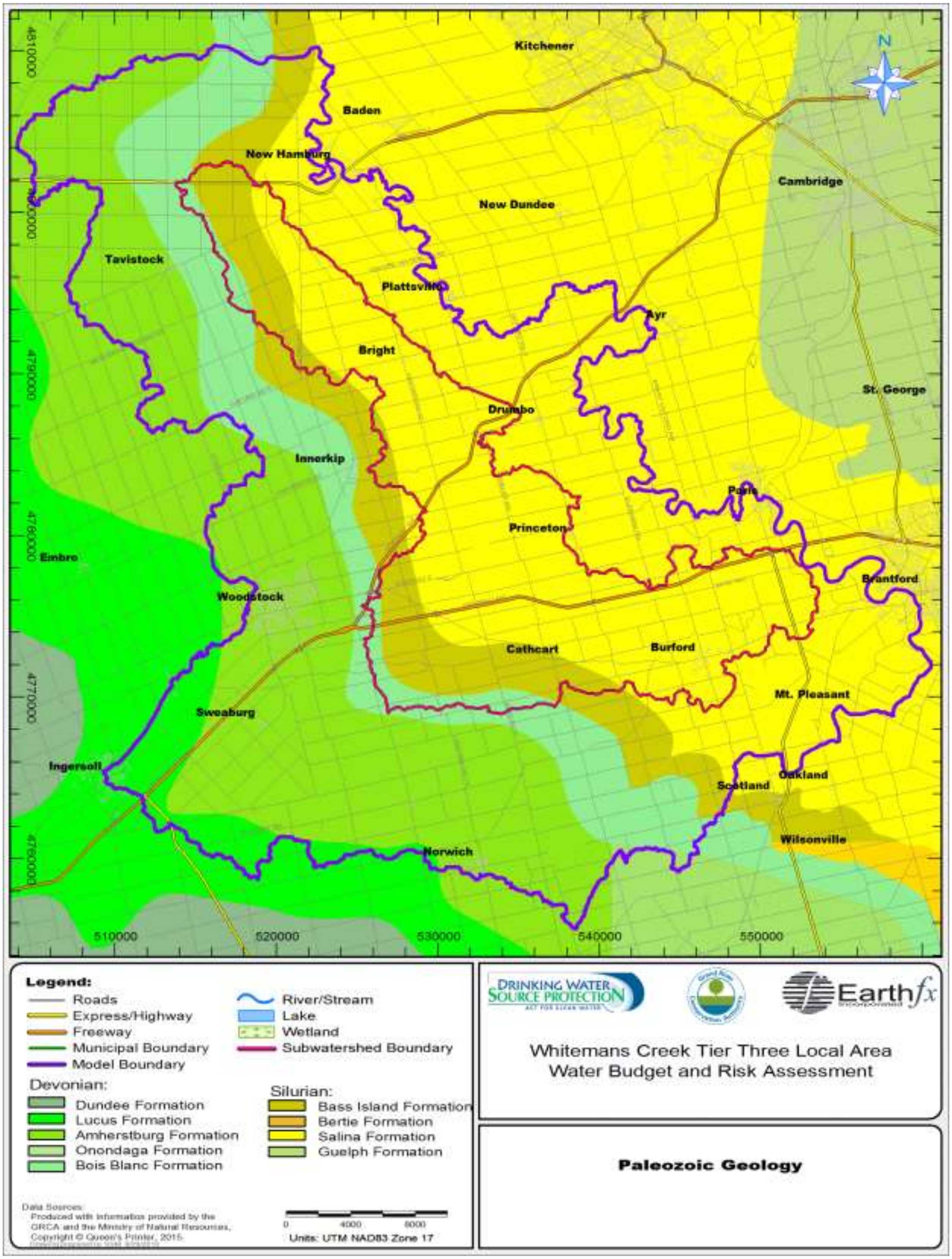


Figure 3.9: Paleozoic geology (from Armstrong and Dodge (2007)). (Note: The Onondaga Escarpment occurs at the boundary between the Bertie and Salina formation subcrops).

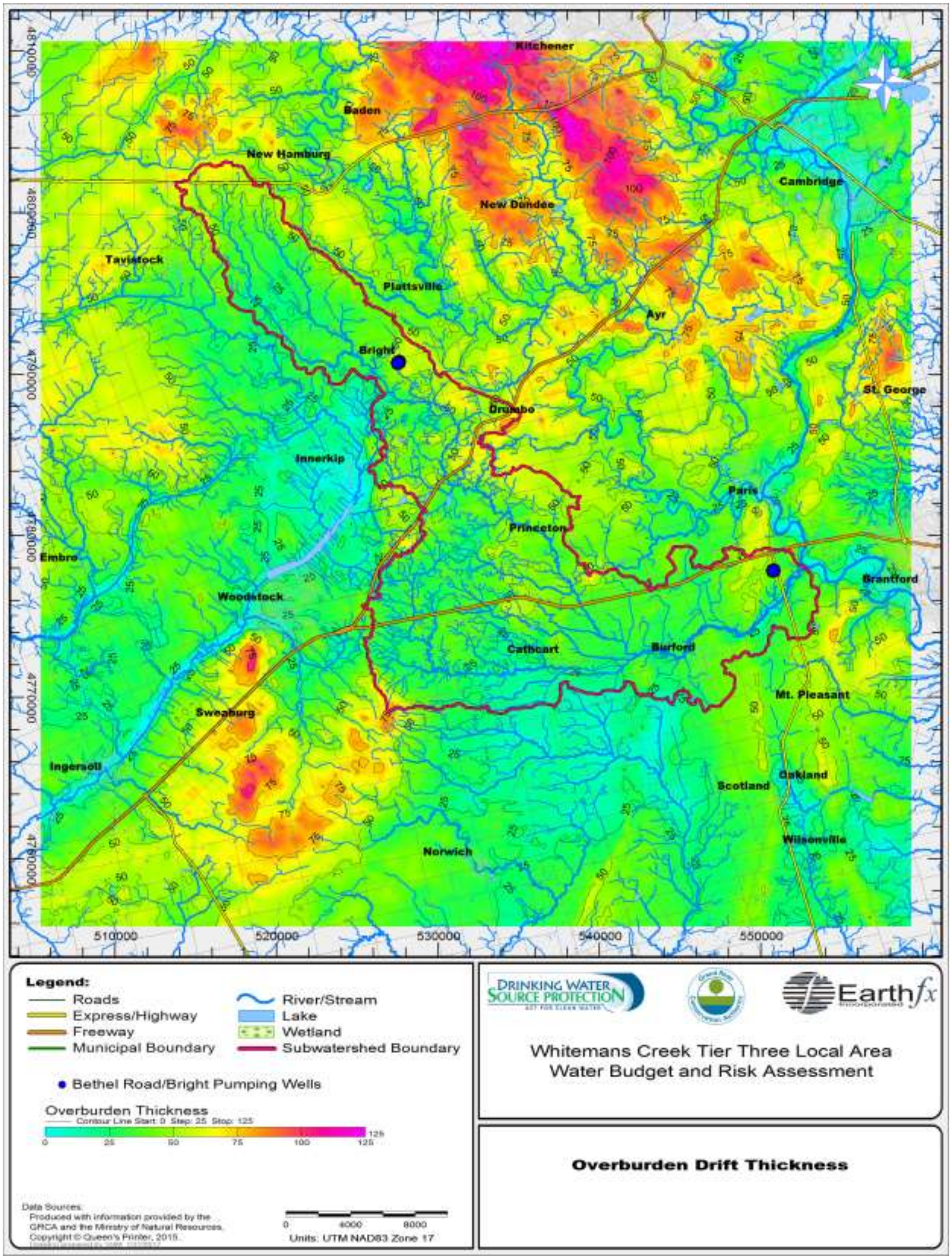


Figure 3.10: Drift thickness (total overburden isopach).

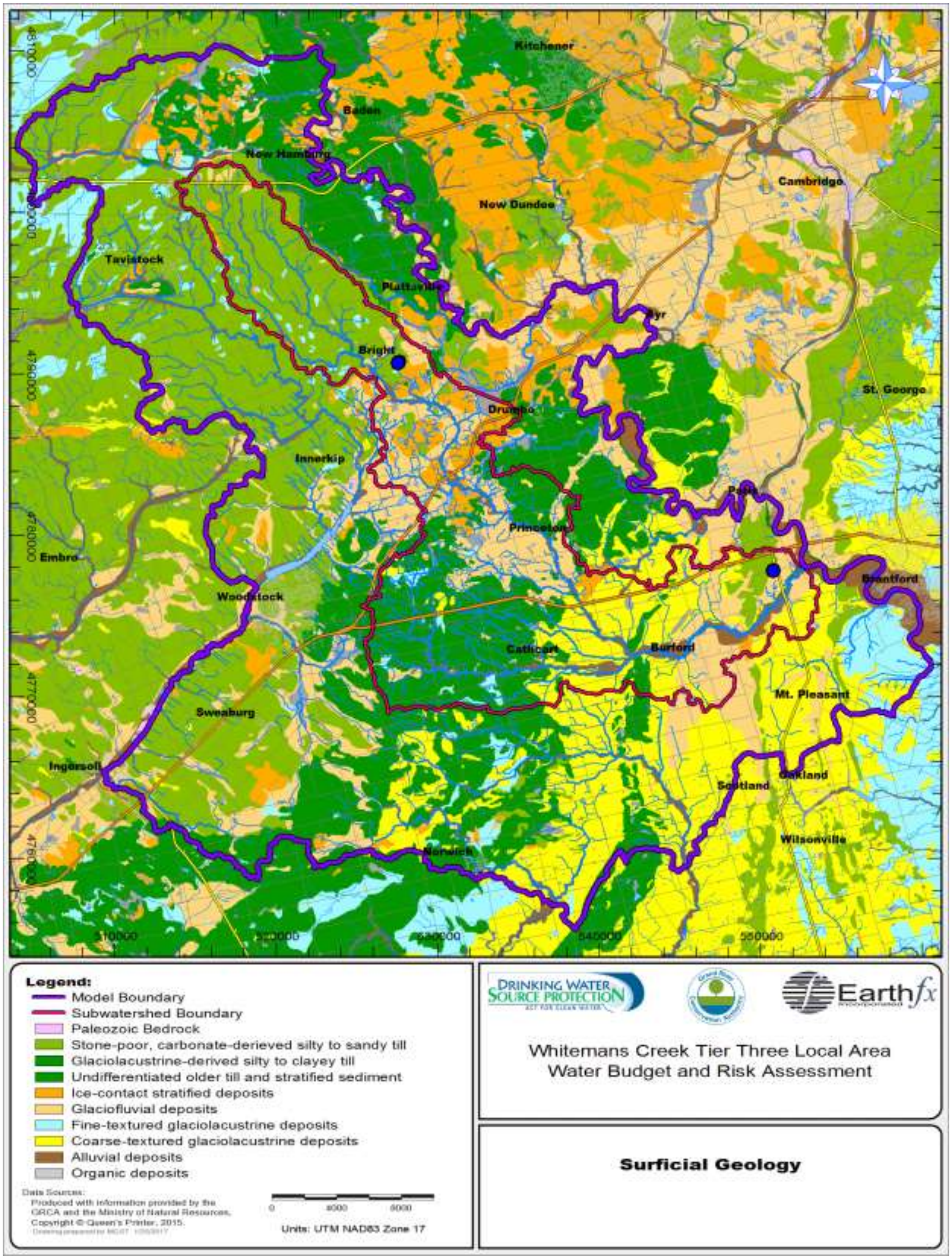


Figure 3.11: Surficial geology (from OGS, 2010).

4 Climatic and Hydrologic Setting

4.1 *Hydrologic Setting*

As introduced in the previous section, the hydrologic response of the Whitemans Creek subwatershed is controlled by the physiography, surficial geology, drainage pathways, and climate patterns. While the study area is complex, the hydrologic setting of the Whitemans Creek watershed can be generally divided into three broad hydrologic regions:

- **Upper Whitemans Till Plains** (*Upper Horner Creek*): This area is dominated by poorly drained till plains with the low permeability Tavistock till at or near surface.
- **Central Whitemans Outwash Area** (*Kenny Creek and Lower Horner Creek*): This is a complex area of moraines, outwash deposits, and till plains. The southern area is characterized by poorly draining Port Stanley Till at or near surface. In the north, glacial outwash has eroded this till unit, and outwash sands and sediments sit directly on the older Maryhill Till. These sediments are host to the many ponds and wetlands (Figure 2.4) in the central portion of the subwatershed, owing to the poor vertical drainage associated with the clay-rich Maryhill Till.
- **Lower Whitemans Sand Plain** (*Lower Whitemans Creek*): This area contains extensive glaciolacustrine and outwash sand deposits with near surface groundwater levels. Intermittent swamps and wetlands are typical in low-lying and riparian areas.

These three general hydrologic regions are presented in Figure 4.1. Moraines formed during the previous glacial retreats are also identified, as they offer moderately higher relief with variable permeability and drainage characteristics.

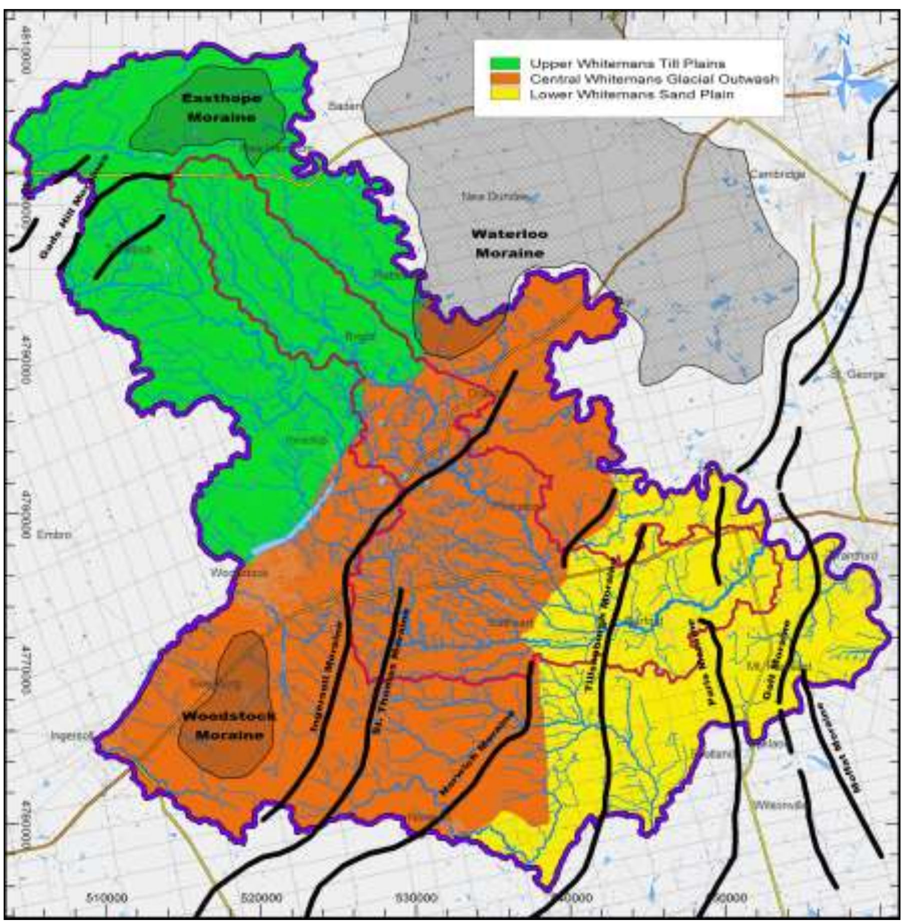


Figure 4.1: Conceptual division of the hydrologic setting.

4.1.1 Stream Network and Wetlands

The mapped streams and channels which drain the subwatershed are presented on Figure 2.4 which also shows significant ponds, swamps, and wetlands. The natural drainage of the Whitemans Creek subwatershed has been heavily altered since European settlement. Figure 4.4 presents the natural stream channels along with constructed drainage features that are listed as municipal drains (according to records complied by OMAFRA (2015a)). Aerial and satellite imagery suggest that numerous private drains connect to these features throughout the watershed. Additionally, much of the areas dominated by poorly-draining Tavistock and Port Stanley till (Figure 3.11) have been drained by field tiles to improve the agricultural output of the land. Areas mapped as tile-drained by OMAFRA (2015b) are presented on Figure 4.5, although an inspection of Southwestern Ontario Orthoimagery Project (SWOOP) imagery collected over the past 10 years suggests that this mapping is incomplete. Regardless, the level of hydromodification due to land use changes (Section 2.1), ditching, and channelization, and the installation of tile drains in the subwatershed is extensive.

4.1.2 Runoff Generation

The low permeability Tavistock Till in the Upper Whitemans Till Plains generates large volumes of runoff in this relatively flashy portion of Horner Creek. Similarly, the southwestern portion of the subwatershed adjacent to Kenny Creek also generates significant runoff volumes. This area has also been heavily ditched and generates higher intensity runoff events than other areas. The sandy, shallow aquifers at surface in the upper Central Glacial Outwash serve to reduce runoff volumes into the lower reaches of Horner Creek; recharge in this area also supports numerous ponds and wetlands. The areas of highest recharge (and hence with lower expected runoff) occurs within the Lower Whitemans Sand Plain. Recharge in this area supports an extensive and thick (up to 65 m) sand aquifer which serves as a supply of cool water to adjacent Whitemans, Kings, Rest Acres, and Landon’s creeks during the summer months. This sand aquifer also represents an important source for both agricultural and domestic water supply.

The subsequent portions of this section of the report present an analysis of historical meteorological conditions within the Whitemans Creek subwatershed. Basin climate averaged normals are derived and discussed in the context of long-term trends and major droughts. Streamflow response within the subwatershed is presented through an analysis of data from key stream gauges. Adjacent watersheds with similar hydrological characteristics are also discussed to provide insight into the regional hydrologic setting. Lastly, ecological streamflow minimums developed for the subwatershed are introduced and compared with precipitation and other factors on an annual basis.

4.2 *Precipitation and Temperature*

To assess the local climate in the Whitemans Creek subwatershed, climate data from Environment Canada’s Atmospheric Environment Service (AES) and GRCA monitoring network were obtained and analyzed. The purpose of this compilation was to conduct a long-term historical analysis of climate patterns and to create a continuous high-quality set of daily climate data for use as input to the integrated groundwater/surface water model.

There are several climate stations sited around the Whitemans Creek subwatershed (Figure 4.6). Data from stations within 15 km of the model boundary were obtained to develop a representative group of stations with which to characterize the subwatershed climate. The boundary of this zone was extended a further 10 km to the west to include additional stations to aid in the delineation of small, intense convective storms. Station information for the selected 79 stations is presented in Table 4.2 and the available period of record for the selected stations is illustrated on Figure 4.7. The available record within the station group is adequate, with data (either precipitation or temperature) available from 1865 onwards. The number of active stations increased during the post-war period and peaked in the mid-1980s. Figure 4.8 presents the number of stations within the analysis group with complete monthly precipitation records post-1945 as determined by the WMO standard “3 and 5” rule discussed below. Due to budgetary constraints, many climate stations have been discontinued in the past decade, with less than 5 stations in the study area providing complete precipitation records from 2014 onward (Figure 4.9).

(*Note: Data used in this analysis were not corrected for differences in synoptic measurement intervals. The climatological day used to derive daily minimum and maximum temperatures and precipitation totals has varied historically. Since July 1st, 1961 principal stations have treated 0600Z the following day as the end of the observation period. At ordinary stations, 0800Z is typically reported; however, 0000Z, 1230Z and 1700Z have also been historically employed. Conclusions related to the long-term climate trend analysis which includes periods pre-1961, may be affected by these differences in daily observation periods.)*

4.2.1 Regional Climatic Variability

To ensure that the selected stations represent a similar hydroclimatic region, the variability of precipitation observations at the 79 stations was analyzed at a monthly and annual time step. Stations without snow observations, such as the automated GRCA tipping buckets at Brantford, Burford, New Hamburg, and Paris were processed to remove cold weather observations. Monthly precipitation averages were calculated at each station following the WMO standard "3 and 5" rule which excludes months with more than 3 consecutive days of missing data or more than 5 days with missing data (WMO, 1989). Water year averages were calculated where complete monthly records were available from October through the following September. Many stations did not record Sunday observations during the 1860s and 1870s. At many active EC stations in the study area, significant gaps are present in the modern record. Many stations with long, continuous records such as Woodstock and Brantford have significant gaps in the recent record, often missing multiple days of observations during a typical week. Accordingly this analysis was centered on the 1980s which features the most complete period of record.

Figure 4.10 presents the average annual precipitation quartiles between WY1960 and WY2010 for the station group. Median annual total precipitation varied from 690 millimetres (mm) to 1,300 mm over this 51-year period with an observed mean annual precipitation of 935 mm. Annual interstation variability is low in the group, with the inter-quartile range (i.e., the difference between the 75th and 25th percentile) averaging 112 mm or 12% of the observed median annual precipitation. Monthly precipitation totals are illustrated in Figure 4.11 for the period spanning WY1980 through WY1990. Over this 11-year period, median monthly precipitation ranged from 8 mm in June of 1988 to 175 mm during September of 1986 with a mean monthly precipitation of 82 mm. Interstation variability was higher on a monthly basis, with the interquartile range averaging 21 mm (26% of the observed median). This variability is primarily observed during the summer months, and is likely due to the influence of intense convective events that cover only parts of the entire study area. For example, the large discrepancy observed in the summer of 1987 was due to a number of storm events which passed over the northern portion of the study area. These storms produced large runoff events in Waterloo and Kitchener with some runoff in the Whitemans Creek subwatershed, but produced no runoff in Big and Otter Creeks to the south. The influence of these summer convective events highlights the need to maintain a climate group with enough stations to effectively represent these events.

An analysis of the average monthly data demonstrated that the automated GRCA stations at Brantford, Burford, New Hamburg, and Paris did not correlate well with neighboring EC stations during some periods. These stations likely require additional QA/QC processing, and were excluded from the dataset used for subsequent analyses.

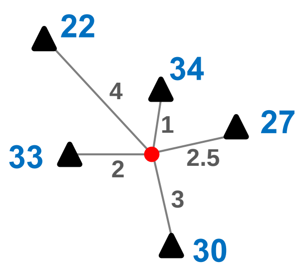
4.2.2 Basin-averaged Normals

To assess the subwatershed climate trends, daily climate data at the remaining 75 climate stations were interpolated to a 1 km by 1 km grid using an inverse-distance-squared weighting technique (Figure 4.2). Inverse-distance-weighting is a computationally efficient way of interpolating the spatial data which assumes the correlation between the data at the nearby stations drops off steeply with distance. The study area sees both frontal and convective storms in the summer months; frontal systems are a result of large (sub-continental scale) air masses with different temperatures and air pressures colliding whereas convective storms are generated by heat and available moisture and generally have a small footprint. Small-scale (2–20 km) circulations termed 'severe deep moist convective storms' can dump several months' worth of precipitation on a relatively small area in a matter of hours. A frontal storm would likely be captured by all the study area climate stations, whereas a convective storm may not be. For this reason it is preferable to capture data from as many climate stations in the study area as possible.

Inverse-distance weighting preserves more spatial information than some other interpolation schemes such as Thiessen polygons and is therefore preferred for spatially distributed models. Given the dense distribution of climate stations in the study area, and the small scale storms that can control the hydrologic response during the summer months, this interpolation technique was used to derived the basin-averaged normal and, ultimately, the climate inputs for the integrated model.

a)

$$P_{cell} = \frac{\sum \frac{P_{gauge}}{dist^2}}{\sum \frac{1}{dist^2}}$$



$$P_{cell} = \frac{\frac{34}{1^2} + \frac{33}{2^2} + \frac{27}{2.5^2} + \frac{30}{3^2} + \frac{22}{4^2}}{1 + \frac{1}{2^2} + \frac{1}{2.5^2} + \frac{1}{3^2} + \frac{1}{4^2}}$$

$$P_{cell} = 32.381$$

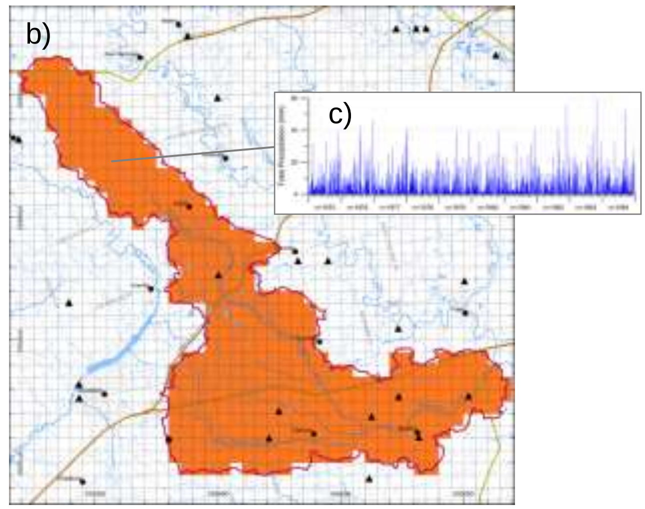


Figure 4.2: a) Inverse-distance-squared formula and example; b) meteorological interpolation grid with climate stations and subwatershed cells for averaging, c) typical interpolated precipitation hydrograph at a grid point.

A complete daily precipitation record (total precipitation, rain, and snow) was generated for the period spanning WY1867 through WY2016 on a gridded basis with the inverse-distance-squared weighting method (i.e., data are interpolated to the 1km by 1km grid array for each day). Similarly, a complete daily temperature (minimum, mean, and maximum) record was gridded for the period spanning WY1872 through WY2016. The gridded data sets were used for the analysis of both the spatial and temporal analysis presented below.

To assess spatial patterns, average annual precipitation for the period of record was calculated from the daily grids. Average annual precipitation varies from a high of 950 mm in the northwest of the study area to a low of 850 mm in the southeast around Brantford (Figure 4.13). Thus, the poorly drained portions of the Upper Whitemans hydrologic sub-region receives, on average, approximately 10% more precipitation than the more permeable sediments of the Lower Whitemans sand plain. Annually averaged daily temperature (Figure 4.14) demonstrates an inverse relationship with elevation, with a 1°C difference observed across the watershed roughly correlating to topography (Figure 2.5).

To assess climate normals, the daily gridded climate data was averaged over the Whitemans Creek subwatershed (Figure 4.2b) to generate a daily time series of basin-averaged precipitation (Figure 4.2c) and temperature. A time-window portion of this daily basin-average dataset is presented in Figure 4.15 and Figure 4.16 for the period spanning WY1975 though WY2014. The following analysis of climate normals and trends was undertaken with this interpolated, basin-averaged time series.

Figure 4.17 presents the annual average precipitation observed over the study watershed for a 151-year period showing long-term trends and the number of stations sourced for the interpolation. Estimated average annual precipitation between WY1867 and WY2016 was 897 mm per year (mm/yr) over the watershed; while over the past 50 years (WY1967-WY2016) annual precipitation has averaged 955 mm/yr (Table 4.1). The precipitation trends follow the general pattern observed in the Great Lakes region; with a major drought observed in the 1890s, an increase in annual precipitation over the first 30 years of the 20th Century, followed by a leveling off during the mid-20th century, and finally an increase in precipitation observed between 1970 and the present day (Bonsal and Shabbar, 2010). Periods of drought in the observed record occur in the 1890s, 1930s, late-1950s to mid-1960s, and the late 1990s.

Table 4.1: Basin-averaged annual precipitation with varing observation periods.

Period	Watershed Average Precipitation (mm)
Total Record	897
Past 100 years	913
Past 50 Years	955
Past 30 Years	949
Past 10 Years	979

Figure 4.18 presents the basin-average annual temperature observed in the study watershed between WY1872 and WY2016. A general warming trend is observed over the period, with a decrease in the middle part of the 20th century as is typically observed in North America (NOAA, 2014). Figure 4.19 overlays the annual mean temperature with the annual precipitation totals. Some years of reduced precipitation correspond to years with a high than normal mean temperature, notably WY1998 and WY2012. Figure 4.20 presents a breakdown of annual precipitation volumes by rain and snow. Some drought periods clearly corresponds to phases of reduced rainfall (e.g., the late 1990s), while some extreme years correspond to average rainfall but with lower than average snowfall (e.g., the 1930s or WY2012).

Figure 4.21 presents a histogram of average monthly precipitation. The winter months have slightly lower median precipitation, with the summer month exhibiting a larger range of variability. Average monthly median precipitation ranges from a mid-winter low of 59 mm to a summer high of about 79 mm; when considering the entire period of record, precipitation appears to be well-distributed over the water year. Figure 4.22 and Figure 4.23 present histograms of monthly mean and daily minimum/maximum temperature, respectively. Daily values range from extreme minimums of -35°C in January to maximums approaching 40°C in July. Variability in the daily and monthly mean temperatures is highest during the winter months with daily normals varying by as much as 20°C.

Figure 4.24 presents the daily precipitation exceedance probability function (EPF) for the period of record. Daily precipitation totals exceed 1 mm for 80% of days with measured precipitation. Only 1% of daily precipitation events exceed 30 mm. A histogram of maximum daily precipitation is shown on Figure 4.25 illustrating that the higher daily maximums occur during the summer months. The relative distributions of daily precipitation totals exceeding 1, 5, 10, 25, and 30 mm are presented in normalized form on Figure 4.26. This figure compares the relative distribution and seasonal frequency of daily rainfall totals greater than a given exceedance. Days with intensities less than 10 mm/d are distributed fairly evenly over the water year. Higher-volume daily totals (>20 mm/d) tend to occur mainly in the summer months (June through September), likely in the form of high-intensity convective storms.

4.3 *Streamflow*

The distribution of Water Survey of Canada (WSC - a division of Meteorological Service of Canada, Environment Canada) stream gauge locations close to or within the study area is shown on Figure 4.28. There are two active and one discontinued streamflow gauges within the Whitemans Creek subwatershed (quaternary watershed ID 02GB-05). There are 21 active or historic Water Survey of Canada (WSC) stream gauge stations within a 10-km buffer of the Whitemans Creek and each of the quaternary subwatersheds adjacent to Whitemans Creek is currently gauged by the WSC. Table 4.3 presents a summary of the properties and streamflow characteristics of the 13 gauges within the model area.

4.3.1 Historical Trends

The WSC gauge on Whitemans Creek near Mount Vernon (02GB008), located immediately downstream of Cleaver Road, is the closest gauge to the stem of the subwatershed and is of prime significance to the Tier 3 Assessment. Streamflow has been monitored continuously at this site since March 1961; a hydrograph of the observed record at this gauge is presented in Figure 4.29. Horner Creek is gauged above Princeton with discharge data are available starting in 1953 (Figure 4.30). This gauge was discontinued between 1992 and 2003, leaving a significant gap in the available record. Kenny Creek was gauged immediately upstream of its confluence with Whitemans Creek between 1961 and 1991. The daily hydrograph of observations is presented in Figure 4.31. While there are some gaps in coverage for each of the three stream gauges, two are available with recent record.

4.3.1.1 Low Flows

The period of record at each of the three gauges overlap within the 1957-1966 drought period and therefore were helpful in assessing the response of the integrated model to extreme low-flow periods. Logarithmic plots of daily streamflow, which enhance the presentation of the low flow record at the three gauges, are presented in Figure 4.32 through Figure 4.34. Extreme low-flow events in the Whitemans Creek subwatershed were observed in WY1962, WY1966, WY1988, WY1999, and WY2012.

4.3.1.2 Average Annual Discharge

Annual average discharge and total runoff for each gauge in the study subwatershed is presented on Figure 4.35 through Figure 4.37. The mean annual streamflow at Whitemans Creek near Mount Vernon (02GB008) is 4.4 cubic metres per second (m^3/s) and equal to a total runoff depth of 363 millimetres per year (mm/yr). The observed record at the three gauges Whitemans Creek overlap for the periods between WY1962 through WY1969 and WY1972 and WY1990. Total observed annual runoff at the Whitemans, Horner, and Kenny stream gauges (02GB008, 02GB006, and 02GB009) for this overlapping period was 356 mm/yr, 392 mm/yr, and 361 mm/yr, respectively. Precipitation for this period averaged 931 mm/yr, resulting in runoff ratios of 38.3%, 42.1%, and 38.9%, respectively. The smallest annual flow occurred in WY1962, part of a significant period of sustained low flow between WY1961 and WY1963 which is generally included as part of the 1957-1966 drought period. WY1999 represents the second-most extreme low-flow period, with the recent WY2012 low-flow period plotting closer to the average on an annual basis. The annual averaged runoff depth is plotted against the basin-averaged precipitation on Figure 4.38 for Whitemans Creek at Mount Vernon (02GB008). The runoff ratio for the entire period of record is 38.1%. Runoff and precipitation appear to be well correlated on an annual basis.

4.3.1.3 Peak Flows

The magnitude and timing of the annual peak flow at the Whitemans Creek gauge near Mount Vernon (02GB008) stream gauge is presented in Figure 4.39. The peak annual flows generally correspond to the spring freshet, which typically peaks during late-March. To provide some context regarding the relative flood return frequencies observed in the Whitemans Creek subwatershed, a simple flood-frequency analysis was undertaken. The peak annual flood series at the three Whitemans Creek stations were fitted to a Log Pearson III distribution as per Bulletin #17B (Water Resources Council (US), Hydrology Committee, 1981) to derive return intervals. Outlier removal via the Grubbs' Test and the estimation of regional skewness were also implemented as per Bulletin #17B. The annual peak return intervals for the Whitemans Creek stream gauges are presented on Figure 4.40. Bankfull discharge on Whitemans Creek is approximately 40 m^3/s (Marchildon *et al.*, 2011), which corresponds to the 1.5 year return interval. The largest observed instantaneous discharge on Whitemans Creek was 84.9 m^3/s which occurred April 1st, 1982. This event has a predicted return interval of 24.6 years, somewhat lower than its plotting position of 43 years.

Interestingly, the peak events generated on Kenny Creek (gauged area: 91.9 km^2) have a higher return interval than events of a similar magnitude generated on Horner Creek which covers an area 50% larger (gauged area: 150 km^2). Kenny Creek is extensively tile drained and has an extensive series of man-made ditches and canals which cut through hummocky areas. While Kenny Creek has a lower annual runoff ratio than Horner Creek, Kenny Creek is capable of generating higher intensity runoff events. This may also be a function of the surface storage present the many wetlands and ponds that drain into Horner Creek. These features, removed through land development in Kenny Creek, buffer intense rainfall events and reduce the peak event discharge generated in Horner Creek.

4.3.1.4 Average Monthly Streamflow

Histograms of average monthly streamflow are provided on Figure 4.41 through Figure 4.43 for each gauge in the study subwatershed. The dominance of the spring freshet on the annual flow regime can be clearly observed, with March and April contributing approximately 40% of the annual streamflow. The interquartile range of flow is highest in March as the freshet is dependent on the timing and duration of melt events as well as the volume of accumulated winter snowfall. Variability in the winter is also higher than during the summer months, as mid-winter rain events are not uncommon in the study area. The lowest flows typically occur during the month of August with recovery starting mid-September. Winter low flow extremes are present in the record. They are not common, however, because fall recharge events and significant groundwater inflow into Whitemans Creek help to sustain flow during the winter months.

4.3.2 Flow Duration Curves

The flow duration curve (FDC) is an analysis plot that characterizes the relationship between magnitude and frequency of flows at a gauge station (Searcy, 1959). In the method, each flow rate is plotted against the percentage of time that flow rate is equalled or exceed. FDCs represent an empirical approximation of the cumulative distribution function of stream flow record at a gauging station (Maidment, 1992). These curves offer a simple and effective method to characterize catchment runoff properties and flow regimes from stream gauge data. Qualitative conclusions can be drawn from the shape of the curve; For example, steep slopes represent highly variable stream flows in a system most likely dominated by surface runoff. Low slopes may suggest a damped runoff response, or the influence of groundwater discharges when observed in the low-flow portion of the duration curve (Healy, 2010).

Flow duration curves derived from the period of continuous record at each of the three gauges in the Whitemans Creek subwatershed are presented on Figure 4.44. Flow is also presented as depth of total runoff, as on Figure 4.45, which normalizes the flow relative to the gauged area. The runoff duration curve on Kenny Creek clearly deviates from the Whitemans and Horner curves; runoff towards the upper end of the hydrologic regime is higher while runoff towards the middle and low end of the regime are lower. In other words, discharge is conveyed faster out of the Kenny Creek watershed than in Horner Creek or when compared to the overall subwatershed characteristics (as measured at Whitemans Creek near Mount Vernon (02GB008)). The difference in behaviour at the upper end of the regime is illustrating on Figure 4.46 and shows the flashier nature of Horner and Kenny relative to Whitemans Creek. Horner, while flashier than Whitemans, likely supports the mid- and low-range of the hydrologic flow regime with discharge from wetlands located in the central portion of the subwatershed.

Figure 4.47 though Figure 4.49 present the duration curves for neighboring gauged catchments and the three Whitemans Creek stations. The Thames River at Ingersoll gauge (02GD0106) exhibits a similar flow duration curve in magnitude to that of Whitemans Creek. The gauged catchment at Ingersoll however is 30% larger than Whitemans Creek and features two major reservoirs which serve to store and release flows. When comparing the runoff duration curve at Whitemans to other naturally-regulated nearby catchments, it can be seen that Whitemans Creek supports the highest runoff below the 50th percent exceeded interval. The flashy Kenny Creek exhibits a similar range runoff duration curve to the Thames River near Tavistock (02GD023) and to the Avon River above Stratford (02GD026) gauges. These catchments also drain till-dominated areas.

4.3.3 Daily versus 15-Minute Instantaneous Measurements

When addressing streamflow gauge data, temporal resolution can be an important consideration (Thompson, 2013). Daily data can often obfuscate characteristics of the natural hydrologic regime as the reported values only represent the total measured daily flow volume. Processes and mechanisms that occur at a higher frequency can be obscured at the daily time scale. This often occurs in flashy urban systems or other well-drained catchments. To check the adequacy of the temporal resolution of the streamflow data within the study area, instantaneous streamflow data collected on a 15-minute time step were obtained from the WSC for the study area gauges for the period spanning 1969 through 2010.

A comparison of the mean daily and instantaneous hydrographs is presented on Figure 4.50 for the Whitemans Creek near Mount Vernon (02GB008) gauge for calendar year 2008. The two hydrographs generally overlap except for a small period around the annual peak in April. Figure 4.51 through Figure 4.53 present the daily and instantaneous flow duration curves for the three subwatershed gauges on a probability axis. The daily flow duration curve was derived only from days with instantaneous record to allow a direct comparison of the relative runoff exceedances. Mean daily streamflow data appear to adequately represent the hydrologic response in Whitemans and Horner Creeks up to 99.99% of the time. In Kenny Creek (02GB009), the instantaneous discharge deviates beyond the 0.1% percent equalled or exceeded interval (which occurs every 500 days). This is likely due to the tile drainage and channelization present in the watershed which aid in moving rainfall off the landscape. The flashier nature of this catchment is shown in Figure 4.54 for the calendar year 1983. Generally, on a subwatershed scale, daily streamflow data describe the hydrologic regime well with some deviation beyond the 2-3 year return interval in well-drained areas.

4.3.4 Baseflow Estimates

Hydrograph separation techniques were applied to the continuous flow data to split the two components of streamflow: (1) overland runoff and (2) baseflow. Baseflow is generally assumed to be primarily composed of groundwater discharge. It should be noted that the separation methods cannot, by themselves, distinguish between groundwater discharge and other relatively steady flows such as discharge from reservoirs or large wetlands. Numerous techniques are available to estimate baseflow including curve processing and statistical techniques.

Baseflow was estimated using the modified United Kingdom Institute of Hydrology (UKIH) smoothed minima method devised by National Water Research Institute and Meteorological Service of Canada (Piggott *et al.*, 2005). This method was applied recently to length-of-record streamflow monitoring information for over 4,000 gauges in the Great Lakes region and has proven to be as efficient and robust as the other approaches in the processing of this streamflow data (Piggott *et al.*, 2005). Figure 4.55 illustrates a typical baseflow hydrograph at Whitemans Creek near Mount Vernon (02GB008) derived with the modified UKIH method. The baseflow index (BFI) is the ratio between baseflow discharge (Q_{BF}) and total discharge (Q). The BFI can serve as an initial estimate into the overall flashiness of the gauged catchment. BFIs are approximately 0.5 for the study catchments and results are typical of rural southern Ontario catchments. The estimated BFI in Kenny Creek is approximately 10% lower than those of Whitemans and Horner creek, owing to man-made changes to the natural drainage and lack of natural storage. The mean baseflow estimates and catchment BFIs are provided in Table 4.3 for each stream gauge in the study area. Median streamflow (Q_{50}) is also often used as an estimate of annual average baseflow and this value correlates well to the estimated baseflow within the study watersheds (Table 4.3).

4.3.5 Spotflows

To support the Tier 3 Assessment modelling efforts, GRCA staff have taken spotflow measurements across the subwatershed during low flow periods (Shifflett, 2015). Spotflow measurements supplement the baseflow calibration targets for the steady-state groundwater model and streamflow calibration targets for the transient integrated model. Thirteen sites were selected for observation, including 10 locations on the main stem of Whitemans, Horner, and Kenny creeks. Landons, Rest Acres, and Kiwanis creeks were sampled upstream of their confluence with Whitemans Creek.

Measurements were obtained over multi-day periods in October 2014 (Figure 4.56), May 2015 (Figure 4.57), and August 2015 (Figure 4.58). Flows during the summer of 2015 in the creeks were very low, with the observed discharge at Whitemans Creek near Mount Vernon (02GB006) dropping to 0.6 m^3/s in late August. The spotflows obtained during the summer low-flow period suggest that Whitemans Creek loses flow to the groundwater system along the Apps' Mill reach between the gauge at Cleaver Road and Robinson Road. An additional set of measurements were taken later in August to confirm this behavior and found a loss of 60 L/s across the reach at Apps' Mill. GRCA staff have recommended a series of manual measurements from Cleaver Road to downstream of Robinson Road to isolate portions of the reach that may be losing or gaining.

4.4 *Environmental Flow Thresholds*

The GRCA has developed environmental thresholds for Whitemans Creek as part of a broader attempt to develop flows and levels for the Grand River basin (GRCA, 2014) and manage ecological effects (Figure 4.3). This study found a threshold of 1.1 m³/s is required to maintain connectivity through the lower reaches of Whitemans Creek near Mount Vernon. The threshold for ecological impairment was estimated at 0.8 m³/s. These thresholds are exceeded over 83.5% and 89.9% of the observed record at Whitemans Creek based on the flow duration curves presented in Figure 4.44. A monthly histogram of log-transformed streamflow is presented on Figure 4.59 with the two thresholds. The threshold for impairment (0.8 m³/s) is near the 25th percentile of mean monthly flow for August and September at Whitemans Creek near Mount Vernon (02GB008). As this threshold value represents a relatively frequent occurrence interval (once in 4 years) and a critical environmental target, the integrated model should be capable of reliably describing the flow regime at this discharge threshold.

Figure 4.3: Posted signage at Apps Mill informing anglers of possible low water restrictions.

4.4.1 Precipitation Drought Response

The relationship between low-water events and annual precipitation was investigated. Annual (calendar year) basin-averaged average precipitation is presented along with the number of low-water events per year in Figure 13.3. The number of low-water events per year was derived from a 7-day moving average streamflow series, with Level 1 and 2 occurring when flows drop below 1.1 m³/s and 0.81 m³/s, respectively. Level 3 events occur when stream flows drop below 0.5 m³/s, which represents a target threshold where permanent ecological damage is possible (e.g., loss of viable habitat eliminates a significant percentage of young-of-the-year trout). Figure 13.4a shows a clear relationship between years with low precipitation and the number of days with streamflow in Whitemans Creek below the prescribed ecological minimums. Low-water events increase linearly with decreases in annual precipitation below 950 mm/yr. This suggests a direct link between precipitation droughts and ecological impairment. Level 2 and Level 3 events (which denote conditions where ecological impairment is likely) are compared with precipitation on Figure 13.4b, these events are almost certain to occur in years when annual precipitation is below 900 mm/yr.

4.5 *Tables and Figures*

Table 4.2: Climate stations proximal to the study watershed.

Name	Climate ID	Station Operator	Easting (m)	Northing (m)	Elevation (m)	Start Date	End Date	Water Years with Data	Average Number of Days with Data per Water Year
APPS MILL	6140286	AES	550,429	4,775,438	230.1	Oct 01 1972	Nov 23 1972	1	54
AYR	6140437	AES	544,626	4,792,056	289.6	May 01 1956	Jul 31 1961	6	306
BRANTFORD	6140941	AES	559,376	4,775,510	205.7	Jan 01 1876	Jun 30 1963	81	330
BRANTFORD AIRPORT	6140942	AES	554,221	4,775,837	245.5	Dec 12 2014	*Realtime*	3	210
BRANTFORD BRANT PARK	6140948	AES	556,917	4,777,710	213.4	Nov 25 1972	Nov 30 1973	2	186
BRANTFORD MOE	6140954	AES	562,629	4,775,539	196	Jun 01 1960	Jan 20 2013	54	339
BRANTFORD MORELL	6140951	AES	558,543	4,777,724	198.1	May 01 1959	Oct 31 1964	7	287
BURFORD	6141040	AES	546,384	4,772,077	259.1	Oct 01 1970	Sep 30 1971	1	184
CAMBRIDGE GALT MOE	6141095	AES	555,128	4,797,686	268.2	Sep 01 1879	Feb 28 1994	70	314
CAMBRIDGE-STEWART	6141100	AES	556,731	4,799,921	289	Sep 01 1973	Dec 31 2000	29	344
CANNING	6141169	AES	544,699	4,780,951	259.1	Apr 19 1968	Nov 30 1971	5	197
CATHCART	6141268	AES	534,980	4,774,230	269.7	Apr 01 1962	Aug 31 1970	9	283
CULLODEN EASEY	6141933	AES	512,248	4,748,611	280	Jun 01 1974	Dec 31 2007	35	346
DELHI CDA	6131982	AES	536,756	4,746,477	231.6	Jun 01 1934	May 31 1997	64	360
DELHI CS	6131983	AES	536,756	4,746,477	231.7	Jun 02 1997	*Realtime*	21	335
DOON	6142065	AES	544,538	4,805,383	312.4	May 08 1948	Dec 31 1953	7	260
DORCHESTER	6142066	AES	497,555	4,760,815	271.3	Apr 14 1976	*Realtime*	42	352
DRUMBO	6142110	AES	536,542	4,786,455	304.8	Aug 01 1965	Oct 31 1976	13	269
DRUMBO HARRINGTON	6142113	AES	538,978	4,786,468	281.9	Jun 04 1974	Sep 30 1975	2	242
EMBRO INNES	6142295	AES	505,682	4,788,580	358.1	Aug 23 1977	Dec 31 2003	28	343
FALKLAND	6142373	AES	544,735	4,775,398	262.1	Apr 01 1962	Aug 31 1969	8	297
FOLDENS	6142420	AES	517,926	4,763,059	328	Jun 01 1963	Jun 12 2016	54	354
FULLARTON	6142627	AES	483,799	4,803,034	335.3	Oct 01 1956	Jul 31 1967	11	347
GLANWORTH CFPL	6142798	AES	483,667	4,747,509	280.1	Jun 01 1961	Dec 31 1982	23	336
HARLEY	6143355	AES	542,336	4,768,719	259.1	Nov 01 1979	Jan 31 1981	2	196

Name	Climate ID	Station Operator	Easting (m)	Northing (m)	Elevation (m)	Start Date	End Date	Water Years with Data	Average Number of Days with Data per Water Year
HAYSVILLE	6143395	AES	550,155	4,775,806	320	Jun 01 1965	Sep 30 1967	3	283
INGERSOLL	6143780	AES	544,623	4,792,426	266.7	Apr 01 1870	Jun 30 1969	24	252
KITCHENER	6144232	AES	559,643	4,775,882	342.9	Oct 01 1914	Dec 31 1977	64	359
KITCHENER CITY ENG 1	6144240	AES	554,376	4,776,301	320	Sep 01 1954	Sep 30 1961	4	95
KITCHENER CITY ENG 2	6144241	AES	556,917	4,777,710	320	Jul 01 1961	Sep 30 1961	1	92
KITCHENER OWRC	6144245	AES	562,355	4,775,907	281.9	Jun 15 1962	Jun 30 1975	14	321
LONDON	6144470	AES	558,272	4,777,722	246.3	Nov 14 1871	Dec 27 1891	19	272
LONDON A	6144473	AES	546,113	4,772,076	278	Mar 20 2012	*Realtime*	6	274
LONDON CS	6144478	AES	555,395	4,798,059	278	Sep 20 2002	*Realtime*	16	319
LONDON INT'L AIRPORT	6144475	AES	556,731	4,799,921	278	Jul 20 1940	Apr 14 2016	77	323
LYONS	6134729	AES	544,696	4,781,321	258.8	Apr 01 1883	Oct 31 1894	13	321
MILLERS LAKE	6145160	AES	535,253	4,773,862	304.8	Jun 01 1964	Aug 31 1971	8	320
MITCHELL	6145239	AES	512,519	4,748,551	335.3	Nov 01 1948	May 31 1964	16	342
MOSSLEY	6145497	AES	536,758	4,746,107	274.3	Sep 01 1962	Aug 31 1966	5	292
MUIR	6145520	AES	536,758	4,746,107	0	Jul 01 1955	Aug 31 1956	2	191
NILESTOWN	614N003	AES	544,538	4,805,383	265	Jun 03 1997	Oct 31 2001	6	253
OXFORD CENTRE	6146166	AES	497,327	4,761,032	297.2	Dec 01 1961	Apr 30 1965	4	311
PARIS	6146240	AES	536,540	4,786,825	266.7	May 01 1870	Oct 31 1967	66	339
POPLAR MILLS	6146563	AES	539,246	4,786,840	297.2	Apr 01 1956	Oct 31 1972	18	325
PRESTON	6146711	AES	505,412	4,788,580	291.1	May 12 1953	Jun 30 1996	44	357
PRESTON WPCP	6146714	AES	544,733	4,775,768	272.8	Oct 15 1970	Feb 28 1997	27	344
PRINCETON	6146728	AES	517,858	4,762,876	285	Apr 01 1883	Aug 31 1913	31	330
REGION OF WATERLOO INT'L A	6149388	AES	483,800	4,803,404	321.3	Oct 03 2002	Apr 17 2010	8	344
ROSEVILLE	6147188	AES	483,668	4,747,879	328	Oct 17 1972	*Realtime*	45	348
SCOTLAND	6147664	AES	542,067	4,768,348	247	May 06 1971	Feb 27 2014	44	349
SIMCOE	6137735	AES	529,716	4,799,748	222.5	Mar 01 1866	Jul 31 1961	62	344
SIMCOE	6137730	AES	509,502	4,766,374	240.5	Jan 01 1962	Dec 16 1986	26	345
SIMCOE (AUT)	6137732	AES	540,467	4,809,059	240.5	Dec 02 1992	Sep 20 1999	7	285

Name	Climate ID	Station Operator	Easting (m)	Northing (m)	Elevation (m)	Start Date	End Date	Water Years with Data	Average Number of Days with Data per Water Year
SPRINGFORD	6137979	AES	541,804	4,810,918	248	Jun 02 1986	Sep 28 1997	12	343
ST GEORGE	6147314	AES	541,804	4,810,918	220.1	Apr 01 1883	Oct 31 1901	20	338
ST MARYS	6147340	AES	545,887	4,805,392	317	Jul 01 1888	May 31 1903	15	311
STRATFORD	6148100	AES	483,694	4,758,983	363	Jan 01 1865	Aug 31 1959	89	341
STRATFORD WWTP	6148105	AES	487,690	4,764,497	345	Oct 15 1959	Jul 27 2016	57	342
TAVISTOCK	6148212	AES	487,780	4,764,527	343.2	Mar 01 1967	Aug 31 1988	22	353
THAMESFORD	6148233	AES	487,690	4,764,497	289.6	Jul 01 1974	Jan 31 1975	2	62
TILLSONBURG	6138267	AES	501,362	4,744,158	236.2	Jan 01 1965	Apr 30 1968	4	273
TILLSONBURG NORTH	6138269	AES	550,032	4,792,464	235	Sep 01 1997	Jun 13 2016	20	340
TILLSONBURG WWTP	6138270	AES	485,170	4,812,656	213.4	Jun 09 1962	*Realtime*	56	347
VANESSA	6139131	AES	502,721	4,751,561	239.3	Aug 01 1961	Oct 31 1961	2	46
WATERFORD	6139356	AES	533,907	4,772,004	222.5	May 24 1971	Feb 28 2014	44	351
WATERFORD	6139355	AES	493,206	4,758,967	232	Mar 23 1948	Jan 31 1959	12	321
WATERLOO FIRE HALL	6149380	AES	525,769	4,771,968	317	Sep 01 1973	Oct 31 1974	3	82
WATERLOO WELLINGTON 2	6149389	AES	544,696	4,781,321	313.6	Dec 01 2003	Apr 14 2016	13	166
WATERLOO WELLINGTON A	6149387	AES	483,738	4,777,492	317	Mar 01 1970	Oct 31 2002	34	351
WATERLOO WPCP	6149386	AES	547,237	4,805,401	327.7	Sep 01 1962	Jul 31 2000	39	330
WILSONVILLE	6139514	AES	552,650	4,803,590	248.4	May 16 1959	Mar 31 1964	6	292
WOODSTOCK	6149625	AES	529,781	4,784,941	281.9	Feb 01 1870	*Realtime*	148	347
WOODSTOCK GOLF COURSE	6149630	AES	550,360	4,811,964	317	May 01 1960	Feb 28 1965	6	186
WOODSTOCK WATERWORKS	6149645	AES	542,657	4,800,219	283.2	May 01 1959	Jun 30 1966	8	237
Brantford	--	GRCA	556,199	4,777,329	210	May 01 2000	Sep 30 2014	14	153
Burford	--	GRCA	542,521	4,773,769	266	May 01 2005	Apr 17 2015	11	187
New Hamburg	--	GRCA	527,527	4,804,795	340	May 01 2001	Sep 30 2014	14	153
Paris	--	GRCA	550,101	4,784,822	246	Aug 13 2004	Sep 30 2014	11	144
Shade's Mills	--	GRCA	557,834	4,802,827	291	Jan 01 1984	*Realtime*	32	361

Table 4.3: Gauged Water Survey of Canada (WSC) catchments contained within the model area by tertiary watershed.

WSC ID	Station Name	Easting (m)	Northing (m)	Available Period of Record	Record Length (years)	Status	Catchment Area (km²)	Mean Discharge (m³/s)	Median Discharge (m³/s)	Estimated Baseflow (m³/s)	Baseflow Index
Whitemans Creek Subwatershed (02GB)											
02GB003	Whitemans Creek near Burford	552,397	4,777,518	1913 - 1916	4	Discontinued	399	4.20	4.49	2.08	0.50
02GB008	Whitemans Creek near Mount Vernon	550,130	4,775,013	1961 - 2015	55	Active	386	4.38	2.44	2.36	0.54
02GB006	Horner Creek near Princeton	536,363	4,780,223	1953 - 2015	54	Active	150	1.92	0.934	0.934	0.49
02GB009	Kenny Creek near Burford	541,616	4,771,957	1961 - 1991	31	Discontinued	91.9	1.05	0.310	0.324	0.31
Big (Ontario)Watershed (02GC)											
02GC011	Big Creek Near Kelvin	545,271	4,759,498	1963 - 2015	26	Active	154	1.58	0.805	0.777	0.50
02GC017	Big Otter Creek above Otterville	537,302	4,757,118	1964 - 2015	41	Active	101	1.22	0.619	0.563	0.46
Upper Thames Watershed (02GD)											
02GD011	Cedar Creek at Woodstock	520,214	4,774,392	1951 - 2015	64	Active	87.8	0.940	0.459	0.375	0.40
02GD012	Thames River at Woodstock	520,239	4,776,858	1952 - 1998	47	Discontinued	254	2.91	1.22	1.27	0.44
02GD016	Thames River at Ingersoll	509,269	4,765,407	1957 - 2015	59	Active	510	5.91	3.14	2.93	0.50
02GD021	Thames River at Innerkip	525,024	4,784,770	1978 - 2015	38	Active	149	1.89	0.572	0.498	0.26
02GD023	Thames River near Tavistock	512,165	4,794,663	1987 - 2000	13	Discontinued	34.2	0.408	0.124	0.112	0.28
02GD024	Webber Drain at Highway No. 59 (Pittock Control)	514,342	4,789,303	1988 - 1992	5	Discontinued	3.72	0.021	0.005	0.006	0.28
02GD025	Goring Drain at Concession No. 3 (Pittock Test)	514,514	4,792,446	1988 - 1992	5	Discontinued	3.51	0.031	0.005	0.006	0.20
02GD026	Avon River above Stratford	505,014	4,802,627	1993 - 2015	11	Active	52.5*	0.766	0.362	0.312	0.41

Notes: All station information and daily data were obtained from the Water Survey of Canada HYDAT MS-Access database version 1.0, release dated 14 July 2016 and available for download at http://www.ec.gc.ca/rhc-wsc.

* The catchment area provided in the HYDAT database of 74.5 km² is erroneous. A recent WSC delineation estimates the watershed area at 52.5 km².

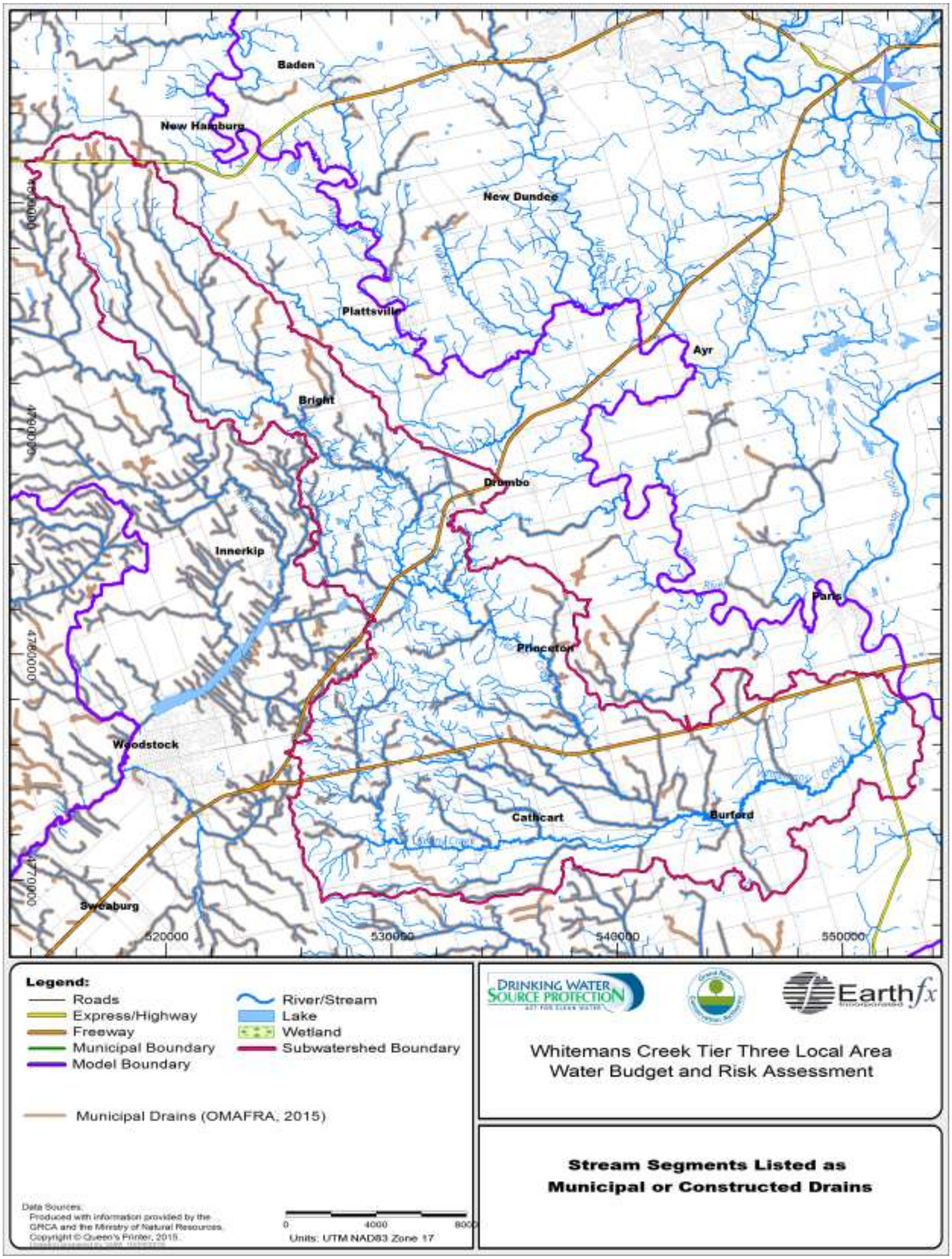


Figure 4.4: Stream segments and constructed drainage (listed as municipals drains) (from OMAFRA, 2015a).

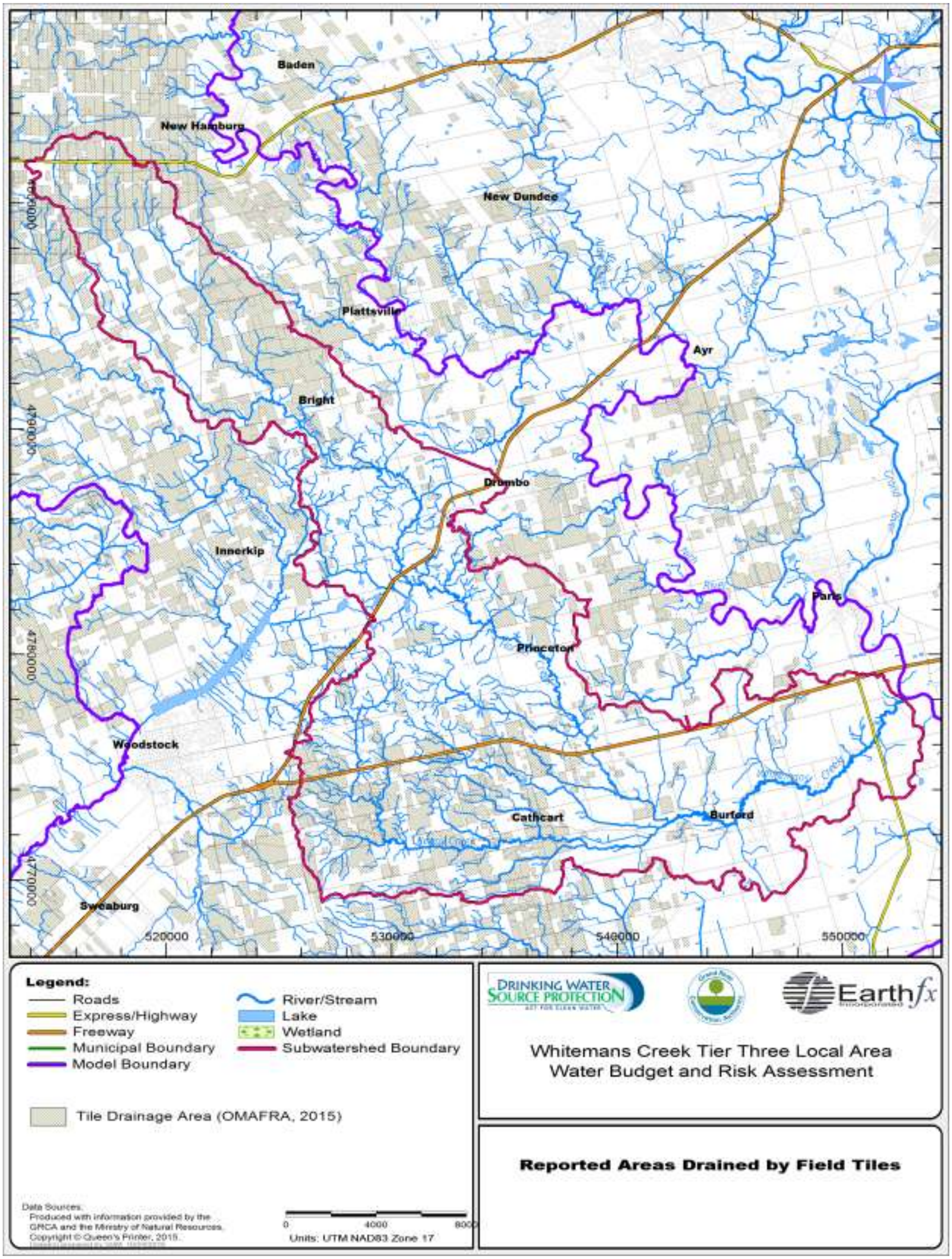


Figure 4.5: Mapped tile drained fields (from OMAFRA, 2015b).

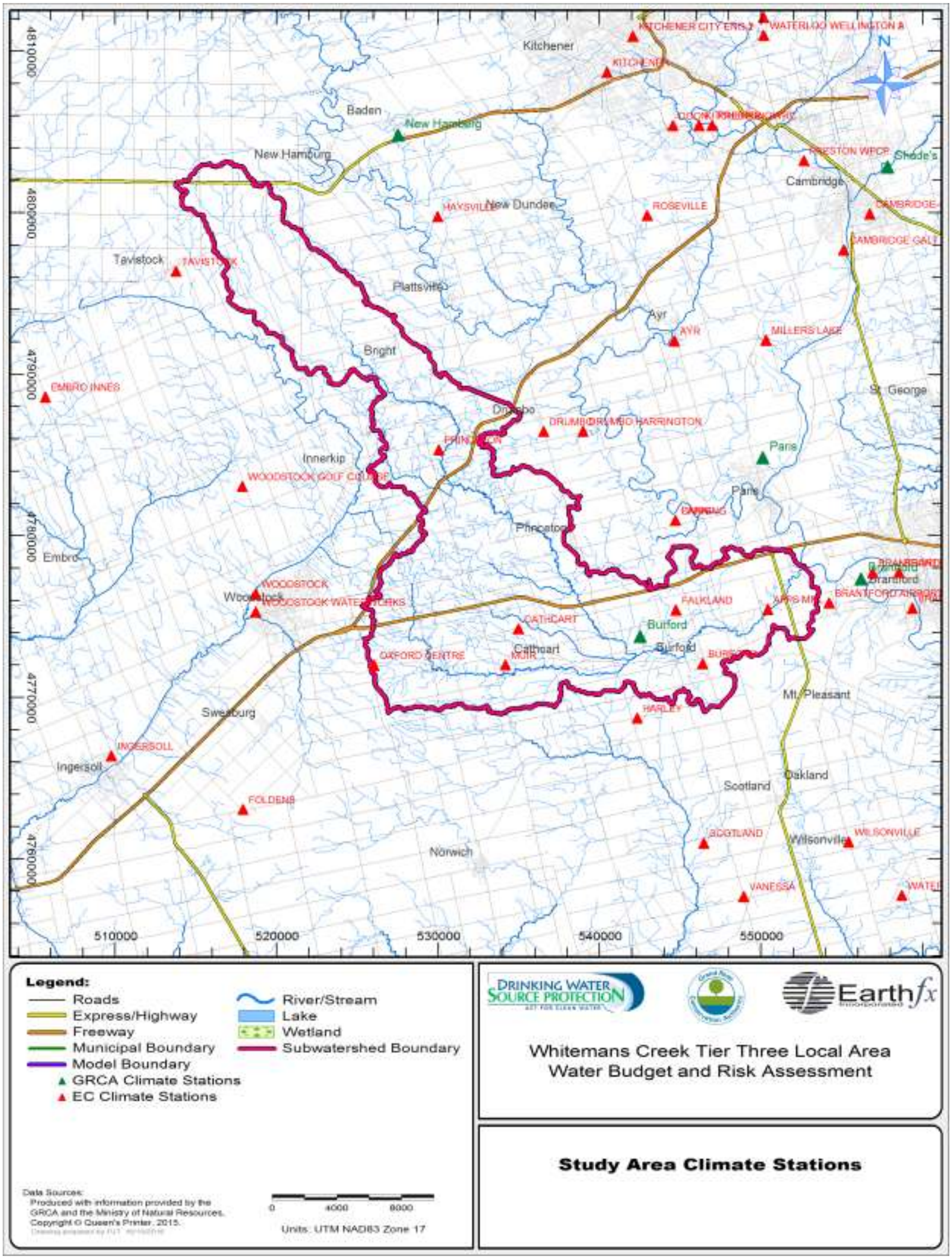


Figure 4.6: Climate stations proximal to the study area.

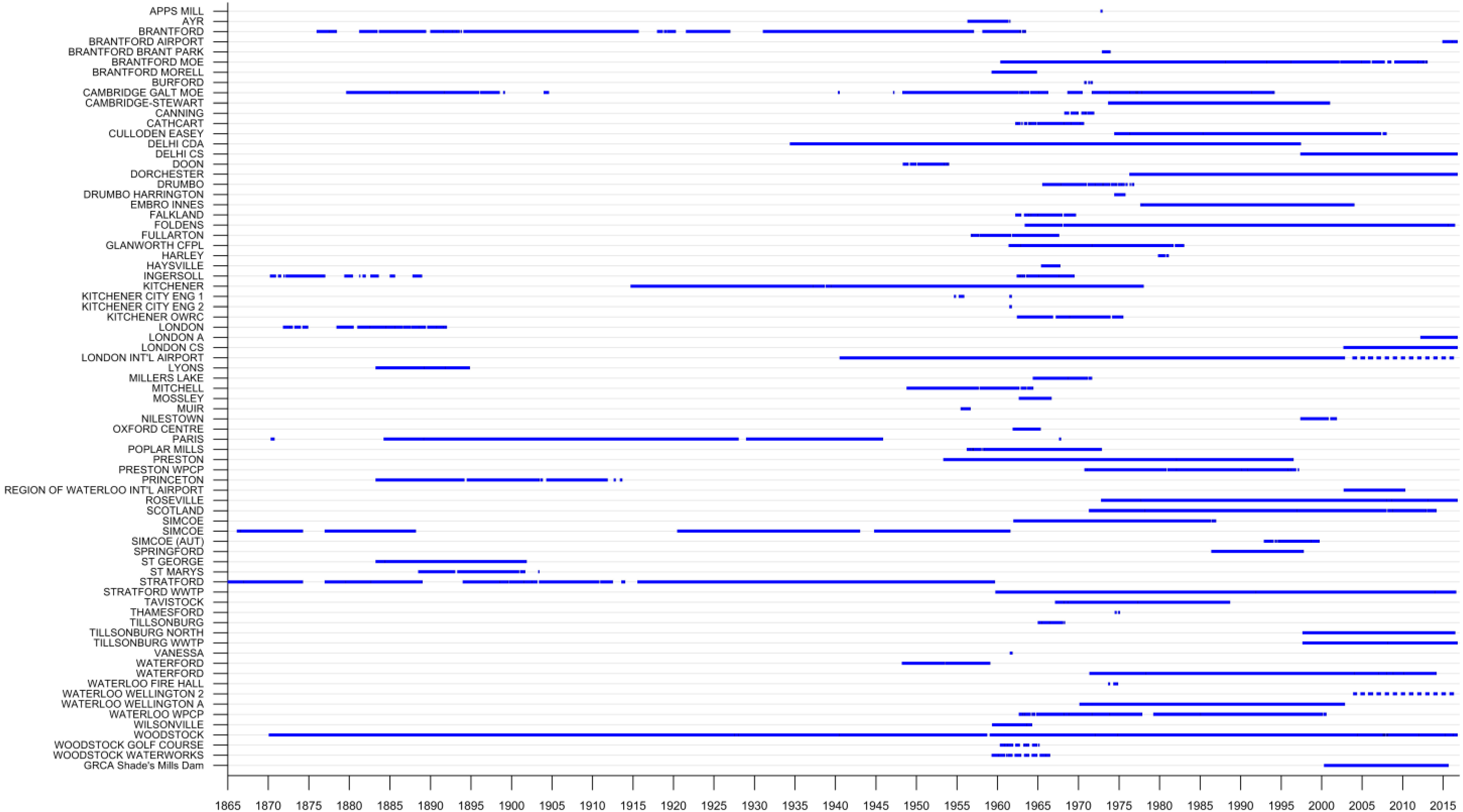


Figure 4.7: Available period of record at climate stations proximal to the study watershed.

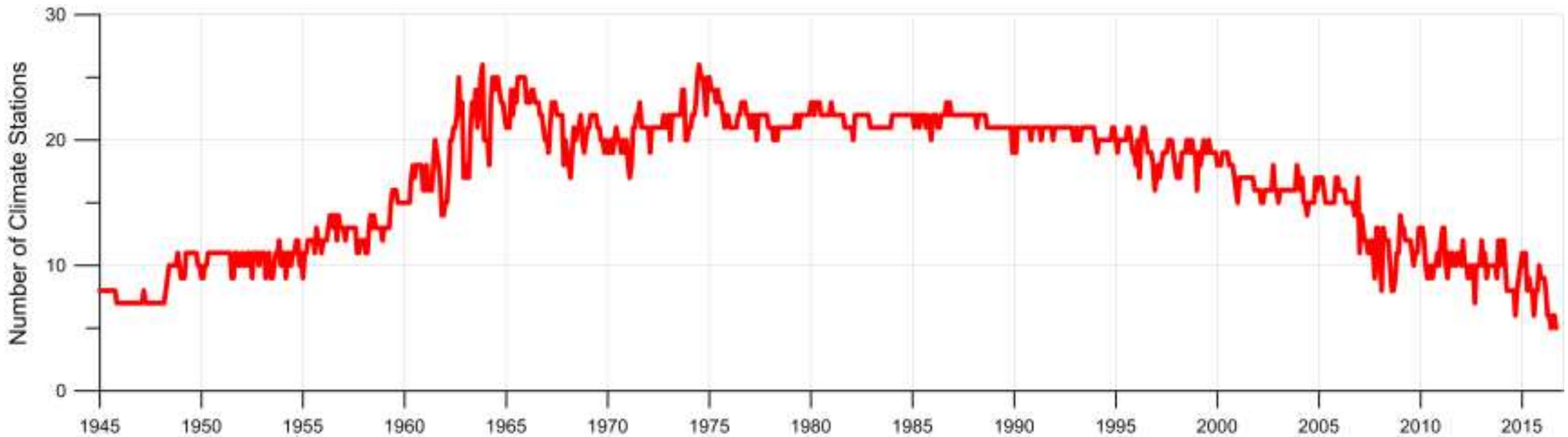


Figure 4.8: Number of climate stations with complete monthly precipitation record (1945 through 2016).

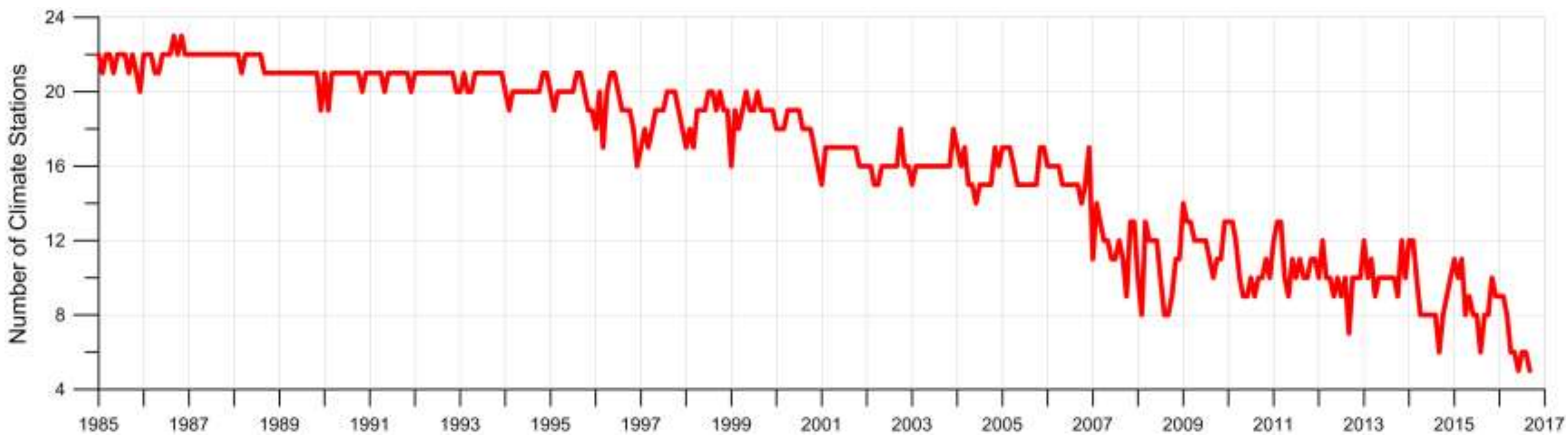


Figure 4.9: Number of climate stations with complete monthly precipitation record (1985 through 2016).

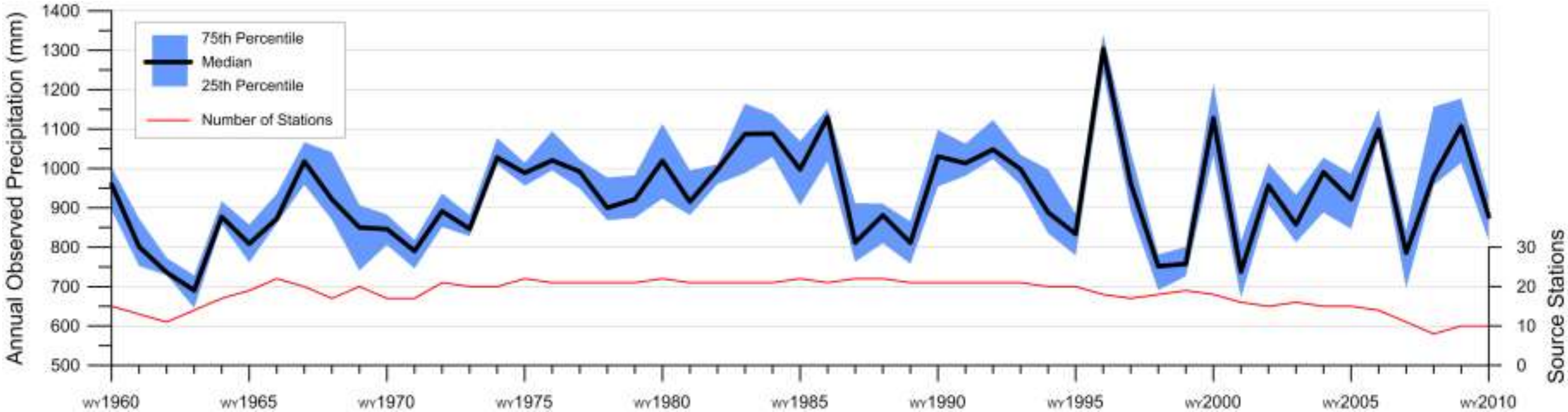


Figure 4.10: Annual precipitation quartiles at study area climate stations (WY1960 through WY2010).

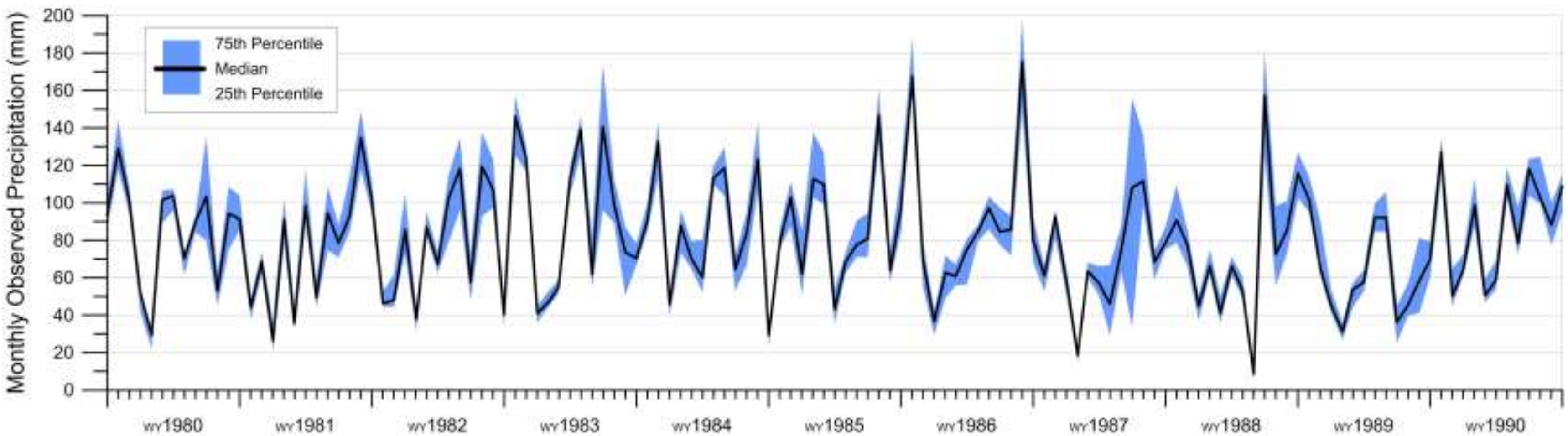


Figure 4.11: Monthly precipitation quartiles at study area climate stations (WY1980 through WY1990).

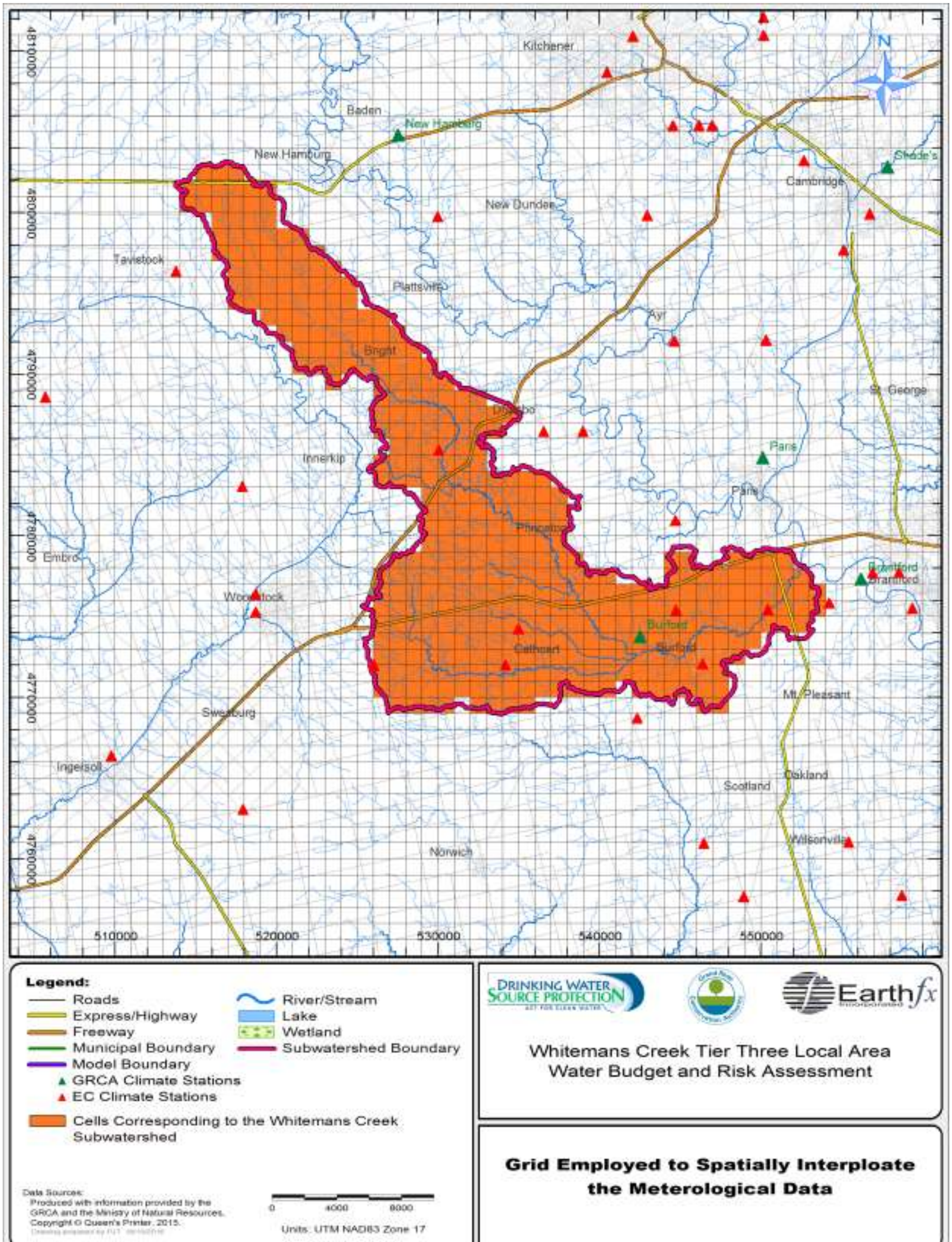


Figure 4.12: Grid employed to spatially interpolate meteorological data and grid cells employed to derive basin-averaged normals for the Whitemans Creek subwatershed.

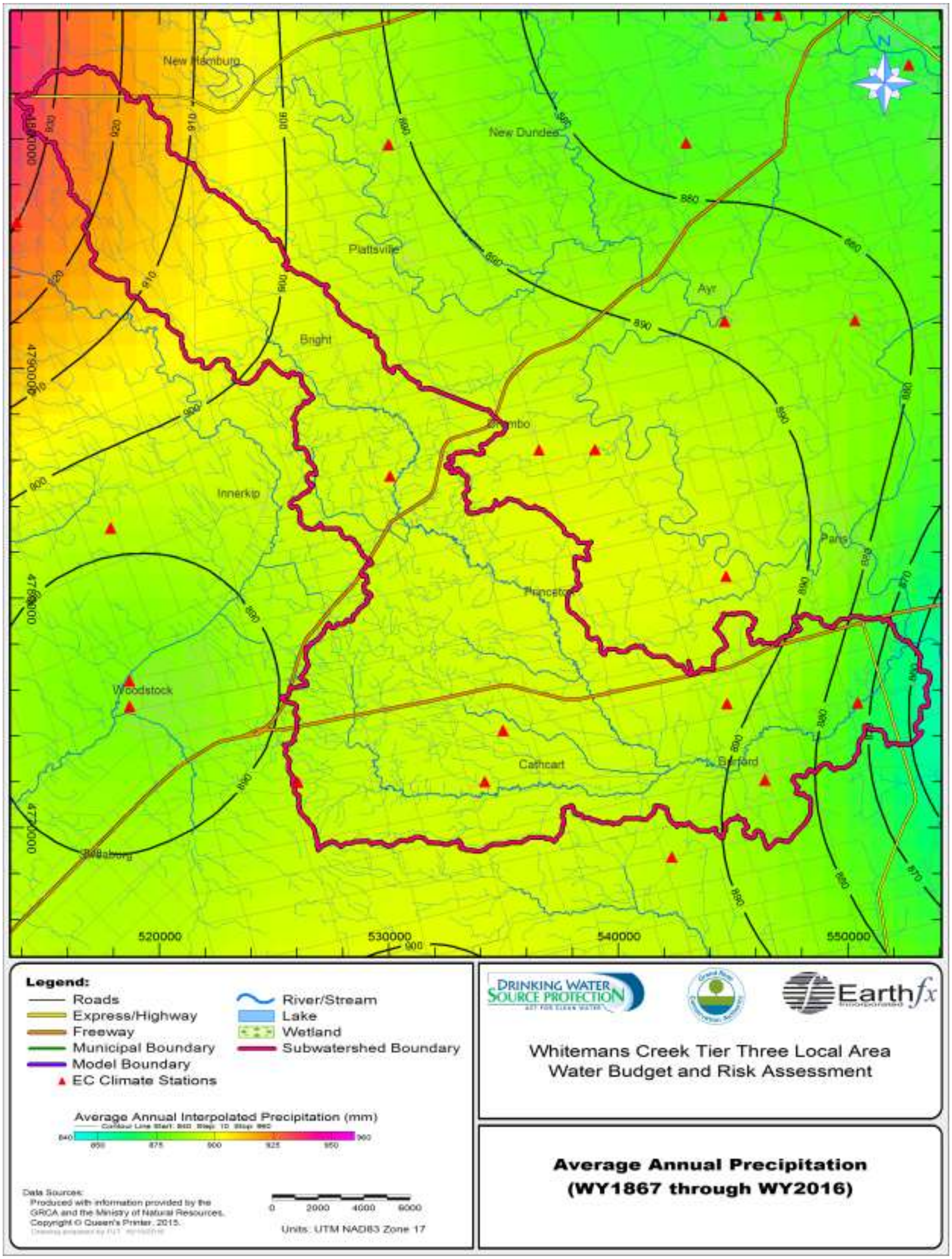


Figure 4.13: Annual average interpolated precipitation (WY1867 through WY2016).

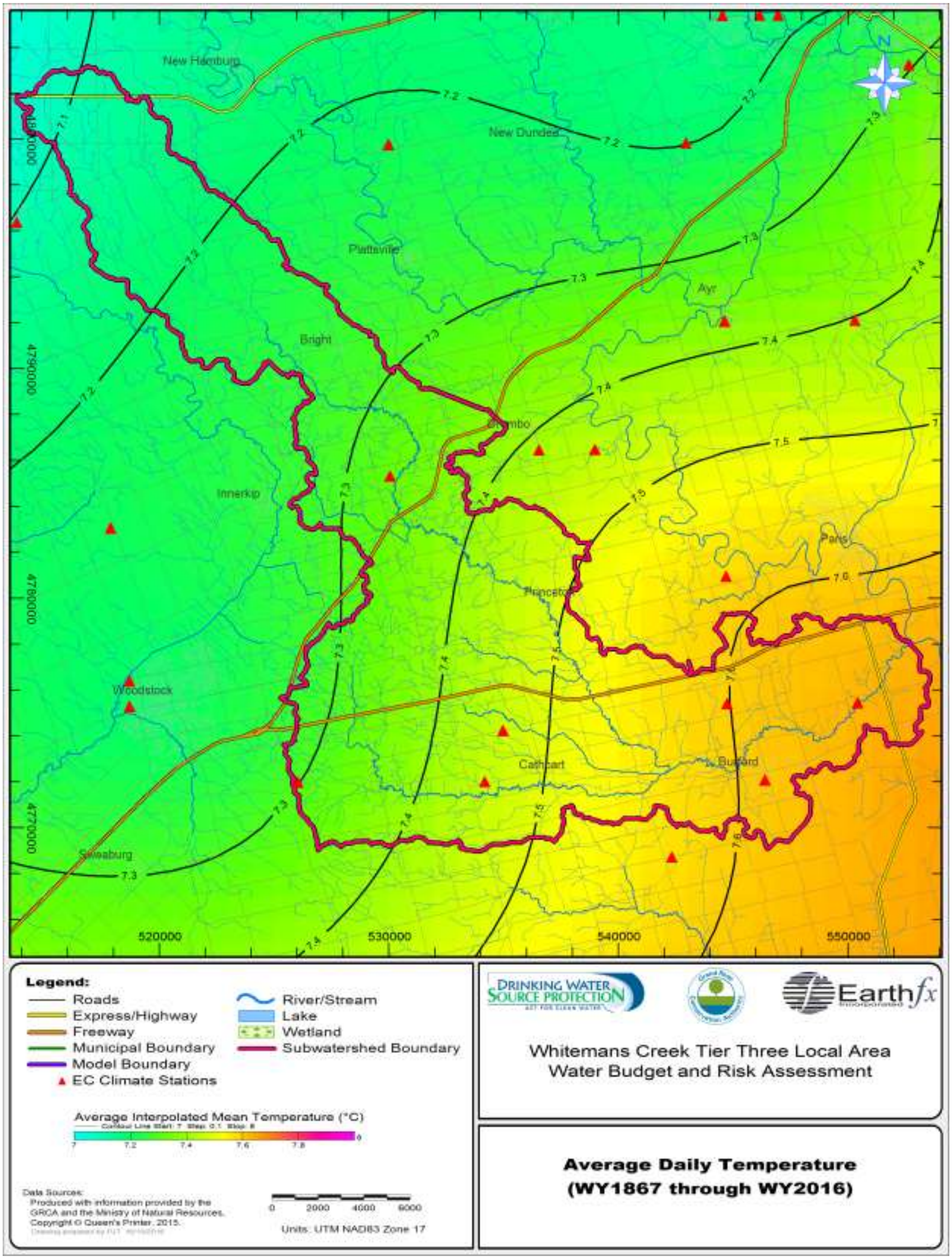


Figure 4.14: Daily average interpolated mean temperature (WY1872 through WY2016).

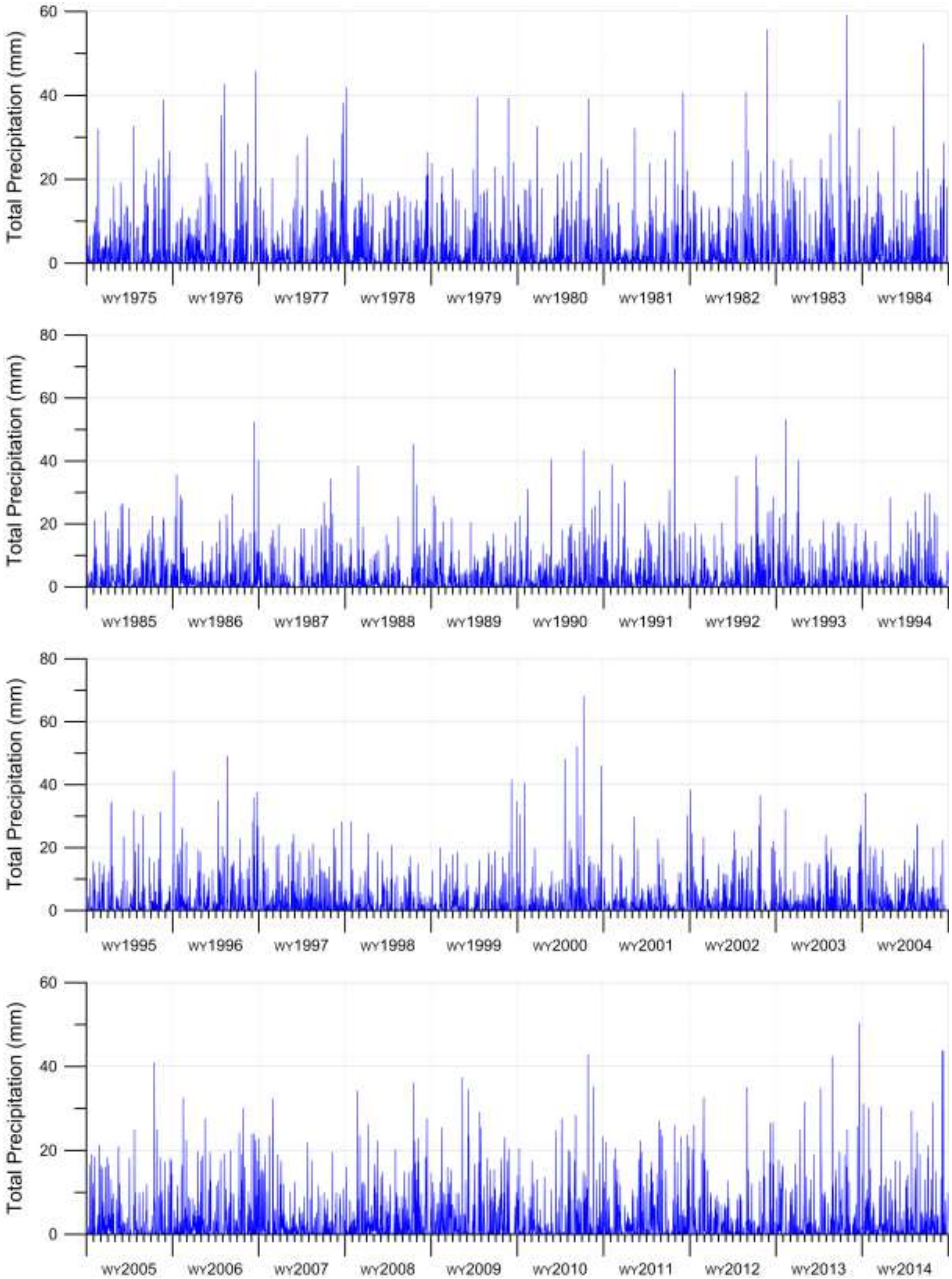


Figure 4.15: Basin-averaged daily precipitation for the period WY 1975 through WY 2014.

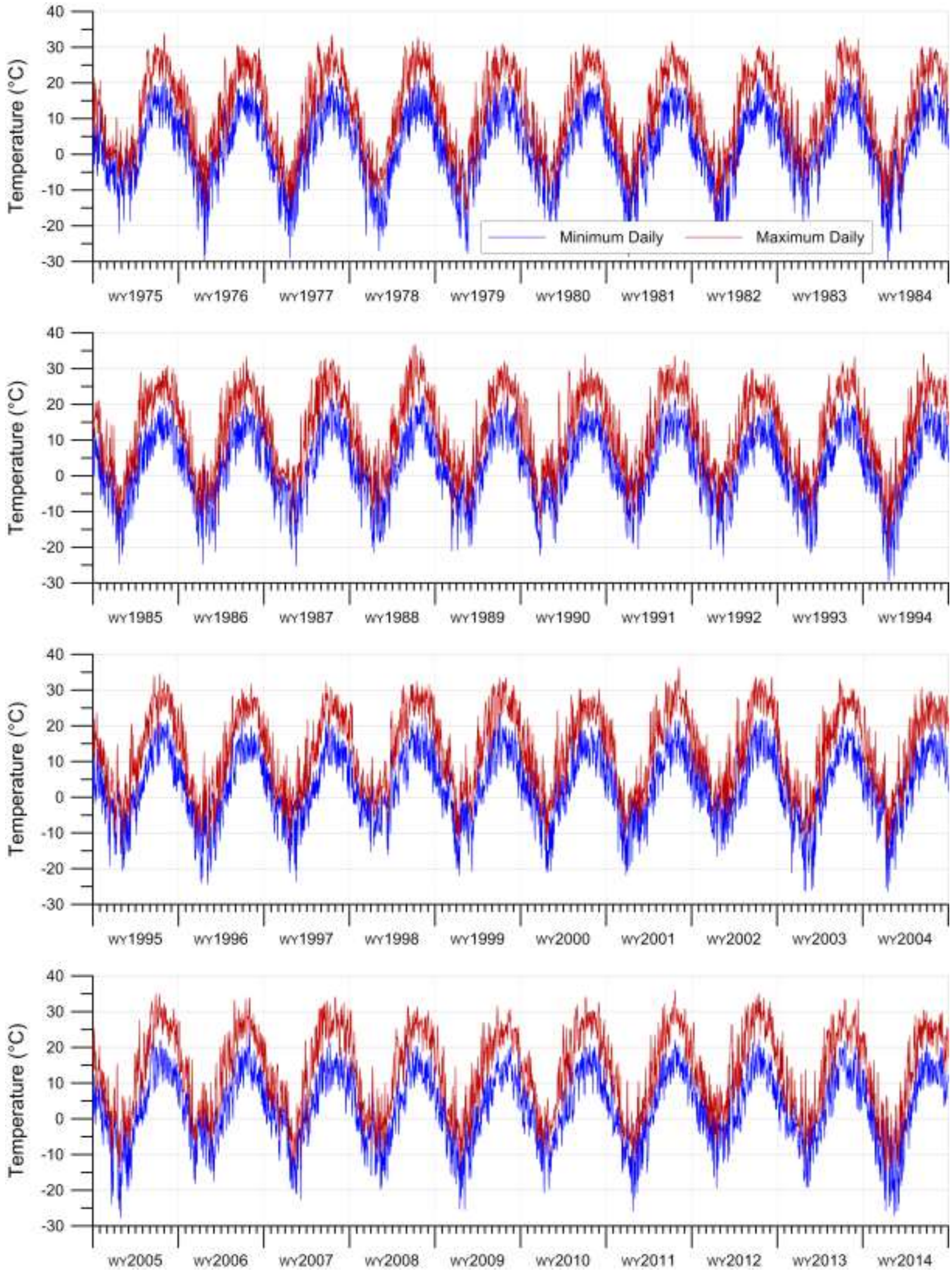


Figure 4.16: Basin-averaged daily minimum and maximum temperature for the period WY 1975 through WY 2014.

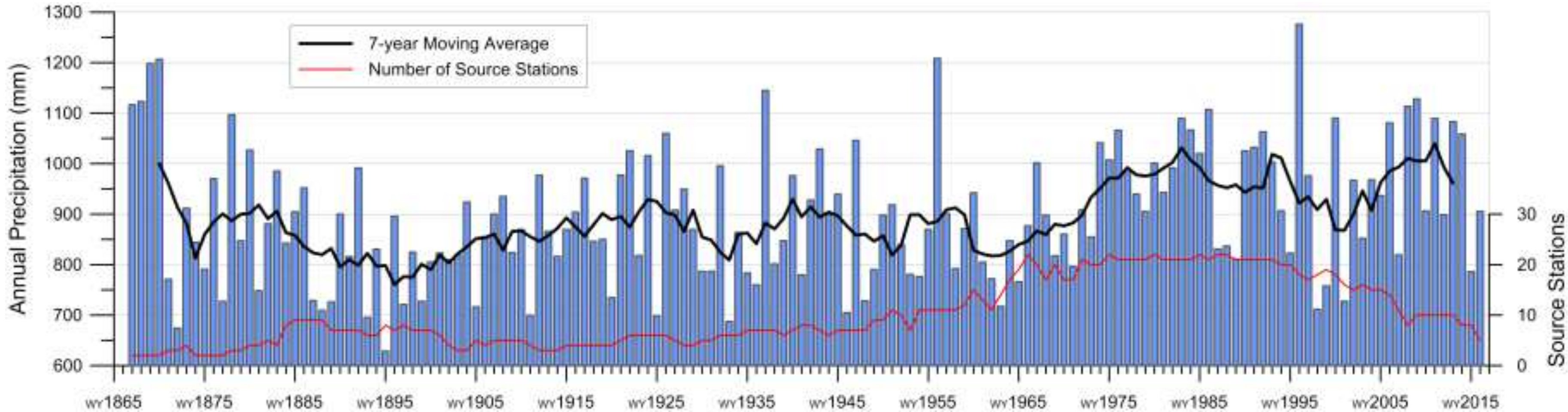


Figure 4.17: Basin-averaged (Whitemans Creek) mean annual precipitation (WY1867 through WY2016).

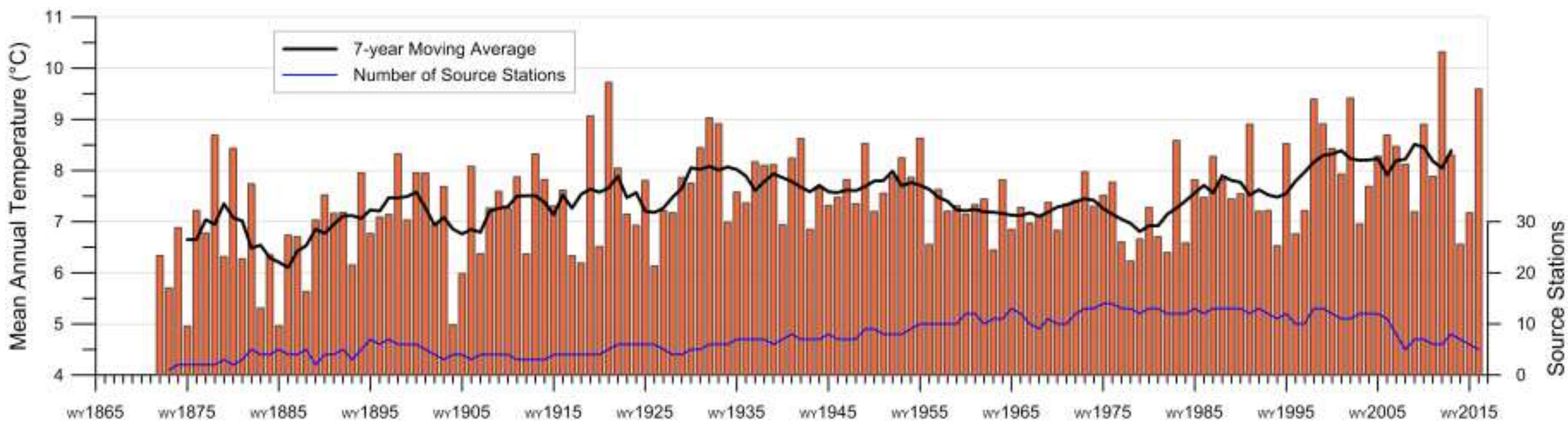


Figure 4.18: Basin-averaged (Whitemans Creek) mean annual temperature (WY1872 through WY2016).

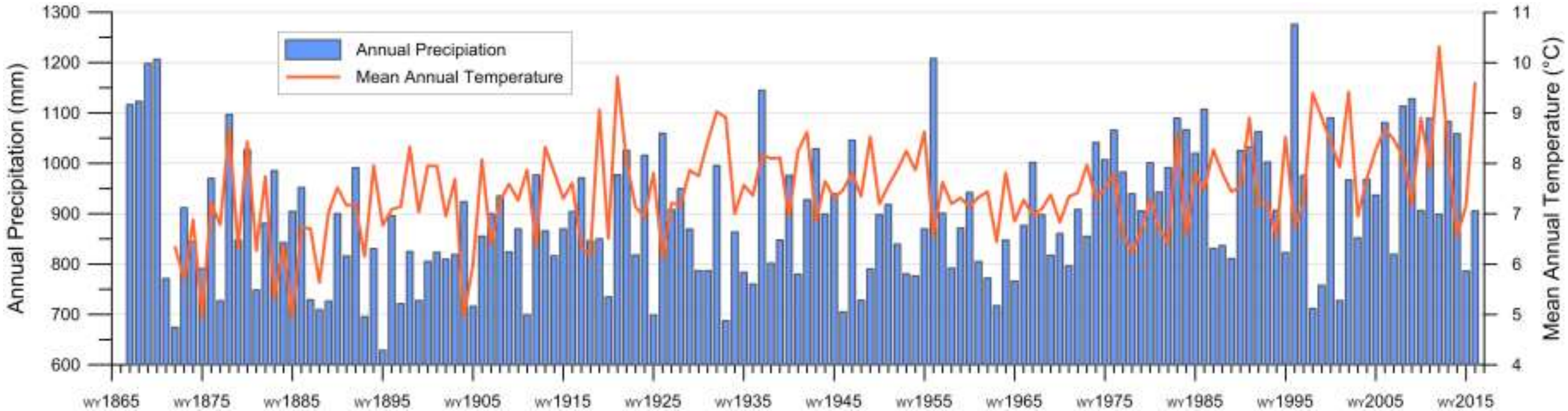


Figure 4.19: Basin-averaged (Whitemans Creek) mean annual temperature and precipitation.

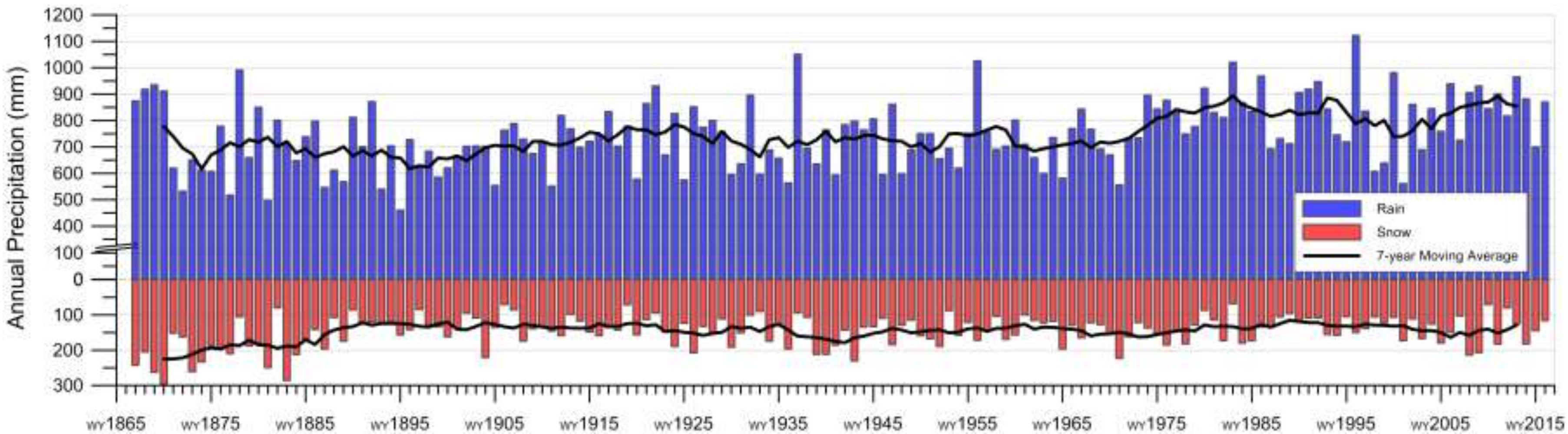


Figure 4.20: Annual summary of basin-averaged (Whitemans Creek) precipitation form.

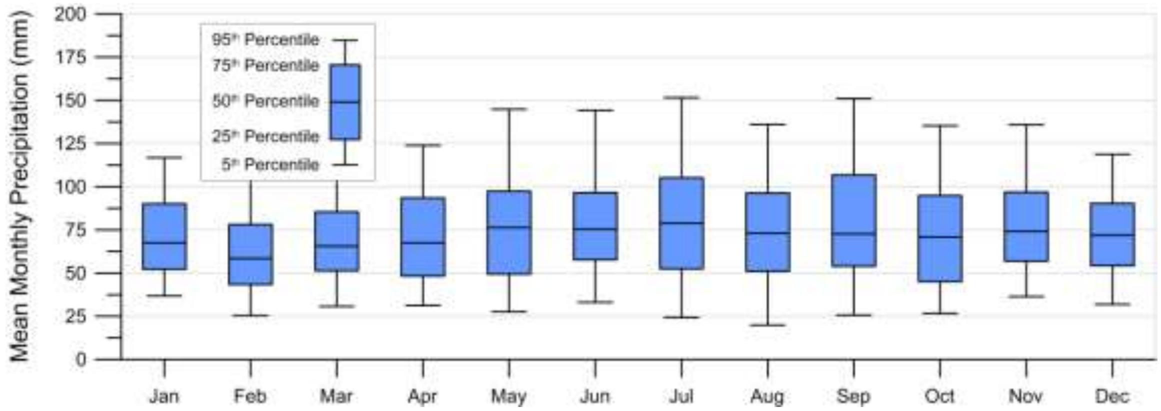


Figure 4.21: Histogram of basin-averaged (Whitemans Creek) monthly precipitation totals.

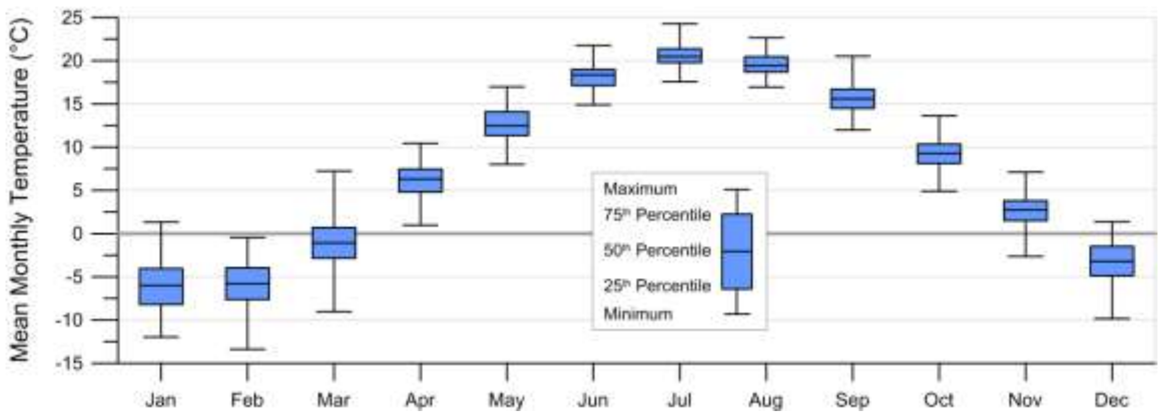


Figure 4.22: Histogram of basin-averaged (Whitemans Creek) monthly mean temperatures.

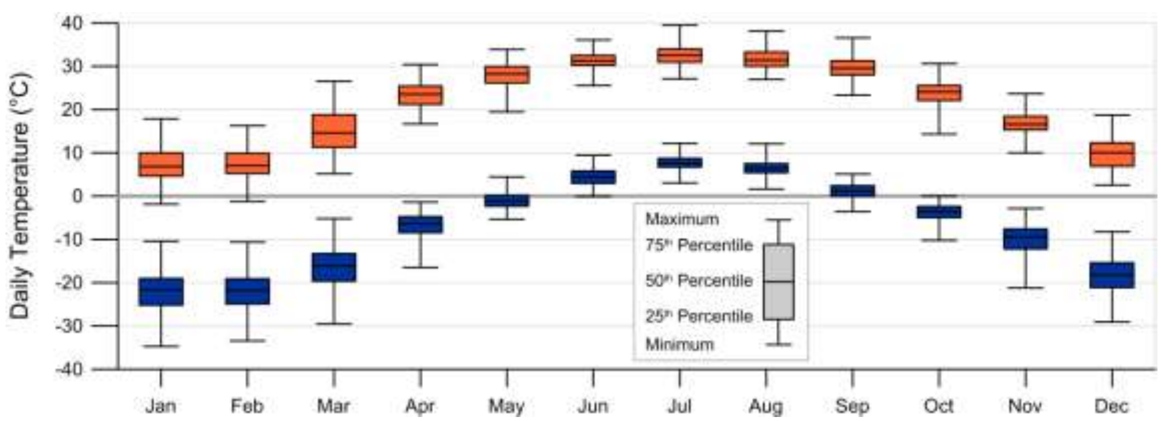


Figure 4.23: Histogram of basin-averaged (Whitemans Creek) daily minimum and maximum temperatures.

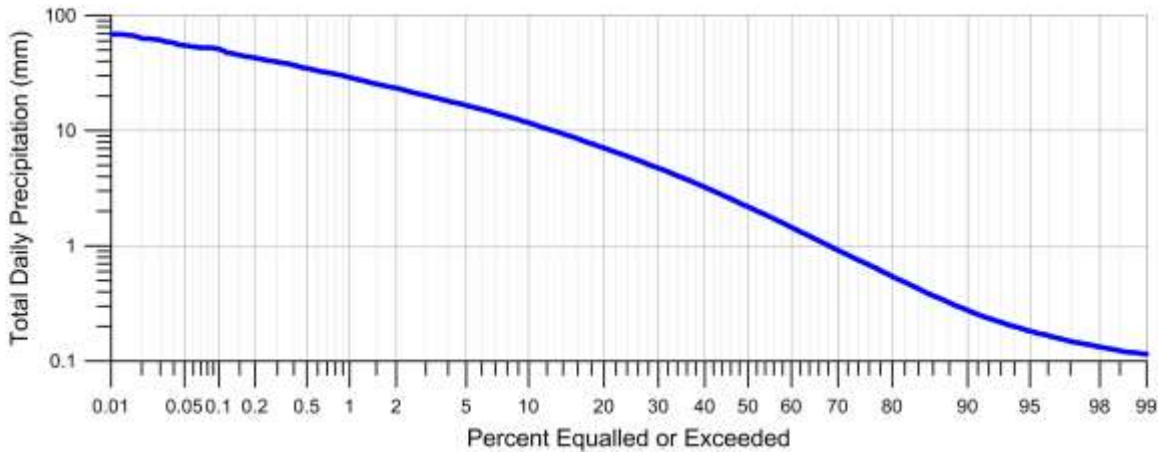


Figure 4.24: Basin-averaged (Whitemans Creek) daily precipitation exceedance plot (WY1867 through WY2014).

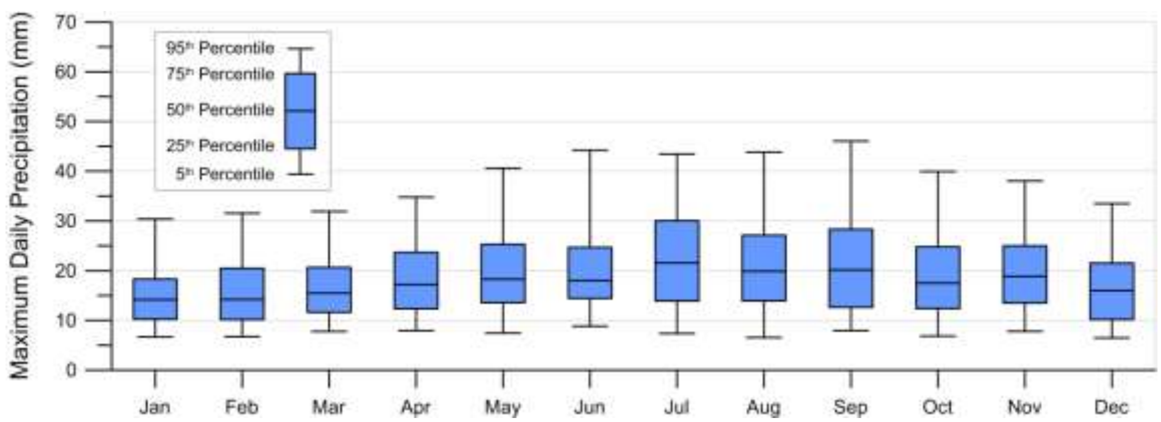


Figure 4.25: Histogram of basin-averaged (Whitemans Creek) daily maximum precipitation.

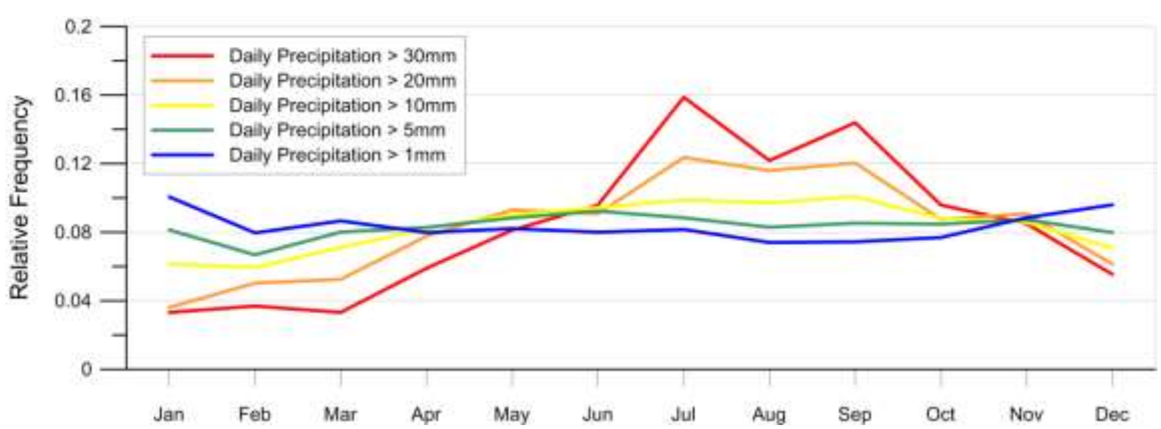


Figure 4.26: Normalized (area under each curve = 1) distribution of basin-averaged (Whitemans Creek) daily rainfall totals.

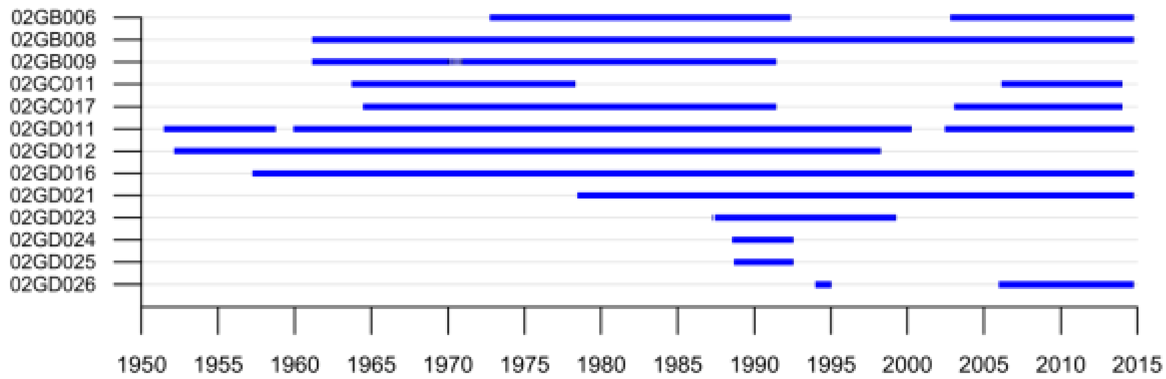


Figure 4.27: Available period of record at WSC streamflow gauges within the study area.

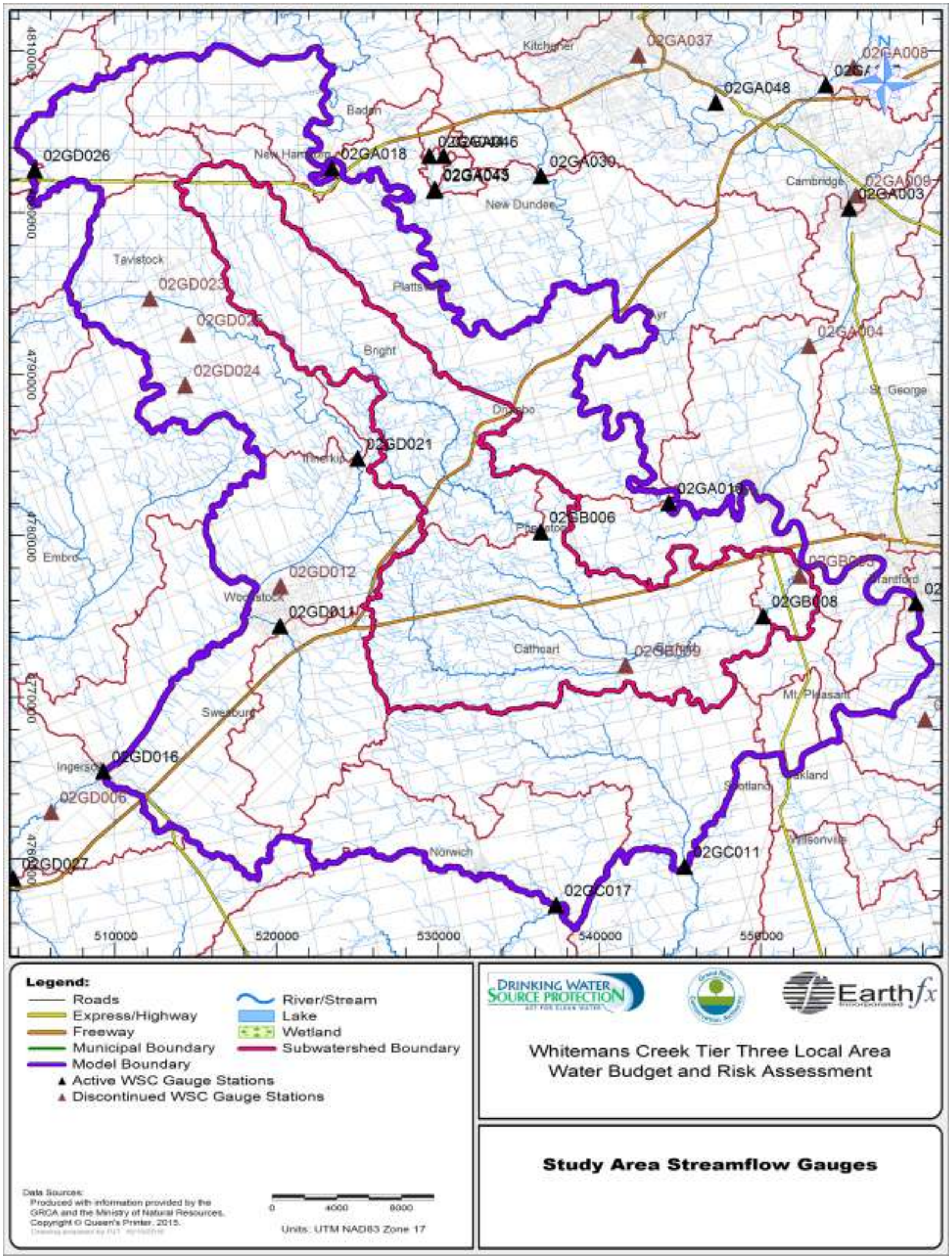


Figure 4.28: Water Survey of Canada (WSC) streamflow gauges proximal to the study area.

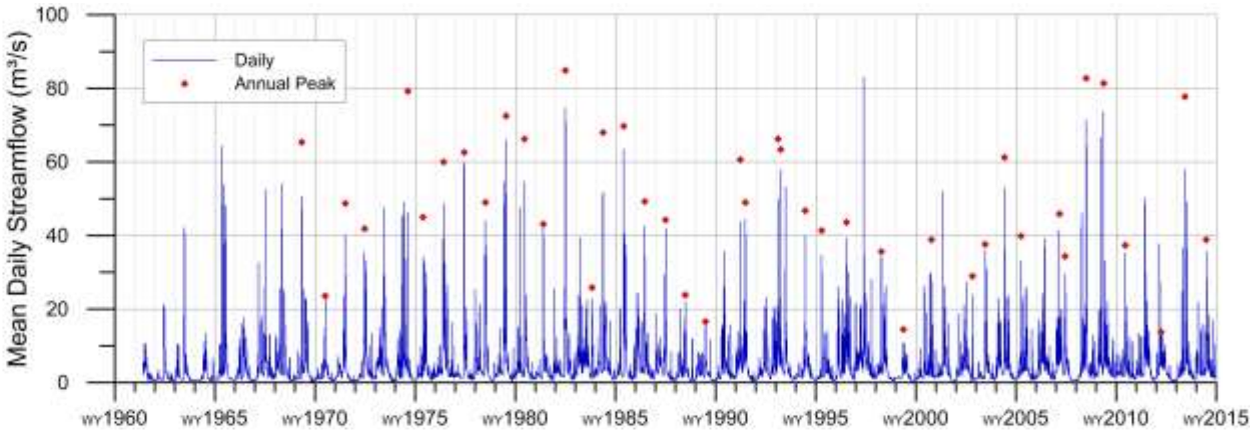


Figure 4.29: Daily discharge and annual peak flow observed at the Whitemans Creek near Mount Vernon (02GB008) WSC stream gauge.

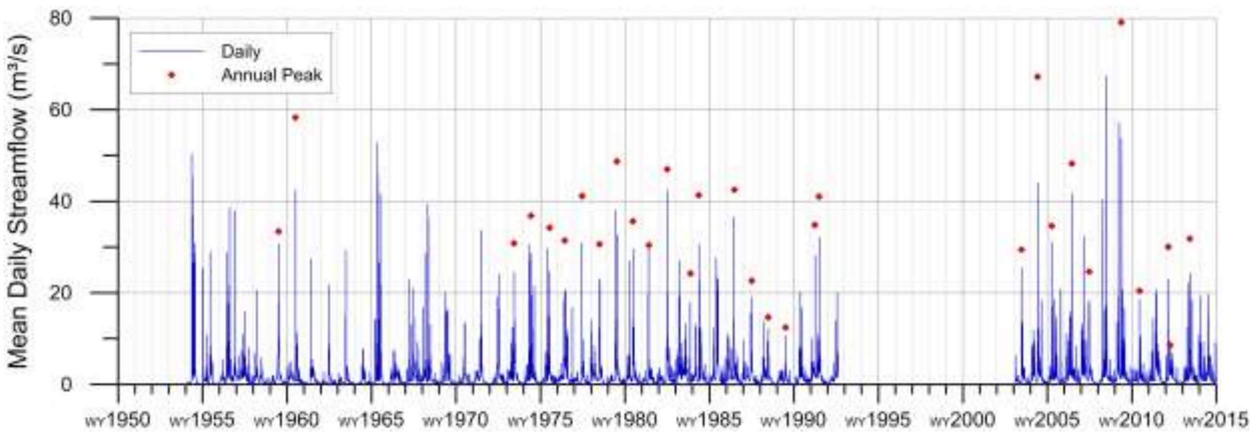


Figure 4.30: Daily discharge and annual peak flow observed at the Horner Creek near Princeton (02GB006) WSC stream gauge.

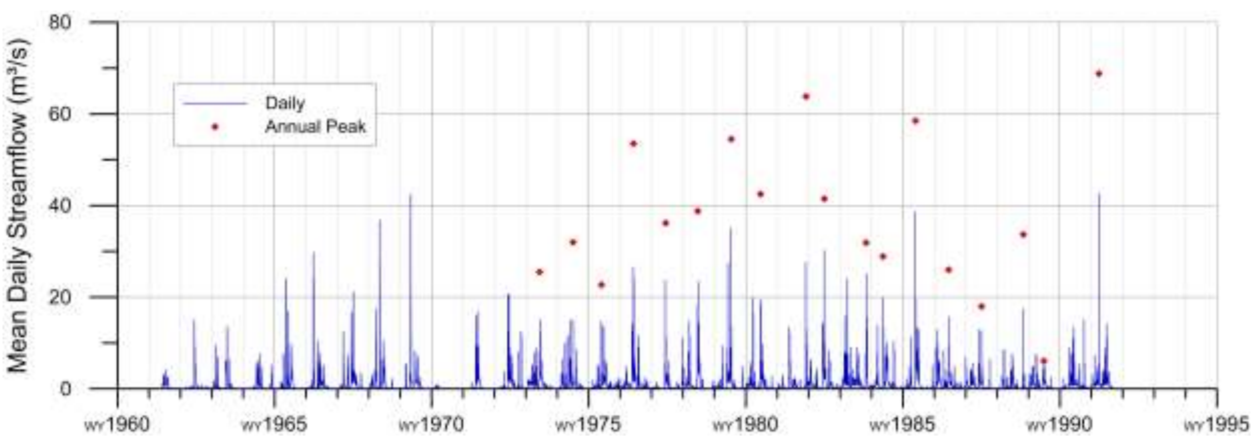


Figure 4.31: Daily discharge and annual peak flow observed at the Kenny Creek near Burford (02GB009) WSC stream gauge.

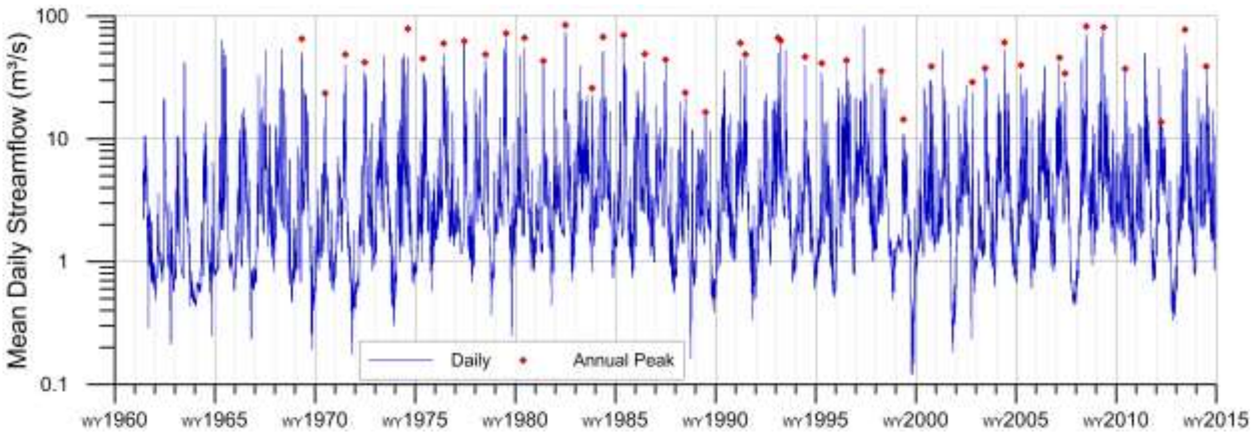


Figure 4.32: Log daily discharge and annual peak flow observed at Whitemans Creek near Mount Vernon (02GB008).

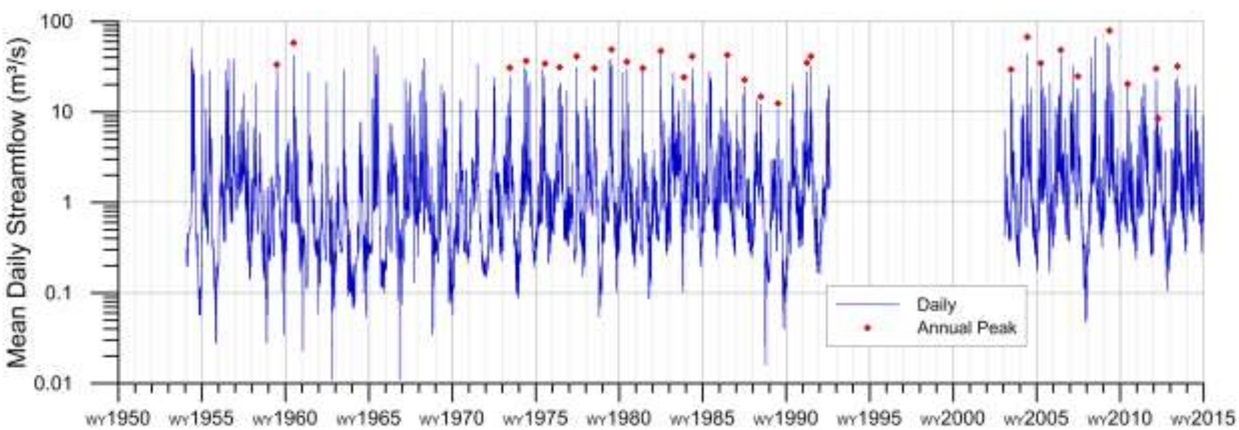


Figure 4.33: Log daily discharge and annual peak flow observed at Horner Creek near Princeton (02GB006).

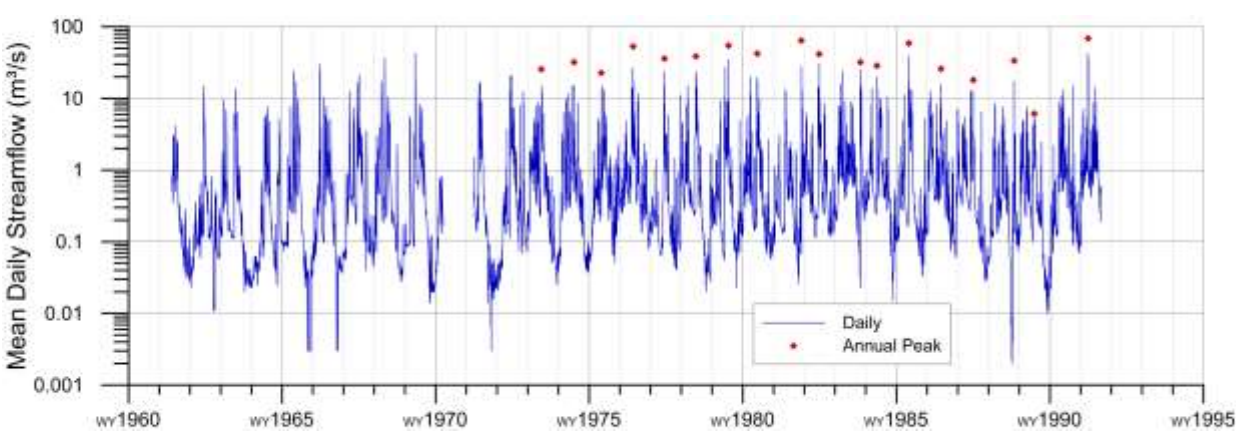


Figure 4.34: Log daily discharge and annual peak flow observed at Kenny Creek near Burford (02GB009).

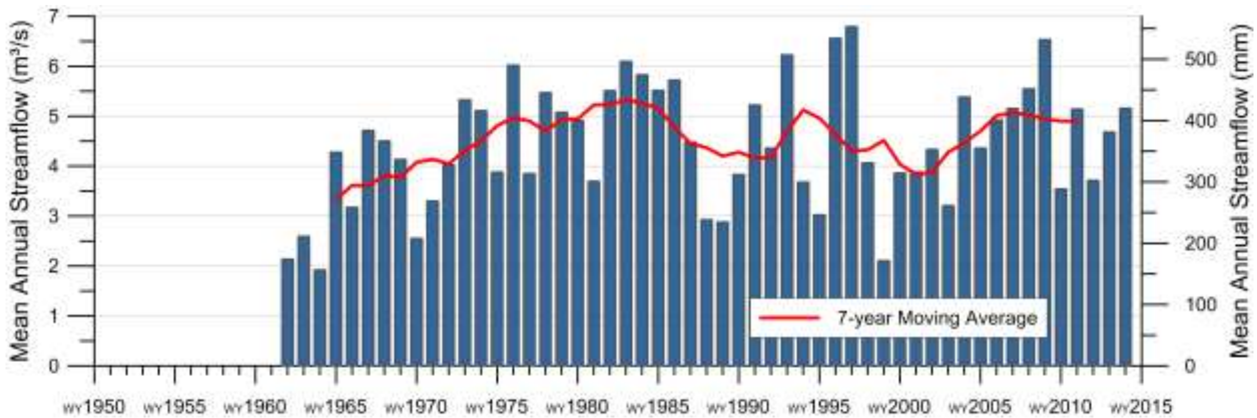


Figure 4.35: Annual observed discharge and runoff at Whitemans Creek near Mount Vernon (02GB008).

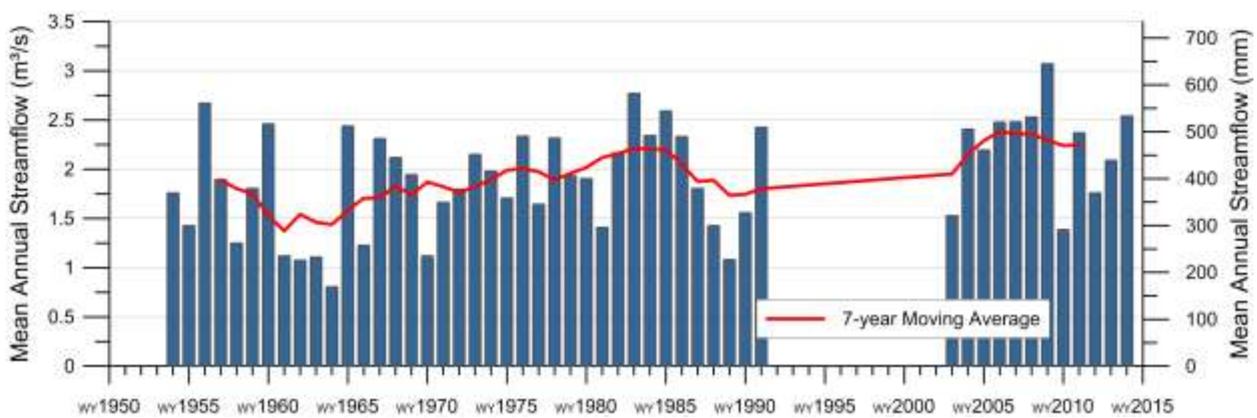


Figure 4.36: Annual observed discharge and runoff at Horner Creek near Princeton (02GB006).

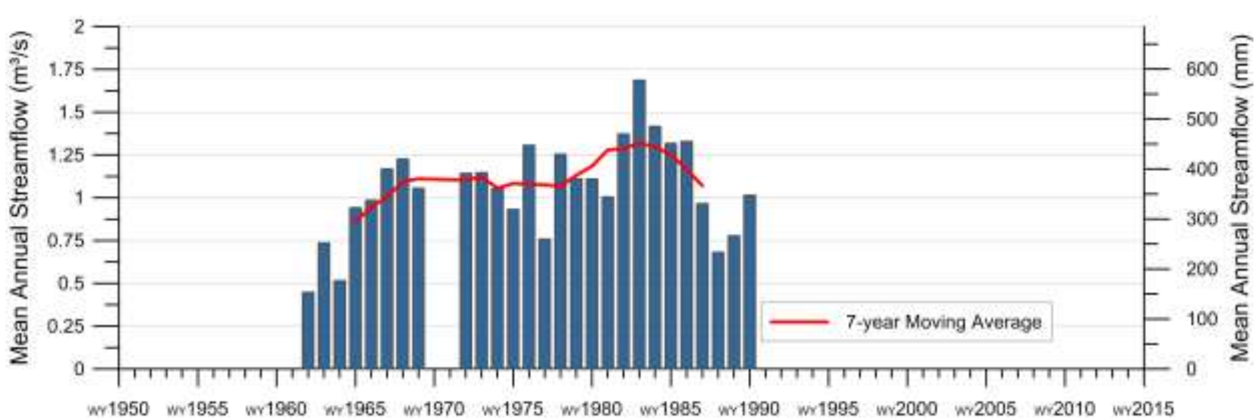


Figure 4.37: Annual observed discharge and runoff at Kenny Creek near Burford (02GB009).

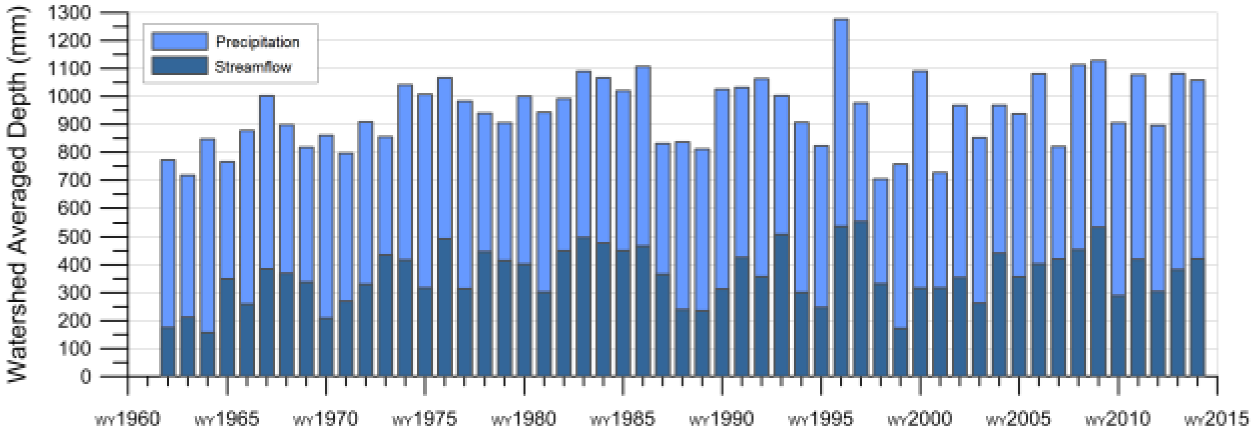


Figure 4.38: Basin-averaged precipitation versus streamflow at Whitemans Creek near Mount Vernon (02GB008).

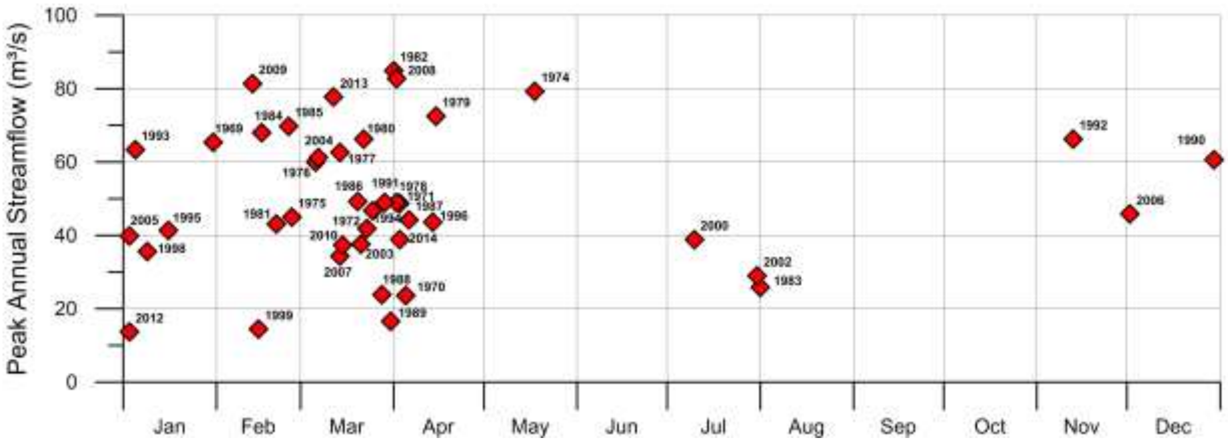


Figure 4.39: Timing and magnitude of the peak annual discharge at Whitemans Creek near Mount Vernon (02GB008).

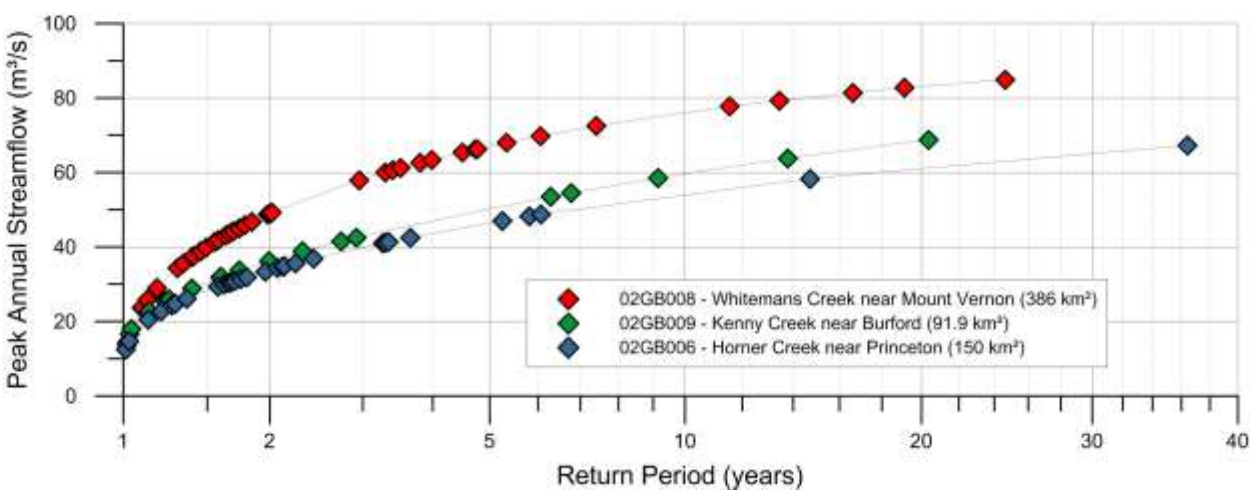


Figure 4.40: Annual peak return intervals (Log Pearson III) at stream gauges in the subwatershed.

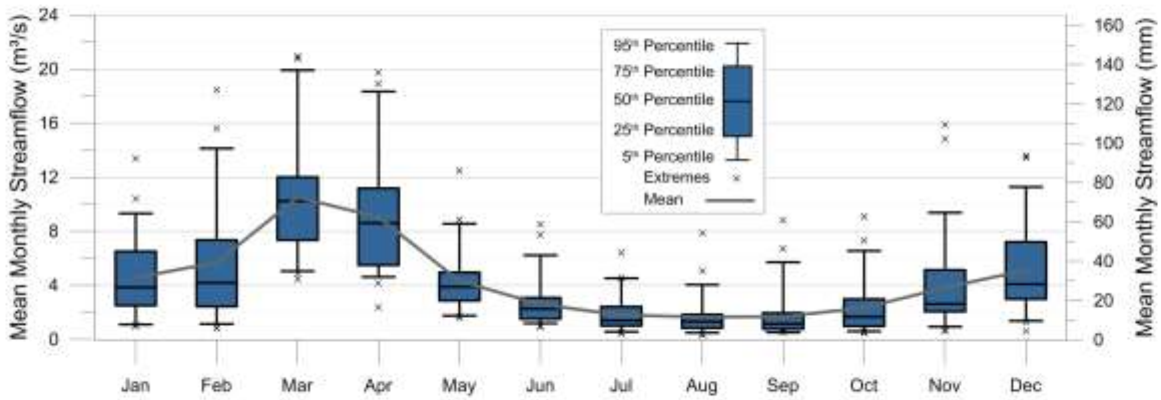


Figure 4.41: Histogram of monthly observed discharge and runoff at Whitemans Creek near Mount Vernon (02GB008).

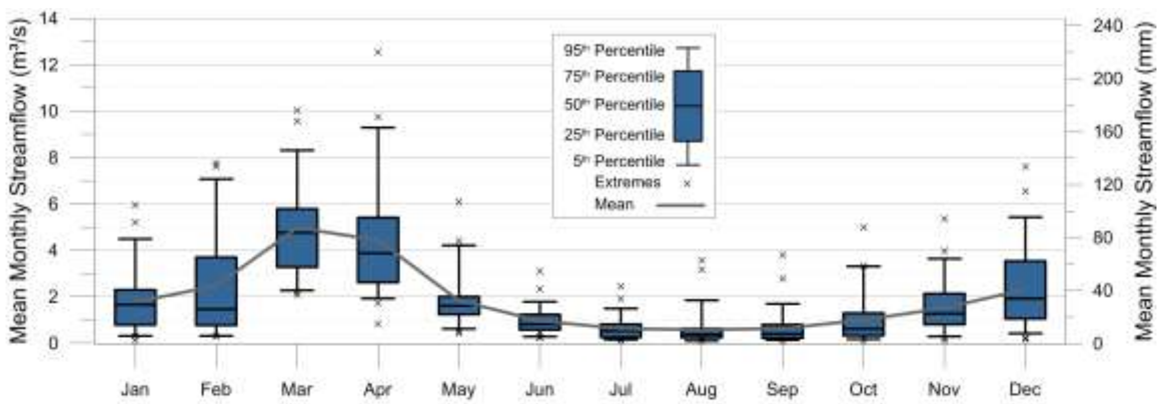


Figure 4.42: Histogram of monthly observed discharge and runoff at Horner Creek near Princeton (02GB006).

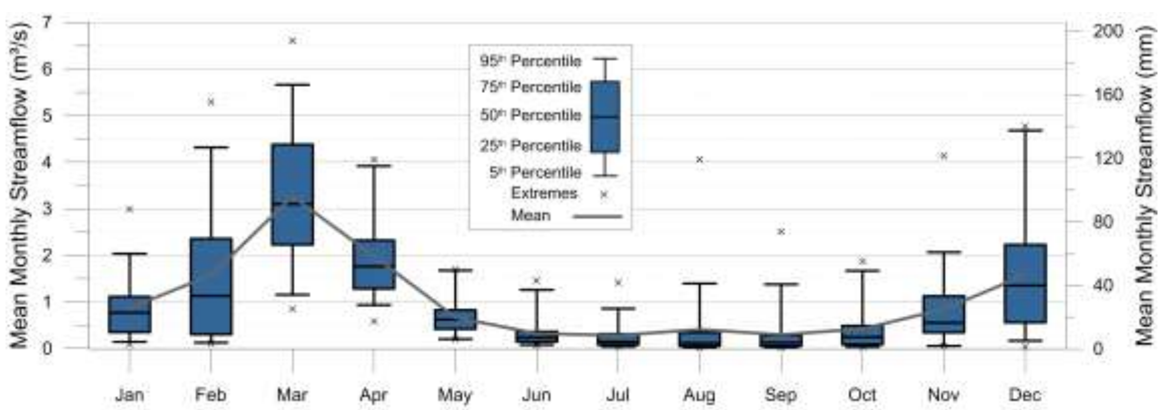


Figure 4.43: Histogram of monthly observed discharge and runoff at Kenny Creek near Burford (02GB009).

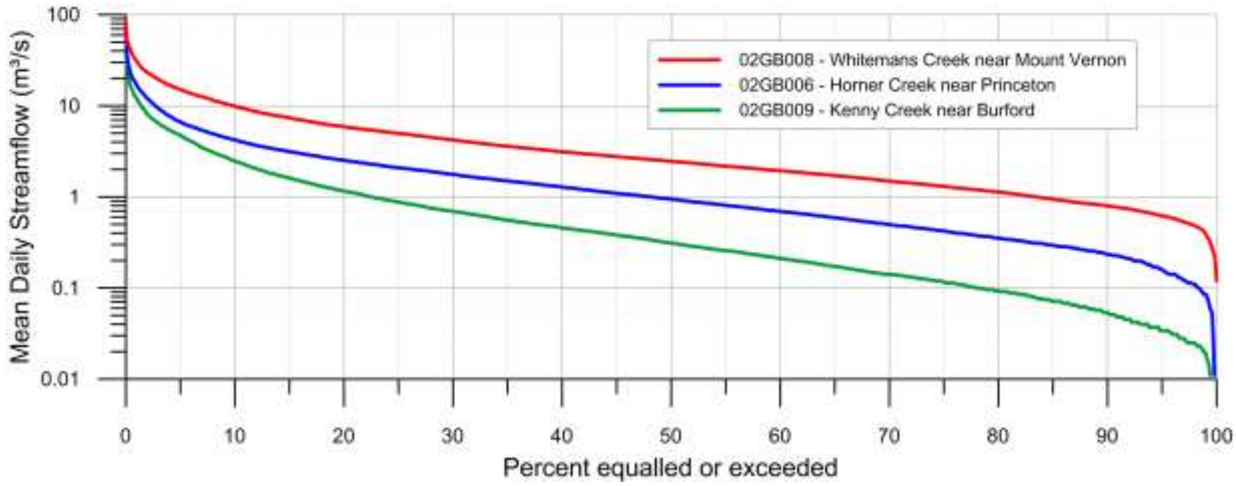


Figure 4.44: Daily flow duration curves for stream gauges in the Whitemans Creek subwatershed.

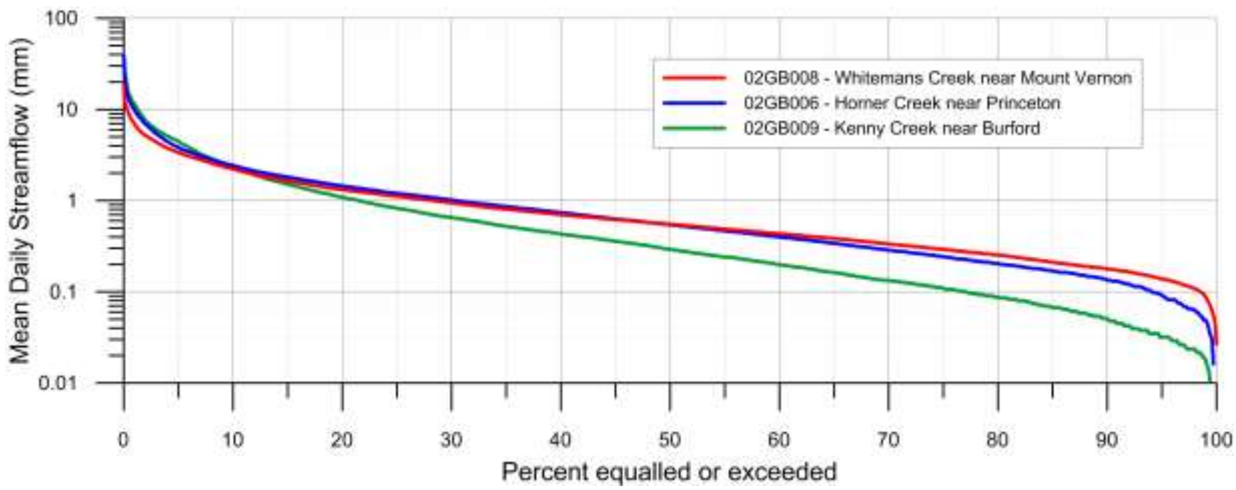


Figure 4.45: Daily total runoff duration curves for stream gauges in the subwatershed.

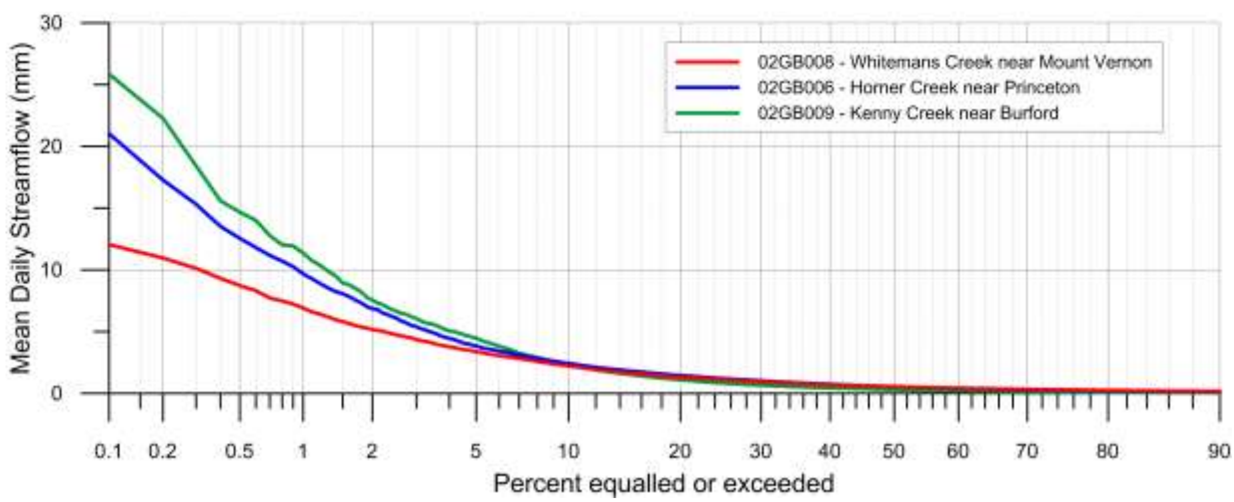


Figure 4.46: Daily total runoff duration curves for stream gauges in the subwatershed with emphasis on high flow.

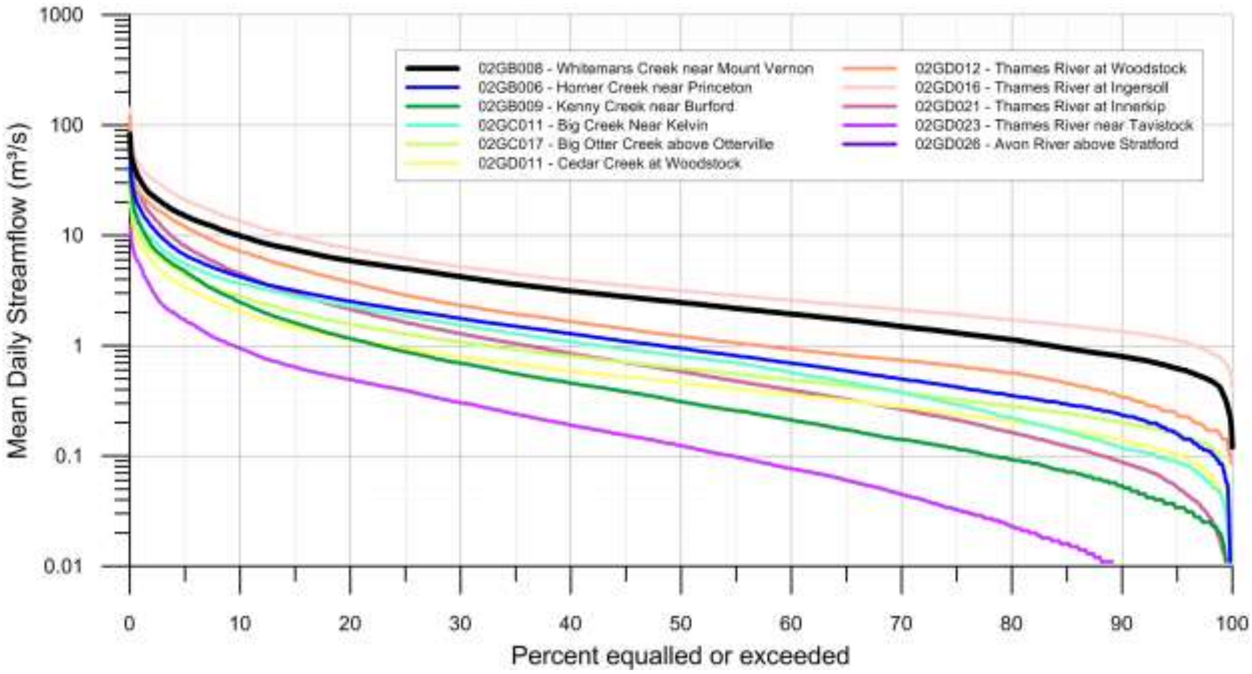


Figure 4.47: Daily flow duration curves for stream gauges in the subwatershed.

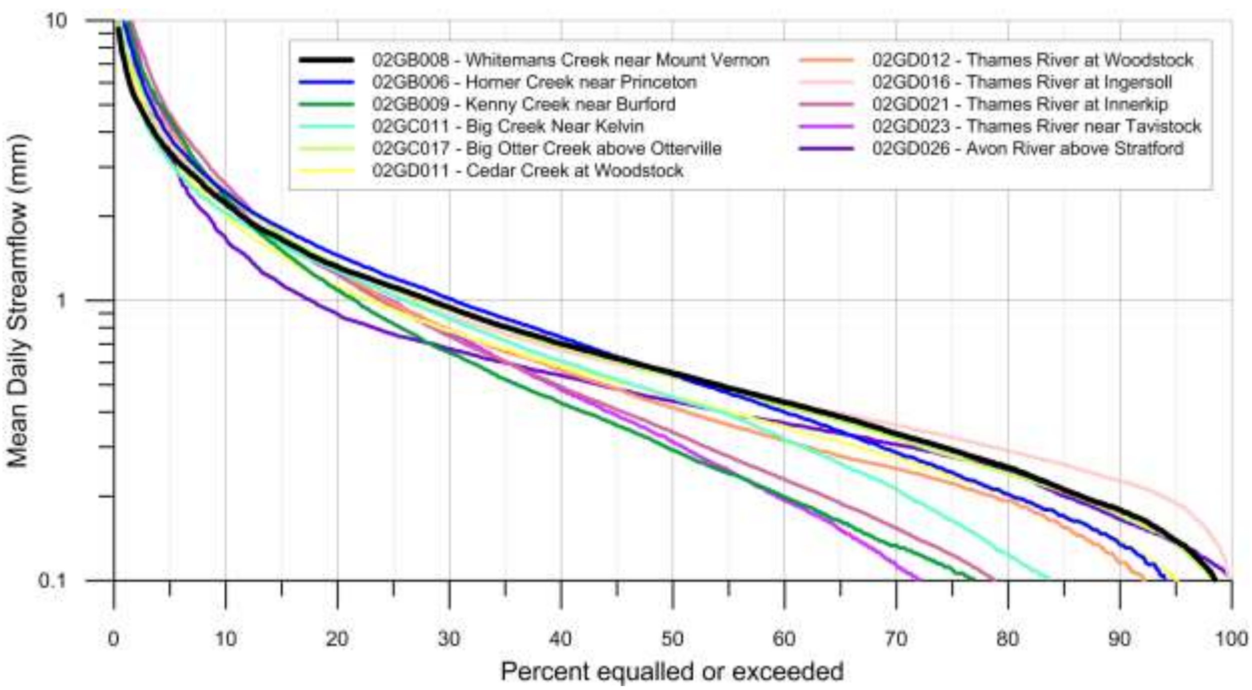


Figure 4.48: Daily total runoff duration curves for stream gauges in the subwatershed.

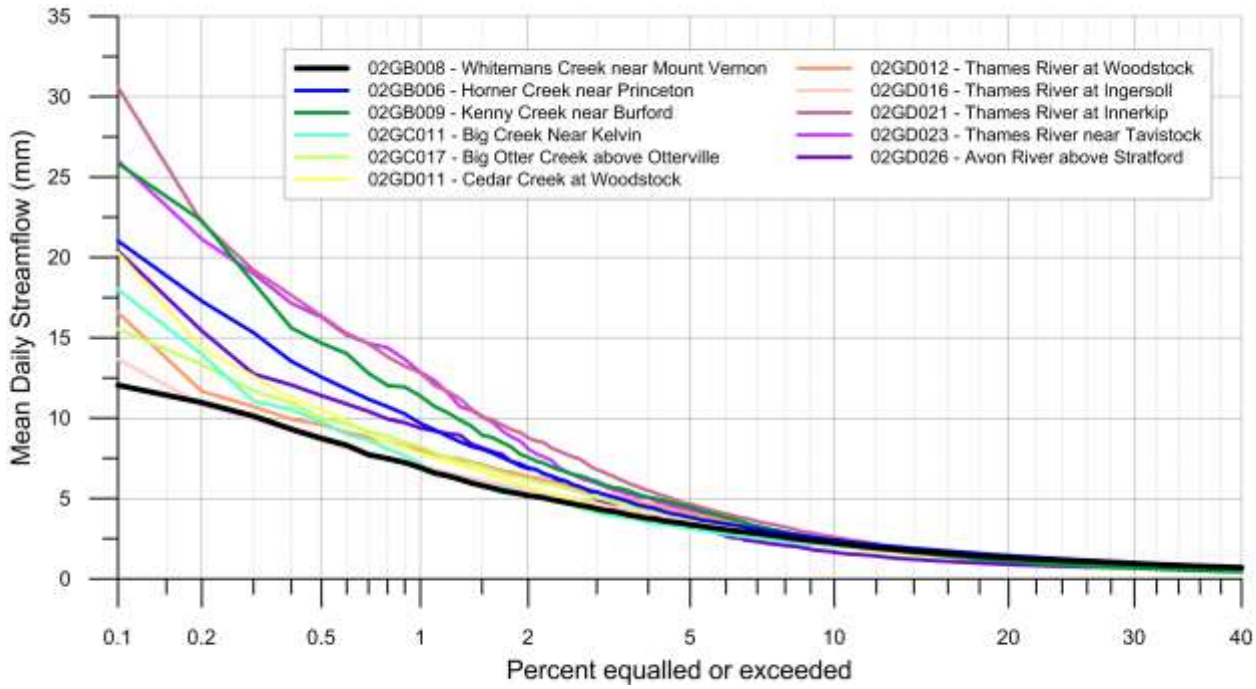


Figure 4.49: Daily total runoff duration curves for stream gauges in the subwatershed with emphasis on high flow.

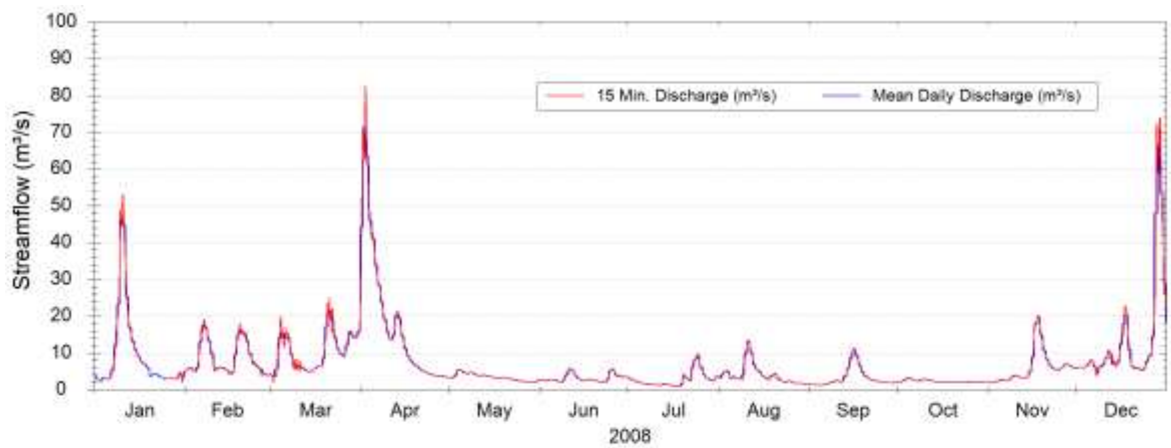


Figure 4.50: Mean daily flow versus 15-minute instantaneous streamflow data at WSC stream gauge Whitemans Creek near Mount Vernon (02GB008) for 2008.

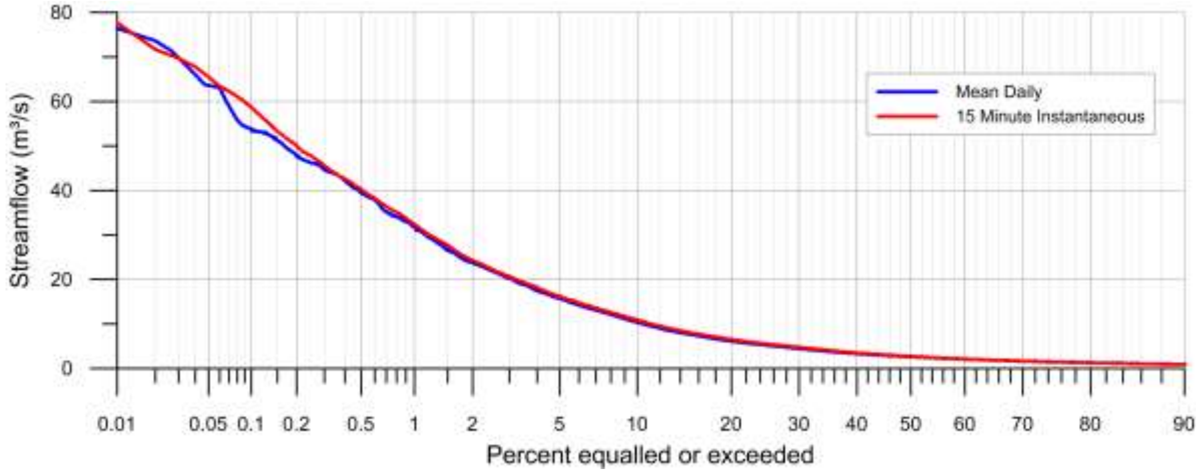


Figure 4.51: Daily flow versus 15-minute flow duration curves observed at Whitemans Creek near Mount Vernon (02GB008).

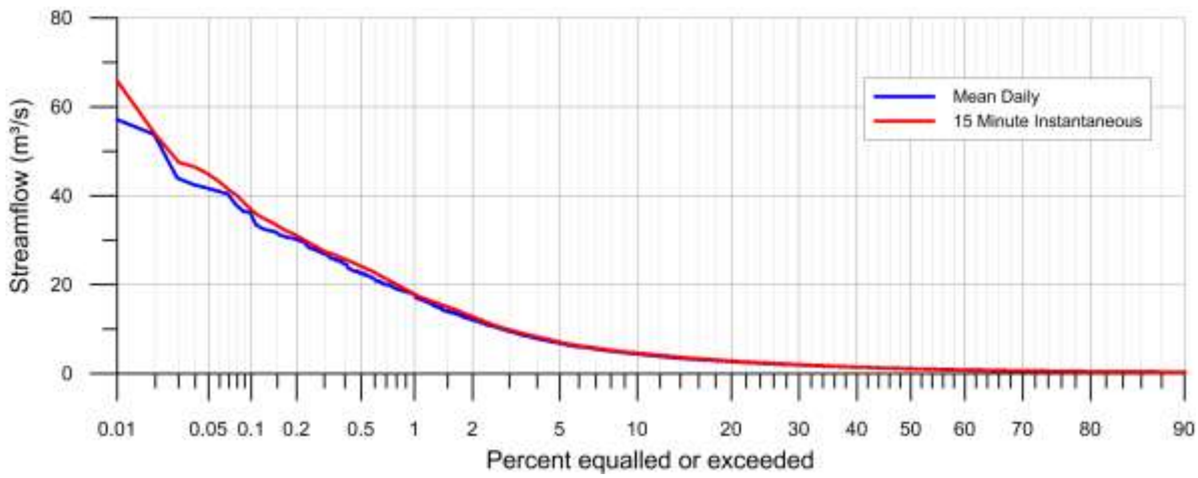


Figure 4.52: Daily flow versus 15-minute flow duration curves observed at Horner Creek near Princeton (02GB006).

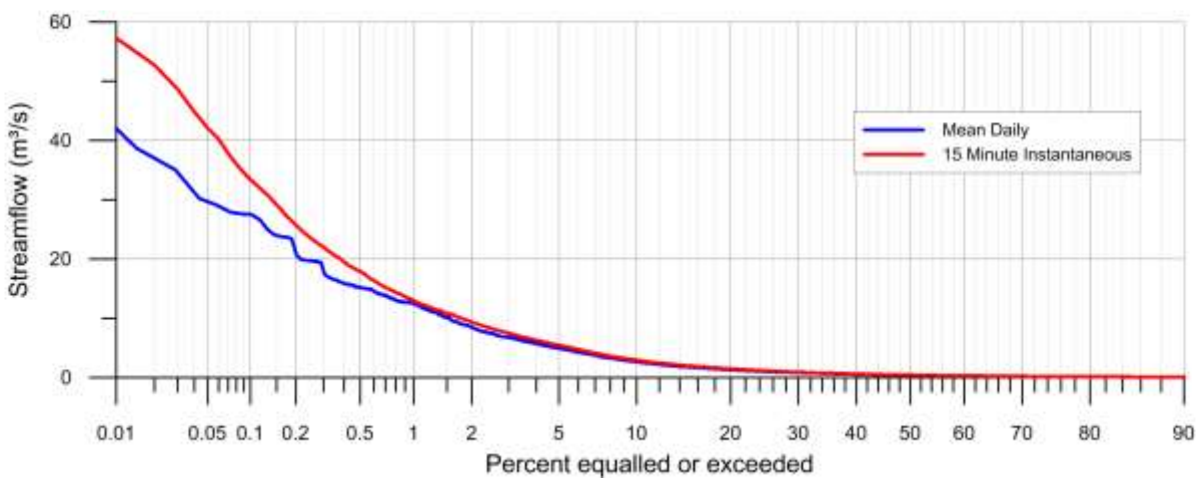


Figure 4.53: Daily versus 15-minute flow duration curve observed at Kenny Creek near Burford (02GB009).

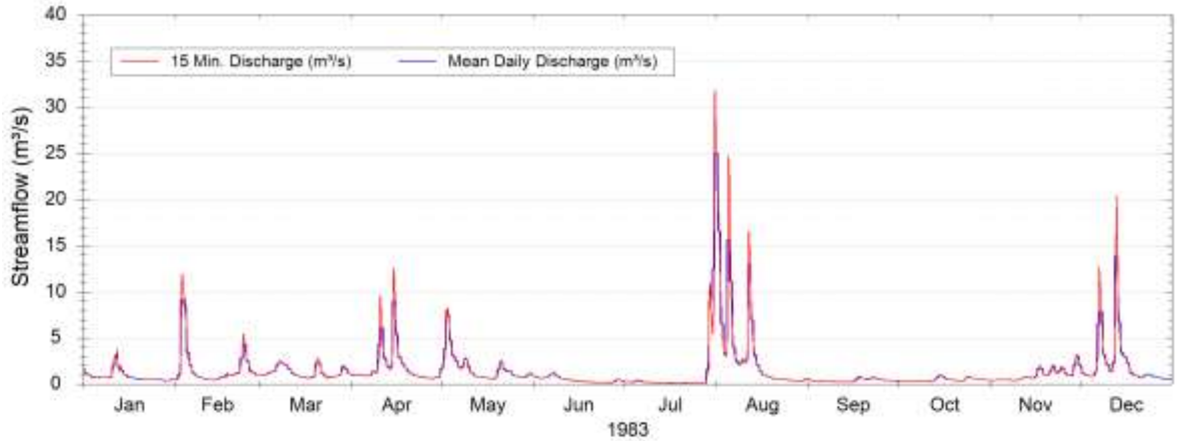


Figure 4.54: Mean daily flow versus 15-minute instantaneous streamflow data at Kenny Creek near Burford (02GB009) for 1983.

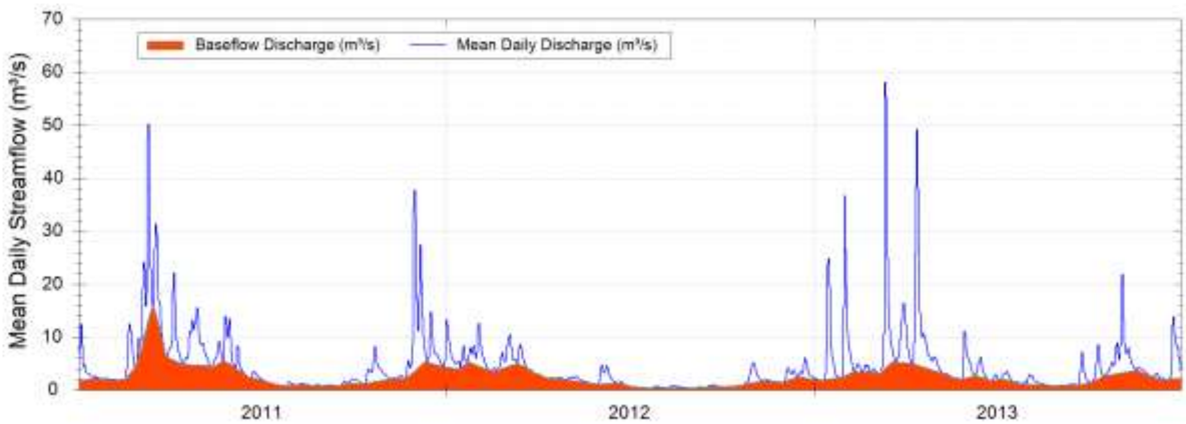


Figure 4.55: Observed daily discharge and estimated baseflow discharge for the calendar years 2011 through 2013 at Whitemans Creek near Mount Vernon (02GB008).

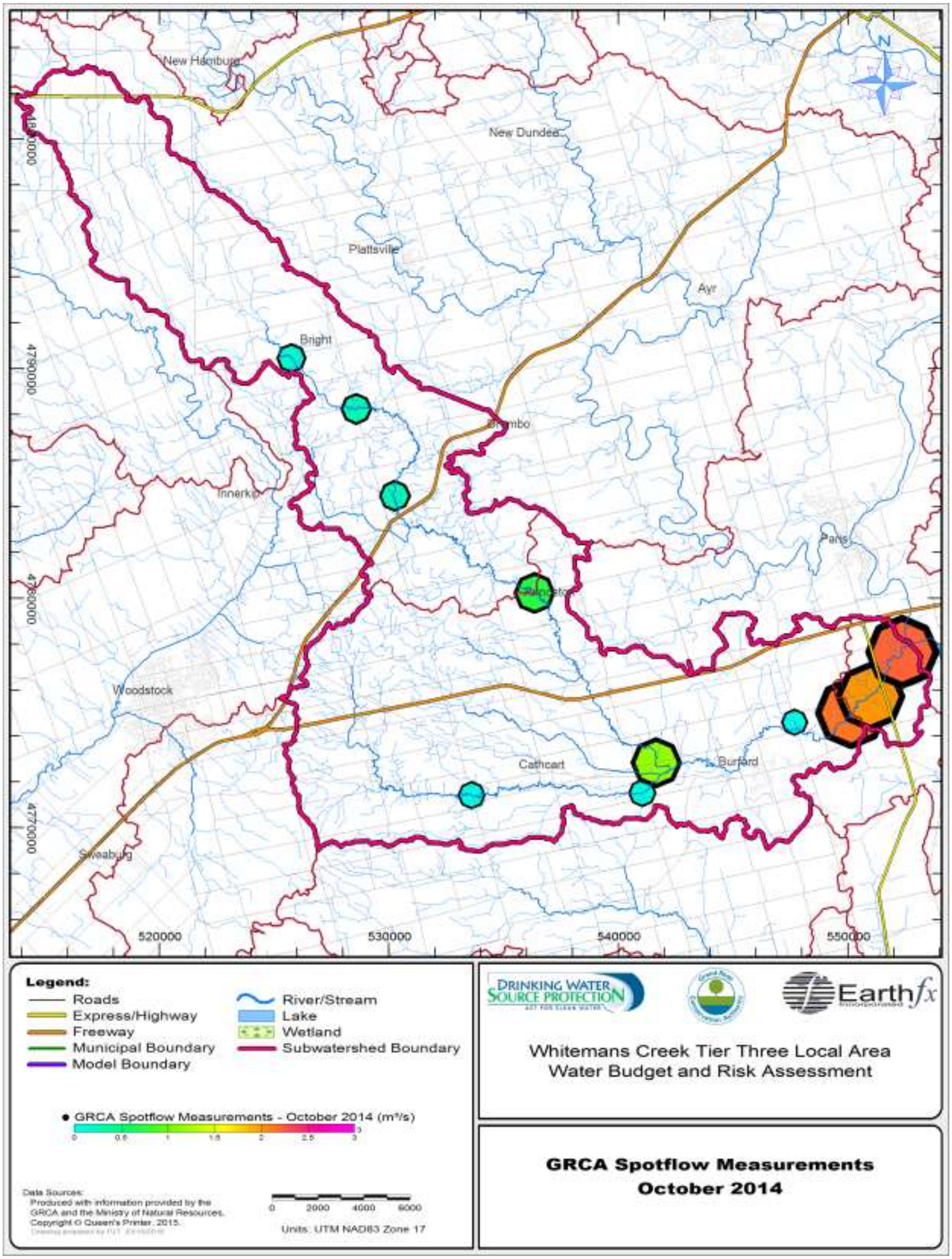


Figure 4.56: Spotflow measurements obtained by GRCA staff - October 2014.

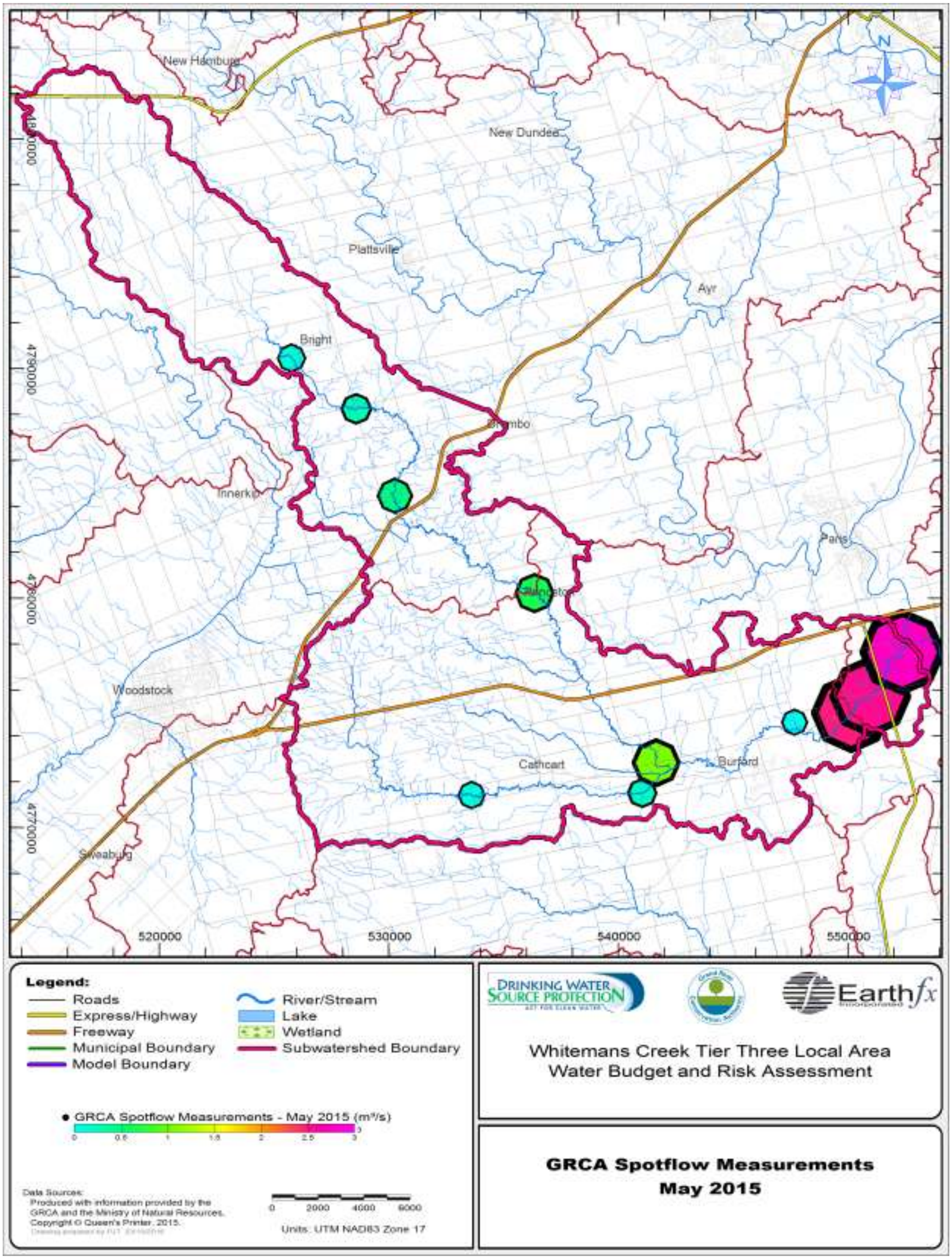


Figure 4.57: Spotflow measurements obtained by GRCA staff - May 2015.

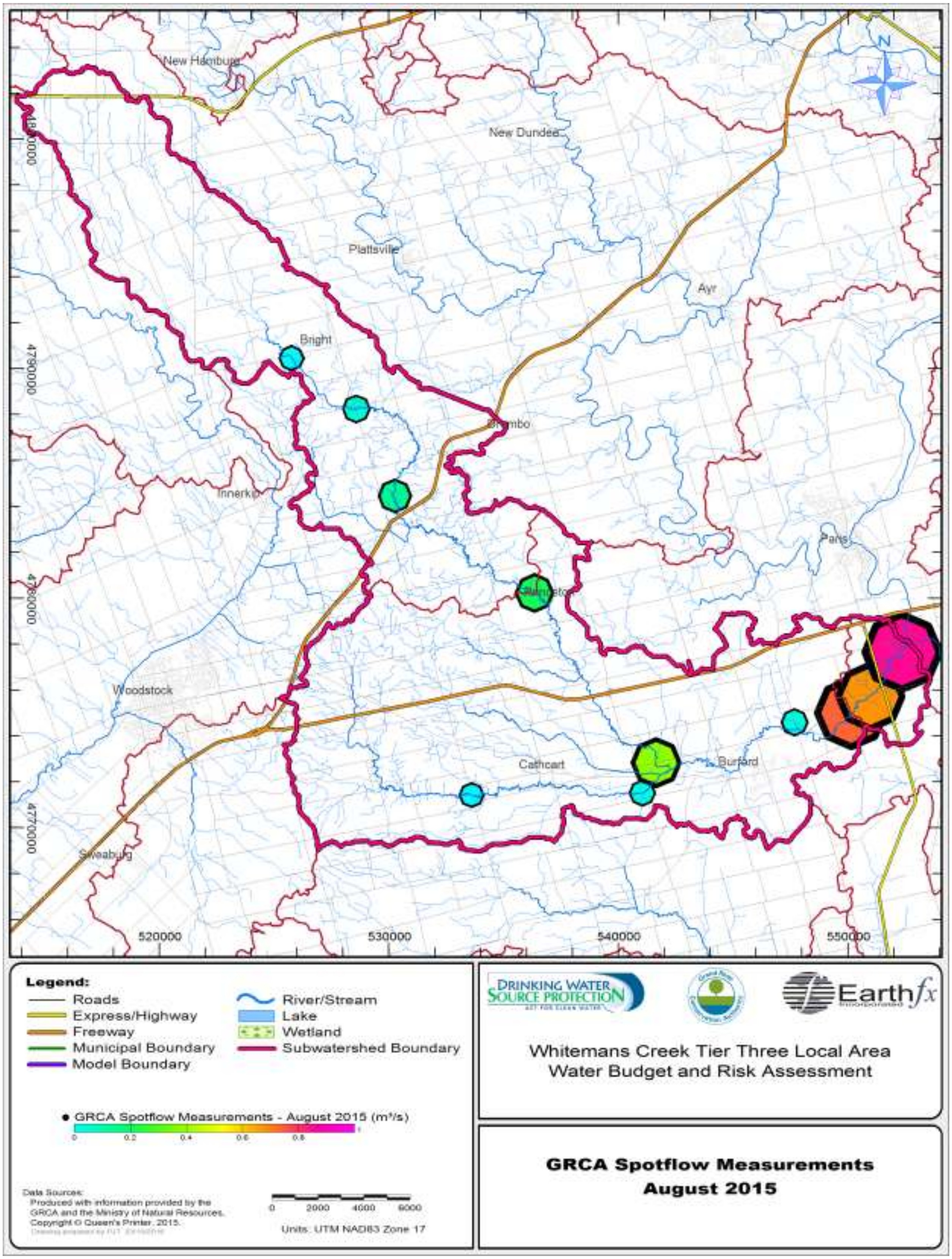


Figure 4.58: Spotflow measurements obtained by GRCA staff - August 2015.

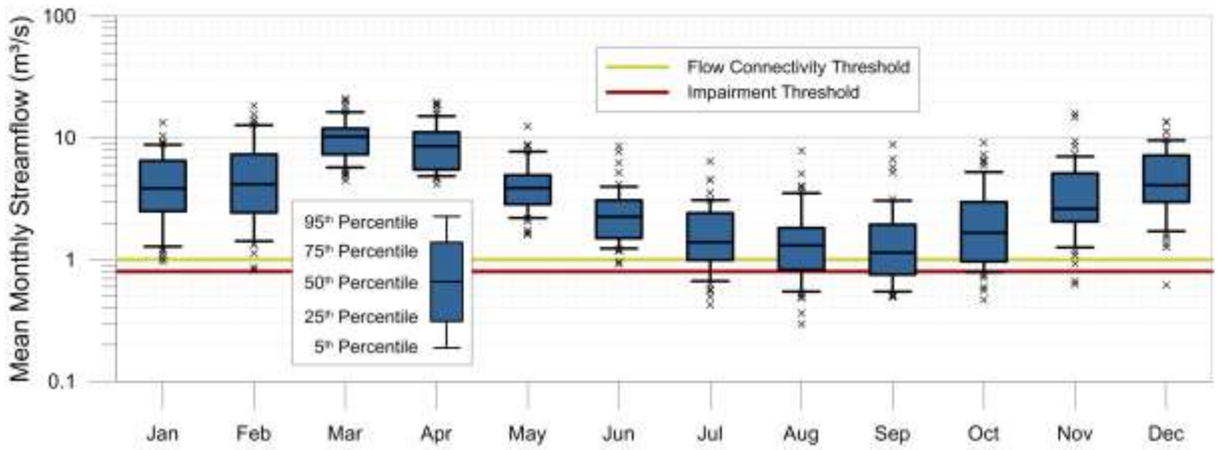


Figure 4.59: Histogram of log-transformed monthly observed discharge and runoff at Whitemans Creek near Mount Vernon (02GB008) with environmental flow thresholds (GRCA, 2014).

5 Hydrogeologic Setting

5.1 *Hydrogeologic Overview*

In Section 4 the Whitemans subwatershed was subdivided into three general hydrologic (physiographic) regions (Figure 4.1). This subdivision provides a useful framework to introduce the complex glacially-modified drift deposits that control subsurface hydrogeologic conditions. Table 5.1, below, summarizes the hydrogeologic conditions in each region, and the cross sections presented in Figure 3.1 and Figure 5.1 further illustrate the subsurface conditions described below.

Table 5.1: Conceptualization of regional hydrogeologic setting.

Upper Whitemans Till Plains	Central Whitemans Outwash Area	Lower Whitemans Sand Plain
Poorly drained till plains due to low permeability Port Bruce Phase aquitards at surface.	Complex system of moraines, outwash deposits and till plains. Upper Erie Phase sands form a shallow, regional aquifer that is confined to the south by the Port Bruce Phase aquitards. To the north, the shallow aquifer is unconfined where glacial outwash events have removed the surficial tills and unconfined sand aquifers occur at surface.	Extensive and thick (up to 65 m) glaciolacustrine and outwash sand deposits form regional unconfined water table aquifer.
Underlain by sequences of thick, continuous till aquitards, which are separated by relatively thin, discontinuous sand aquifer units.		Underlain by largely uninterrupted sequence of till aquitards down to bedrock.
Regionally confined bedrock aquifer system, except locally where rivers or outwash channels have scoured through drift deposits (e.g., bottom of Whitemans Creek, Thames River near Woodstock). The southwestern half of study area is underlain by productive Devonian limestone aquifers (the Onondaga limestone aquifers). The northeastern half of study area is underlain by the poorer quality Salina Formation aquifer.		

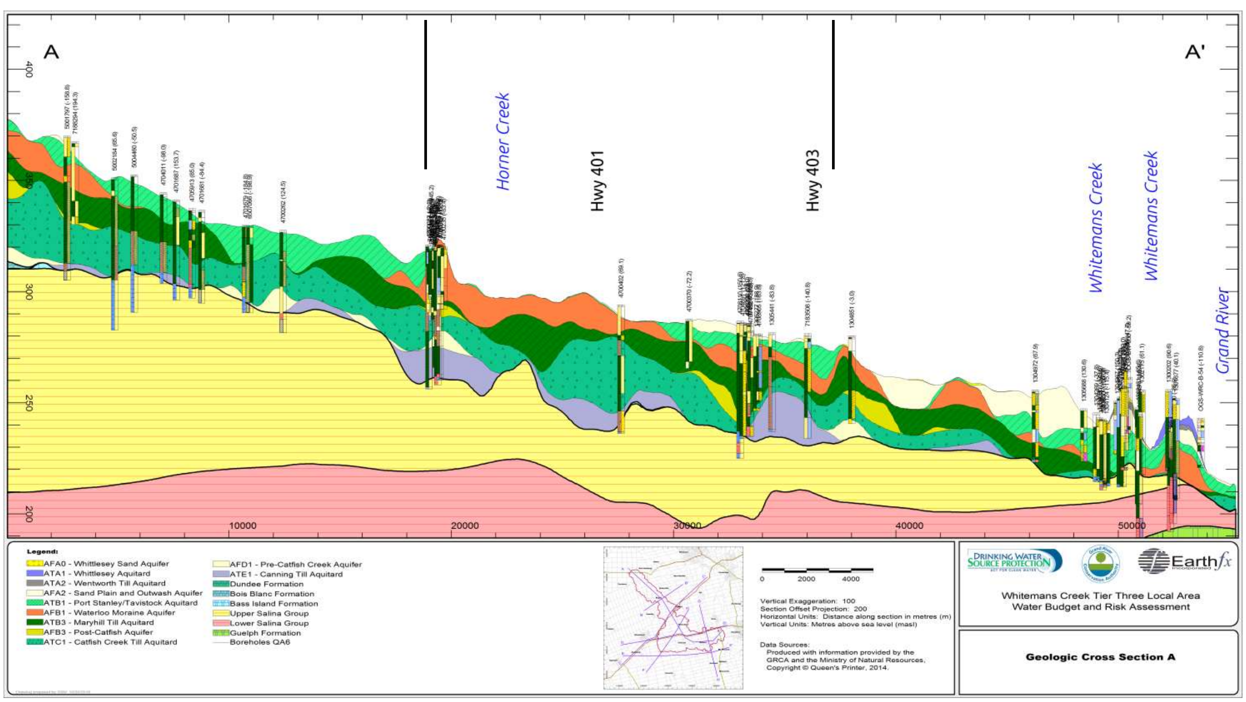


Figure 5.1: Hydrogeologic cross section down the central axis of the subwatershed.

The cross section shown in Figure 5.1 illustrates the complexity of the shallow Quaternary aquifer and aquitard layers. The cross section traverses the watershed along its central axis, and the three hydrologic zones (upper, middle and lower) each correspond to one third of the cross section. This chapter begins with a general description of the hydrogeologic conditions in each of the zones and then proceeds to document the development of a detailed 3D conceptual model of the subsurface (presented in Figure 5.1).

5.1.1 Upper Whitemans Till Plains

As noted, the upper portion of the Whitemans Creek subwatershed (from 0 to 2000 m on the cross section in Figure 5.1) is characterized by poorly-drained till plains associated with the Tavistock Till aquitard. The shallow overburden aquifers within this area are typically under confined conditions. The deeper aquifers are separated from each other by intervening till aquitards. The shallowest and most extensive of the overburden aquifers in this area is the Waterloo Moraine (and equivalent) aquifer. This aquifer supplies the municipal wells for the Community of Bright. Below this aquifer, the low permeability clays of the Maryhill Till aquifer separate the shallow Waterloo Moraine aquifer from the deeper, and less extensive, Lower Erie Phase sand aquifer. Here also, the low-permeability Catfish Creek Till aquitard serves as a regionally-extensive lower confining unit between the upper overburden aquifers and the older underlying aquifers, including the discontinuous pre-Catfish Creek sands and gravels and the Paleozoic bedrock aquifers.

5.1.2 Central Whitemans Outwash Area

To the west of the Norwich Moraine, hydrogeologic conditions within the central portion of the study area (2000 to 4000 m on the cross section in Figure 5.1) are characterized by the interlobate processes that produced the complex, interwoven landscape of moraines, outwash deposits, and till plains. East of Innerkip, Grand River outwash deposits occur as unconfined surficial aquifers in direct contact with the underlying Upper Erie Phase sands (equivalent to the Waterloo Moraine), which represent a continuous shallow aquifer unit within the central portion of the study area. To the south, the low-permeability Port Bruce Phase Tills (Port Stanley and Tavistock tills) occur at or near ground surface, resulting in poor drainage conditions and confinement of the underlying Upper Erie Phase sand aquifer. Below the Port Bruce Phase aquitard are thick sequences of regionally- extensive aquitards (Maryhill, Catfish Creek, and Canning Tills), separated by relatively thin and discontinuous aquifers (Lower Erie Phase sands and the pre-Catfish Creek aquifers) extending down to bedrock.

5.1.3 Lower Whitemans Sand Plain

East of the Norwich Moraine, the extensive glaciolacustrine deposits of the Norfolk Sand plain (4000 to 6000 m on the cross section in Figure 5.1) form a regional water table aquifer that is largely unconfined except where locally overlain by the Wentworth Till aquitard. Across the majority of this area, the unconfined sand plain aquifer is in direct contact the sands and gravels of the Grand River Valley outwash aquifer, forming a single unconfined sand and gravel aquifer unit with thicknesses up to 65 metres. Due to the lack of any significant confining unit at surface, groundwater recharge in this area is high. Below the surficial aquifer, the underlying silts and clays of the Port Stanley Till aquitard, the lower Maryhill Till aquitard, and the older Catfish Creek Till aquitard provide vertical confinement for the deeper overburden aquifers and bedrock.

5.1.4 Bedrock and Surrounding Watershed Areas

The overlying thickness of till aquitards serve as a confining layer for the Salina Formation bedrock aquifer, which is occasionally exploited as a water supply source within the area, despite the tendency for poor water quality due to the dissolution of evaporite salts found within the bedrock. The aversion to relying upon the Upper Silurain bedrock aquifer as a water supply is clearly reflected in the completion details for water well records within the study area (shown in Figure 5.3), where the distribution of bedrock-screened wells become more prevalent moving from east to west approaching the limestone aquifers atop the Onondaga Escarpment.

To the immediate west and south of the Whitemans subwatershed, the limestones of the buried Onondaga Escarpment serve as productive groundwater supply aquifers, for both municipal and private water users.

The next section discusses the construction of the hydrostratigraphic model and the synthesis of hydrogeologic datasets, which capture the conceptual hydrogeologic setting described above.

5.2 *Hydrostratigraphic Model Layers*

The hydrostratigraphic model for the Whitemans Creek Tier 3 Assessment is based extensively upon work completed by the Ontario Geological Survey (OGS) in the Brantford Woodstock area (Bajc and Dodge, 2011). The OGS study developed a three-dimensional hydrostratigraphic model of the regional Quaternary deposits, based on field investigations and computer modelling. An earlier OGS modelling study of the Region of Waterloo (Bajc and Shirota, 2007) used the same general stratigraphic nomenclature but covers only the northern part of the study area (Figure 5.4). There are, however, some marked differences between the earlier Waterloo Moraine model and the Brantford model, so it was decided not use the earlier Waterloo model layers to extend the Brantford-Woodstock surfaces.

The OGS model is hydrostratigraphic in focus (i.e., it defines the occurrence and lateral extent of aquifers and aquitards); however it is strongly rooted in the established Quaternary lithostratigraphy of the region (as discussed in Section 3.2). The OGS hydrostratigraphy is summarized in Table 5.2 wherein major aquitard and aquifer units are represented by green and yellow shading, respectively. Many of the units are of limited areal extent and were classified as “minor” by the OGS (indicated in white in Table 5.2).

The OGS model provided a sound conceptual foundation for the hydrostratigraphic and numerical groundwater flow model for the Whitemans Creek Tier 3 Assessment. Both localized and regional processing of the OGS model were undertaken, as part of this study, to construct the final hydrostratigraphic model, as described below.

5.2.1 **OGS Model Surface Processing**

The first step in developing the conceptual hydrostratigraphic surfaces for the Whitemans Tier 3 Assessment numerical model was to convert and extend the OGS surfaces into a set of continuous hydrostratigraphic layers and extend them to cover the entire study area. This intermediate processing step was needed to address the following issues:

1. The OGS model surfaces did not cover the entire study area.
2. The OGS model included some units that were very minor in extent. Including these highly localized units in the numerical model would unnecessarily slow down the simulations.
3. The OGS surfaces did not include any bedrock layers.

5.2.1.1 OGS Layer Integration

Some of the OGS units are only present to a limited extent within the model boundaries, or, as with unit ATA3, are entirely absent. Units listed as “minor” in the OGS model (as shown in Table 5.2) were assessed as to whether they could be integrated with underlying or overlying units. For example, the minor Upper Erie Phase aquitard (ATB2) was limited in extent to two small (< 1.5 km²) patches near New Dundee and was therefore merged into the underlying, regionally-extensive Maryhill Till aquitard (ATB3).

Table 5.2: OGS Hydrostratigraphic Model (modified from Table 2 of Bajc and Dodge (2011)).

Hydrostratigraphic Unit	Lithostratigraphic Unit	Lithology	Importance*
AFA0	Whittlesey regressive aquifer	Very fine to coarse sand	moderate
ATA1	Whittlesey aquitard	Silt and clay	major
AFA1	Whittlesey aquifer	Very fine to coarse sand	minor
ATA2	Wentworth Till aquitard, may contain stratified sediments	Stony, sandy till	major
AFA2	Outwash deposits; mainly Grand River valley outwash	Coarse sand and gravel	major
ATA3	Fine-grained deposits confined to Grand River valley under AFA2	Sandy silt and silt	absent
ATB1	Port Bruce Phase aquitard; includes Upper Maryhill Till, Port Stanley Till, Tavistock Till, Stratford Till	Silty to clayey till, locally sandy	major
AFB1	Upper Erie Phase aquifer; Waterloo moraine and equivalents	Fine sand, some gravel	major
ATB2	Upper Erie Phase aquitard	Silty to clayey till, silt, clay	minor
AFB2	Middle Erie Phase aquifer; Waterloo moraine and equivalents	Fine sand, some gravel	minor
ATB3	Lower Erie Phase aquitard; includes Lower Maryhill Till	Silty to clayey till, silt, clay	major
AFB3	Lower Erie Phase aquifer; includes stratified deposits associated with initial break up of Catfish Creek ice	Sand, some gravel	major but patchy
ATC1	Upper/Main Catfish Creek Till	Stony silty to sandy till	major
AFC1	Catfish Creek stratified deposits	Sand and gravel	minor
ATC2	Lower Catfish Creek Till	Stony silty to sandy till	minor
AFD1	Pre-Catfish coarse-textured glaciofluvial and/or glaciolacustrine deposits	Sand and gravel	moderate to major
ATE1	Canning Drift (till and associated fine- textured glaciolacustrine deposits)	Silty to clayey till, silt, clay	moderate
AFF1	Pre-Canning coarse-textured glaciofluvial and/or glaciolacustrine deposits	Sand and gravel	minor
ATG1	Pre-Canning coarse-textured till	Stony, silty to sandy till	minor
Bedrock	Guelph Formation, Salina Group; Bass Islands, Bois Blanc, Amherstburg, Lucas and Dundee Formations		

*based on the extent of the units from isopachs calculated from the continuous versions of the Bajc and Dodge (2011) surfaces

It was also important to recognize that, in some cases, more than one *lithostratigraphic* unit has been incorporated into a single *hydrostratigraphic* unit in the OGS model. For example, the ATB1 aquitard comprises several named till units (Upper Maryhill Till, Port Stanley Till, Tavistock Till and Stratford Till). Also, in some cases the OGS used a single hydrostratigraphic unit to represent the two aquifer units in areas where they were in contact. When this situation occurred, Bajc and Dodge (2011) generally opted to use the nomenclature of the lower hydrostratigraphic unit to name the combined aquifers. The main reason for combining units is the difficulty in distinguishing between aquifers in direct contact using typical water well borehole data (A. F. Bajc, written communication, 2015). For example, in the northern part of the study area, outwash deposits (aquifer AFA2) commonly overlie older ice-contact stratified deposits (AFB1) but both are presented as a single unit (AFB1). Similarly, most of the extensive sand deposits of glacial Lake Whittlesey (AFA0) have been merged into the AFA2 outwash aquifer.

5.2.1.2 Model Area Extension

The numerical model area extends beyond the Whitemans Creek subwatershed to properly capture groundwater inflows and outflows across the subwatershed boundaries and to include several adjoining gauged subwatersheds to improve model calibration. As noted, the OGS model surfaces were extended and refined to include those catchments. The OGS model extents (Brantford and Waterloo models) and the Tier 3 model extents are shown in Figure 5.4.

New geology picks were made in the model extension areas on cross sections in VIEWLOG-GIS v4 using all available and updated borehole data. Interpretive polylines were drawn, where needed, on registered cross sections to help guide interpolation in areas with limited or inconsistent data. Data in the model extension areas were interpolated with the VIEWLOG edge matching option so as to create a seamless extension of the surfaces. After interpolation, the surfaces were corrected for crossovers and new isopachs were calculated.

5.2.1.3 Paleozoic Bedrock Layers

The bedrock units were not modelled as part of the OGS Brantford-Woodstock project but they are part of the hydrostratigraphic model for this study. The Salina Formation subcrops across a significant portion of the study area and is generally considered a “poor aquifer” from both water quality and quantity perspectives. Within the western portion of the model area, the limestones and dolomites above the Onondaga Escarpment are a significant source of water supply, and therefore warranted inclusion in the numerical model for the Tier 3 Assessment.

Geologic picks from the borehole information provided by the Ontario Oil, Gas and Salt Resources Library (OGSR) were used to interpolate surfaces for the Paleozoic rock units. Because of limited data in the area, the Devonian Dundee, Lucas, and Amherstburg formations were combined into a single unit. Top surfaces of the Salina and Guelph Formations were interpolated from geologic picks and corrected using the bedrock topography (top of bedrock) surface. Isopachs for the Bass Islands and Bois Blanc formations were interpolated using thickness values calculated from the OGSR picks and constrained spatially by their respective lower boundaries. The interpolated Bass Islands Formation isopach was added to the corrected top of Salina surface using grid algebra to produce a top of Bass Island surface. The Bois Blanc isopach was then added to the new top of Bass Islands surface to get a top of Bois Blanc surface. These surfaces were corrected (clipped) to the bedrock topography.

5.2.1.4 Local Model Revisions

Local refinement of the OGS model was also undertaken in the vicinity of three municipal wellfields: 1) the Bethel Road wellfield, 2) the Community of Bright wellfield, and 3) the Brantford Airport wellfield to provide a detailed representation of local hydrostratigraphic conditions. These local revisions were needed to address the wellfield-scale focus of the Tier 3 Risk Assessment and represent a level of detail not achieved in the regional-scale OGS model. In addition, new geologic and hydrogeologic data collected after the 2011 OGS study provided additional information to update the understanding of local subsurface conditions. This was particularly true in the case of the Bethel Road wellfield where three of the municipal supply wells (PW1/12, PW2/12 and PW4/12) were completed after 2011. Although the Brantford Airport wellfield is not a focus of this study, the GRCA requested that attention be placed on local conditions at this wellfield in anticipation of upcoming source protection investigations in the area.

The areas of refinement for the three wellfields are shown in Figure 5.2. As can be seen, these areas comprise only a small portion of the Tier 3 Assessment model area (less than 9%) and all adjustments were conducted within the existing regional framework. To ensure a seamless re-integration of the local refinements into the regional model, the geometry along the edges of the refinement areas were carefully controlled, such as by the selection of edges that correspond to incised river valleys where some or all of the overburden layers were pinched out. All local revisions were undertaken on a 15 m square grid, offering additional resolution compared to the 100 m grid used in the OGS model.

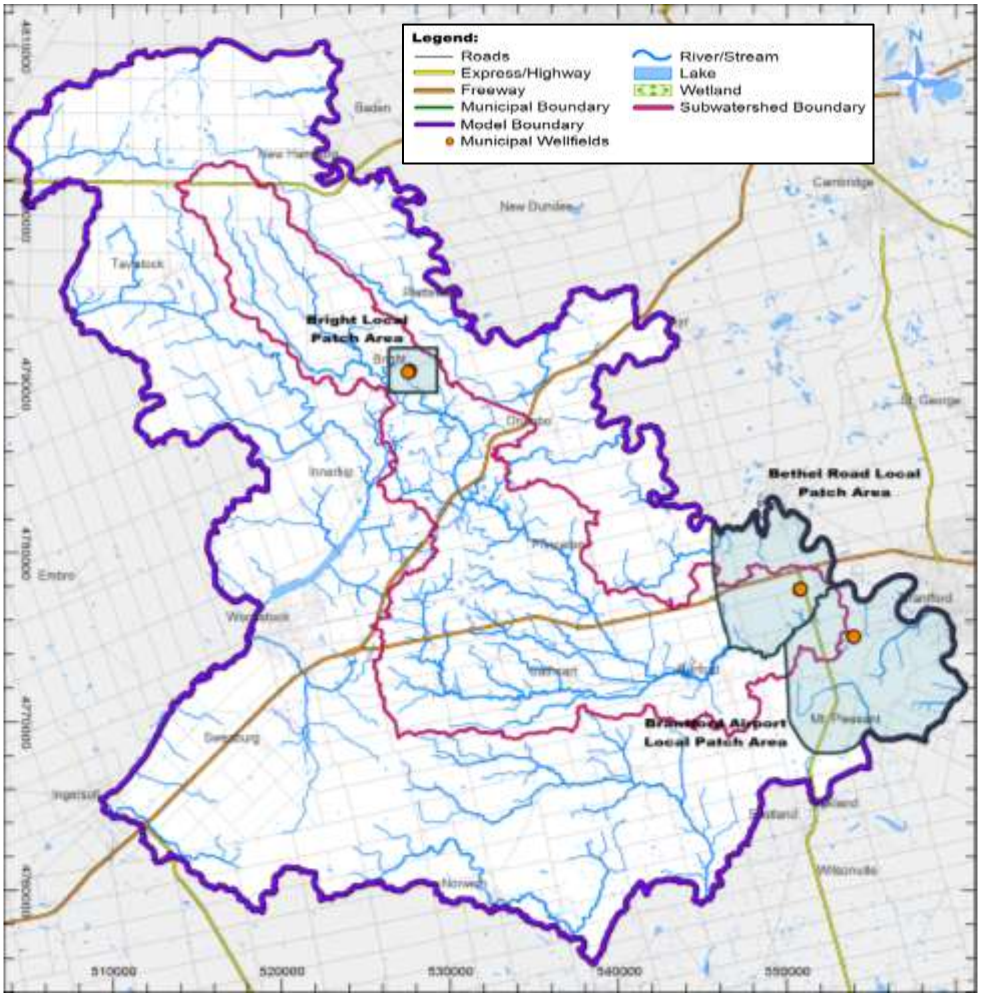


Figure 5.2: Local model refinement areas for the Bright, Bethel Road, and Brantford Airport municipal wellfields.

In the vicinity of the Bethel Road wellfield, the refinement area was extended to the incised river valleys of the Nith River to the north, the Grand River to the east, and Whitemans Creek to the south to provide elevation control when re-merging into the regional model (shown in Figure 5.2). Figure 5.5a presents an east-west cross section through the wellfield showing the original OGS model layers; Figure 5.5b shows the locally refined model layers. An increased thickness of the upper Wentworth Till (ATA1) was incorporated as part of the local revisions, which is consistent with geologic logs from wells north of Bethel Road, including pumping well TW 1/05, as was noted by Lotowater (2005). The historical interpretation of the municipal aquifer at the Bethel Road wellfield is that it is a deep sand aquifer which is locally confined by a till unit north of Bethel Road, transitioning to an unconfined coarser sand aquifer to the south (IWC, 2010; IWC, 2012). The middle till and local confinement of the municipal aquifer were absent from the original OGS model, and were therefore incorporated in the local refinement. This unit was assumed to be equivalent to the Port Stanley Till (ATB1), while the deeper aquitard is now interpreted to be the older Catfish Creek Till (ATC1); an interpretation noted by IWC (2011). Minor corrections to the bedrock surface were also applied based on borehole data from municipal monitors MW 1/04 and MW 3/04.

A relatively small refinement area was used in the vicinity of the Bright wellfield (Figure 5.2). To ensure a smooth transition between the local and regional models, an interpolative smoothing technique was applied along the edges of the local refinement area. Figure 5.6a presents a north-south cross section through the Bright wellfield showing the original OGS model layers; Figure 5.6b shows the locally-revised Tier 3 Assessment model layers. The differences between the original and revised layers in the vicinity of Bright are subtle. Of note, however, is the removal of the Pre-Canning Aquifer (AFD1) beneath and to the north of the Bright well based on the sparse supporting evidence for its presence in the local borehole logs. The thickness of the upper confining till unit (Port Bruce Aquitard ATB1) has also undergone slight adjustments in the vicinity of Bright Well 4A to better match the available well records.

The refinement area for the Brantford Airport wellfield was also sized to incorporate more reliable edge-control features, including Whitemans Creek to the northwest, the Grand River to the north and northeast, and Mount Pleasant Creek to the south. Figure 5.7a presents an east-west cross section through the Brantford Airport municipal wellfield showing the original OGS model layers; these are compared with the locally-refined model layers (Figure 5.7b). In general, only minimal local revisions were undertaken in the vicinity of the Brantford Airport wellfield, as evidenced by the similarity between the two sections. Though adjustments to the OGS model were not dramatic in this area, the process of revising local layers produced a high-resolution version of the hydrostratigraphic model that was used to refine the numerical flow model grid in the vicinity of the Airport wellfield.

5.2.2 Whitemans Tier 3 Hydrostratigraphic Model

As outlined in the previous section, the key OGS surfaces were extended and refined to create a set of conceptual surfaces for the Whitemans Tier 3 study. The 20 OGS surfaces were reduced to 11 major overburden aquifer and aquitard units. In addition, seven Paleozoic bedrock units were also created, as well as an upper weathered bedrock contact sequence. This set of digital layers is referred to as the "Tier 3 Hydrostratigraphic Model" and the layers are listed in Table 5.3. (Note that these layers are further processed into a format that is used in the numerical model, as described in Section 0)

To illustrate the extents and thicknesses of the 18 layers of the Tier 3 Hydrostratigraphic Model, a series of layer thickness (isopach) maps are presented in Figure 5.8 to Figure 5.24. It should be noted that because the weathered bedrock contact aquifer was assumed to have a uniform thickness of 10 m extending down from the top of bedrock, an isopach for this unit has not been included.

In addition, cross sections showing the Tier 3 Hydrostratigraphic Model layers have been prepared to illustrate the complex layering of the hydrostratigraphic units across the study area. The locations of the eight cross sections are shown in Figure 5.25. In addition, two river cross sections are drawn up the thalwegs of Whitemans and Kenny creeks (locations shown in Figure 5.26). Cross section A through G are presented in Figure 5.27 to Figure 5.33, and the two sections down the centrelines of Horner Creek (Section H) and Kenny Creek (Section K) are presented in Figure 5.34 and Figure 5.35, respectively.

Table 5.3: Whitemans Tier 3 Hydrostratigraphic Model Layers

Layer	Conceptual Unit Name	Main OGS Unit	Comments
Overburden Units			
1	Whittlesey Sand Aquifer	AFA0	
2	Whittlesey Aquitard	ATA1	
3	Wentworth Aquitard	ATA2	
4	Sand Plain and Outwash Aquifer	AFA2	
5	Port Stanley/Tavistock Aquitard	ATB1	includes absent ATA3
6	Waterloo Moraine Aquifer	AFB1	
7	Maryhill Till Aquitard	ATB3	includes negligible ATB2
8	Post Catfish Aquifer	AFB3	
9	Catfish Creek Till Aquitard	ATC1	Includes negligible AFC1 and ATC2
10	Pre-Catfish Aquifer	AFD1	
11	Canning Till Aquitard	ATE1	Includes patchy AFF1 and ATG1
Bedrock Units			
*12	Weathered Bedrock Contact Aquifer		Assumed 10 m across model
13	Dundee-Lucas-Amherstburg Aquifer		
14	Bois Blanc Aquifer		
15	Bass Island Aquifer		
16	Upper Salina Poor Aquifer/Aquitard		Salina Units A-F
17	Lower Salina Shale Aquitard		Salina G Unit
18	Guelph-Eramosa Aquifer		

5.2.2.1 Surficial Deposits and Moraines

Layers 1 through 4 in Table 5.3 represent surficial deposits and the Wentworth Till moraine. The Wentworth Aquitard includes the Paris, Galt, and Moffat moraines of the lower Whitemans Creek subwatershed, but the units are not extensive or very thick, as shown in Figure 5.10. The Whittlesey Sand Aquifer and Whittlesey Aquitard are limited to the eastern-most portion of the study area (Figure 5.8 and Figure 5.9).

The most significant shallow aquifer unit (referred to as the “Sand Plain and Outwash Aquifer”; OGS unit AFA2 in Table 5.2 and Layer 4 in Table 5.3) includes the Norfolk Sand Plain and the Grand River Outwash sediments. These units were combined by the OGS, owing to their similar sand-dominated composition, which could not be differentiated in the available borehole data. The thick nature of this unit can be seen on Section E (Figure 5.31) and Section G (Figure 5.33). Section E (Figure 5.31) is particularly interesting, for it illustrates how the Sand Plain and Outwash Aquifer deposits appear to be constrained by a depression in the bedrock surface.

5.2.2.2 Post-Catfish Aquifer and Aquitard Systems

For the remainder of the discussion, the hydrostratigraphic units will be grouped as “Pre” and “Post’ Catfish Creek Till. The term “Pre-Catfish” has been used throughout the region, while Post-Catfish is used here for convenience.

The Post-Catfish units include the Port Stanley/Tavistock Till Aquitard Complex (Figure 5.12) and the regionally-extensive AFB1 or Waterloo Moraine Aquifer (Figure 5.13). The Waterloo Moraine aquifer is frequently unconfined, except in the middle portions of the Whitemans Creek subwatershed where it is confined by the Port Stanley/Tavistock Till Aquitard as seen in Cross Section A (Figure 5.27). The Post-Catfish Aquifer (Layer 8 or AFB3) is limited to lenses that can be considered locally significant but patchy in terms of regional continuity (Figure 5.15). This aquifer unit sits on the Catfish Creek Till Aquitard and has been referred to as “re-worked” Catfish Creek Till.

The lateral extents and continuity of the Catfish Creek Till Aquitard is clearly illustrated in Figure 5.16 and on Cross Section K in Figure 5.34. The isopach map illustrates that the Catfish Creek Till Aquitard is essentially continuous across much of the Whitemans Creek subwatershed. Cross Section K follows Horner Creek from its headwaters to the outfall at the Grand River, and shows near continuous Catfish and Maryhill Aquitards.

5.2.2.3 Pre-Catfish Aquitard and Aquifer Systems

The Pre-Catfish Aquifer (Layer 10 or AFD1) isopach, shown in Figure 5.17, suggests that the unit is only locally significant. Recharge to this unit is likely limited by the relatively continuous overlying Catfish Creek Aquitard.

The deeper Canning Till Aquitard is frequently found in bedrock depressions as shown in Cross Section H (Figure 5.34) and is also not continuous (Figure 5.18). Two localized pre-Canning Till aquifer zones, sitting on bedrock, were too limited, deep, and isolated to be included as full layers and were therefore combined in with the Canning Till Aquitard.

5.2.2.4 Onondaga Escarpment Aquifer Units

The Onondaga Escarpment is a unique and potentially significant feature in the study area. Above the escarpment (i.e., in the western part of the study area), the overburden is generally thinner and the majority of the private and public wells are completed in the limestones and dolomites units. Recharge in these areas may also supply groundwater to the deeper units of the Whitemans Creek subwatershed to the east. Outwash channels south of Bright may also interconnect with the units above the escarpment and potentially support cross-watershed flow into the headwaters of the Thames River.

Attempts to individually map the Dundee, Lucas and Amherstburg bedrock units in the southwestern portion of the study area were unsuccessful because of limited OGSR data. The three units have been combined in the Whitemans Conceptual Hydrostratigraphic Model as Layer 12 (Figure 5.19). The largest exposure of this unit is found in Cross Section C (Figure 5.29), which follows Highway 401 from Ingersoll towards Woodstock, and shows the large number of private wells completed in this unit.

Mapping the Bois Blanc and Bass Island Aquifers as separate units using data from the OGSR database was both successful and insightful. Mapping of the top of the Bass Island Formation indicated that a significant portion of the southwestern region of the Whitemans subwatershed is underlain by limestones as much as 20 m in thickness (Figure 5.21). This extension of the limestone aquifers of the Onondaga Escarpment was not shown in the existing OGS Paleozoic compilation map (Figure 3.9, Armstrong and Dodge, 2007); however, it has been incorporated into the Whitemans Tier 3 Assessment conceptual model due to the availability of supporting data from oil and gas wells, and the regional significance of these units as a water resource in the study area.

5.2.2.5 Salina Formation

The Salina Group consists of a number of sub-elements. Eight units of formational rank have been recognized in the Salina Group (Armstrong and Carter, 2010), with the lower two members exhibiting an increase in shale content. While data were insufficient to map all eight units, the lower two members were identified and mapped as the Lower Salina Aquitard (Figure 5.23). Previous studies have referred to the Salina as a “poor aquifer”.

The Guelph and Eramosa formations sub-crop beyond the northeast extent of the study area. These units were originally mapped to help constrain the base of the model (Figure 5.24). Cross Section C (Figure 5.29) illustrates the rise in the Guelph Formation to the northeast.

5.3 *Groundwater Flow Regimes*

5.3.1 Static Water Level Data

Static water level data from wells in the MOE WWIS database (current to 2013) were compiled and analyzed to determine regional patterns in the groundwater heads for the shallow overburden and deeper bedrock aquifers. Assignment of the static water level data to specific model units was also done to provide calibration targets for the numerical groundwater flow model.

WWIS well locations are shown in Figure 5.3. The water levels recorded in the WWIS database represent a one-time measurement taken when the well was constructed. Numerous biases and errors are known to exist in the water well record data. Assessment of the intrinsic error and variation in this data set is discussed in Kassenaar and Wexler (2006). Despite these limitations, the WWIS data set has a good regional coverage. A total of 16,994 MOE static water levels were used in the characterization of groundwater patterns.

The static water level data were analyzed and measurements were assigned to either the bedrock or overburden aquifer. Data were also filtered to reduce the number of obviously erroneous data points. Regionally, 10,753 wells were mapped as overburden and 6,241 were mapped as bedrock wells. Because the population density is low in the more rural parts of the subwatershed, water well data are relatively scarce in some areas. Of the 2,005 records within the Whitemans Creek subwatershed, approximately one-third are located proximal to the urbanized areas of Bright and Burford. Despite the sparsity in some areas, there were sufficient data to create interpolated regional water level surfaces.

5.3.2 Transient Water Level Data

Transient groundwater level data were obtained from multiple sources (locations shown in Figure 5.36) and processed to identify and correct spikes and shifts in the data, reconcile logger data with manual measurements (where appropriate), and generally prepare the data for use as transient model calibration targets. A discussion of the primary sources of transient groundwater level data is provided below:

Provincial Groundwater Monitoring Network: Water level data for 10 Provincial Groundwater Monitoring Network (PGMN) wells in the study area were obtained from the MOE and GRCA. Of these PGMN wells, three are located within the Whitemans Creek subwatershed. Well depth and location information is provided in Table 5.4, and locations are shown in Figure 5.36. The PGMN wells are distributed in the study watershed and provide useful information on natural seasonal and climactic variation in water levels. Two of the PGMN monitors are completed in the weathered bedrock aquifer, while seven monitors are screened within the overburden aquifer and aquitard units. One of the PGMN monitors, W0000481-1, was missing well screen information.

Municipal Monitoring Networks: Water level monitoring data are collected from the municipal supply wells and at nearby monitoring wells as part of the operation of municipal water supply systems. A total of 36 data sources for transient groundwater levels from municipal sources were provided by the GRCA, and the Counties of Oxford and Brant; specifically, for the municipal systems of Bright (5), Bethel (20), Woodstock (7), Tavistock (3), Innerkip (2), Plattsville (2), and Drumbo (3). With the exception of Bright and Bethel, water level monitoring data for the municipal systems were for the supply wells only.

Field Program Groundwater Data: To supplement the available groundwater level data, a field program was developed and undertaken by Earthfx and Whitewater Hydrogeology. Drive point piezometers were completed at 19 locations and equipped with data loggers for February to November of 2015. In addition, 10 private wells were equipped with water level loggers for the same period to access deeper hydrogeologic units. Locations of the field monitoring locations are shown in Figure 5.36.

Table 5.4: Summary of PGMN well details.

Well Name	Sub-watershed	Screen Formation	Easting	Northing	Ground Elevation (masl)	Well Depth (m)	Top of Screen (masl)	Bottom of Screen (masl)
W0000015-1	Big Otter Creek	Sand Plain Aquifer	540375	4761249	251.5	9.9	242.3	241.6
W0000016-3	Big Otter Creek	Sand Plain Aquifer	540024	4761565	251.3	24.3	227.5	227.1
W0000065-4	Whitemans Creek	Outwash Aquifer	547481	4771253	259.1	25.3	240.8	237.8
W0000180-1	Thames River	Bedrock Aquifer	523486	4781358	301.4	41.9	285.2	259.4
W0000218-3	Avon River	Waterloo Moraine Aquifer	513351	4803035	368.9	6.7	365.3	362.2
W0000218-4	Avon River	Post-Catfish Aquifer	513351	4803035	368.9	24.1	347.9	344.8
W0000218-5	Avon River	Bedrock Aquifer	513351	4803035	368.9	61.0	308.8	307.9
W0000477-1	Whitemans Creek	Waterloo Moraine Aquifer	542577	4773875	261.0	38.4	246.1	243.1
W0000478-1	Whitemans Creek	Waterloo Moraine Aquifer	529065	4785860	308.0	58.4	294.0	291.0
W0000481-1	Thames River	Unknown	516739	4766811	331.5	79.7	-	-

5.3.3 Regional Water Level Trends

Regional water level patterns were evaluated using the MOE WWIS static water level data. Water level patterns provide information on the general direction of groundwater flow, which is perpendicular to contours of equal groundwater elevation. Because most of the aquifers are thin relative to their areal extent, flow can be treated as being predominantly horizontal (Bear, 1979). Vertical flow can dominate in some local areas such as in the immediate vicinity of partially penetrating wells and streams.

As noted above, there are multiple problems that have been identified in the static water level data in drillers' logs submitted to the MOE. Sources of error include positional and depth measurement errors and questions as to whether static conditions were achieved prior to measurement. Seasonal and year-to-year water level variations also introduce noise in the data which is noticeable when analyzing clusters of water level data. Although the data were filtered to reduce the number of erroneous data points, some degree of uncertainty as to the accuracy of individual measurements remains. The accuracy of the maps produced from these data is similarly affected. Despite these limitations, the MOE WWIS data remains the only data set with sufficient spatial coverage to allow mapping of potentiometric surfaces over the entire study area. Transient water levels were averaged over time and used to supplement the MOECC WWIS static water level data.

Water-level data were interpolated using a geostatistical technique known as "kriging". Kriging is a weighted-average interpolation method that attempts to minimize variance and bias in the results while honouring the local values at the data points. The kriged water level data for the shallow groundwater system is shown in Figure 5.37. The variance of the kriged overburden water levels is presented on Figure 5.38. Areas of high variance indicate relatively high uncertainty in the kriged water levels and are indicative of significant gaps in spatial coverage. For example, the areas of high variance in the Upper Horner and Kenny Creek subwatersheds are areas where the majority of wells are completed in bedrock rather than the overburden.

As noted above, the potentiometric surface maps for the overburden can be used to infer patterns of groundwater flow. In general, groundwater flow in the shallow system is from topographic highs in the northwest and north (corresponding to the Waterloo Moraine) toward topographic lows in the southeast. A region of high groundwater levels is also noted to the south of the City of Woodstock (corresponding to the Woodstock and Ingersoll moraines). Prominent "v-shaped" groundwater contours can be seen pointing upstream along the main branches of the Thames River, Whitemans Creek, the Nith River and the Grand River, indicating the river valleys are areas of significant groundwater discharge.

Figure 5.39 presents a map of the depth-to-water table calculated by subtracting the interpolated water levels from land surface elevation. Areas with the water table at or above land surface are shown in blue and are likely regions of groundwater discharge. Wells that were flagged as free flowing in the WWIS database are also shown on Figure 5.39 and suggest a good correlation to the mapped areas of potential groundwater discharge.

The interpolated bedrock water levels are presented in Figure 5.40. The variance of the kriged bedrock water levels is presented on Figure 5.41. Of note is that the variance is low for the Upper Horner and Kenny Creek subwatersheds where the majority of wells are completed in bedrock. Large data gaps exist in areas where the overburden is highly productive and wells tend to be shallow.

The regional water level patterns are relatively consistent between the bedrock and overburden aquifers: regional highs corresponding to the Waterloo and Woodstock Moraines are visible in the bedrock, as are v-shaped contours around the main river branches. Figure 5.42 illustrates the difference between the interpolated water levels in the shallow and deep groundwater systems. Red shading indicates interpolated heads are higher in the overburden and that groundwater flow would be downward while blue shading indicates that heads in the bedrock are higher and that flow would be upward.

5.3.4 Water Level Fluctuations

A review of long-term water level data was conducted to quantify seasonal fluctuations in groundwater levels across the study area. The range in fluctuations is important for assigning drawdown thresholds for the Tier 3 risk assessment.

Observed groundwater levels from monitors in the municipal well fields were added to the project database and examined to gain insights into the extent of impacts from municipal pumping. In particular, a review of the groundwater level monitoring data from the Community of Bright and the Bethel Road wellfield has been provided as part of the following discussion.

5.3.4.1 PGMN Monitoring Wells

The majority of the PGMN monitors (locations shown on Figure 5.36) are situated away from the municipal wellfields and were assumed to be outside the influence of the municipal pumping wells. Data from these wells provided insight into natural seasonal water level fluctuations. Hydrographs for the selected wells are presented along with corresponding monthly precipitation in Figure 5.43 to Figure 5.48. Seasonal trends in the PGMN well data are generally consistent across the study area, and are characterized by the following annual patterns:

- Peak water levels occur around mid- to late-April corresponding to thawing of the ground and recharge from spring snowmelt.
- Following the spring freshet, water levels exhibit an overall decline through the summer months when evapotranspiration is at its most intense; this downward trend typically persists until late-September.
- Water levels begin to recover from late-September through November due to increased precipitation and decreased evapotranspiration in the fall.

PGMN monitoring locations W0000015-1 and W0000016-3 are completed in the Norfolk Sand Plains surficial sand aquifer and Bois Blanc bedrock aquifer, respectively. Due to their similar behaviour and relatively close proximity to one another (< 500 m), both time series are presented together in Figure 5.43. Water levels in these two monitors show similar patterns of seasonal variation and, fluctuate across a range of approximately 1 m. Seasonal highs and lows in each monitor are in phase with one another suggesting that the shallow and deeper groundwater systems are in good hydraulic connection in this area. Observed water levels in the glacial outwash aquifer at W0000065-4 (shown in Figure 5.44; located north of W0000015-1 and W0000016-3) exhibit a good match both in seasonal fluctuation and absolute water level elevations to those in the Norfolk Sand Plains. Interpretation of a hydraulic connection between the two aquifers is not likely due to the presence of the Tillsonburg Moraine, which runs longitudinally between the two monitoring locations. However, similar seasonal fluctuations are not unexpected as both aquifers are composed of coarse-grained sands and gravels and are considered to be unconfined at both monitoring locations.

Well W0000477-1 is screened across the upper part of the Maryhill Till aquitard (Figure 5.45), which underlies the Waterloo Moraine aquifer. Water level fluctuations are generally consistent with those observed in W0000065-4, fluctuating over a range of approximately 1 m. Confining till units between the surficial outwash aquifer and the older Waterloo Moraine aquifer are relatively discontinuous in this area. This could account for the good match between the observed water levels at these two wells. Well W0000478-1 is screened within the Waterloo Moraine aquifer south of the Town of Bright (Figure 5.46), where the aquifer is considered to be unconfined. Seasonal water level fluctuations and responses to wet (2009) and dry (2010) years are generally consistent between W0000478-1 and W0000477-1.

Water levels in the bedrock monitor W0000180-1 (Figure 5.47) show a typical fluctuation of approximately 2 m. As illustrated in Figure 5.47, water levels at W0000180-1 regularly fluctuate by approximately 0.5 m on a daily basis, which is likely caused by municipal pumping from the nearby Innerkip municipal supply wells. Seasonal fluctuations at this monitoring location may also be influenced by the changes to the stage in the nearby Pittock Reservoir.

Figure 5.48 presents the observed water level data for well nest W0000218, which is screened across the Waterloo Moraine aquifer (W0000218-3), the Post-Catfish aquifer (W0000218-4) and the Bois Blanc Formation bedrock aquifer (W0000218-5). The largest water level fluctuations, in a range of approximately 1.5 m, are observed in the shallow monitor (W0000218-3), which is strongly influenced by soil zone processes (recharge and ET). Water level fluctuations in the two deeper intervals have a range of approximately 1 m. Throughout the period of record, the water level fluctuations in all three intervals exhibit a similar timing although with some lag and are consistently within 2 m of one another, despite being vertically separated by approximately 10 m of Maryhill Till aquitard and approximately 16 m of Catfish Creek Till aquitard. These data seem to suggest that pressure response through the confining units is relatively quick and that storage in the aquitards is relatively small. The relative water levels are puzzling because levels in the intermediate well are consistently higher than those in the upper and lower wells. There does not appear to be any significant pumping or hydrologic feature nearby that might be preferentially draining the upper aquifer, therefore, a likely explanation is a survey error associated with the shallow well. Further investigation may be warranted.

5.3.4.2 Field Monitoring Data Analysis

The field program undertaken for this study included installation and monitoring of drive-point piezometers, as well as the placement of water level loggers in several private wells. Drive-point piezometers were used to monitor areas where the water table is shallow and groundwater-surface water interactions are more likely to occur (e.g., adjacent to coldwater stream reaches and wetland features).

Hydrographs of groundwater levels obtained through the field monitoring program are presented in Figure 5.49 to Figure 5.54 and completion details for each monitor are summarized in Table 5.5. The time series cover nine months of continuous water level measurements. Relative water levels (in this case, the differences between the observed levels and level at the start of WY 2016 (October 1, 2015)) are presented because the spatial variation in absolute water levels made direct comparison difficult. The seasonal response in the water levels is generally consistent between monitors, and is characterized by the following behaviour:

- Peak water levels occurred around mid- to late-April corresponding to thawing of the ground and recharge from seasonal snowmelt.
- Following the spring freshet, water levels declined into the summer months when ET was at its most intense.
- An unseasonably wet June, produced a second peak in groundwater levels. Following this peak the levels declined steadily into the late summer.
- Water levels began to recover starting in late-September and more sharply in late November due to increased precipitation and decreased ET in the fall.

Table 5.5: Summary of field monitoring program drive point and private well completion details.

Monitor Name	Easting (m)	Northing (m)	Depth (mbgs)	Hydrostratigraphic Unit
Drive Point Monitors				
DP5	546866	4777640	1.76	Sand Plain/ Outwash Aquifer
DP6	546914	4775385	2.09	Sand Plain/ Outwash Aquifer
DP7	548097	4774252	2.16	Sand Plain/ Outwash Aquifer
DP8	544759	4772057	1.97	Sand Plain/ Outwash Aquifer
DP9	543716	4770402	1.82	Waterloo Moraine Aquifer
DP11	530129	4782871	2.57	Waterloo Moraine Aquifer
DP12	528329	4783970	1.65	Sand Plain/ Outwash Aquifer
DP13	534268	4779751	1.84	Sand Plain/ Outwash Aquifer
DP14	528894	4777550	2.21	Port Stanley/Tavistock Aquitard
DP15	533380	4788523	2.00	Waterloo Moraine Aquifer
DP18	528212	4789686	2.23	Waterloo Moraine Aquifer
DP19	526459	4772048	1.66	Port Stanley/Tavistock Aquitard
DP20	545100	4774952	2.17	Sand Plain/ Outwash Aquifer
Link Property	541191	4774132	1.65	Sand Plain/ Outwash Aquifer
Rest Acres-1	550991	4775664	2.82	Port Stanley/Tavistock Aquitard
Rest Acres-2	551034	4775609	1.40	Sand Plain/ Outwash Aquifer
Rest Acres-3	551075	4775551	1.38	Sand Plain/ Outwash Aquifer
Blandford Stn.	529019	4785762	1.67	Waterloo Moraine Aquifer
Bright-1	527585	4790751	11.51	Port Stanley/Tavistock Aquitard
Private Well Monitors				
PR2	542559	4773740	18.60	Maryhill Till Aquitard
PR3	546091	4773412	12.9[1]	Unknown
PR4	530893	4786040	24.7[1]	Unknown
PR5	517118	4802921	96.06	Upper Salina
PR6	524329	4789975	12.3[1]	Waterloo Moraine Aquifer
PR7	519397	4800972	>60[1]	Bedrock (unknown)
PR8	517317	4801851	31.64	Waterloo Moraine Aquifer
PR9	519131	4802036	37.30	Post Catfish Aquifer
PR10	516257	4801734	79.46	Upper Salina
PR11	549102	4775588	26.59	Sand Plain/ Outwash Aquifer

[1] Depth unknown

The southeastern region of the Whitemans Creek subwatershed is characterized by intensive agricultural irrigation due to the Sand Plain/Outwash aquifer comprising much of the surficial sediments. Seven drive-point piezometers were installed in this region to monitor shallow groundwater levels (DP5-DP9, DP20, and Link Property). Figure 5.49 presents the time series data for each piezometer. All piezometers were completed in the unconfined Sand Plain/Outwash aquifer layer with the exception of DP8, which was completed within an unconfined portion of the Waterloo Moraine aquifer. Groundwater levels follow the seasonal precipitation trends increasing between 0.25 m (DP7) up to 0.75 m (DP8 and Link Property) in response to the freshet and declining thereafter. The most dramatic change in water level occurred at DP20, located immediately adjacent to a dugout pond that supplies irrigation water to a sod farm operation. Here, large drawdowns of up to 1 m were measured in response to water takings.

Water levels in all monitors increased rapidly and remained elevated throughout the unseasonably wet June. This includes DP20, likely because irrigation was not necessary during the wet conditions. Water levels in all monitors steadily declined into the fall apart from DP20 where large drawdowns of up to 1 m were observed in July and August suggesting that irrigation was required for the remainder of the growing season. The depressed water levels at DP20 recovered rapidly through the fall.

Two intermediate depth private wells, PR2 and PR3, were also monitored in the southeastern region of the subwatershed. The time series of observed water levels are presented in Figure 5.50. PR2 is completed in the Maryhill Till aquitard and located at the site of a tree nursery. While the tree nursery has an active PTTW, it is unclear if PR2 is the supply well linked to this permit because it was originally installed for domestic purposes. PR3 is a domestic well believed to be completed in the Sand Plain/Outwash aquifer; however, well records could not be found to confirm this assumption. Both monitors exhibit fluctuations that appear to be dominated by seasonal patterns. The seasonal response of PR2 is slightly lagged in comparison to PR3 and the shallower measurements discussed above. This is likely the result of the lower hydraulic conductivity of the Maryhill Till Aquitard in comparison to the Sand Plain/Outwash Aquifer. Water levels at PR2 also exhibit high frequency fluctuations of approximately 0.25 m attributed to irrigation requirements of the tree farm.

Three additional shallow drive-point piezometers were installed further east towards the bottom end of Whitemans Creek. These were installed in a transect perpendicular to the creek to analyze groundwater level variability as a function of distance from the creek. Hydrographs are presented in Figure 5.51 where RA-1 represents the drive-point installed closest to the stream and RA-3 represents the drive-point furthest away. Large fluctuations were observed in groundwater levels at RA-1 in response to the spring freshet that were not observed or were dampened in monitors located further away. Event-based peaks in groundwater levels were observed all monitors in the summer months. This suggests that groundwater levels in the shallow system near to the stream are strongly influenced by stream stage whereas fluctuations further away are more influenced by seasonal fluctuations and precipitation events.

Six drive-point piezometers were installed to a depth of 2 to 3 m below ground surface (DP11-DP13, DP15, DP18 and Blandford Station) in the central portion of the Whitemans Creek subwatershed. Figure 5.52 presents the time series of water levels for each piezometer. The density of permitted water users in this part of the subwatershed is less than that of the southeastern region discussed above. None of the shallow monitors are located near any permitted water users and consequently, the water level fluctuations appear to be seasonally driven. Similar conclusions can be made about two deeper private wells, PR4 and PR6, also located in the central portion of the subwatershed. The high frequency fluctuations ranging between 0.05 and 0.25 m are attributed to domestic water use. While their depths could not be confirmed, the relatively smooth response to seasonal fluctuations suggest the wells may be screened in a deeper unit with less connection to the surface in comparison to the shallow drive-points. [The Bright-1 monitor, also located in this area, is discussed further on in Section 5.3.4.3].

Five private wells, located at the north end of the Whitemans Creek subwatershed are shown in Figure 5.53. Both PR5 and PR10 are completed in the Upper Salina bedrock formation at depths greater than 60 m. PR7 is also completed within the bedrock although its depth was not known. However, given the nearly identical behavior observed in all three monitors, it is expected that PR7 is completed in the same bedrock unit as PR5 and PR10. Bedrock water levels exhibit a similar, albeit dampened, seasonal response as the shallower wells, with a freshet-driven peak in late April followed by an overall decline into late summer. Higher frequency fluctuations, ranging between 0.25 and 0.75 m, are also observed throughout the time series and may be due to nearby pumping for domestic and livestock use.

Lastly, two shallow drive-point piezometers (DP14, DP19) were installed in the west/southwest portion of the Whitemans Creek subwatershed. These monitors are located adjacent to Kenny Creek, in an area with limited permitted water use. Groundwater level fluctuations observed in DP19 appear to be seasonally driven showing the characteristic high levels in the spring, several event-based peaks in the summer, and low levels in the fall. The behavior at DP14 differs as it does not exhibit any clear seasonal trend, nor does it appear to be influenced by any anthropogenic stresses. Consequently, no definitive conclusions can be made regarding its behavior. Because it is not in close proximity to the Bright and Bethel Road municipal wellfields, further investigation was not warranted at this time.

5.3.4.3 Municipal Wellfield Patterns

Groundwater level monitoring data from the municipal wellfields within the Whitemans Creek subwatershed were reviewed to assist with characterizing the local hydrogeologic conditions. Transient groundwater level data from municipal wellfields show local response of the aquifers to pumping (and recovery) as well as the typical responses to climatic factors.

A summary of completion details for wells in the County of Brant Bethel Road wellfield is provided in Table 5.6; including the four municipal supply wells (shaded). Well screens for the monitoring wells are typically completed in either the upper Sand Plain-Outwash Aquifer or the deeper Waterloo Moraine Aquifer. It should be noted that the intervening Port Stanley Till aquitard is considered to be discontinuous in the wellfield vicinity, particularly to the south of Bethel Road. As a consequence, water levels in nested well MW2/04, presented in Figure 5.56, exhibit a very close match between the shallow (MW2/04-2) and deep (MW2/04-1) intervals. Water levels in both wells also exhibit daily fluctuations related to pumping from the municipal aquifer (intercepted by MW2/04-1).

Table 5.6: Completion details for pumping wells and monitors in the Bethel Road municipal wellfield.

Well Name	Screen Formation	Easting	Northing	Ground Elevation (masl)	Borehole Depth (m)	Top of Screen (masl)	Bottom of Screen (masl)
PW1/12	Waterloo Moraine Aquifer	550768	4777831	256.0	30.5	233.4	227.1
PW2/12	Waterloo Moraine Aquifer	550782	4777834	256.1	30.5	233.5	227.2
TW1/05	Waterloo Moraine Aquifer	550782	4777852	256.0	35.7	228.6	222.5
PW4/12	Sand Plain-Outwash Aquifer	550746	4777821	257.0	30.5	232.8	226.5
MW1/04-1	Waterloo Moraine Aquifer	549735	4777577	266.0	54.3	240.1	237.0
MW1/04-2	Sand Plain-Outwash Aquifer	549735	4777577	266.0	54.3	250.8	247.7
MW2/04-1	Waterloo Moraine Aquifer	550770	4777823	256.4	40.5	227.4	224.4
MW2/04-2	Sand Plain-Outwash Aquifer	550770	4777823	256.4	40.5	240.2	237.2
MW3/04-1	Waterloo Moraine Aquifer	550429	4777722	265.2	53.0	232.3	230.8
MW3/04-2	Waterloo Moraine Aquifer	550429	4777722	265.2	53.0	240.5	239.0
MW3/04-3	Sand Plain-Outwash Aquifer	550429	4777722	265.2	53.0	248.4	246.9
SMW5/12	Sand Plain-Outwash Aquifer	550684	4777838	258.2	13.5	246.2	244.7
SMW6/12	Sand Plain-Outwash Aquifer	550784	4777844	256.1	10.8	246.9	245.3
MW1/14	Sand Plain-Outwash Aquifer	550762	4777834	256.5	25.3	234.3	231.3
TW2/11	Sand Plain-Outwash Aquifer	550745	4777822	257.0	36.6	235.7	229.6
TW3/12	Waterloo Moraine Aquifer	550675	4777824	258.6	30.5	235.9	231.1
PW2/09*	Sand Plain-Outwash Aquifer	550797	4777762	256.0	31.1	231.6	225.5
PW5/07*	Sand Plain-Outwash Aquifer	550800	4777780	256.0	30.5	233.8	226.1
TW3/07*	Sand Plain-Outwash Aquifer	550802	4777774	255.9	28.5	231.7	228.5
TW4/07*	Sand Plain-Outwash Aquifer	550796	4777794	256.0	27.9	231.8	228.6

Notes: * well has been decommissioned.

Figure 5.57 presents the observed water levels at monitoring wells MW1/14, TW2/11 and SMW6/12 – all located within close proximity to the four Bethel Road municipal supply wells. The influence of municipal pumping on water levels in these monitors suggests a strong local connection between the deeper municipal aquifer (Waterloo Moraine aquifer) and the shallow Sand Plain-Outwash aquifer, in which these wells are completed.

Monitoring wells SMW5/12 and TW3/12, located approximately 65 m west of the municipal wellfield, show minor influences of municipal pumping in their recorded water levels, with daily fluctuations of about 0.3 m (Figure 5.58). Despite an apparent water level difference of up to 2.5 m, similar patterns can be seen in the two wells, once again suggesting a good hydraulic connection between the upper outwash sand aquifer and the deeper Waterloo Moraine Aquifer. Monitoring well nest MW3/04 is located approximately 330 m west of the municipal wellfield, and consists of a deep, intermediate, and shallow monitoring interval. As shown in Figure 5.59, water levels in deeper intervals (MW3/04-1 and MW3/04-2) closely match one another, reflecting their completion in the same aquifer unit (Waterloo Moraine aquifer). Observed levels in shallow interval MW3/04-3 follows a similar pattern, though noticeable sharp spikes can be seen in the data, approximately corresponding to the spring period. These spikes were noted in IWC (2014) during the testing at PW4/12 and were attributed to unspecified recharge events, though it was also noted that these spikes did not occur in any of the other monitoring wells.

Table 5.7 summarizes the construction details for the Community of Bright municipal wellfield. A single nested observation well, MW1, is monitored as part of the regular operations of the wellfield. It should be noted that the screened intervals for this monitoring well nest are approximately 10 to 20 m above the interval targeted by the municipal pumping wells, and the Bright monitors are interpreted to be screened across the overlying Tavistock Till aquitard. Figure 5.60 presents the observed water levels in the shallow and deep monitoring intervals of MW1, compared to historical monthly rainfall and total municipal pumping. Heads are lower in the deep monitoring interval, as evidenced by a consistent difference in observed heads of approximately 4 m, indicating vertically downward groundwater flow is occurring. Water levels in both wells show a steep decline in response to the 2007 and 2012 droughts, and otherwise follow a consistent seasonal pattern of peaking in the spring and declining into the late-fall months. The seasonal fluctuations were found to be approximately 3 to 5 m in MW1 Shallow and 1 to 3 m in MW1 Deep.

Table 5.7: Community of Bright municipal wellfield well completion details.

Well Name	Screen Formation	Easting	Northing	Ground Elevation (masl)	Borehole Depth (m)	Top of Screen (masl)	Bottom of Screen (masl)
Well 4	Waterloo Moraine Aquifer	527587	4790760	317.1	38.4	295.5	293.6
Well 4A	Waterloo Moraine Aquifer	527587	4790765	317.2	30.5	296.6	290.5
Well 5	Waterloo Moraine Aquifer	527515	4790696	319.7	25.9	294.8	293.8
MW1 Shallow	Port Stanley-Tavistock Tills	527583	4790748	317.1	11.9	315.1	311.6
MW1 Deep	Port Stanley-Tavistock Tills	527583	4790748	317.1	11.9	307.4	305.2

As shown in Figure 5.60, municipal pumping tends to peak in the summer months, coinciding with the natural water level declines caused by low seasonal precipitation and high evapotranspiration. This makes it difficult to deduce from water levels alone, the degree of connectedness between the municipal aquifer and the two monitors. However, a step test completed on Well 4A in August of 2009 resulted in a 0.3 m drawdown in MW1 Deep, and no measureable drawdown in MW1 Shallow (ARL, 2010). Water levels in both wells are considered to be strongly influenced by seasonal climate variability, while only MW1-Deep is impacted by municipal pumping from the underlying Waterloo Moraine Aquifer.

5.4 *Summary*

The hydrogeologic conditions in the study area can be generally subdivided into the upper, middle and lower portions of the watershed. Groundwater resources in the upper watershed, including the town of Bright, are limited to thin, intermittent confined aquifers with limited recharge and storage. The only significant aquifers are found to the north towards the Waterloo moraine or to the west in the dolostones of the Onondaga Escarpment.

The Central Whitemans Outwash portion of the watershed is the most hydrogeologically diverse. Where unconfined, the shallow outwash sediments can provide productive water supplies. Significant portions of the central watershed aquifers are till-covered and support significant wetlands. Both the wetlands and shallow groundwater aquifers provide significant storage.

Finally, the lower Whitemans Sand Plain exhibits nearly the opposite hydrogeologic conditions to the upper watershed. The thick unconfined sands provide significant, but potentially sensitive, groundwater resources.

The Whitemans Tier 3 Hydrostratigraphic Model developed and presented in this section represents a detailed and comprehensive representation of the subsurface. The model builds on the extensive previous work by the OGS, but has been extended, locally refined, and transformed to a format suitable for integrated model simulations.

Considerable groundwater data have been collected and compiled to support the calibration of the model. New field data collected under this project provided additional insight into key watershed features, particularly the shallow subsurface where groundwater and surface water interactions occur. The detailed analysis and interpretation of spatial and temporal groundwater data presented in this section provided a foundation for the analysis of the model simulation results.

Additional analyses were carried out related to the effect of short and longer-term drought on groundwater levels in the Whitemans Creek subwatershed. Because these are not related directly to the Tier 3 Risk Assessment, these discussions have been included in Appendix E to this report.

5.5 *Figures*

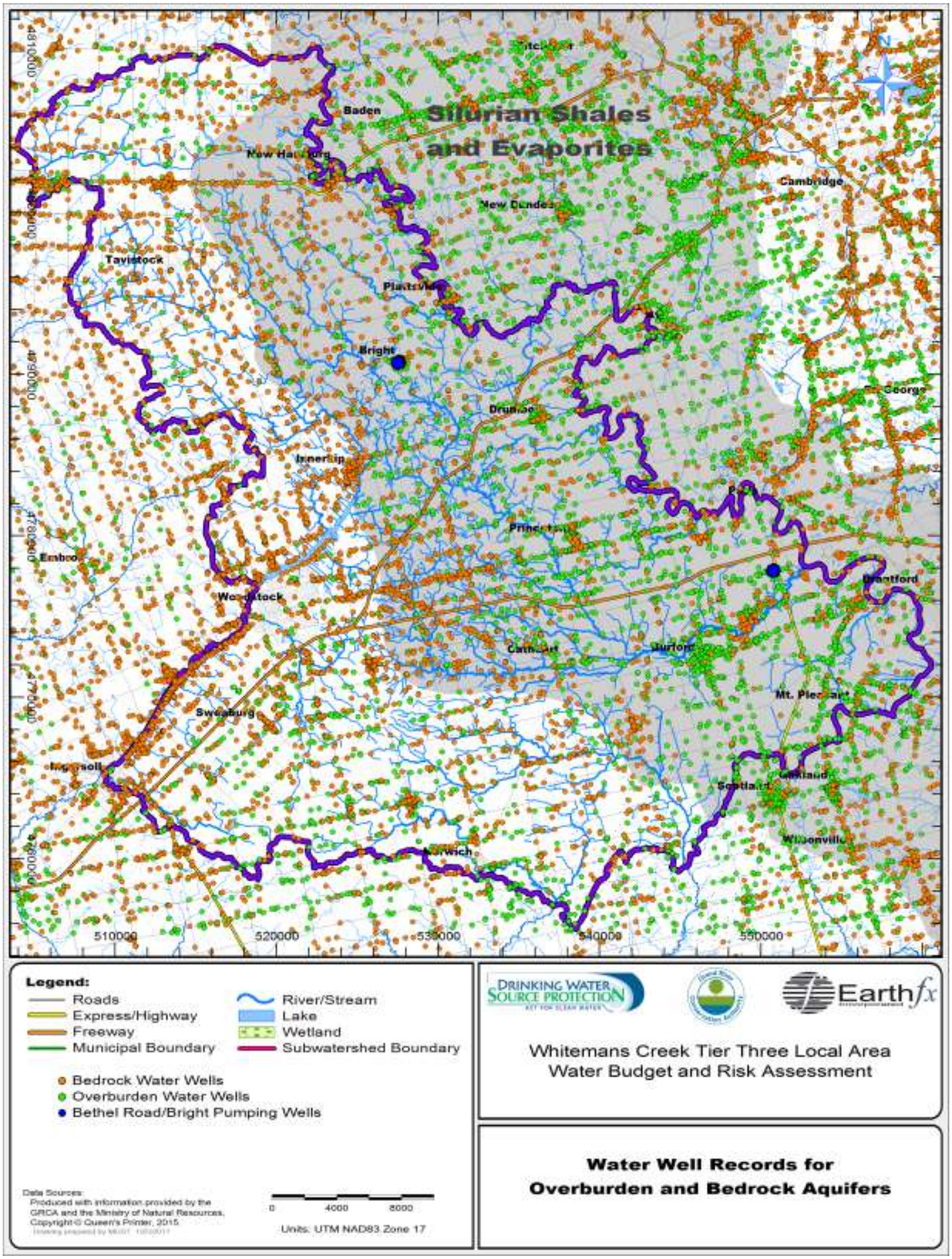


Figure 5.3: Distribution of water well records completed in overburden and bedrock aquifers.

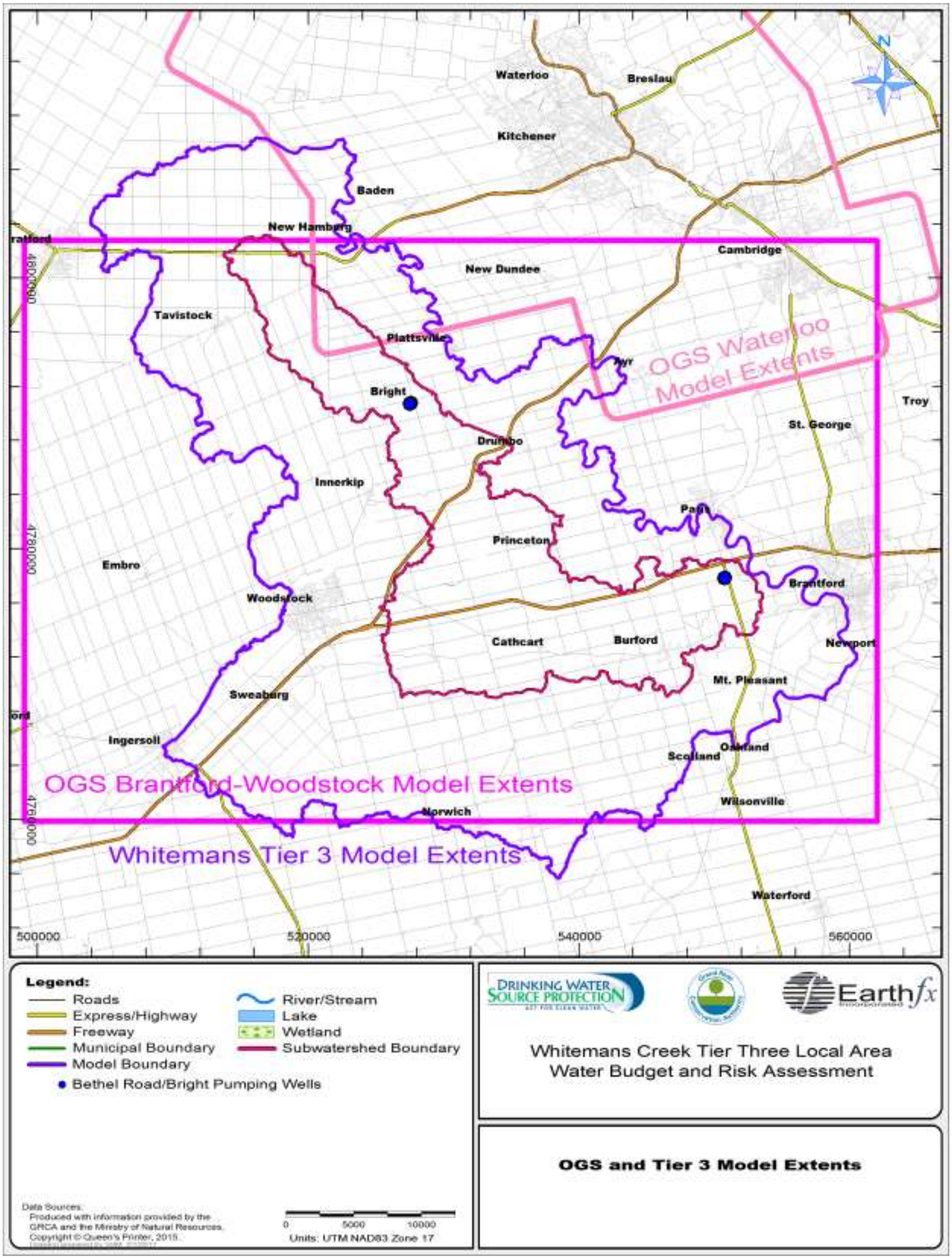
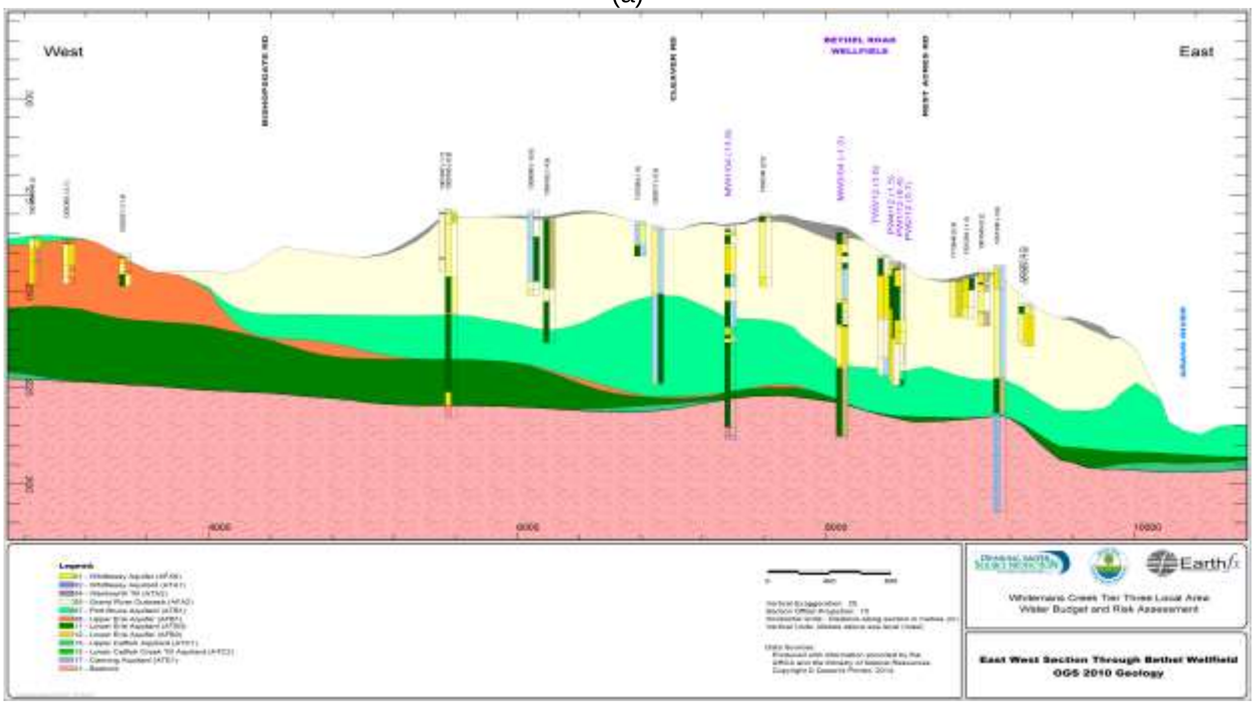


Figure 5.4: OGS Hydrostratigraphic models and the Tier 3 study area.

(a)



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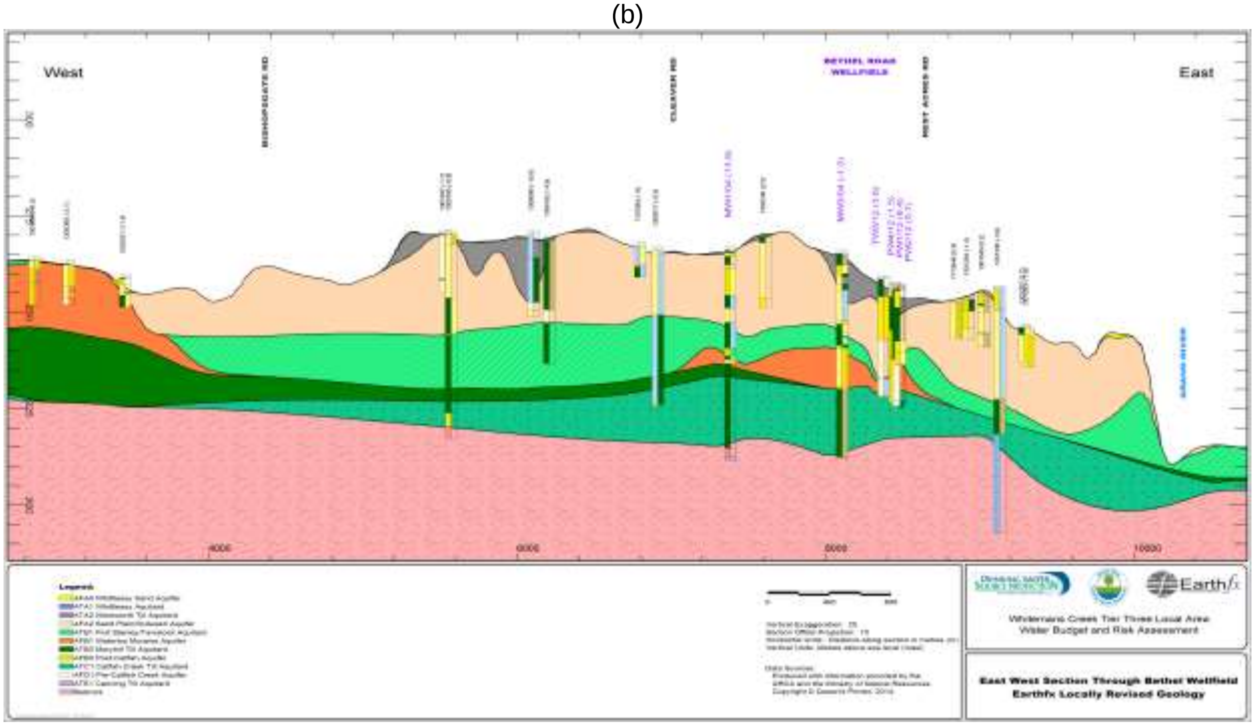
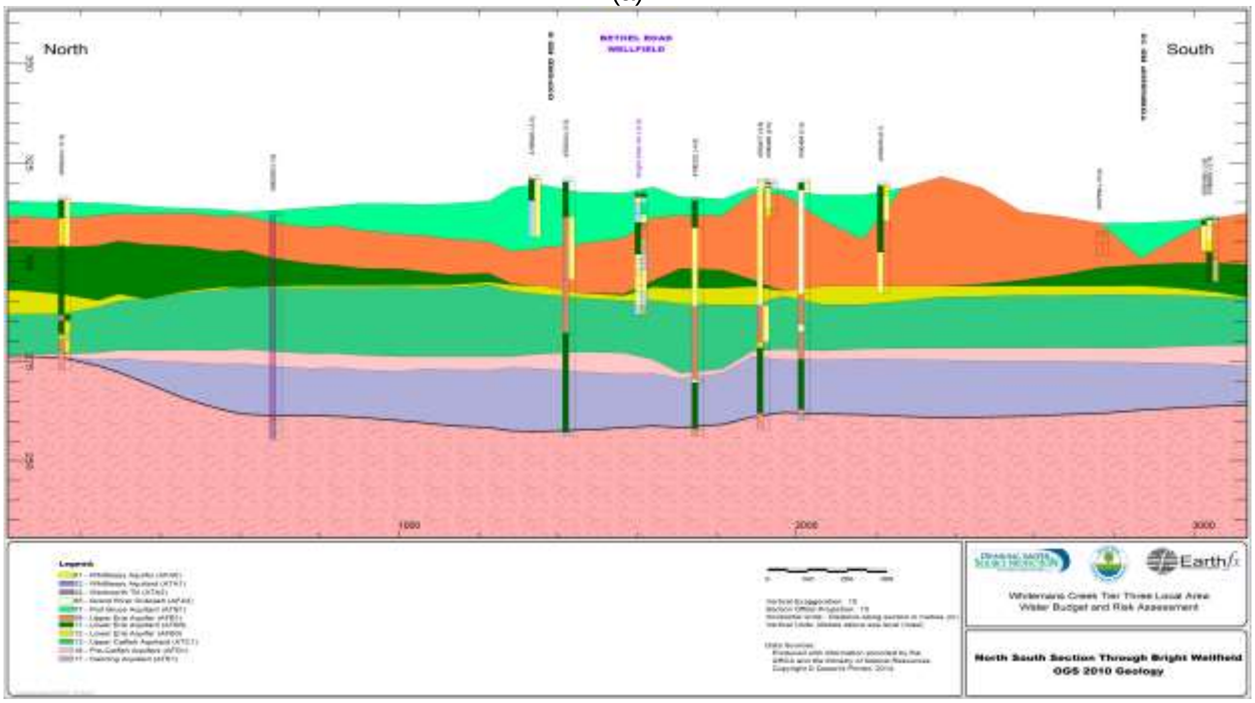


Figure 5.5: East-West section through the Bethel Road wellfield showing hydrostratigraphic model layers from (a) Bajc and Dodge (2011), and (b) locally-refined layers for this study.

(a)



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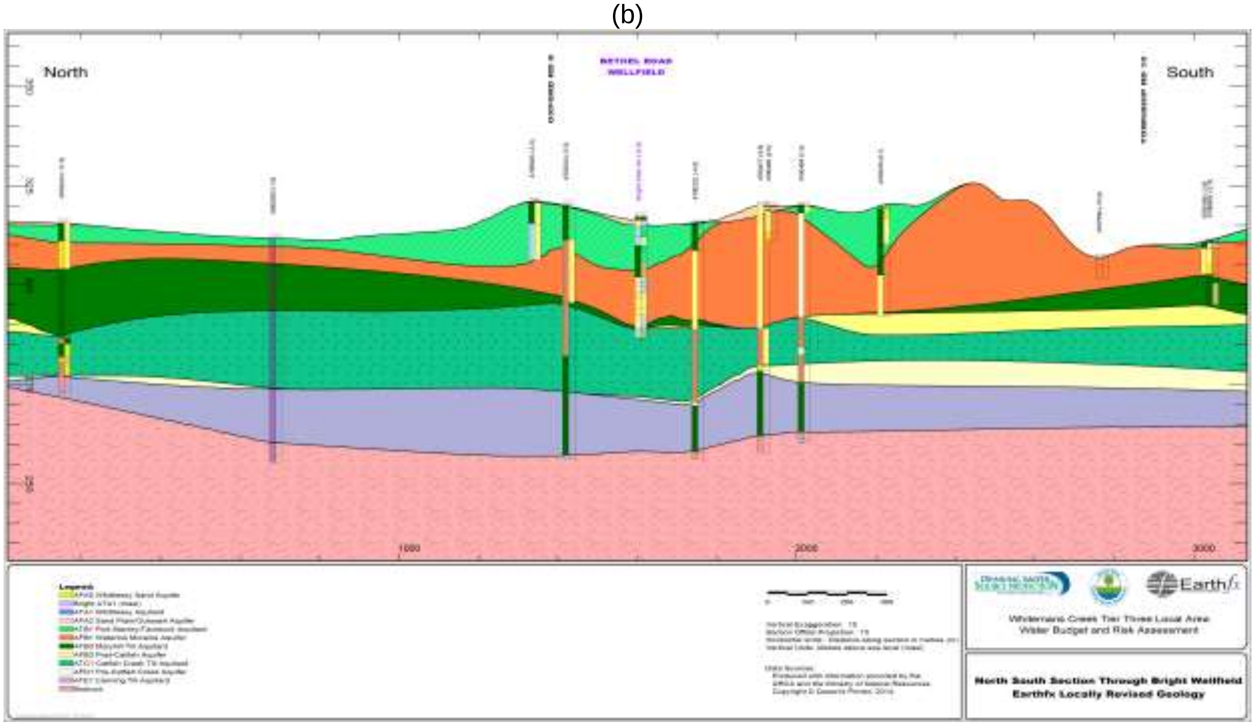
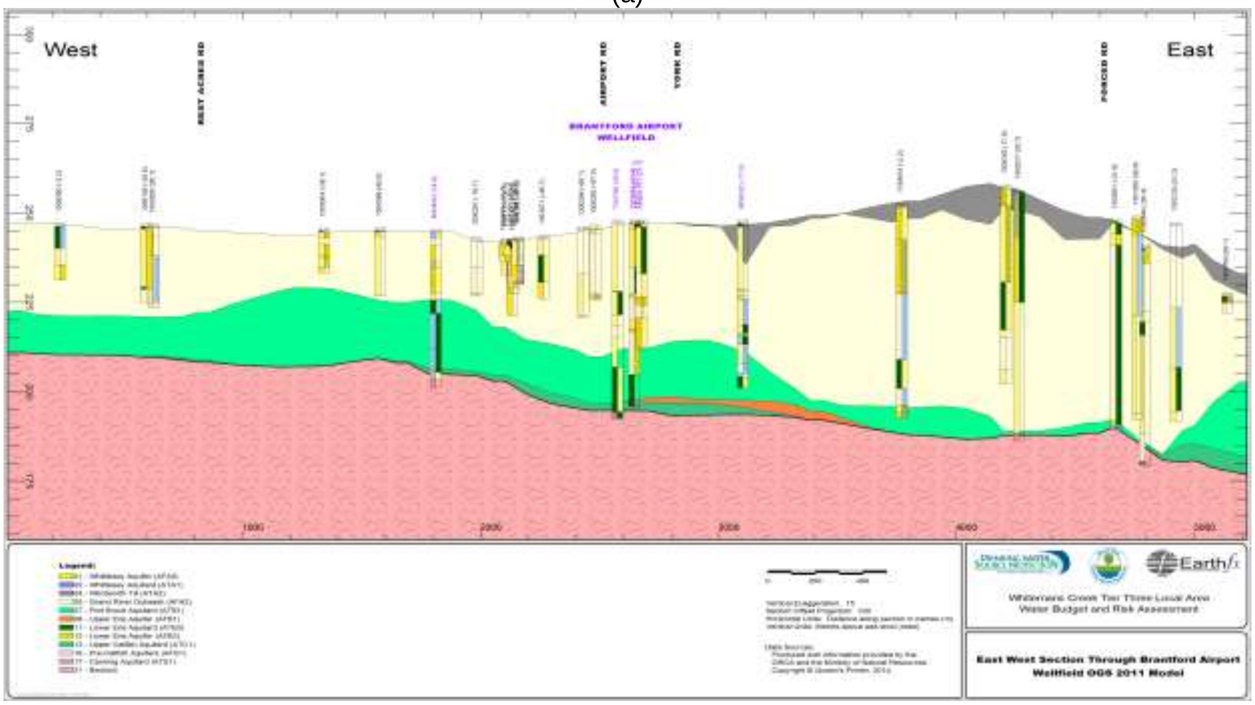


Figure 5.6: North-South section through the Bright wellfield showing hydrostratigraphic model layers from (a) Bajc and Dodge (2011), and (b) locally-refined layers for this study.

(a)



(b)

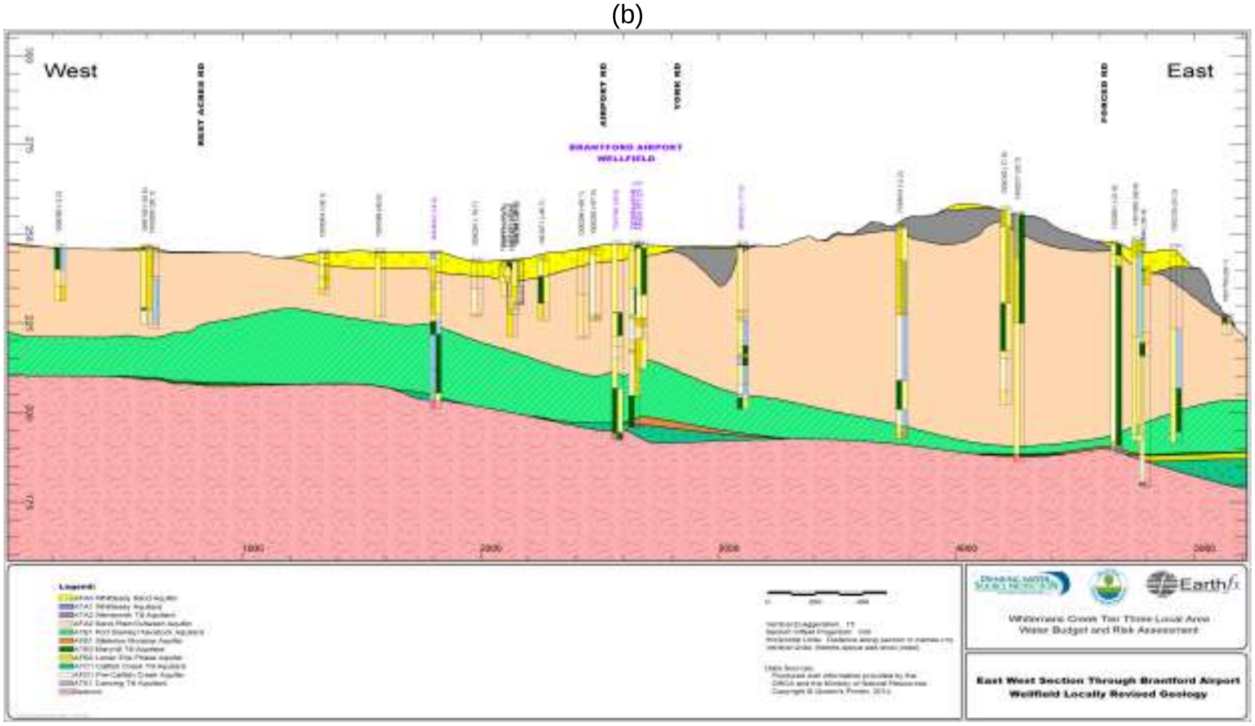


Figure 5.7: East-West section through the Brantford Airport wellfield showing hydrostratigraphic model layers from (a) Bajc and Dodge (2011) and (b) locally refined layers for this study.

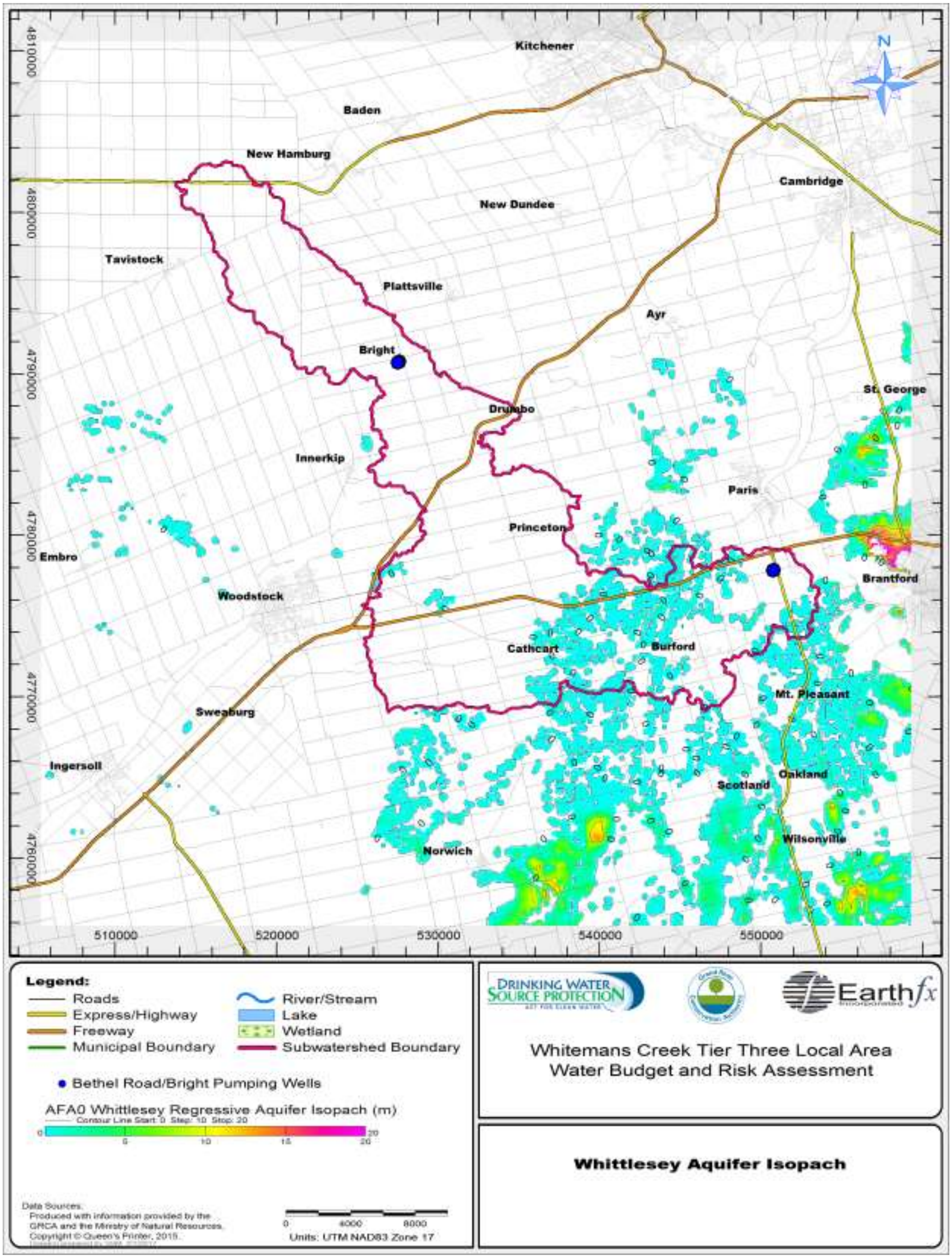


Figure 5.8: Whittlesey Aquifer isopach.

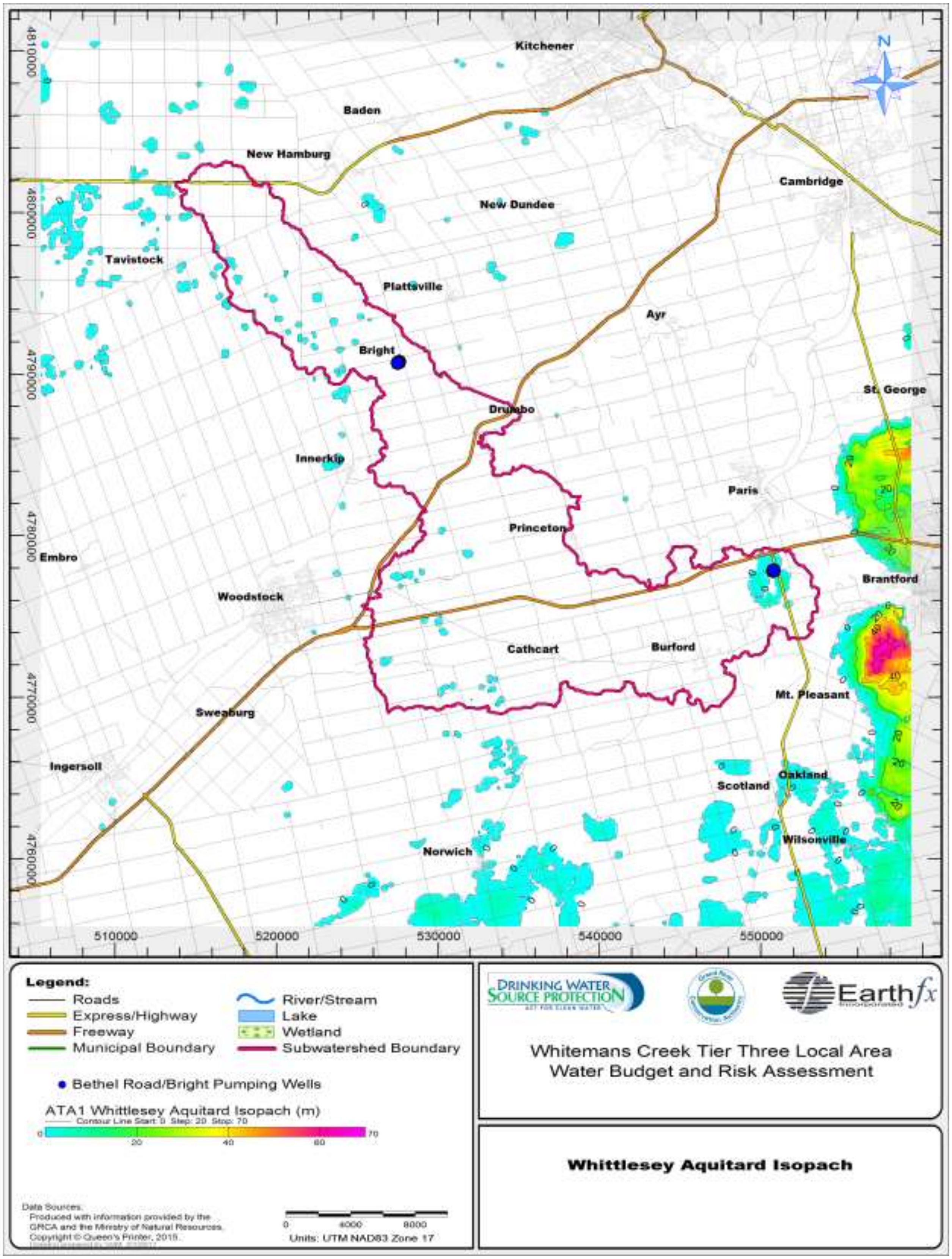


Figure 5.9: Whittlesey Aquitard isopach.

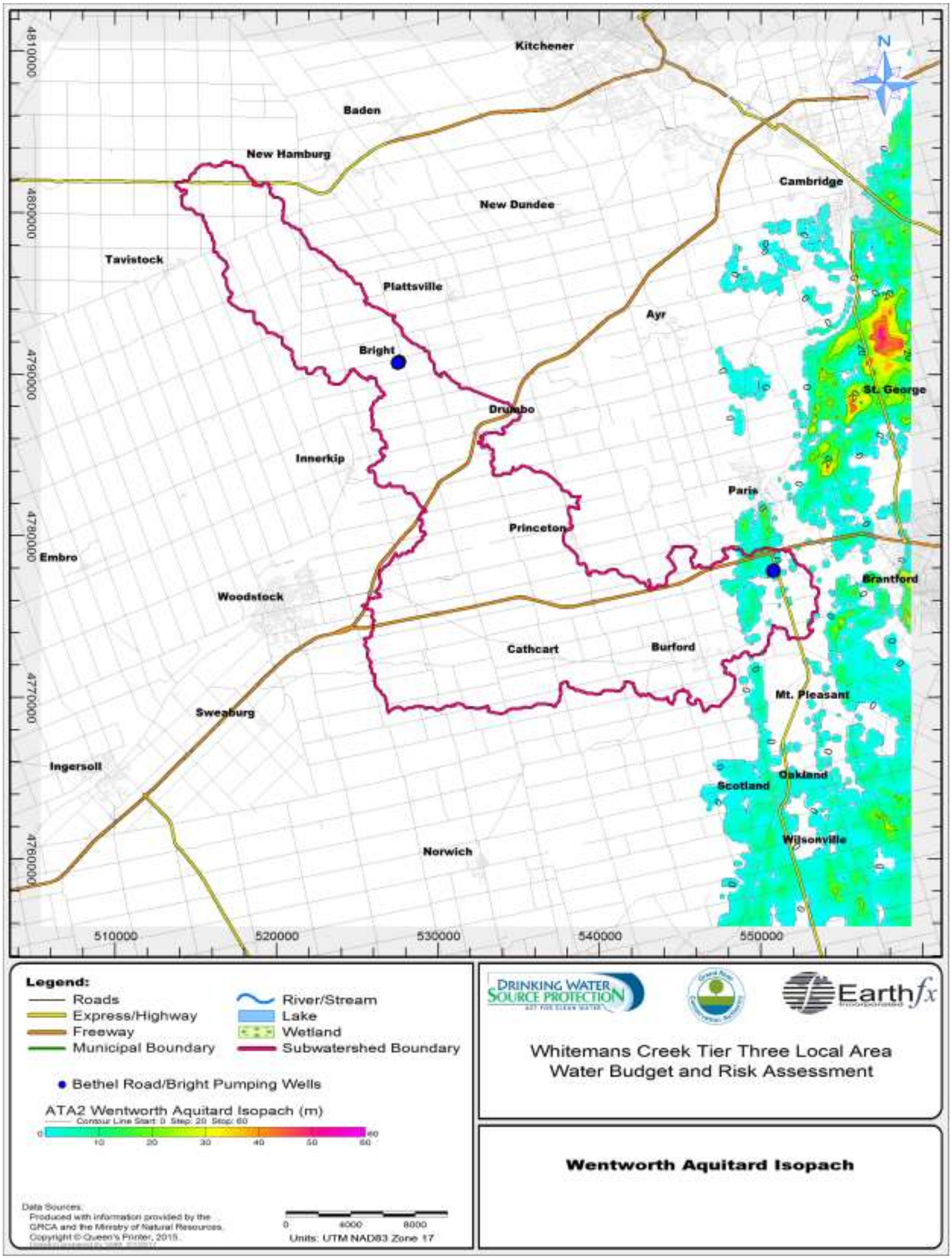


Figure 5.10: Wentworth Till Aquitard isopach.

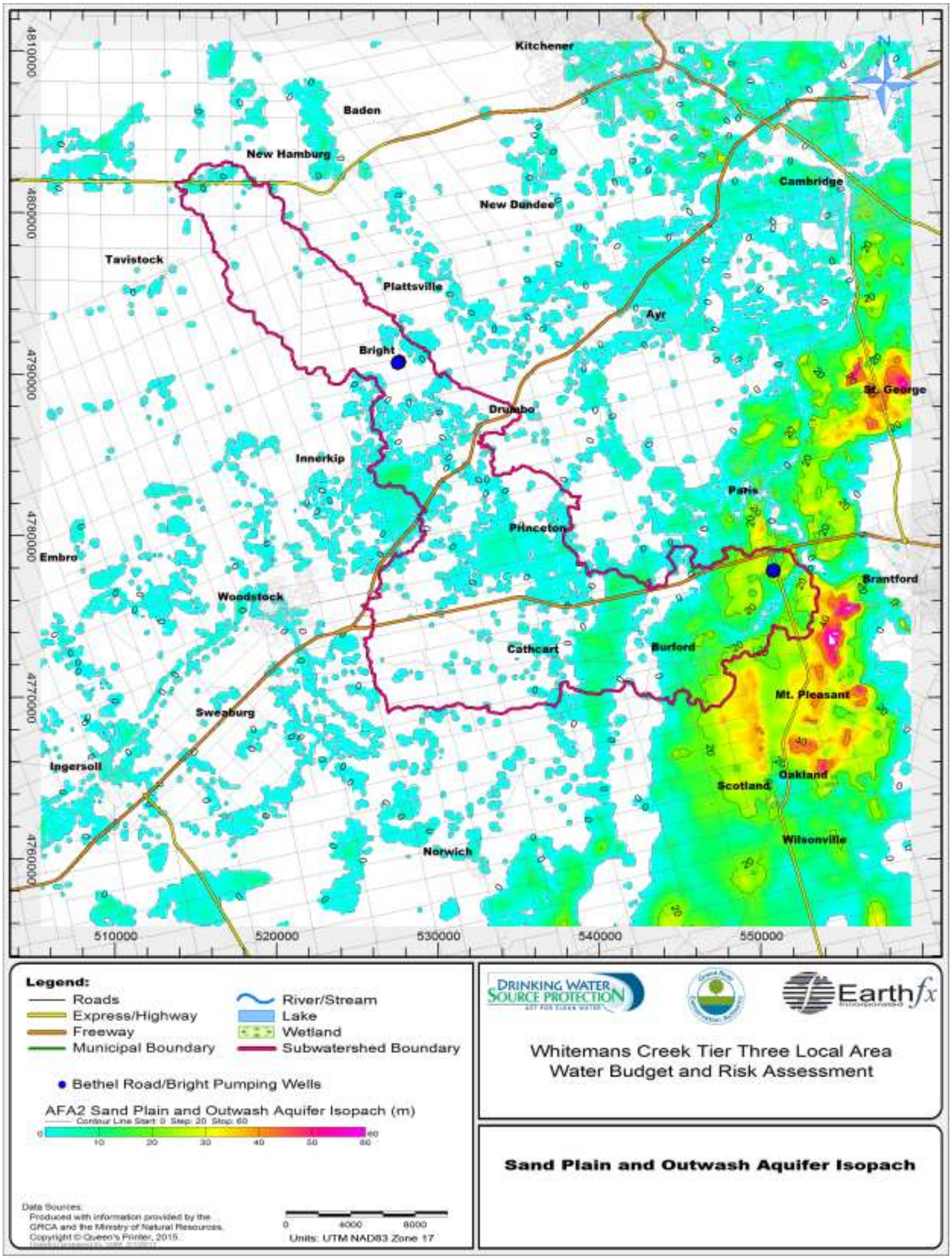


Figure 5.11: Sand Plain and Outwash Aquifer isopach.

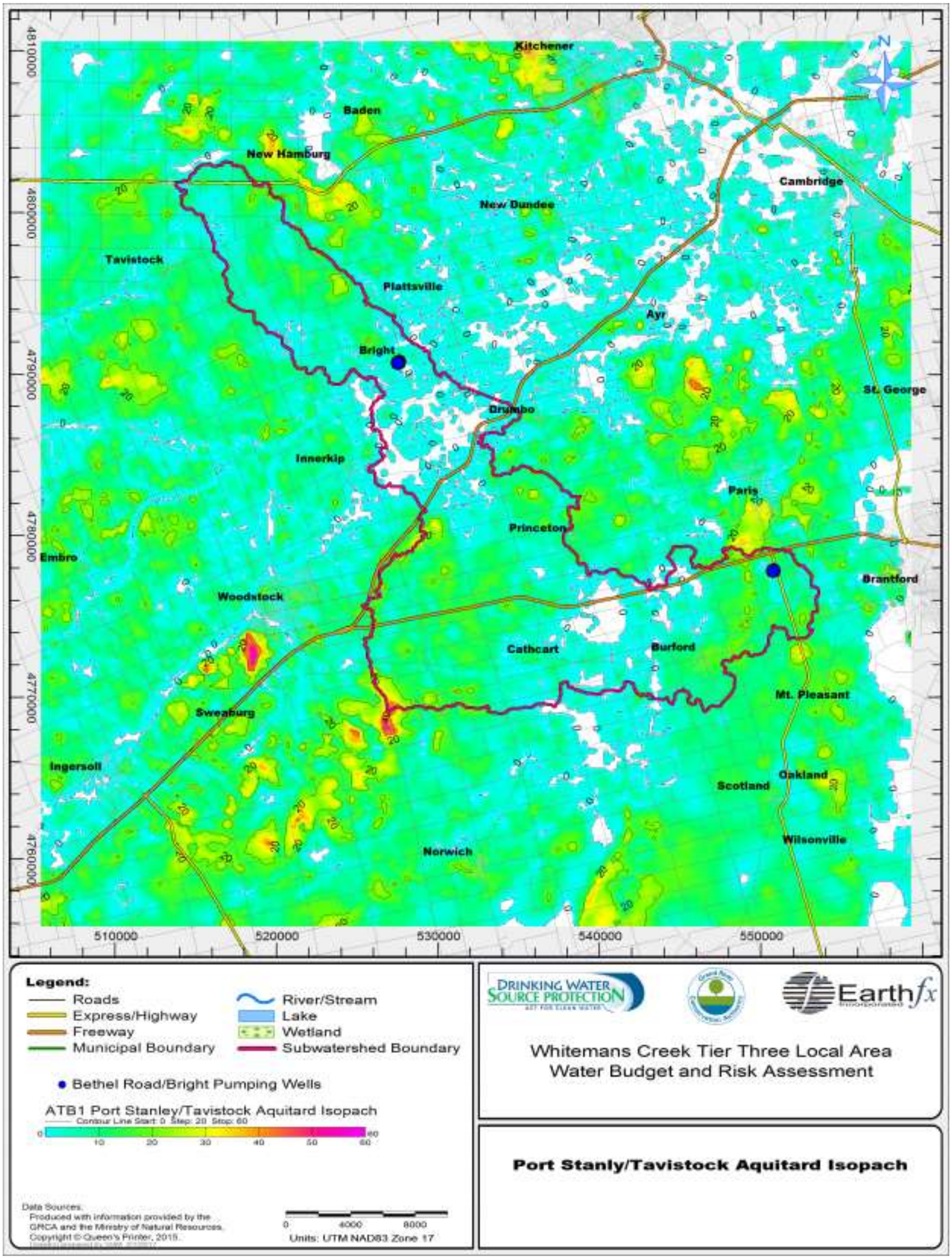


Figure 5.12: Port Stanley/Tavistock Till Aquitard Complex isopach.

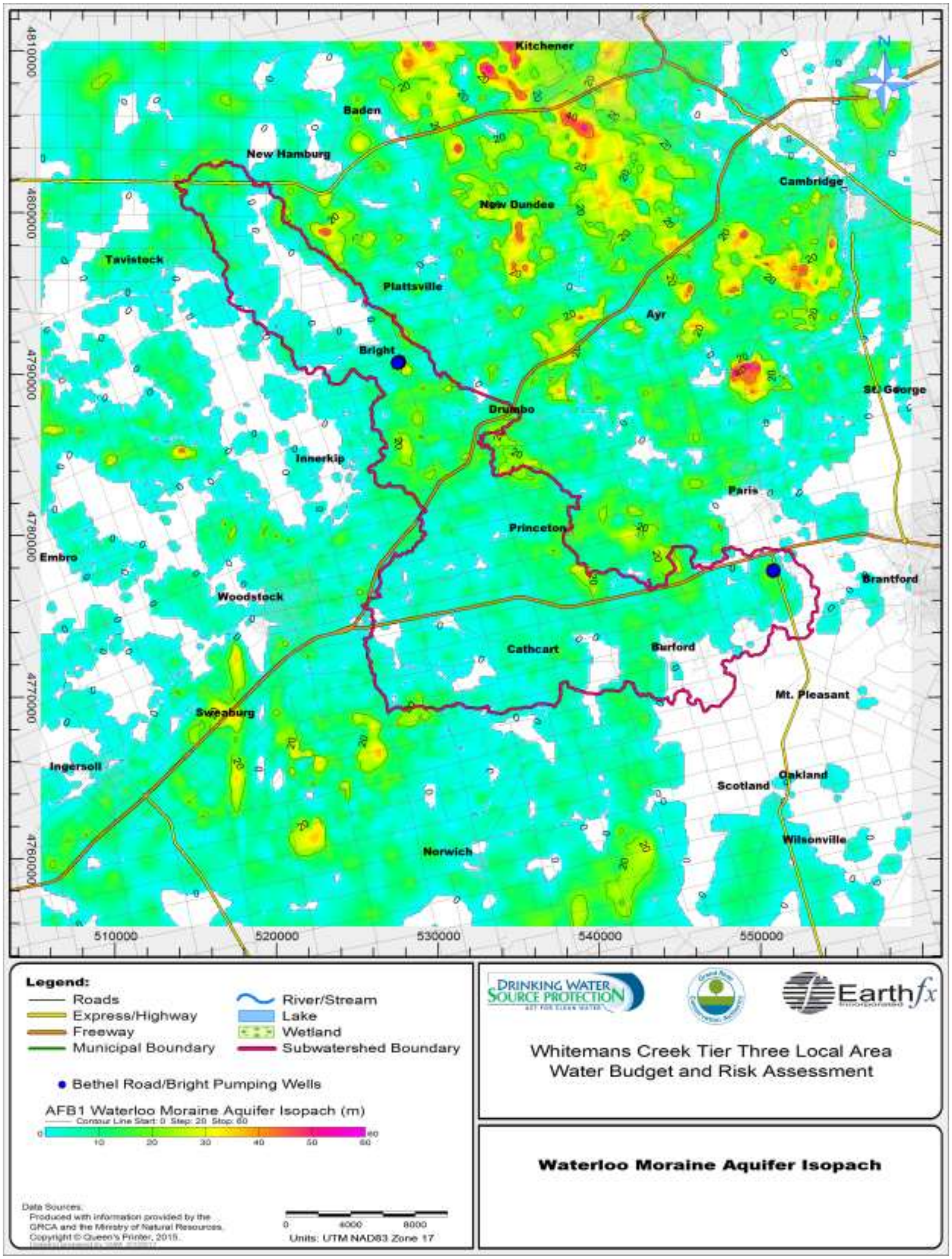


Figure 5.13: Waterloo Moraine Aquifer isopach.

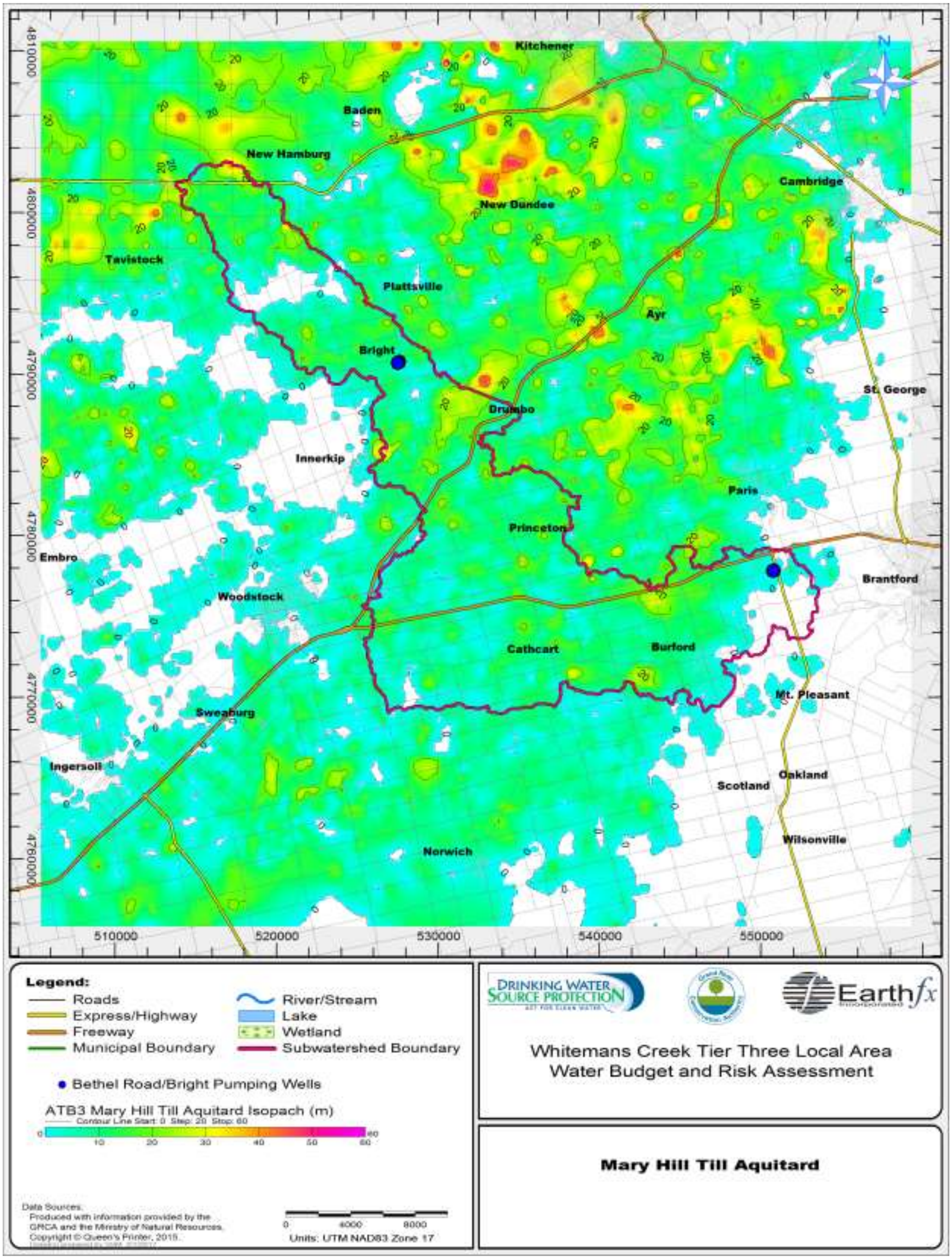


Figure 5.14: Maryhill Till Aquitard isopach.

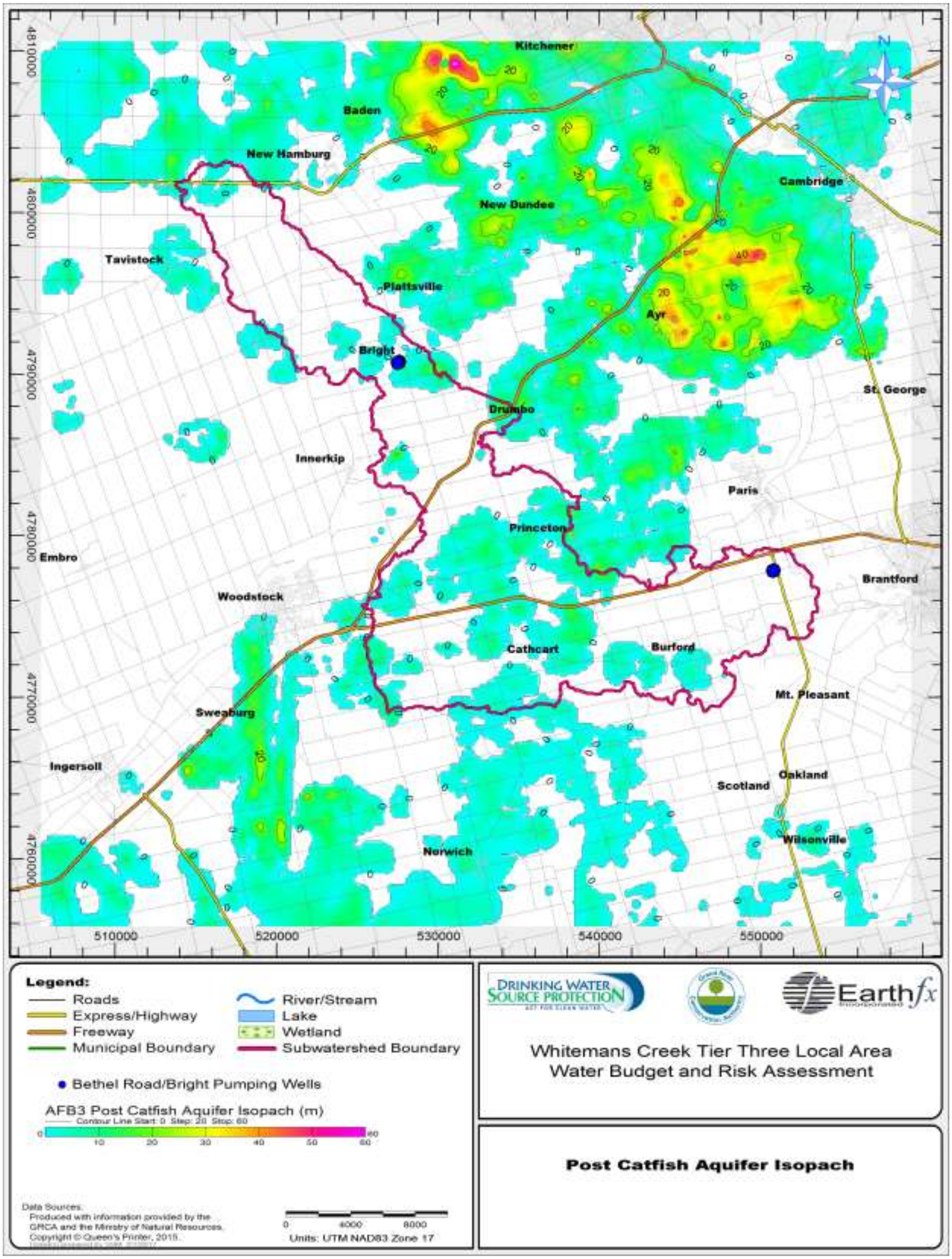


Figure 5.15: Post-Catfish Aquifer isopach.

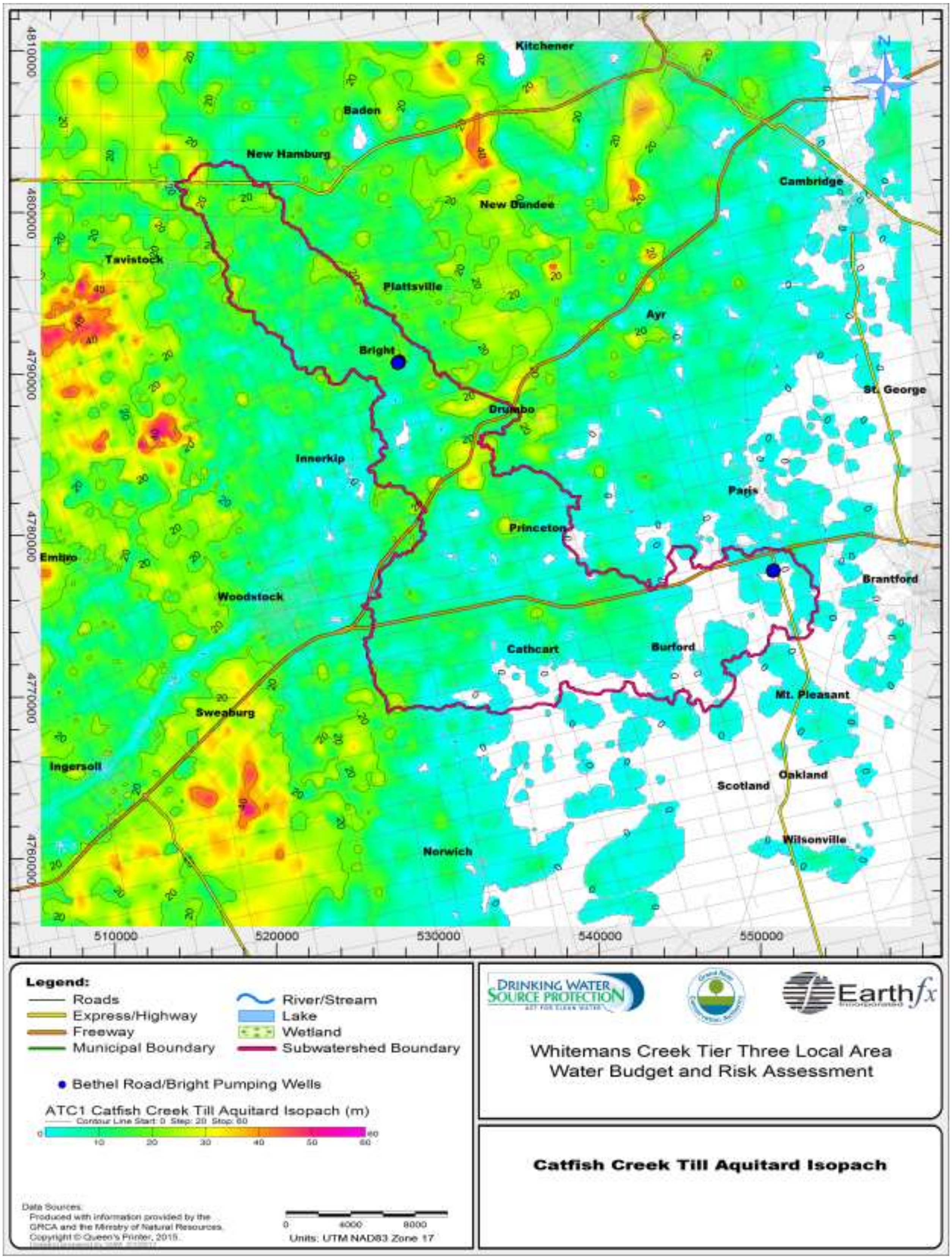


Figure 5.16: Catfish Creek Till Aquitard isopach.

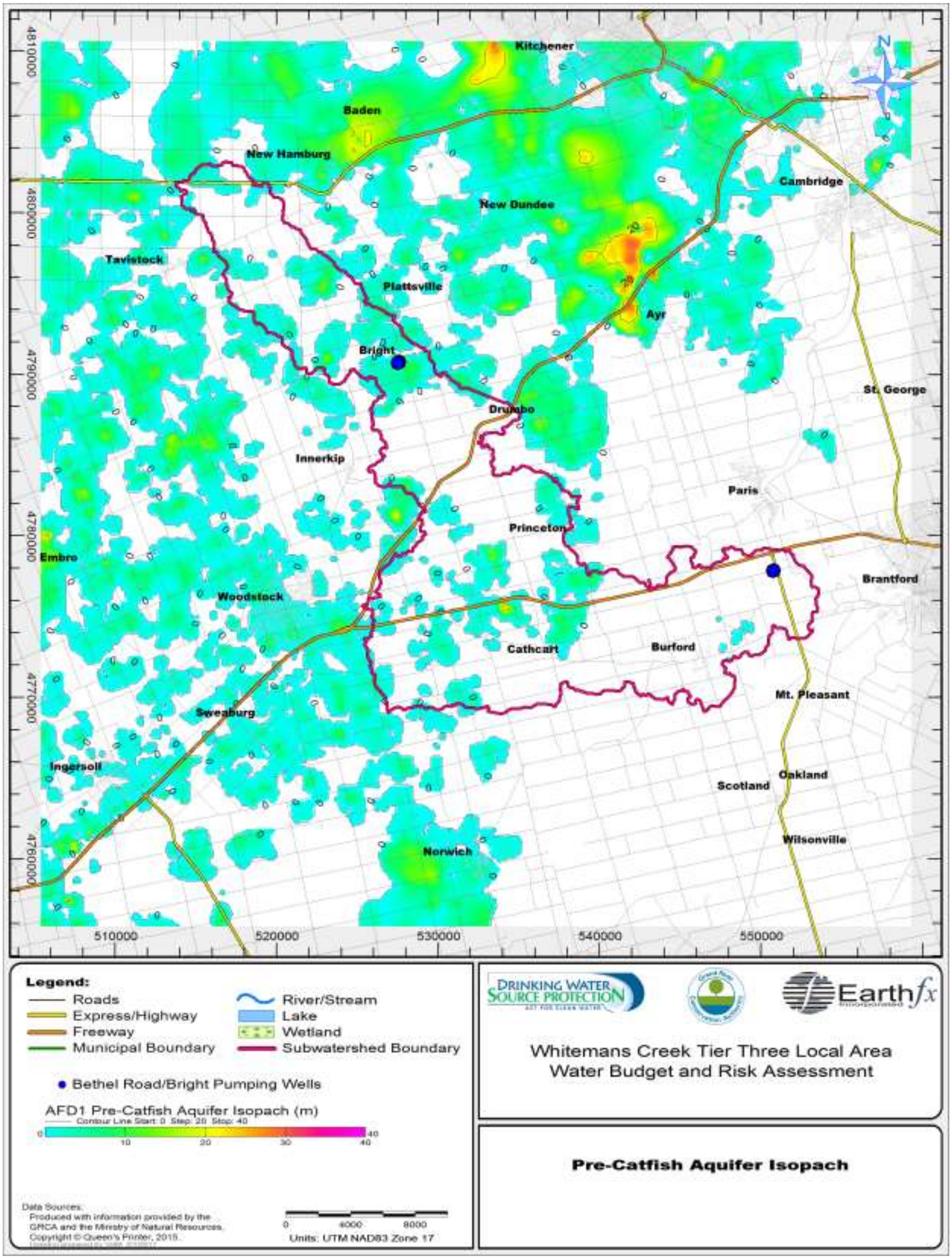


Figure 5.17: Pre-Catfish Aquifer isopach.

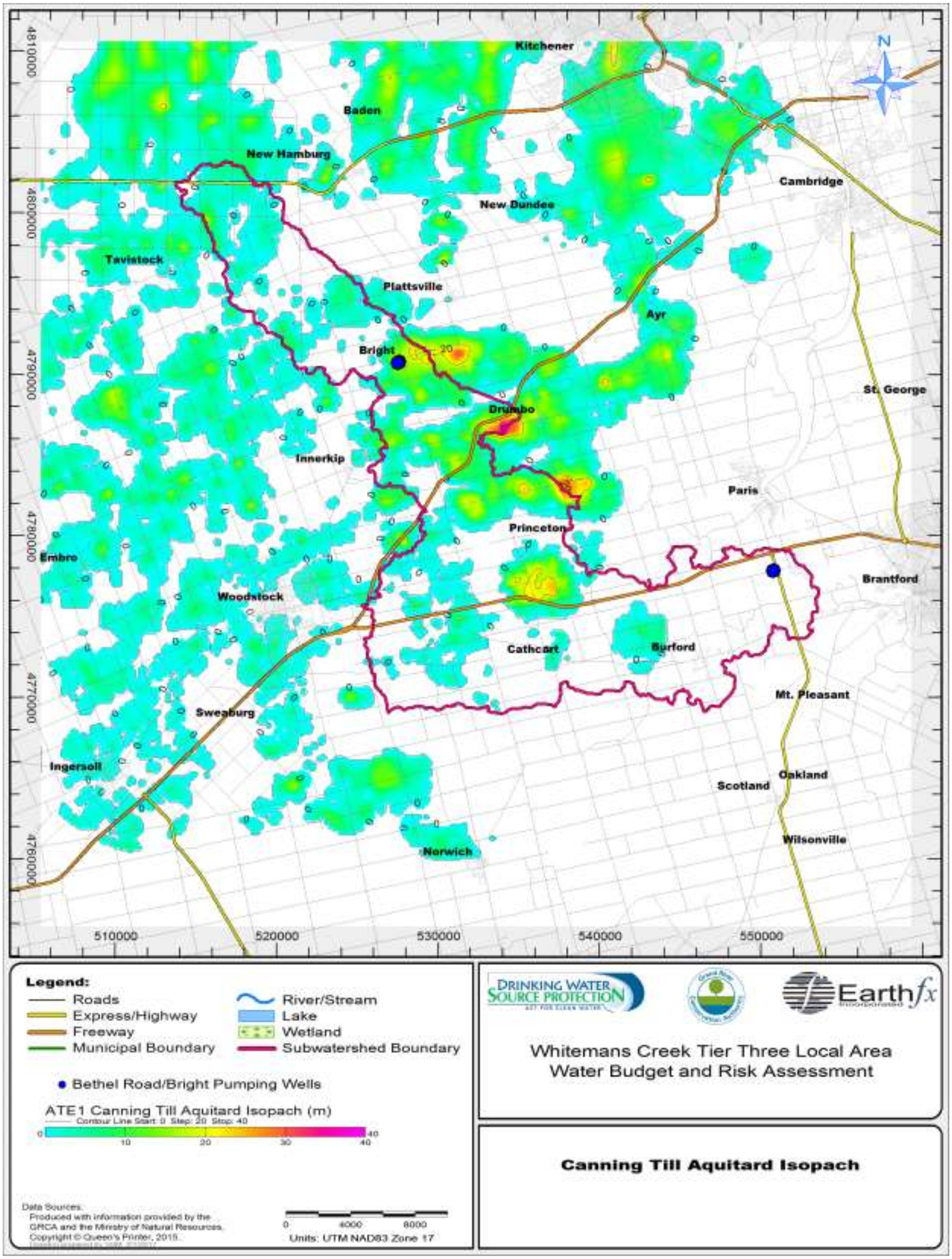


Figure 5.18: Canning Till Aquitard isopach.

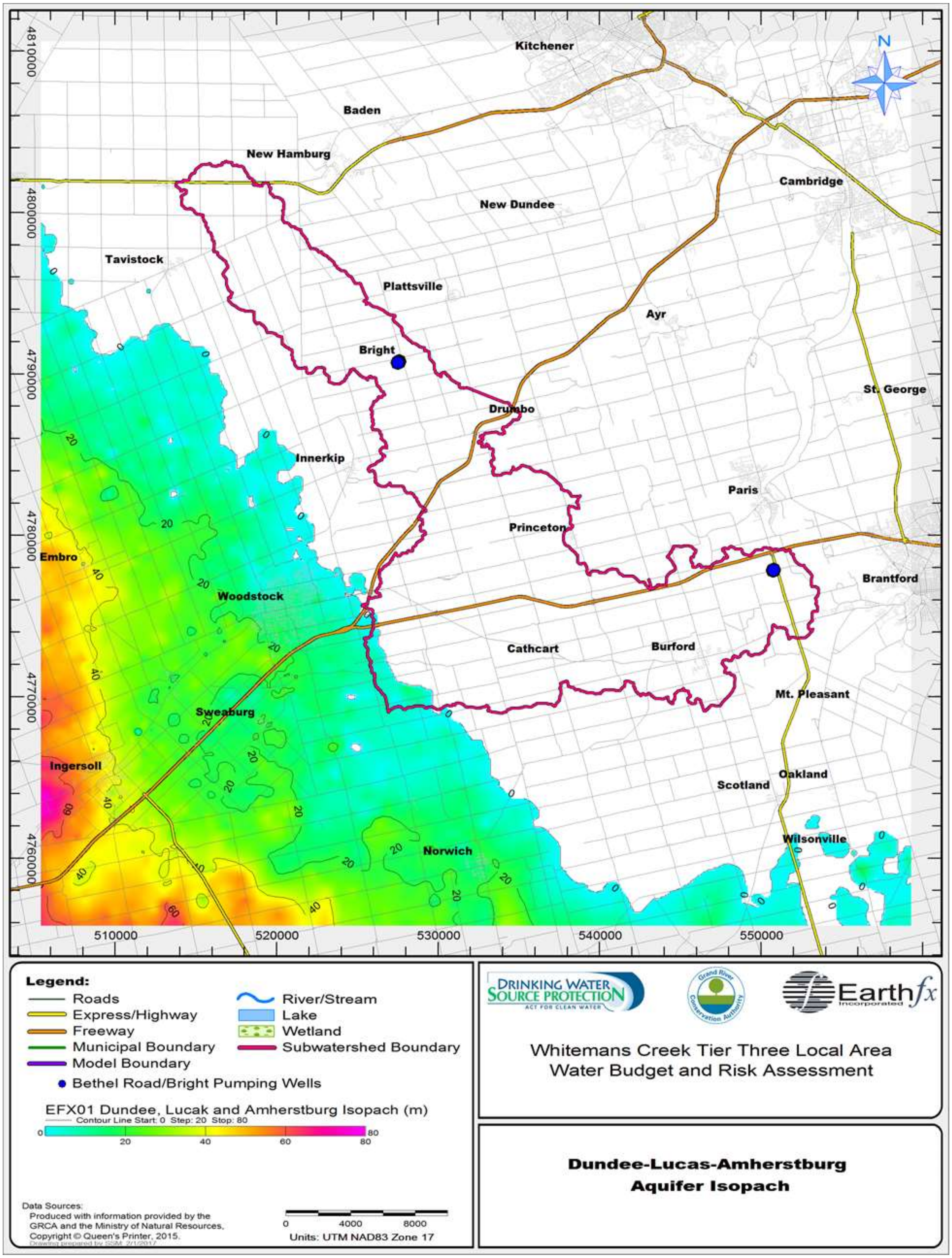


Figure 5.19: Dundee-Lucas-Amherstburg Formation isopach.

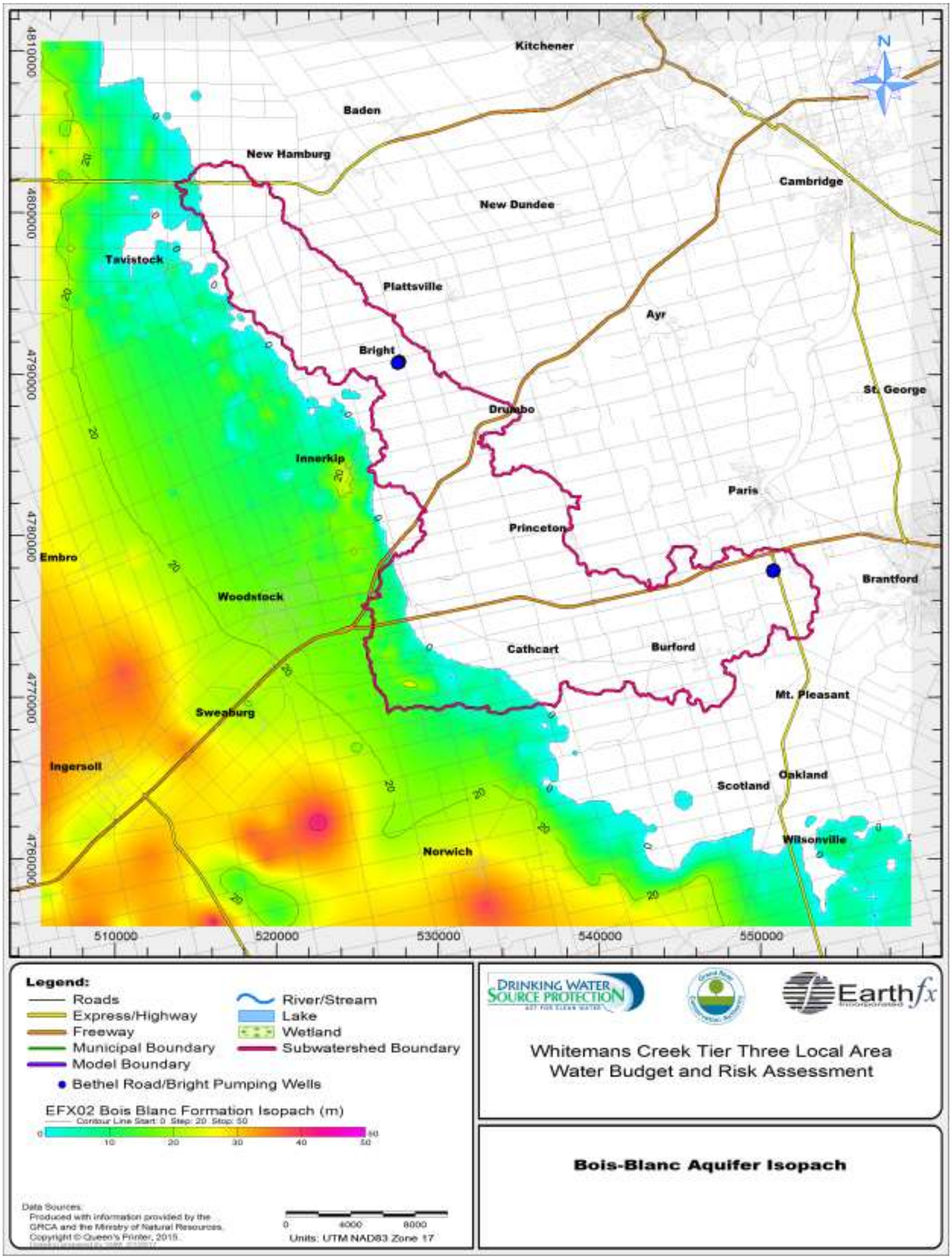


Figure 5.20: Bois Blanc Formation isopach.

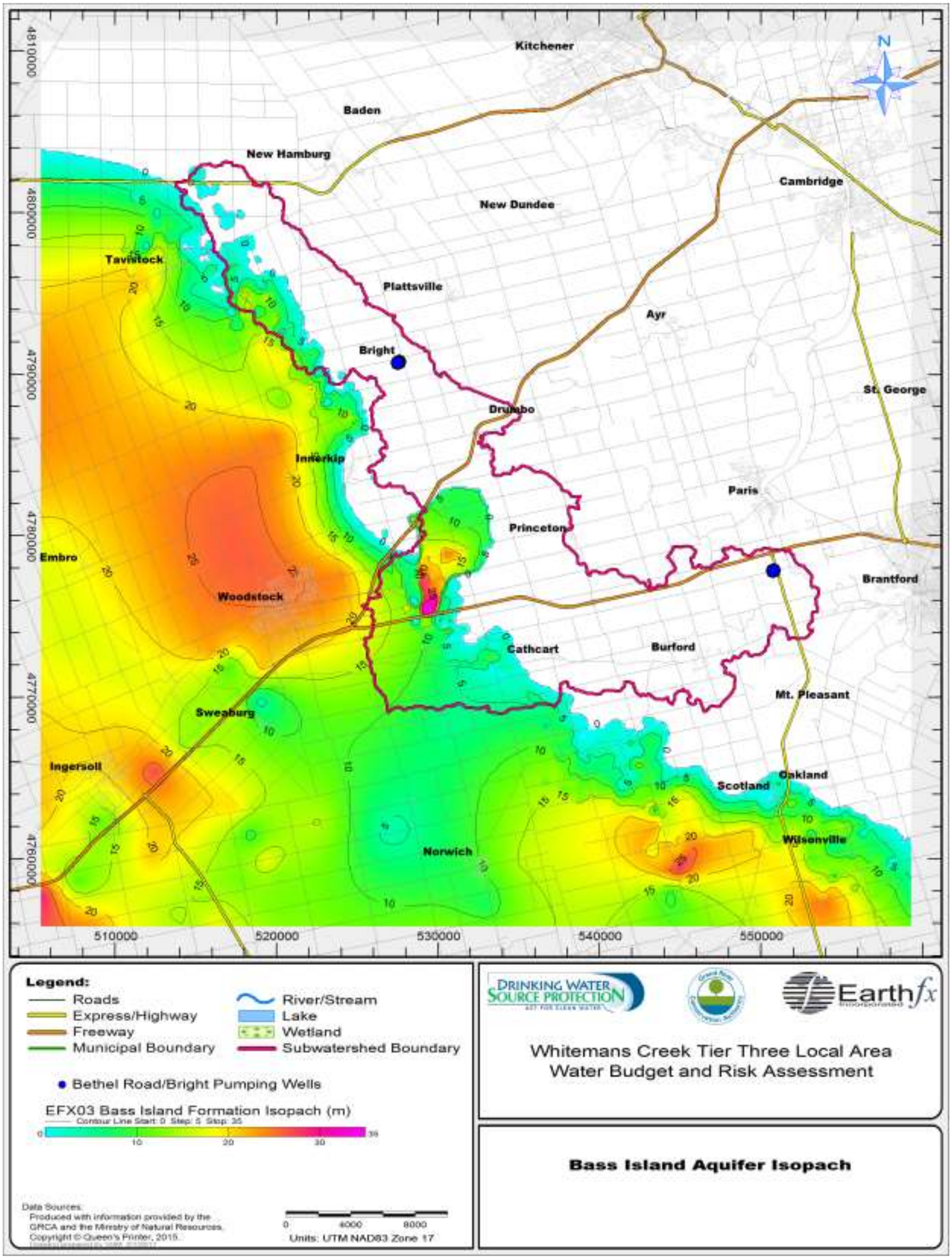


Figure 5.21: Bass Island Formation isopach.

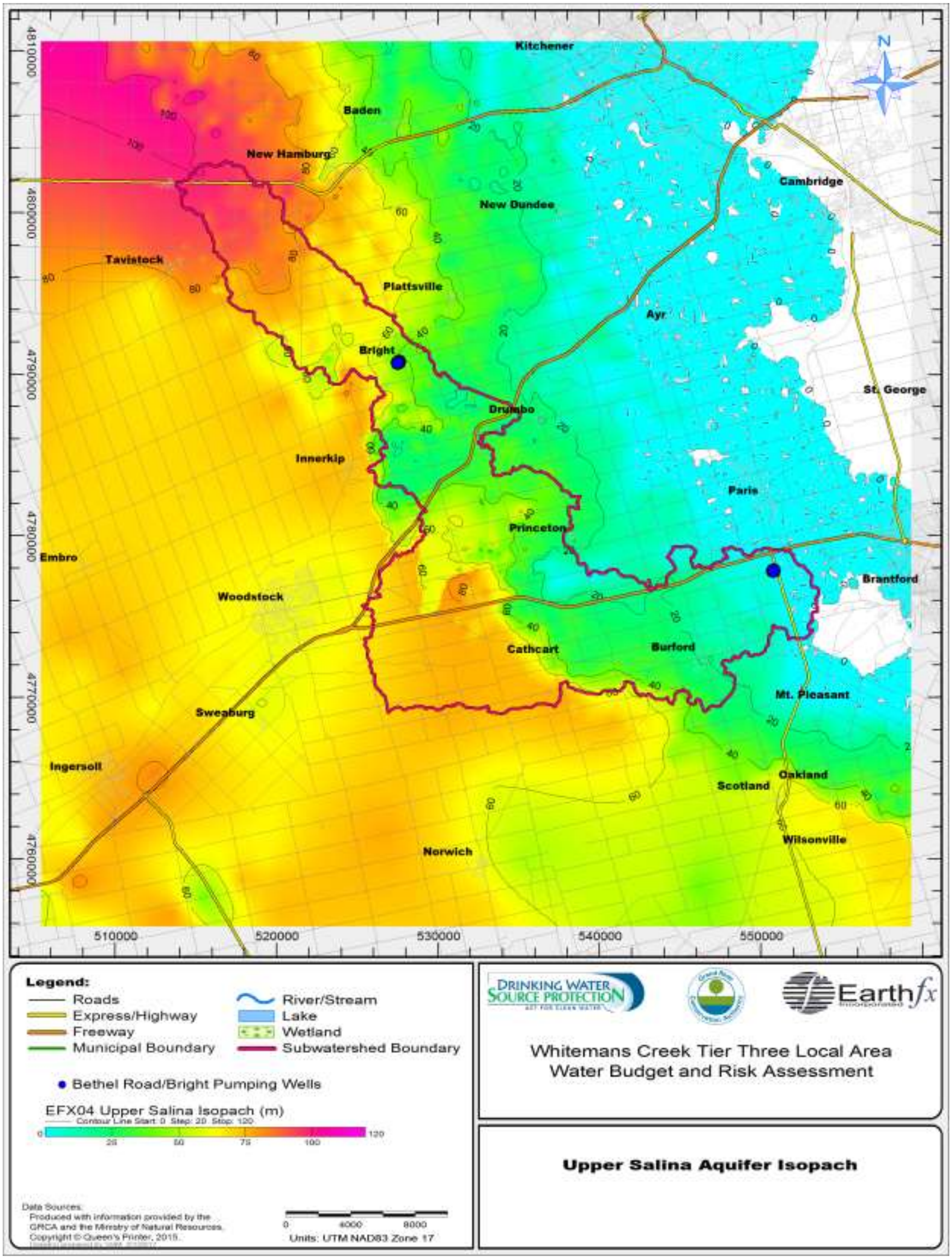


Figure 5.22: Upper Salina Formation isopach.

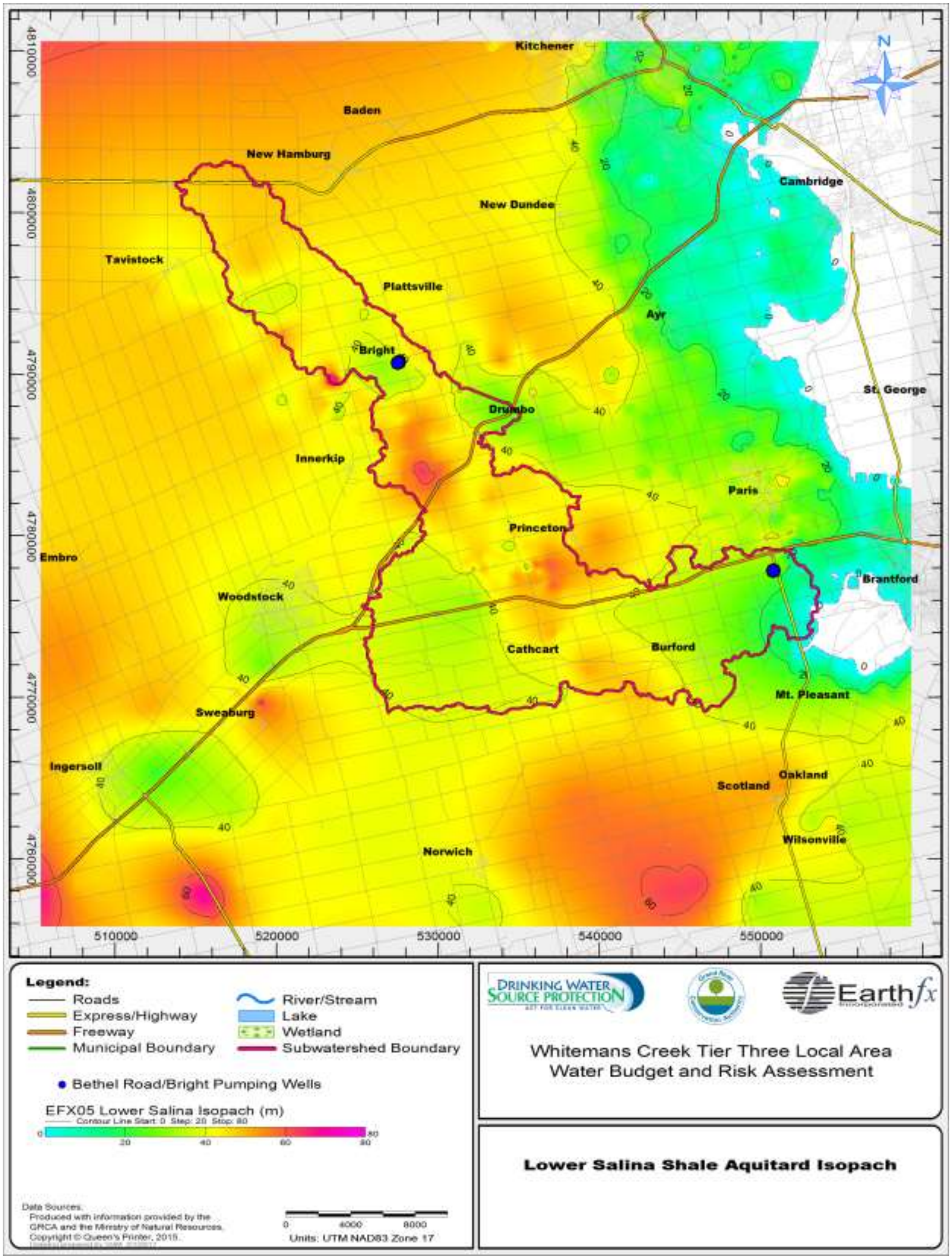


Figure 5.23: Lower Salina Formation isopach.

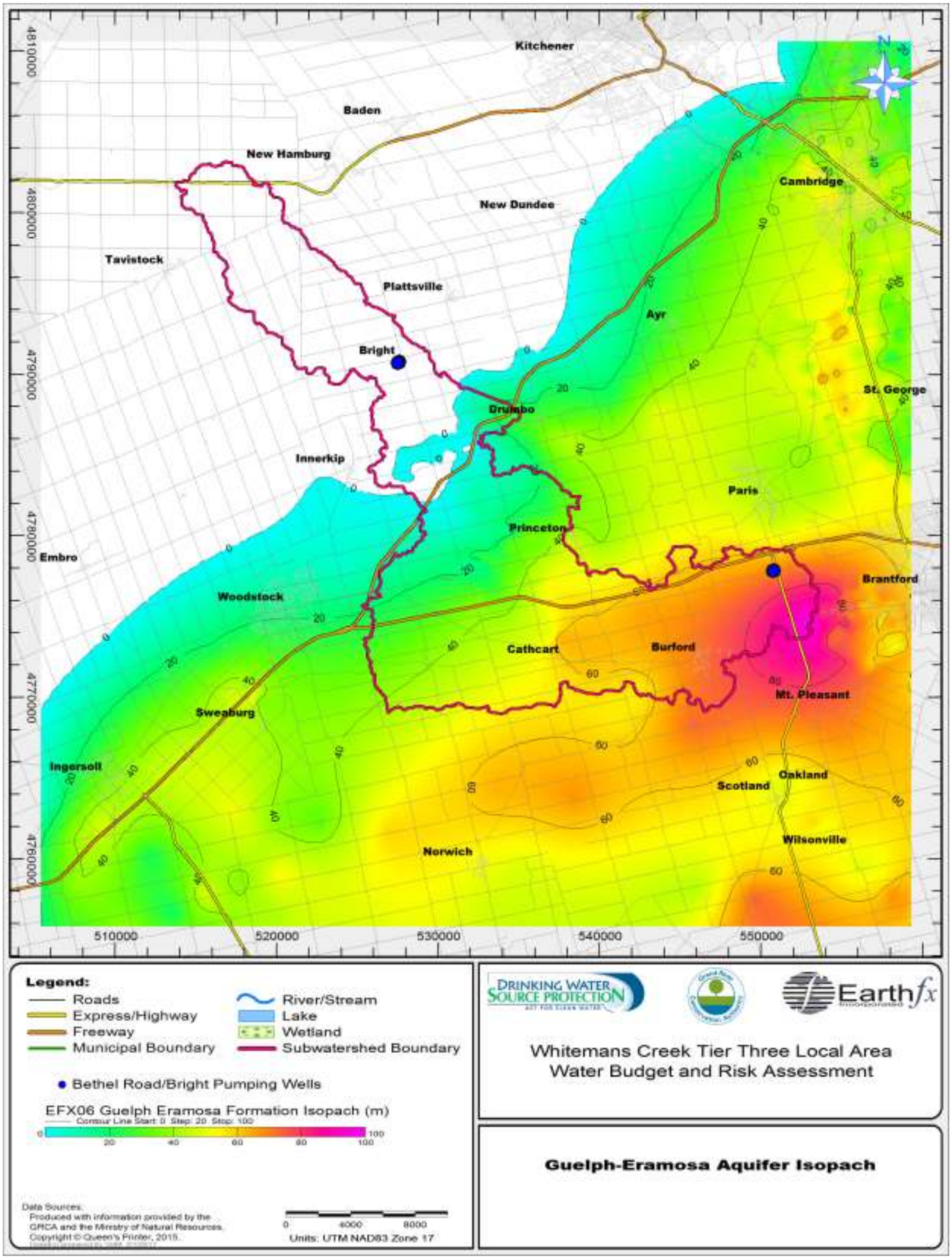


Figure 5.24: Guelph-Eramosa Formation Aquifer isopach.

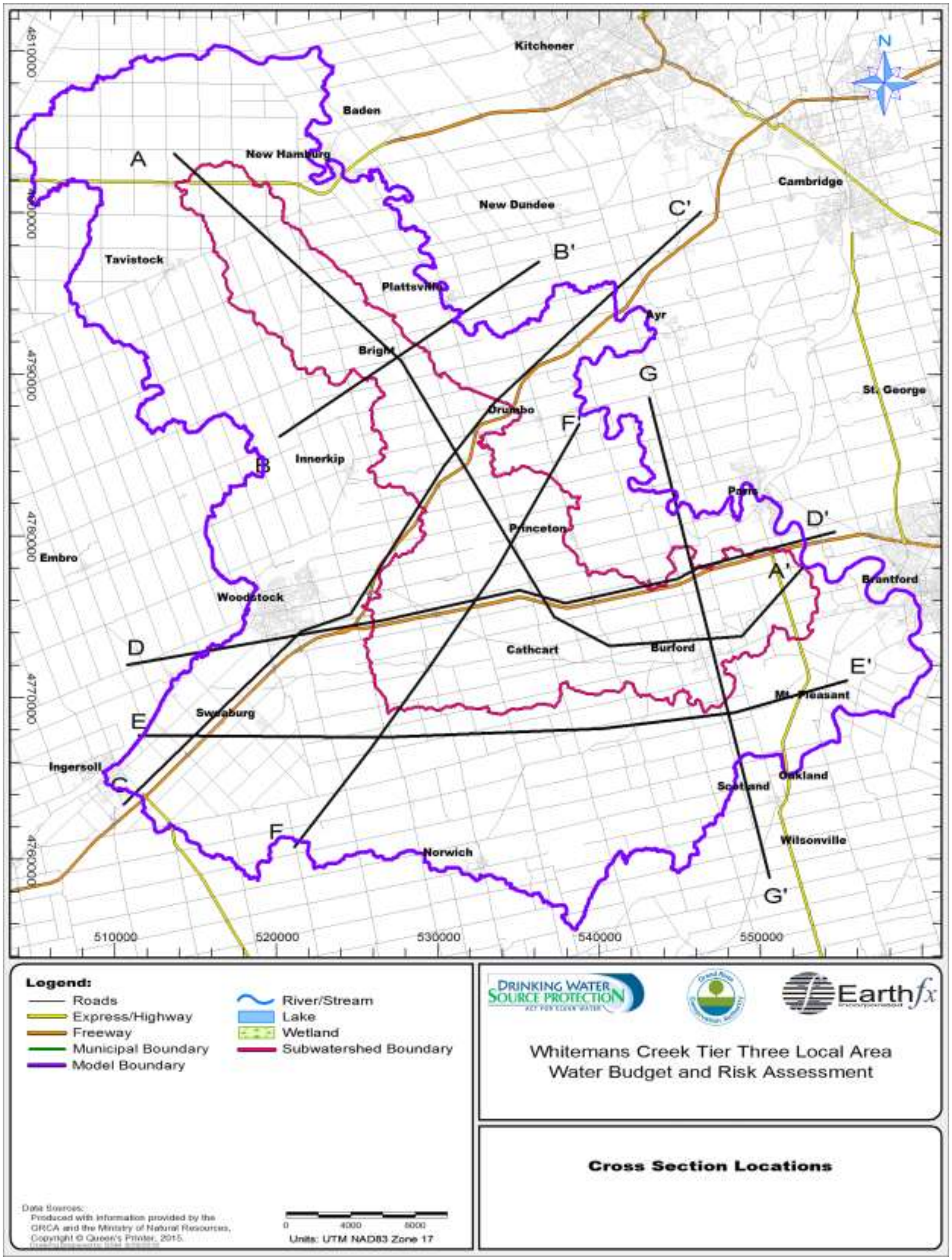


Figure 5.25: Cross-section line locations.

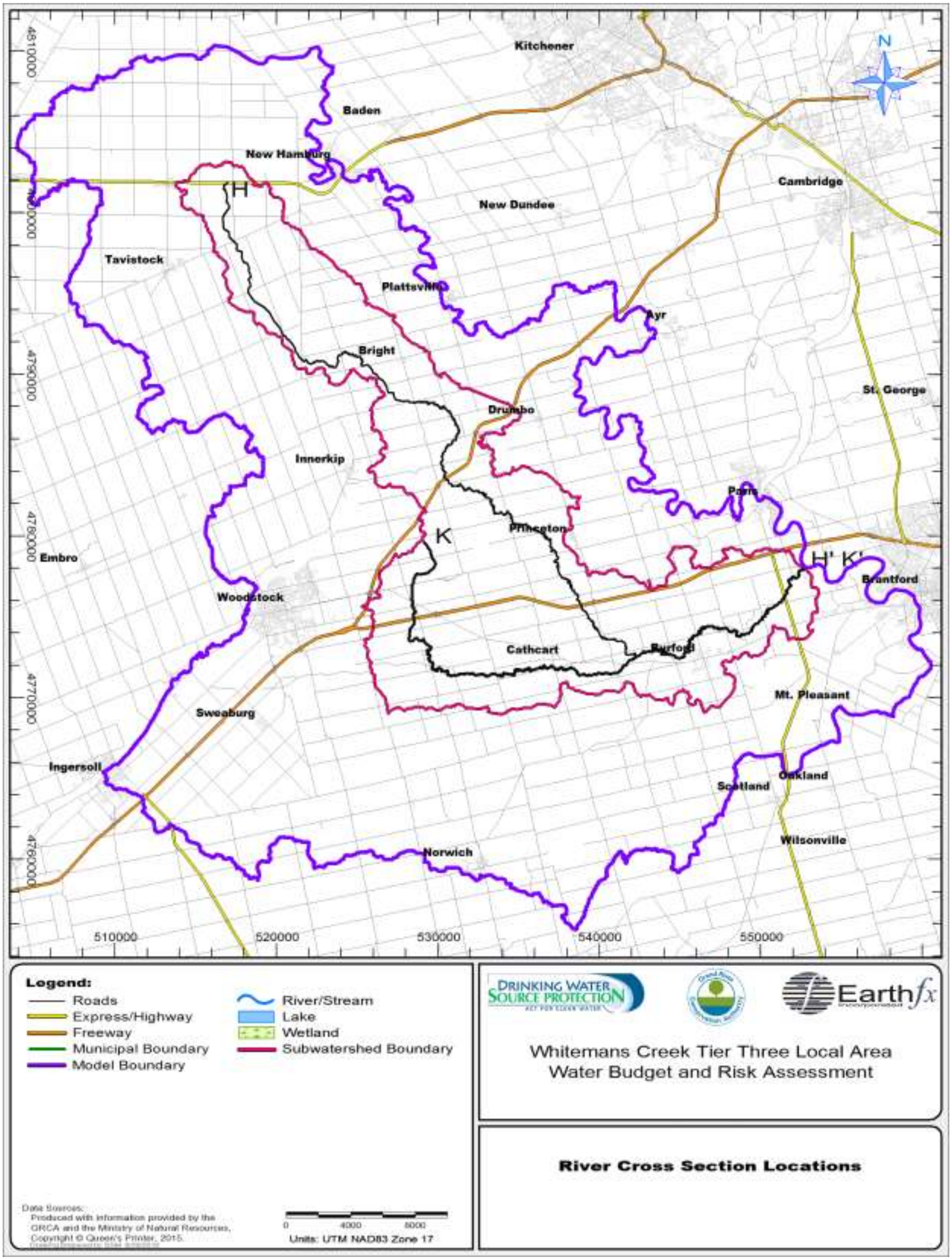


Figure 5.26: River cross-section line locations.

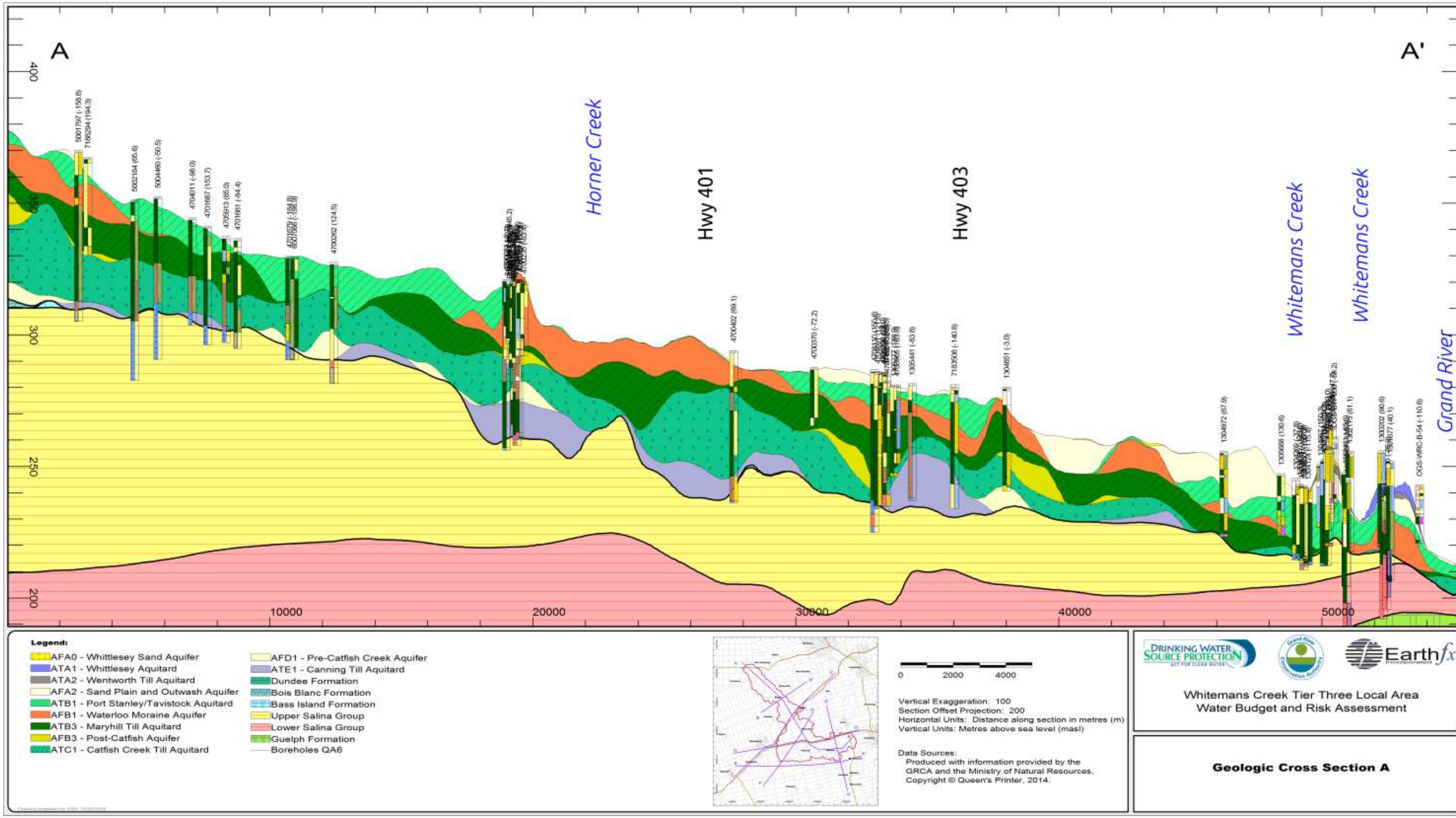


Figure 5.27: Northwest-southeast cross section A-A'.

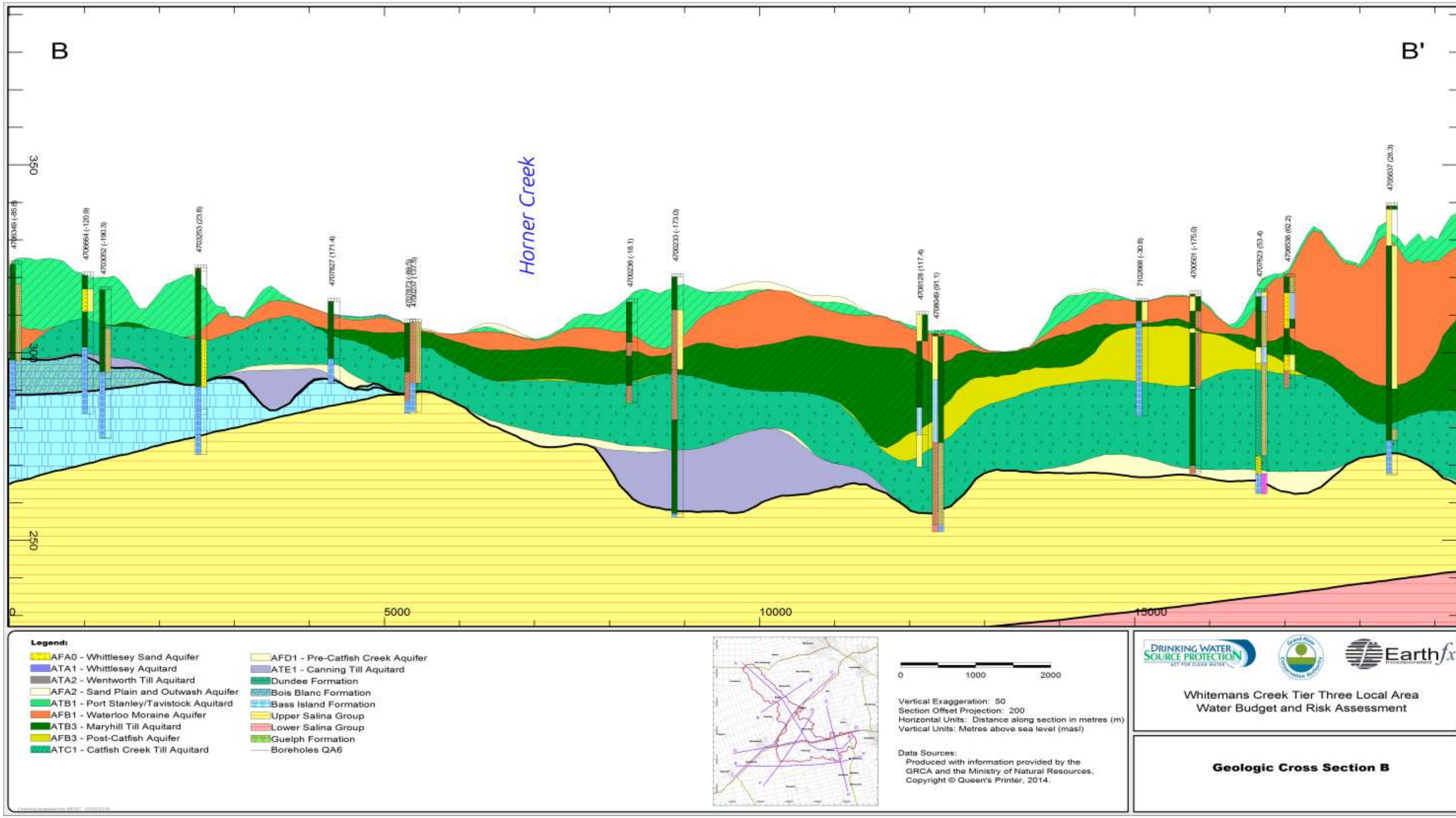


Figure 5.28: Southwest-northeast cross section B-B'.

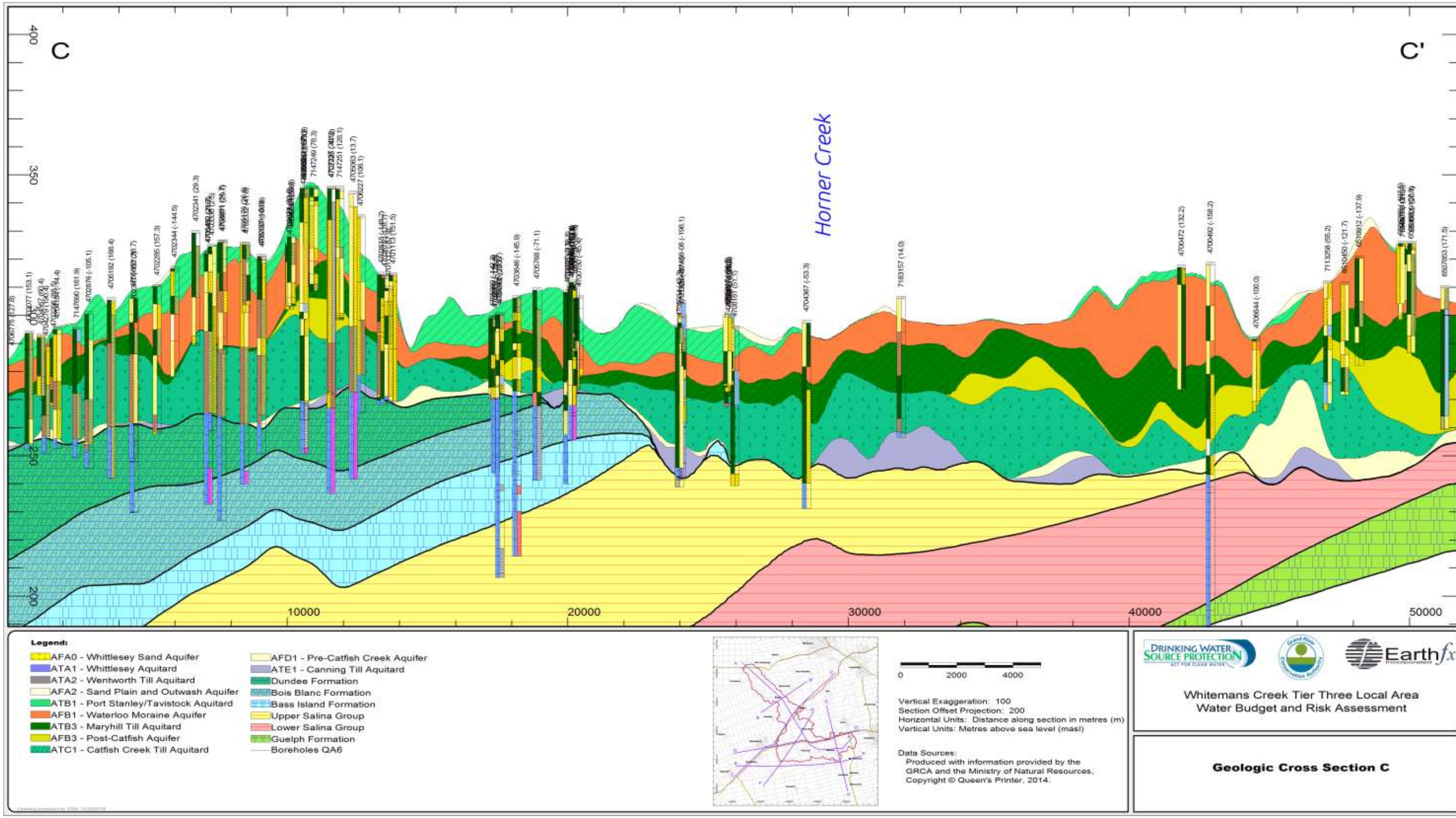


Figure 5.29: Southwest-northeast cross section C-C'.

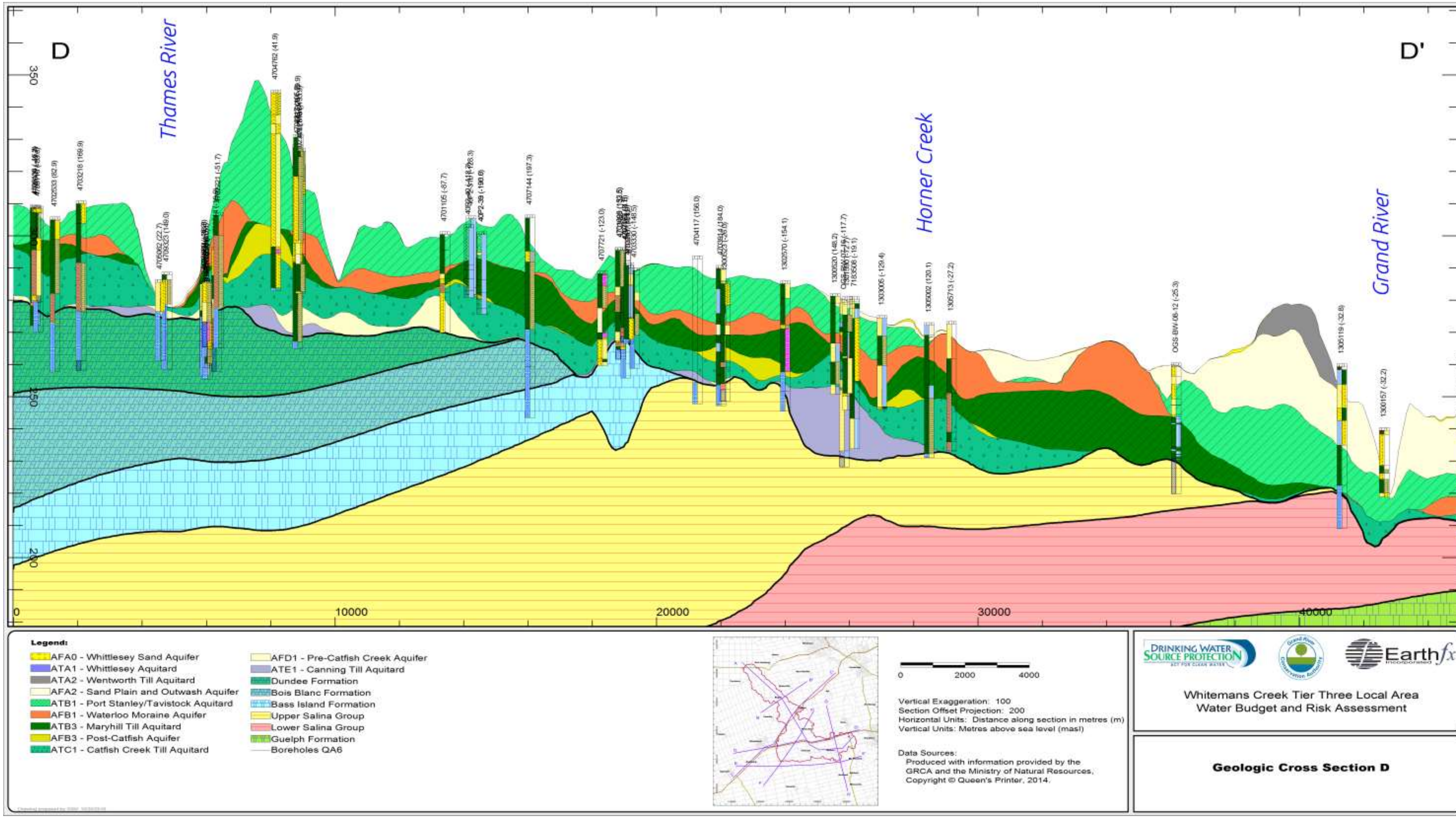


Figure 5.30: West-east cross section D-D'.

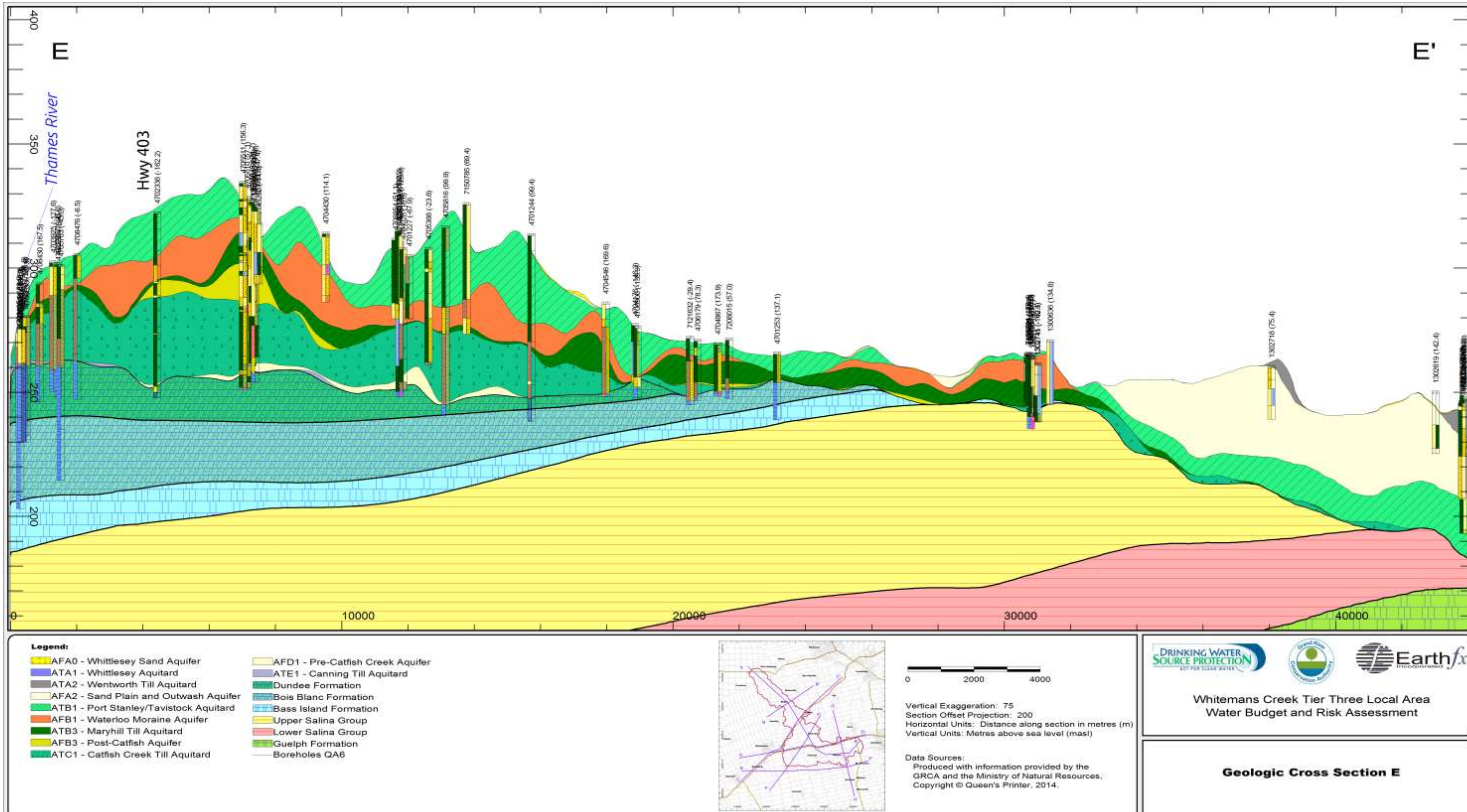


Figure 5.31: West-east cross section E-E'.

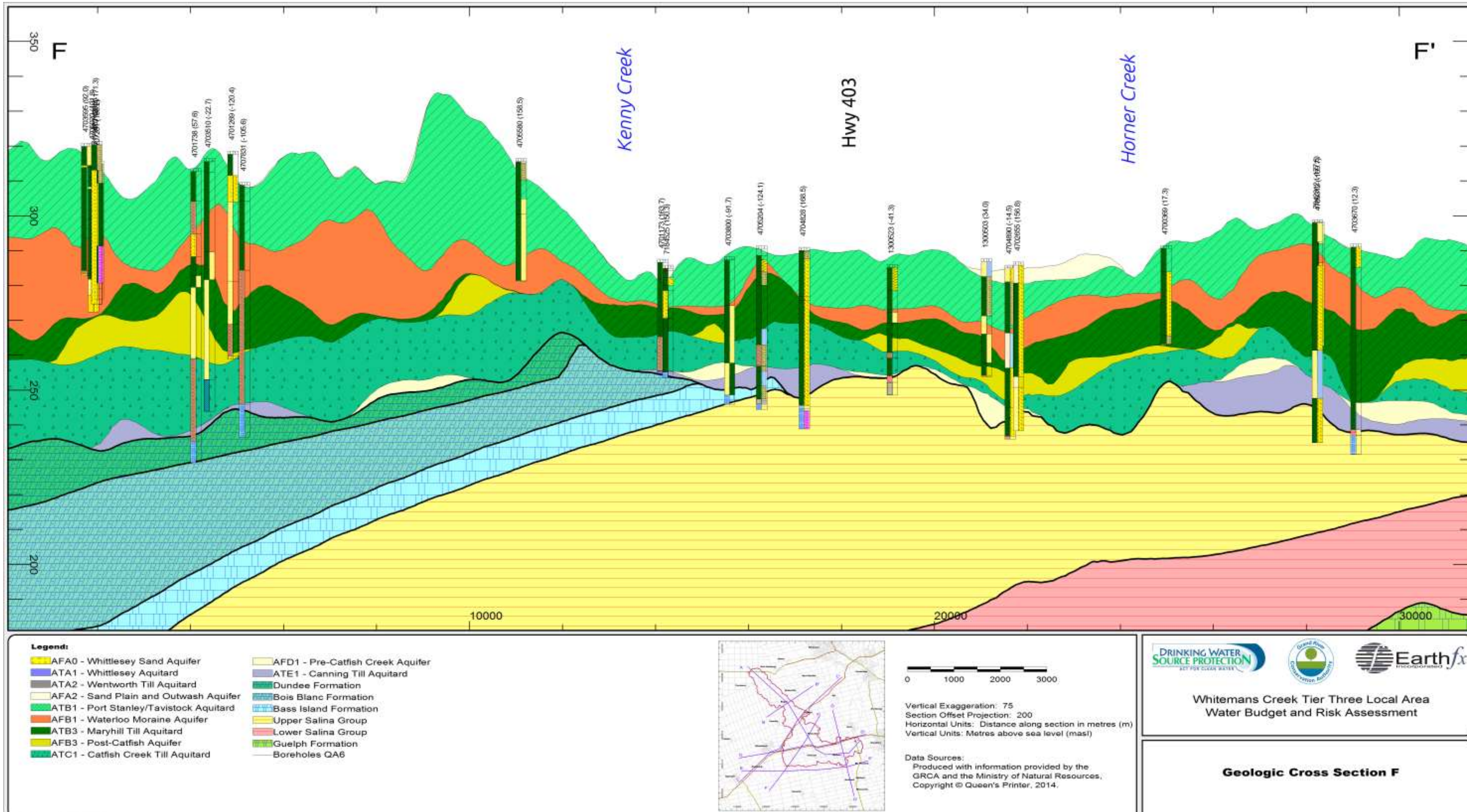


Figure 5.32: Southwest-northeast cross section F-F'.

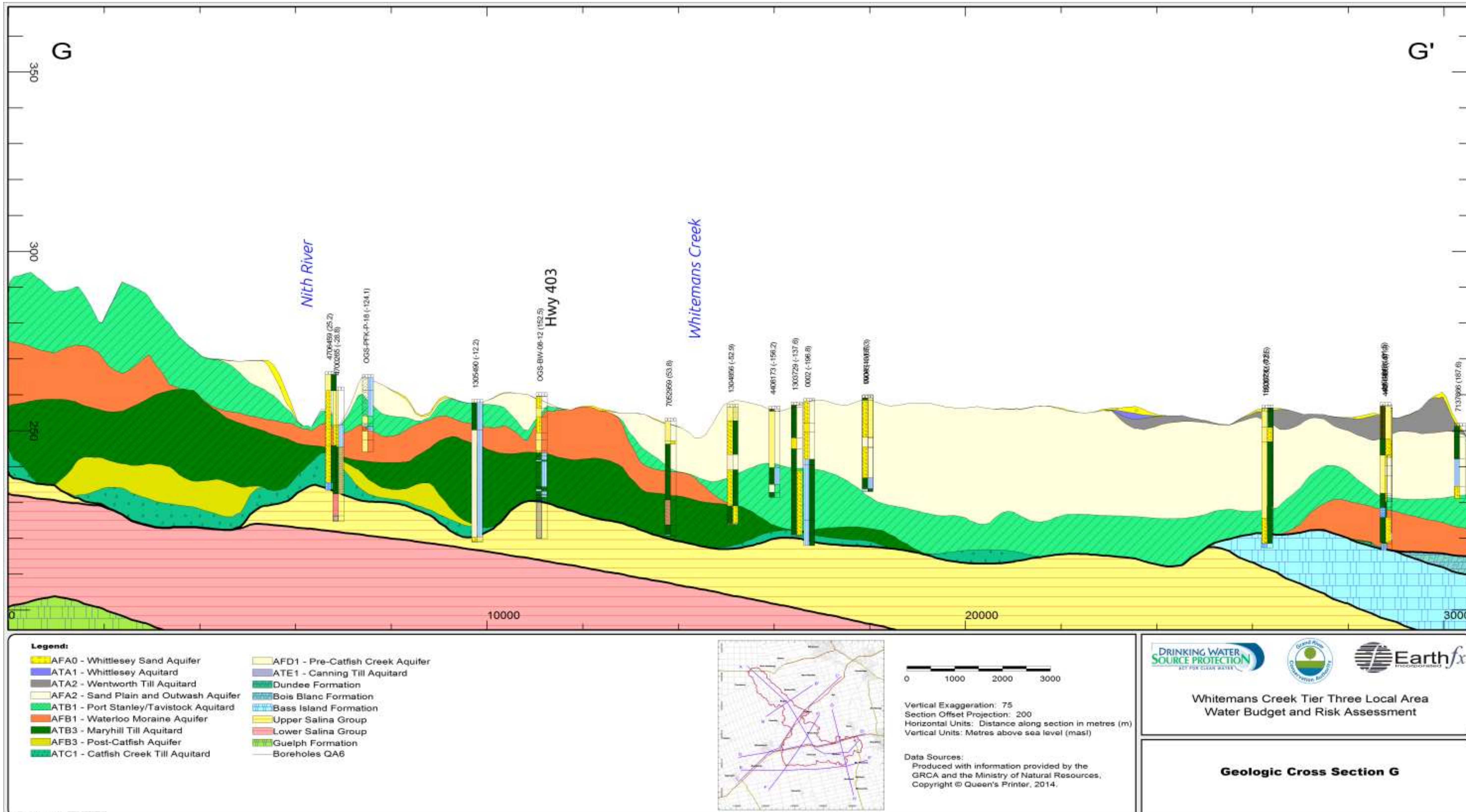


Figure 5.33: North-south cross section G-G'.

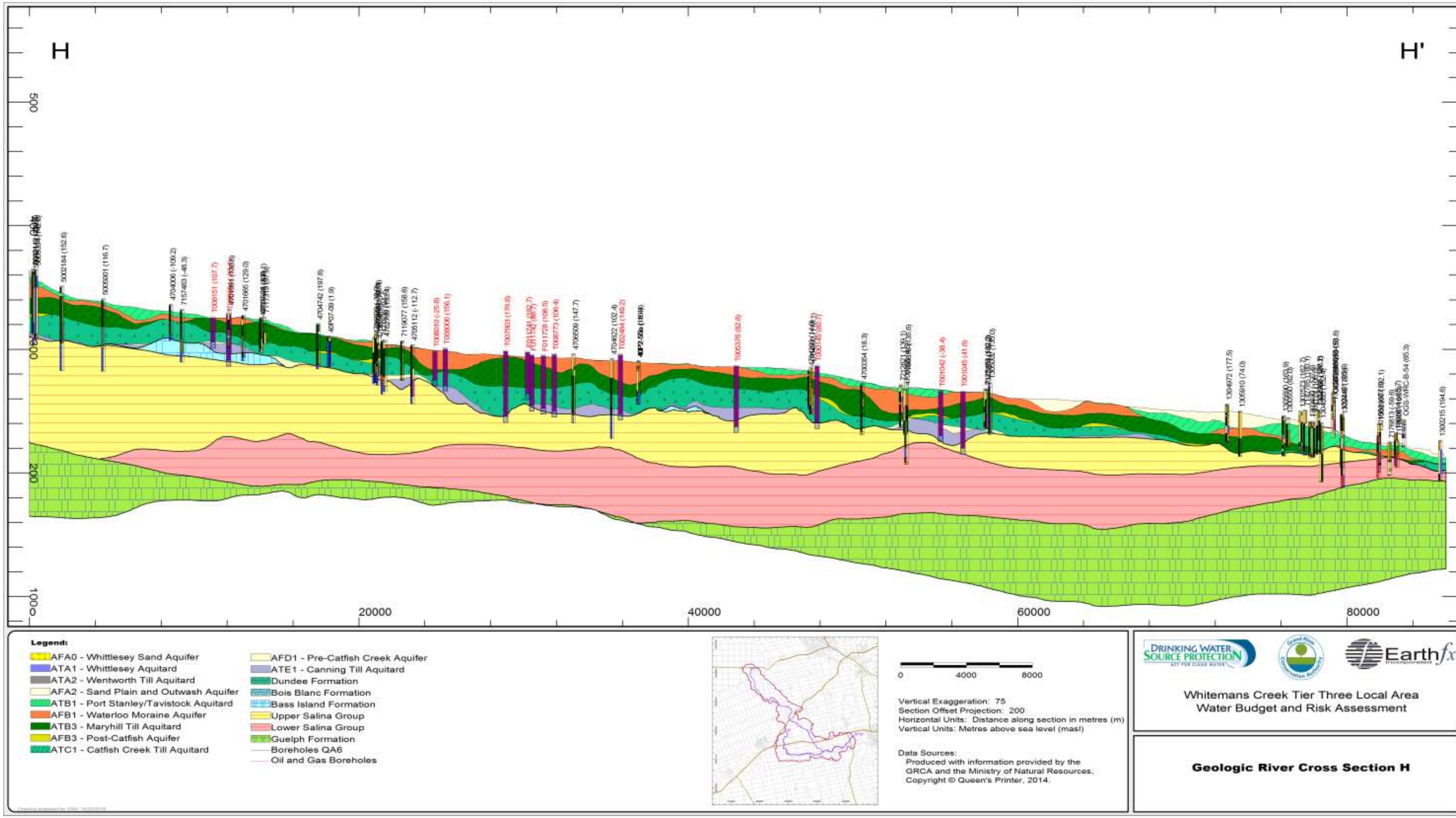


Figure 5.34: River cross section H-H' along Horner and Whitemans creeks.

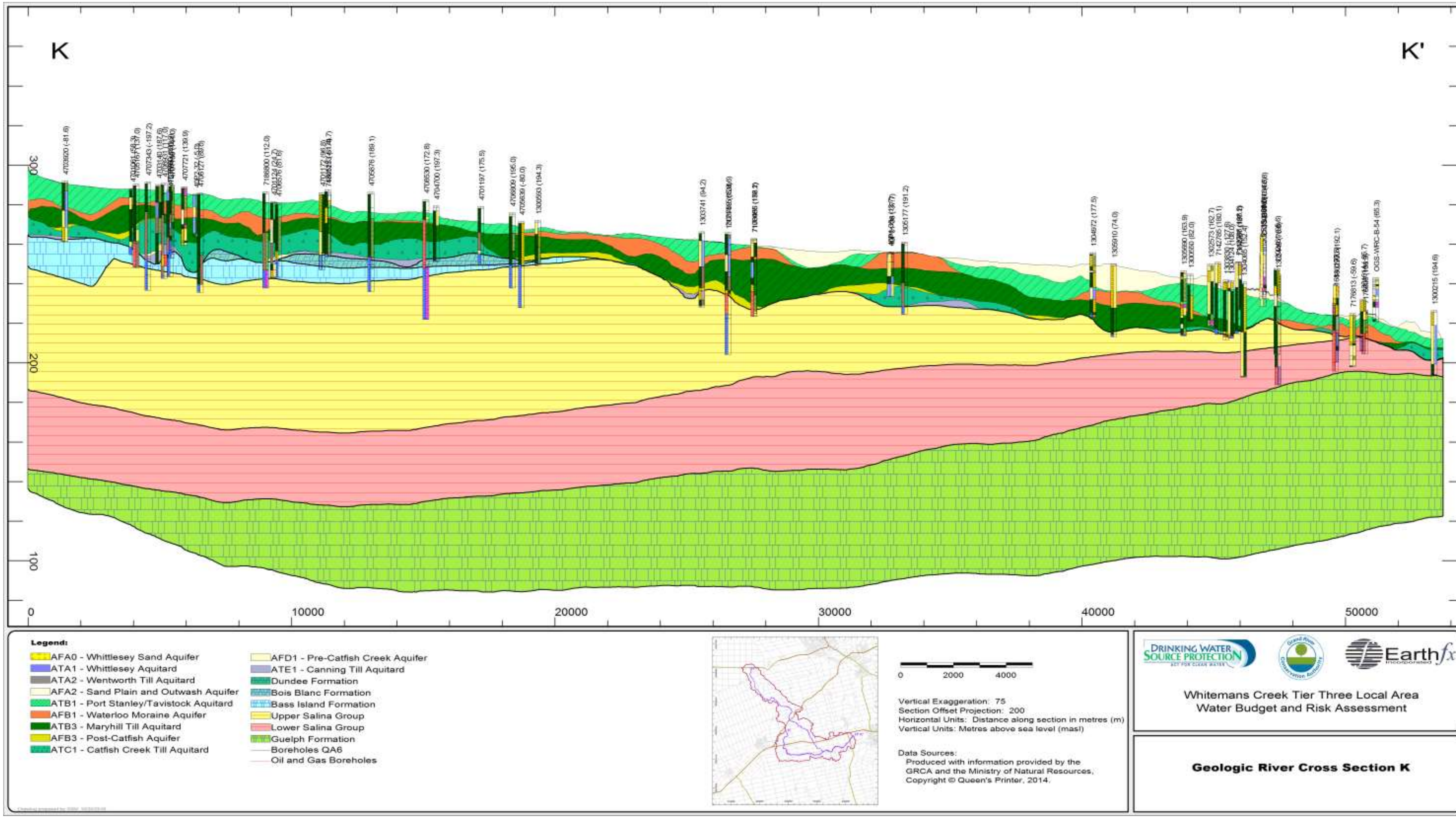


Figure 5.35: River cross-section K-K' along Kenny and Whitemans creeks.

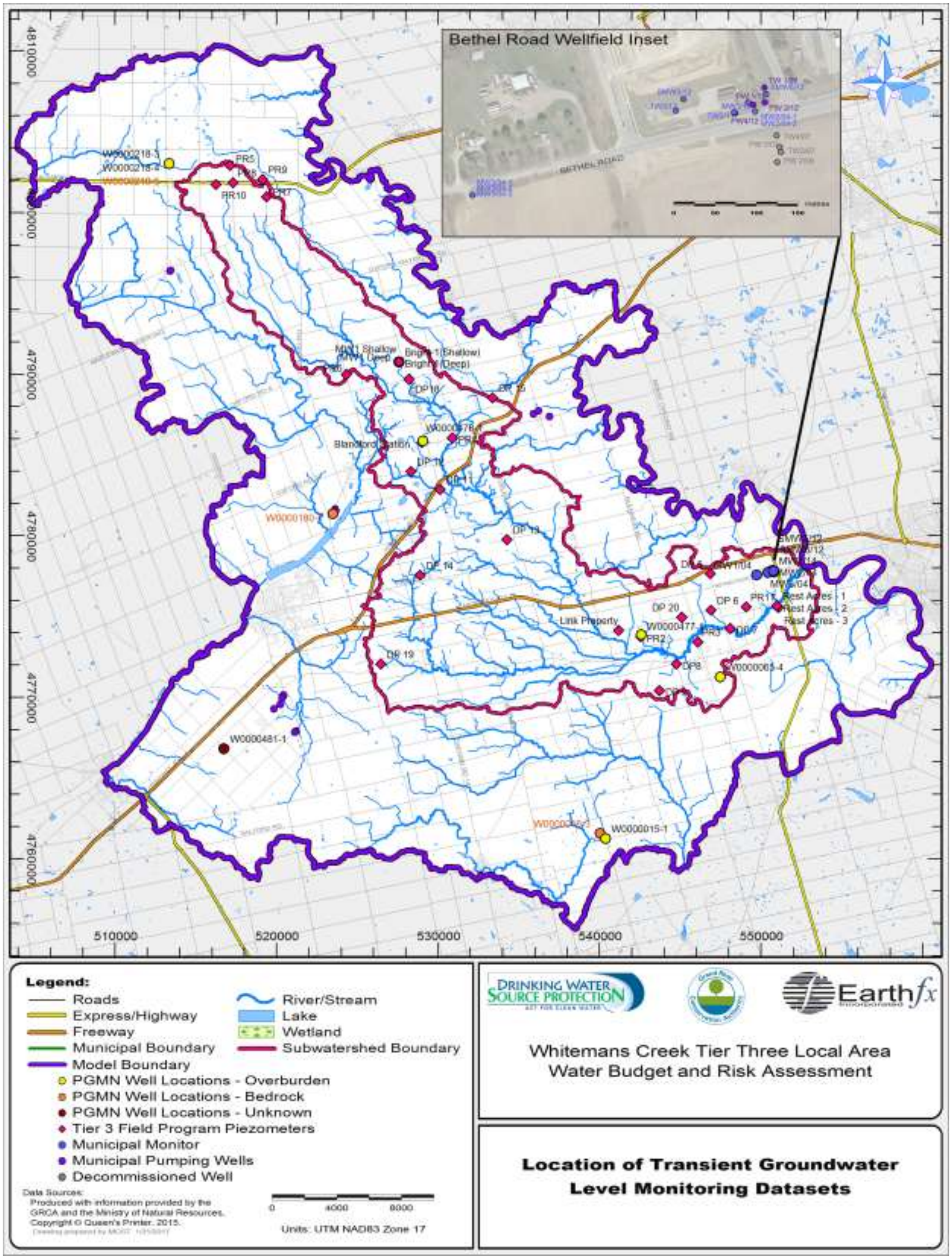


Figure 5.36: Location of transient groundwater level data sources.

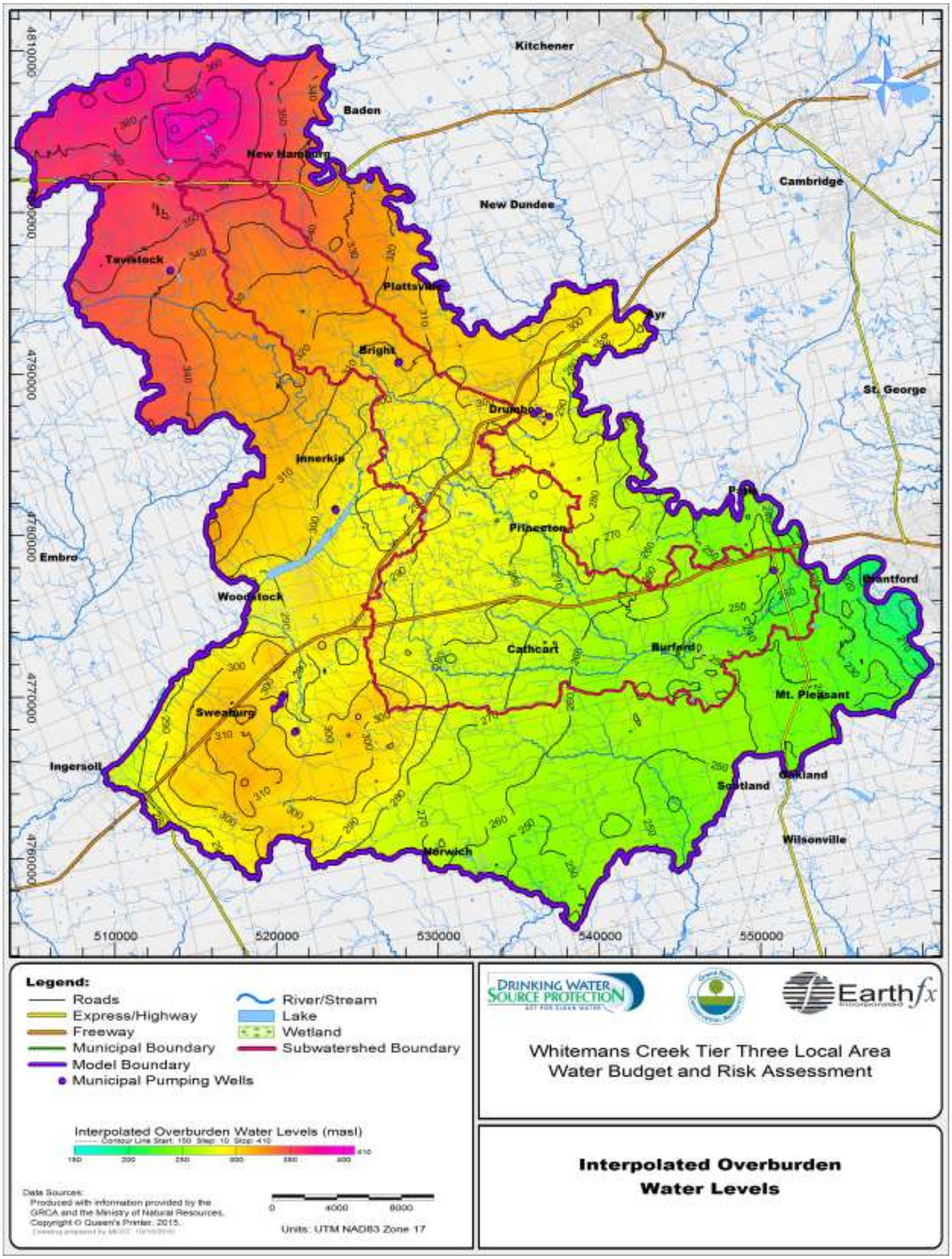


Figure 5.37: Interpolated static water levels in the overburden wells.

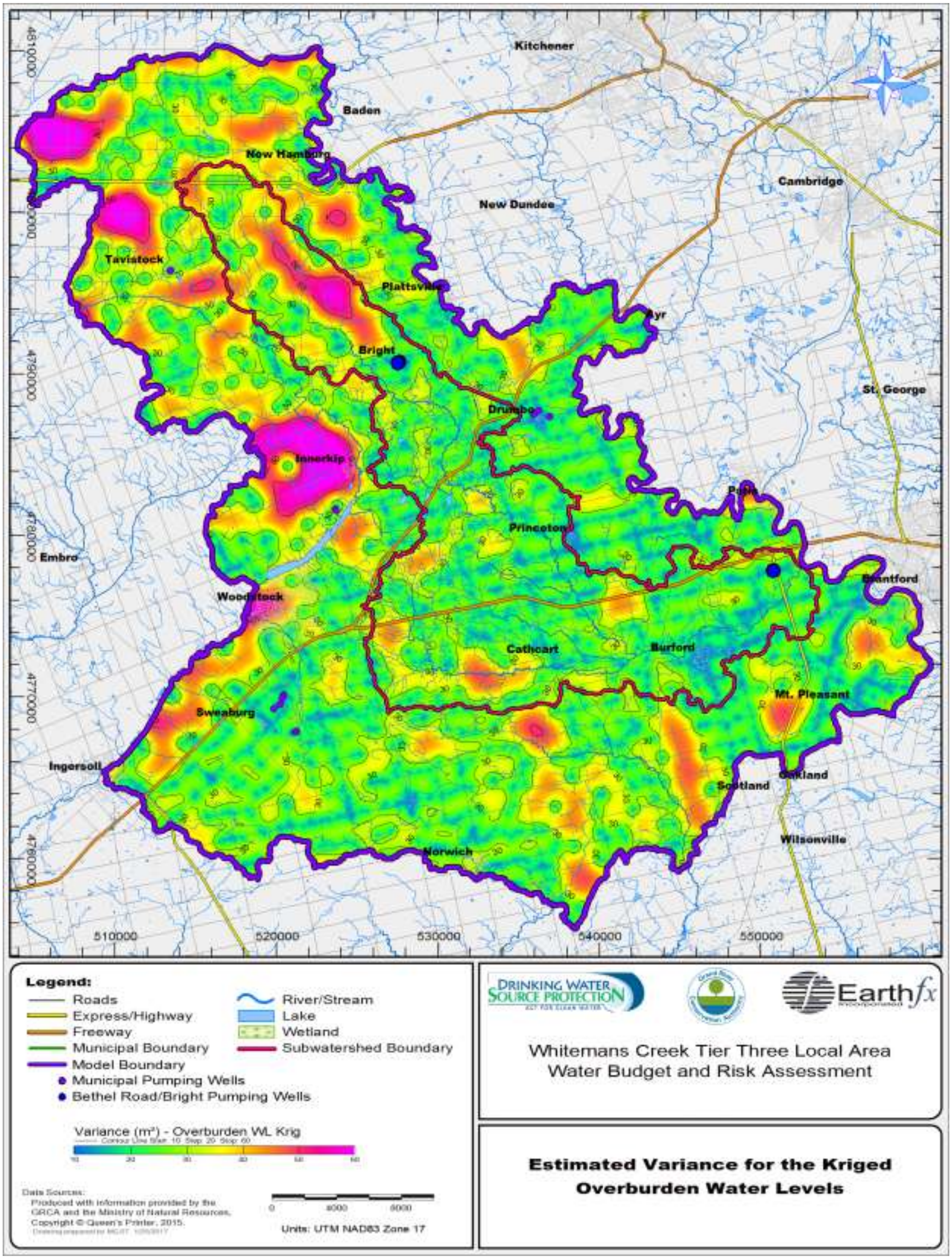


Figure 5.38: Estimated variance for the kriged overburden water levels.

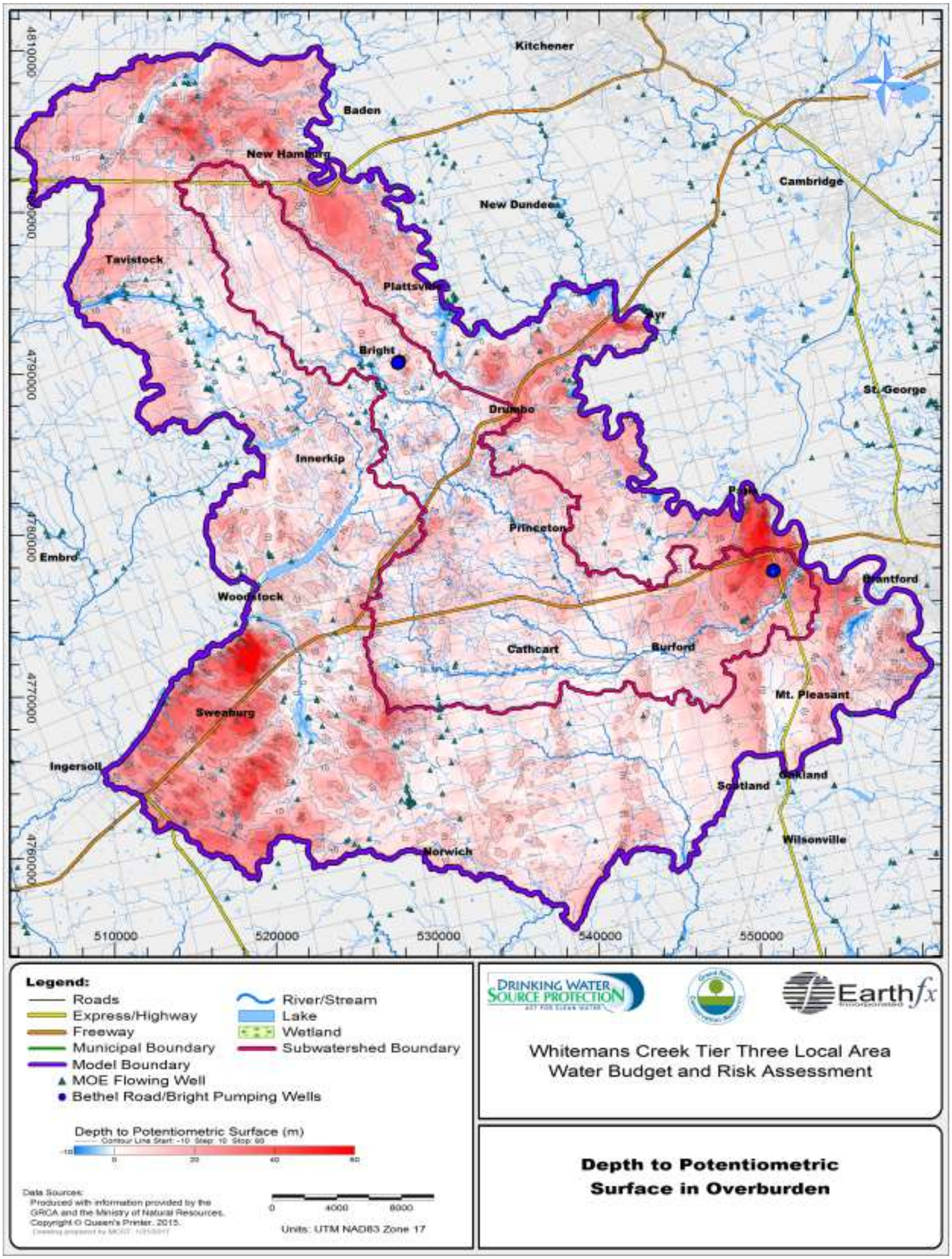


Figure 5.39: Depth from land surface to the water table in the study area.

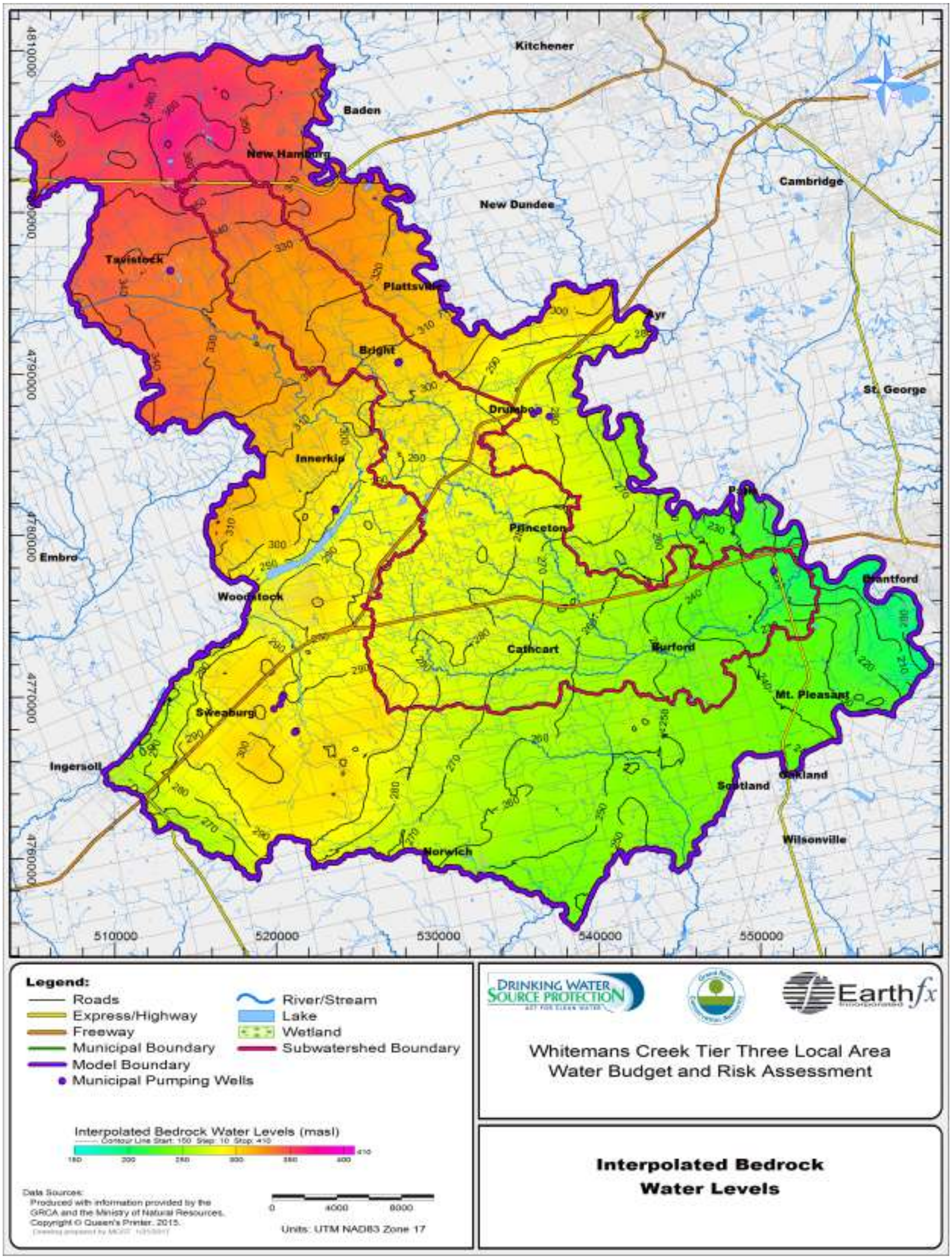


Figure 5.40: Interpolated static water levels in the bedrock wells.

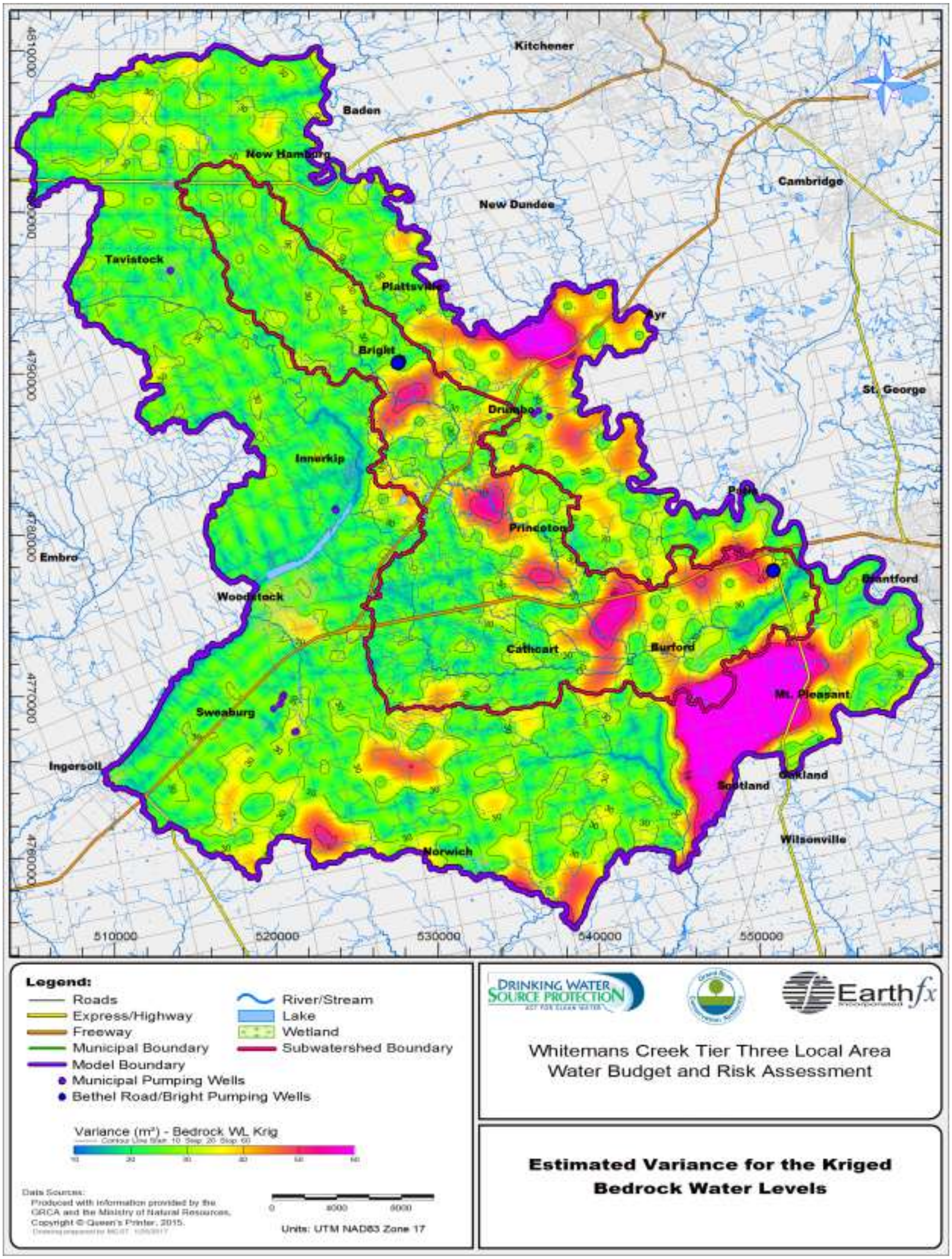


Figure 5.41: Estimated variance for the kriged bedrock water levels.

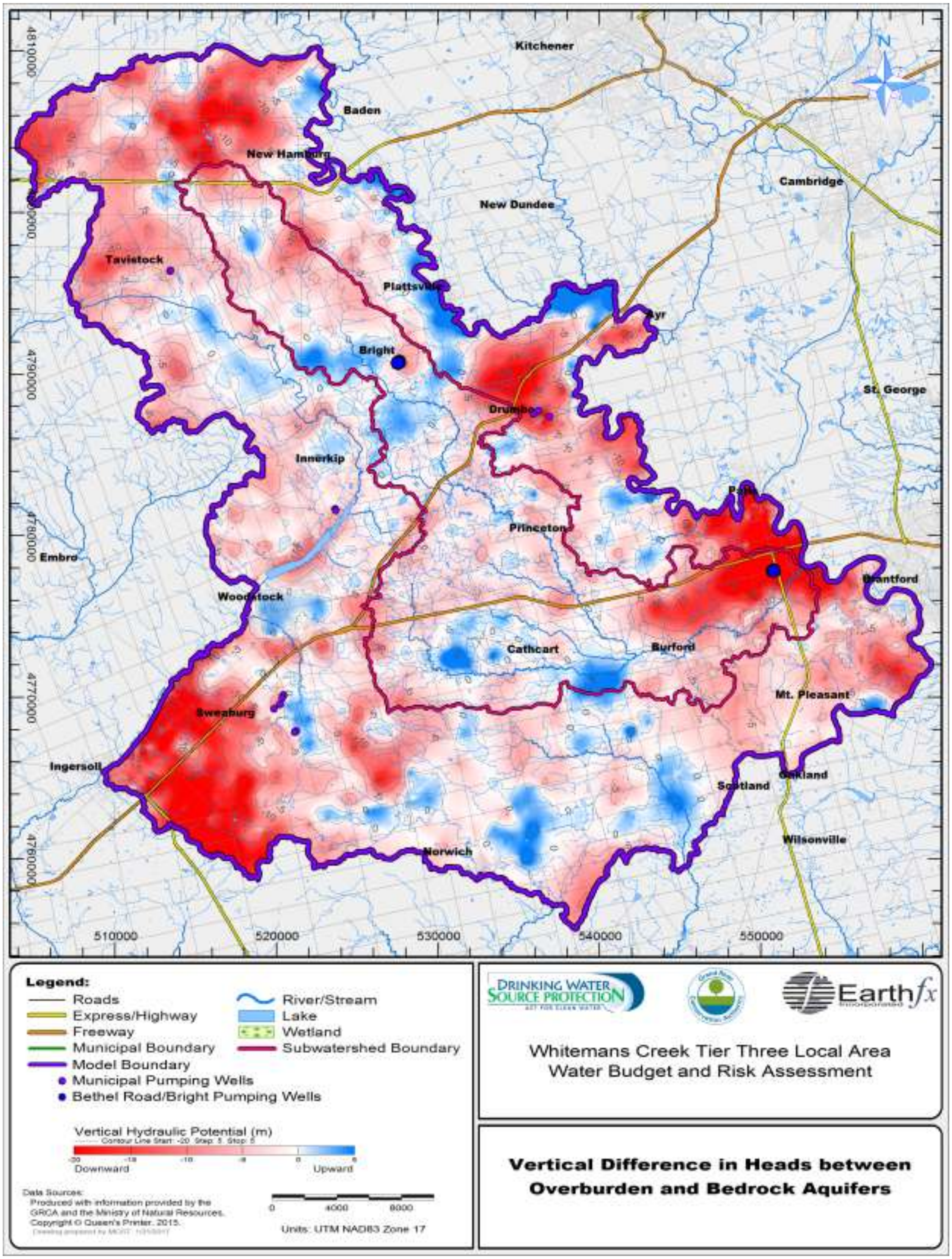


Figure 5.42: Estimated vertical head differences between the overburden and bedrock aquifers.

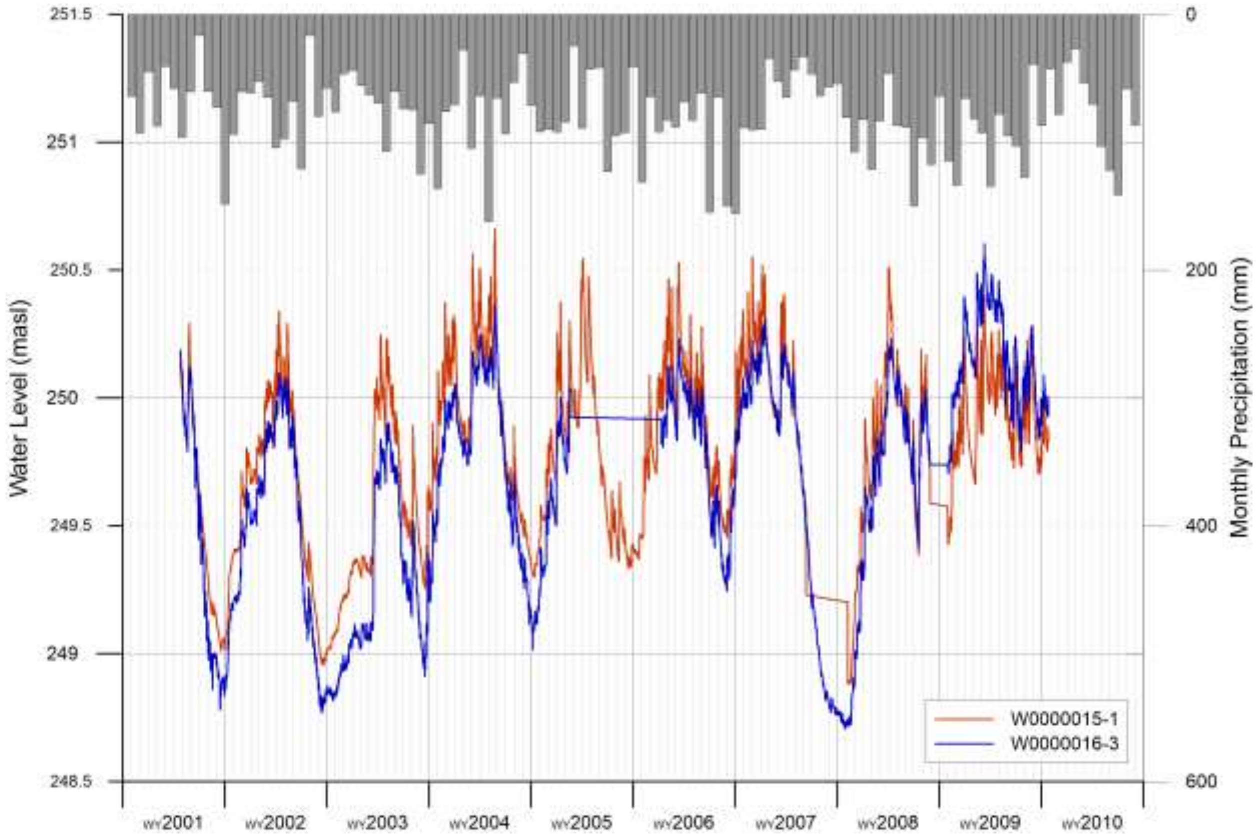


Figure 5.43: Time series of PGMN wells W0000015-1 and W0000016-3 and monthly precipitation.

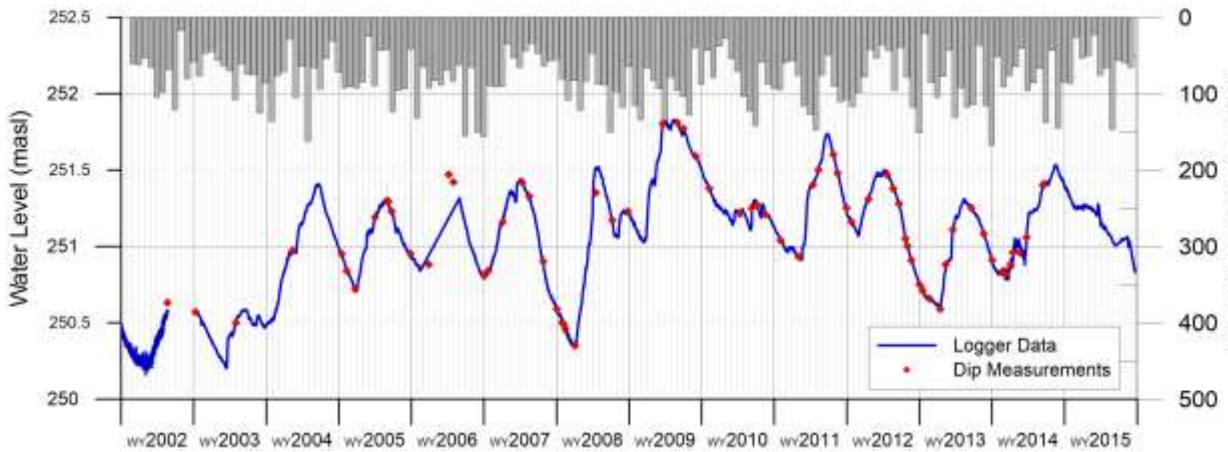


Figure 5.44: Time series of PGMN well W0000065-4 and monthly precipitation.

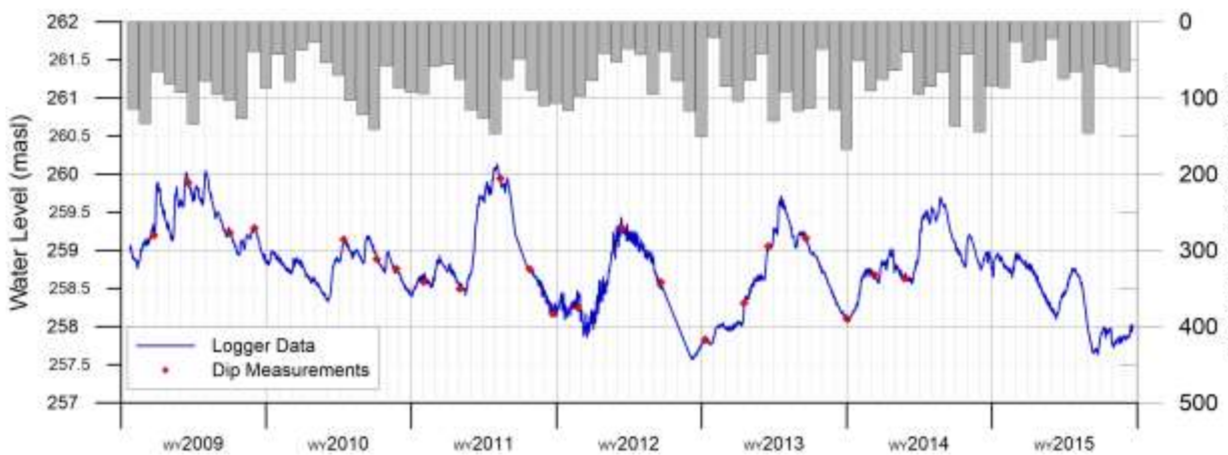


Figure 5.45: Time series of PGMN well W0000477-1 and monthly precipitation.

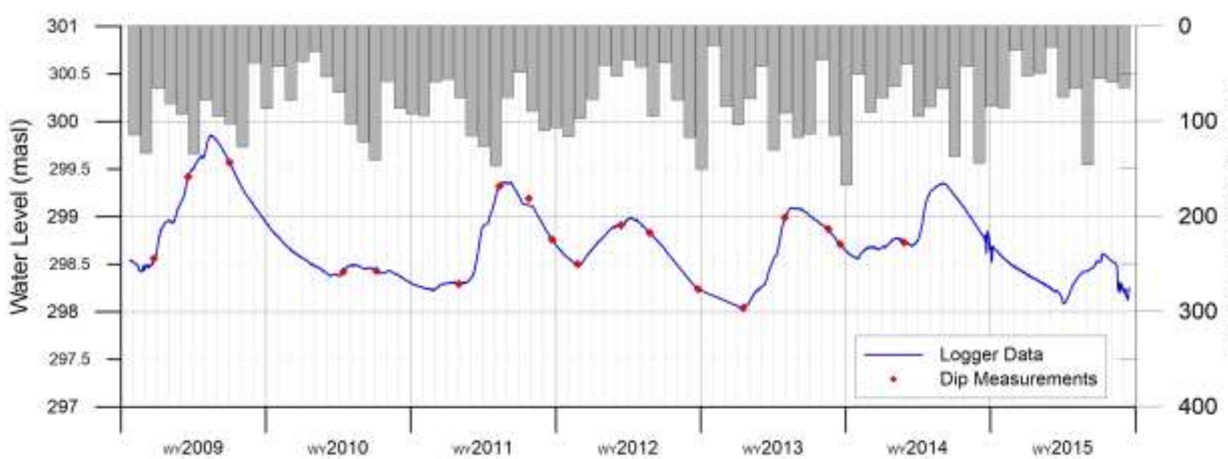


Figure 5.46: Time series of PGMN well W0000478-1 and monthly precipitation

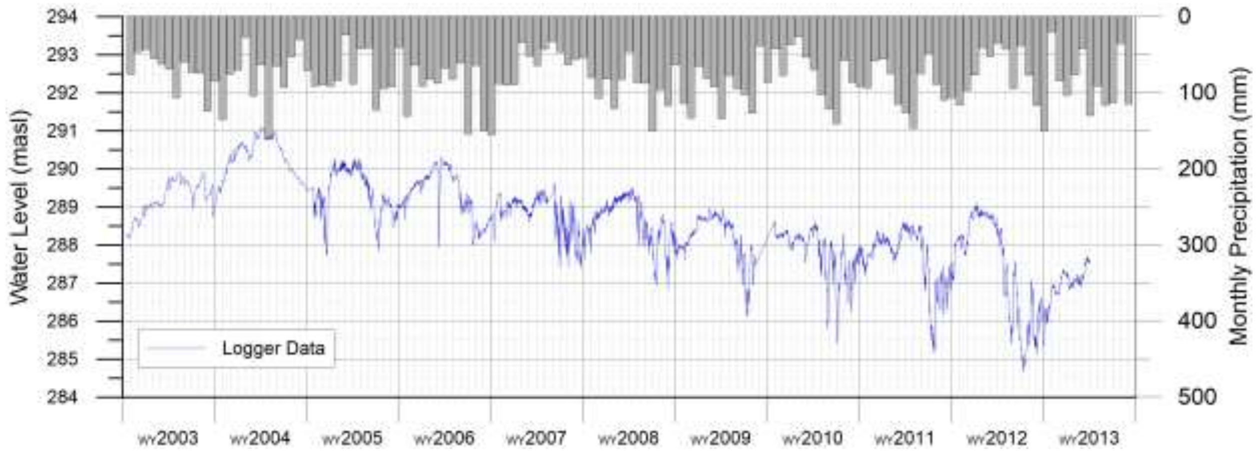


Figure 5.47: Time series of PGMN well W0000180-1 and monthly precipitation

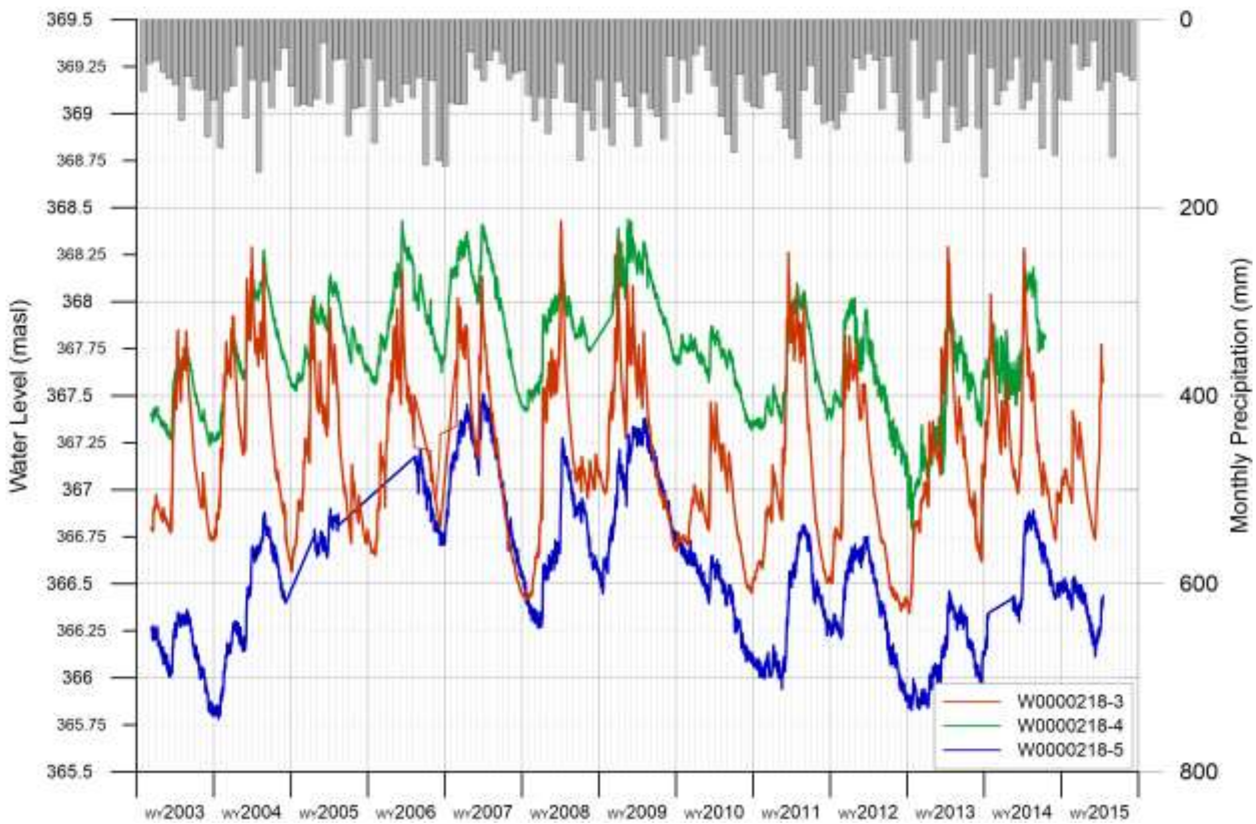


Figure 5.48: Time series of PGMN wells W0000218-3, 4, and 5 and monthly precipitation

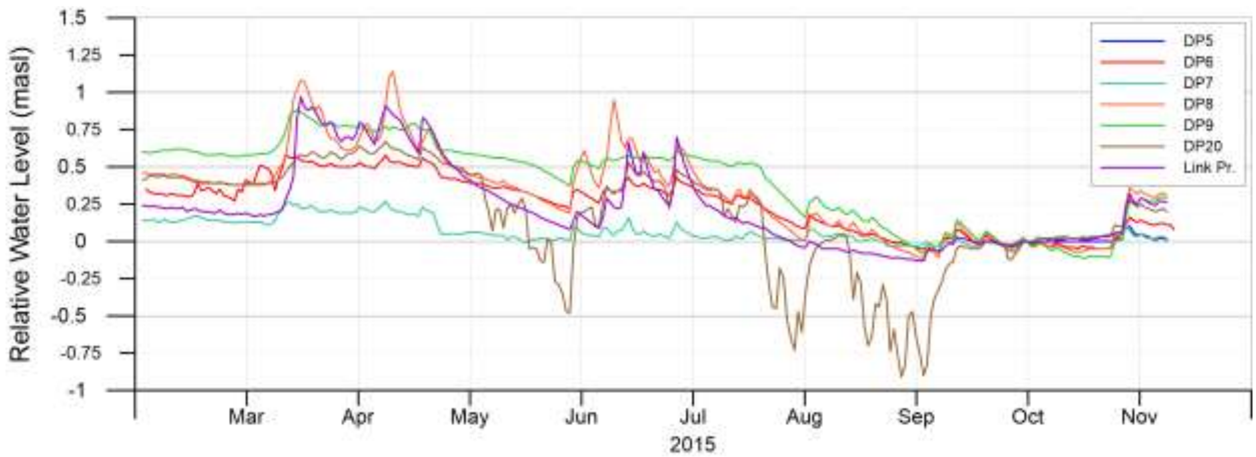


Figure 5.49: Drive-point water levels in the southeastern region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

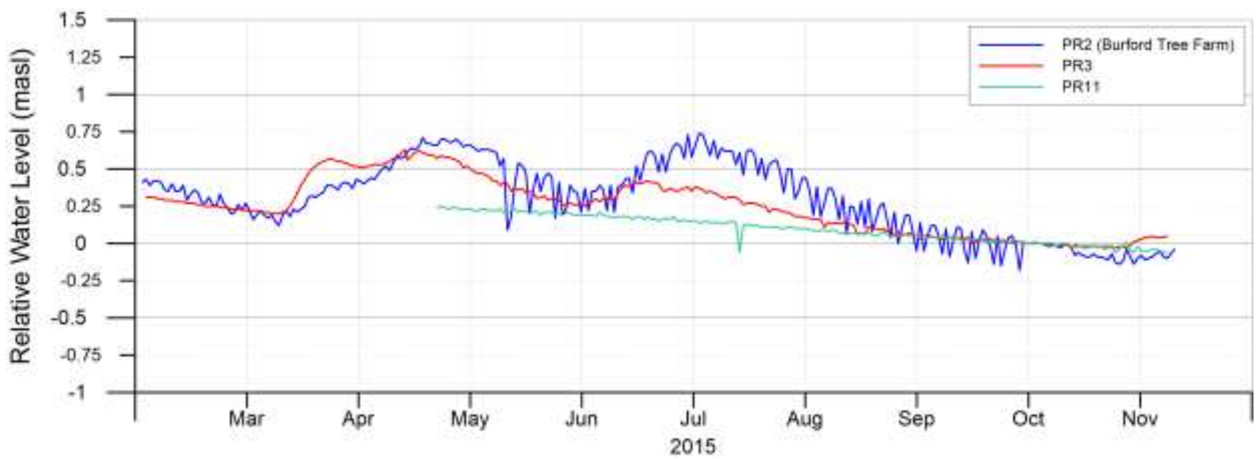


Figure 5.50: Water levels measured in private wells in the southeastern region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

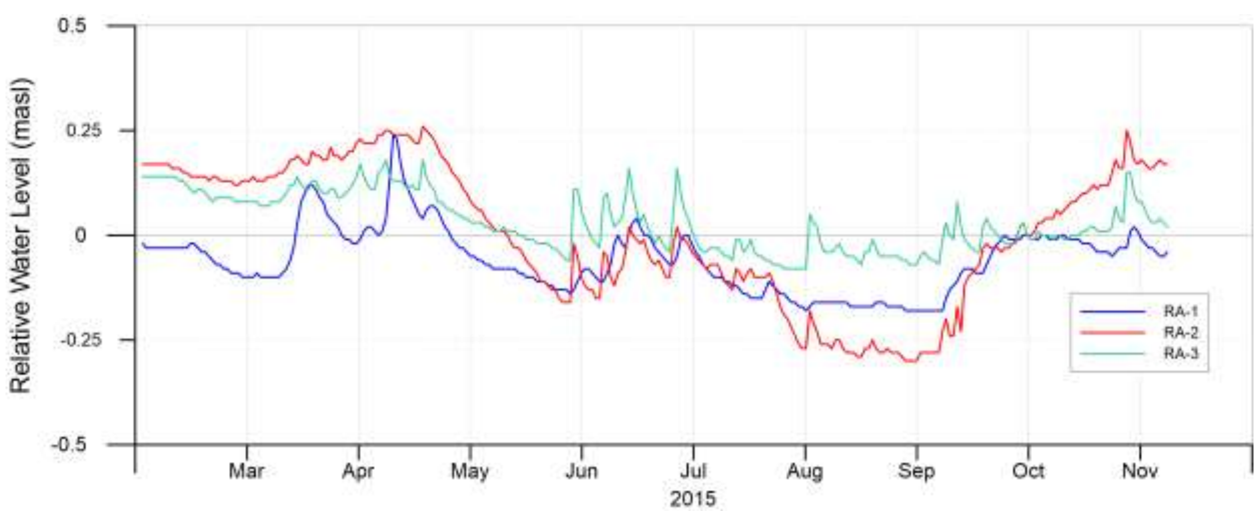


Figure 5.51: Shallow well water levels at the Apps Mill Nature area in the southeastern region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016

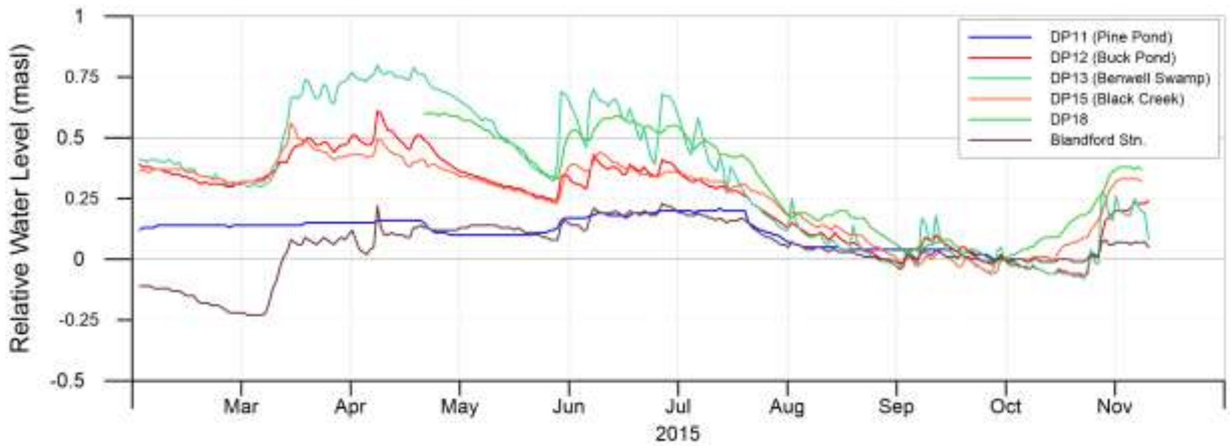


Figure 5.52: Drive point water levels in the central region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

Figure 5.53: Water levels in private wells in the central region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

Figure 5.54: Intermediate/deep water levels in the northern region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

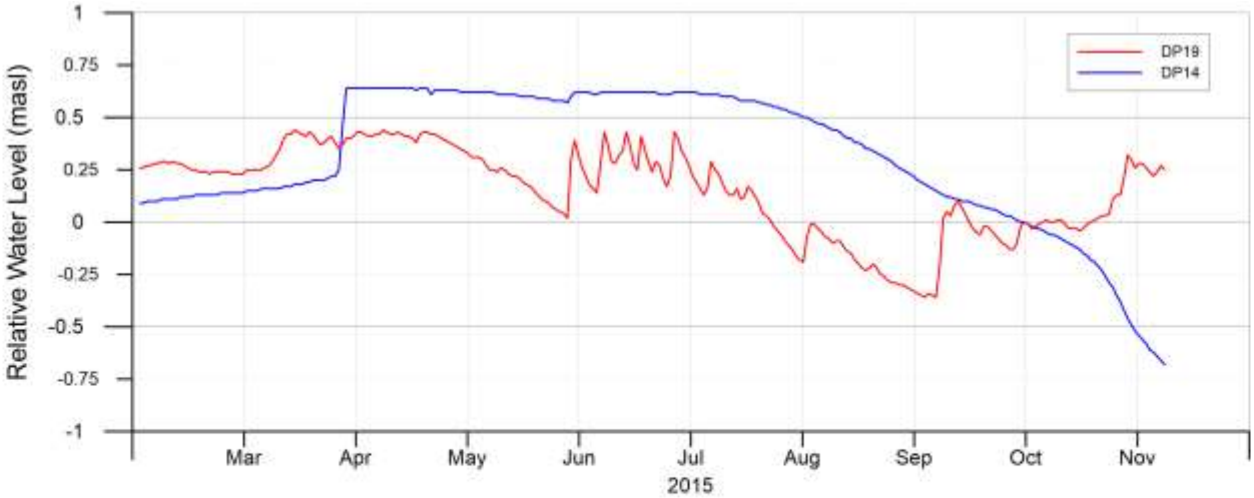


Figure 5.55: Water levels measured in drive points in the southwestern region of the Whitemans Creek subwatershed. Note that water levels are relative to the start of WY2016.

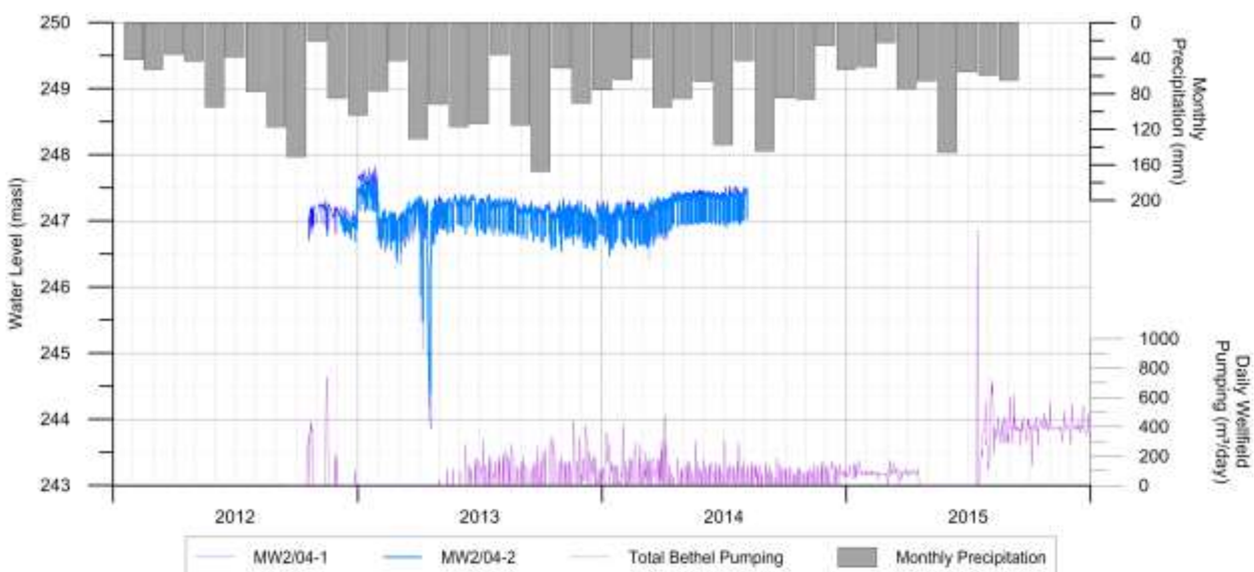


Figure 5.56: Hydrograph of observed water levels at Bethel Road monitoring well MW2/04-1 and MW2/04-2.

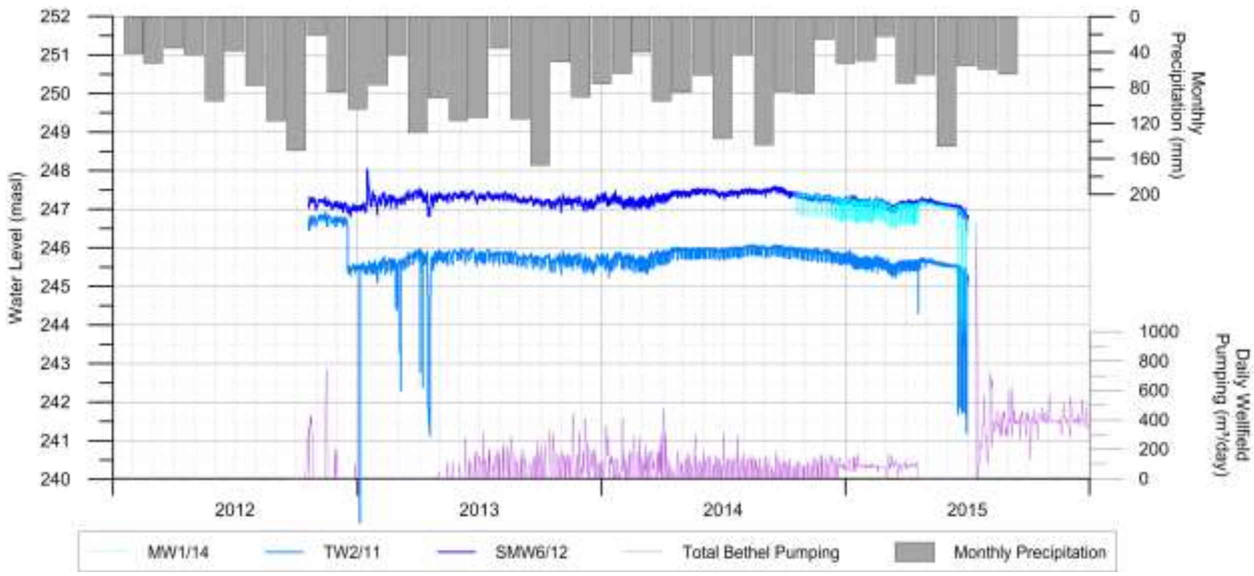


Figure 5.57: Hydrograph of observed water levels at Bethel Road monitoring wells MW1/14, TW2/11 and SMW6/12.

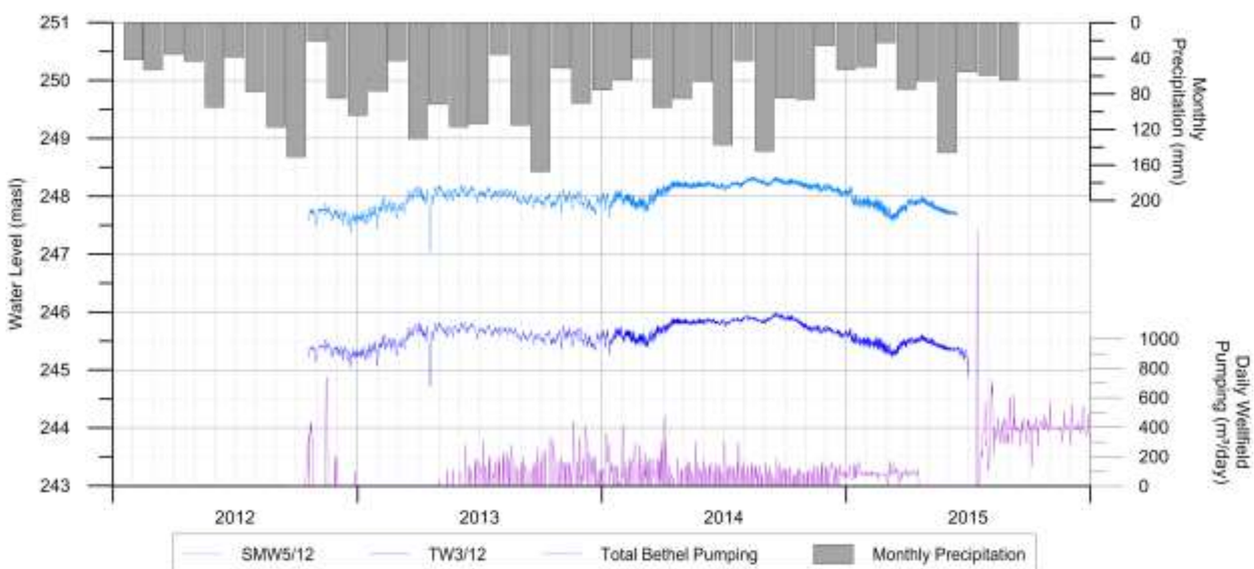


Figure 5.58: Hydrograph of observed water levels at Bethel Road monitoring wells SMW5/12 and TW3/12.

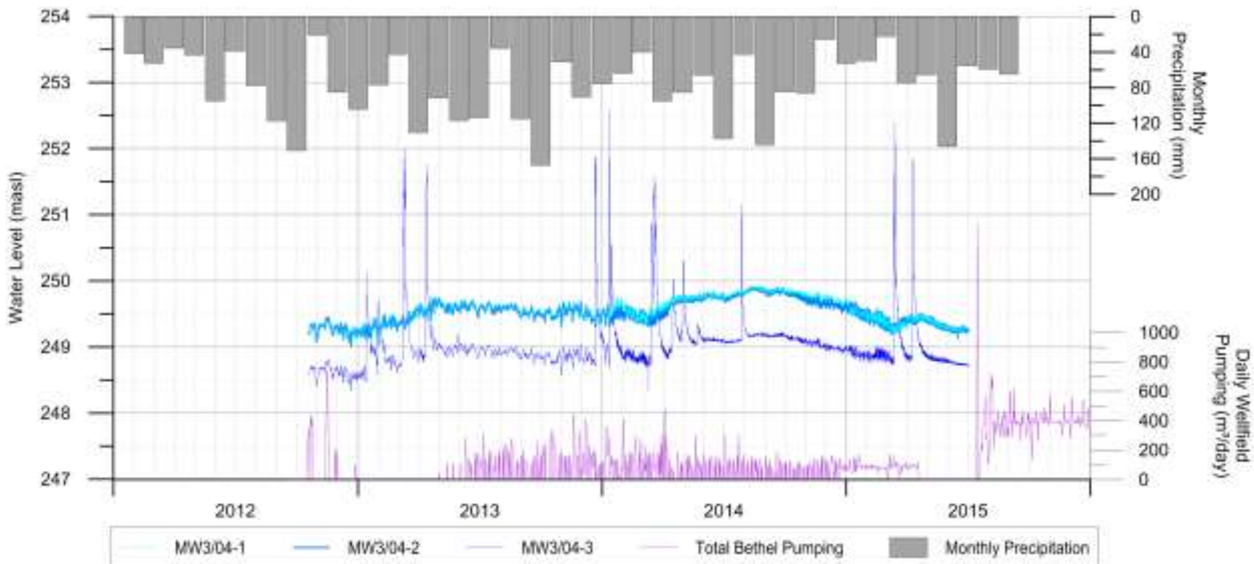


Figure 5.59: Hydrograph of observed water levels at Bethel Road monitoring well MW3/04-1, MW3/04-2 and MW3/04-3.

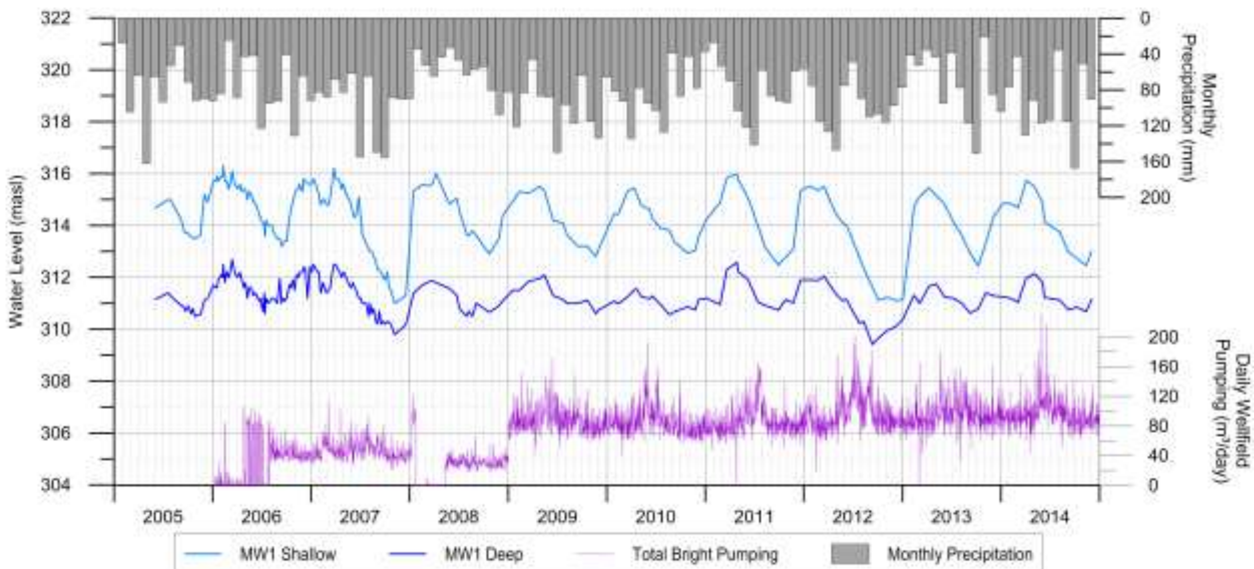


Figure 5.60: Hydrograph of observed water levels at Bright monitoring well MW1 Deep and Shallow.

6 Water Use

A key task in this study was to obtain the best estimates of groundwater and surface water takings and consumptive use within the Whitemans Creek subwatershed and surrounding Tier 3 Assessment area. These estimates were incorporated into the integrated groundwater/surface water model analyses to assess interference between the water takings, as well as interaction between the water takings and the surface water system.

The data analyzed include information about rates of municipal water use as well as water use for agriculture and other purposes. As specified in the Technical Rules for Assessment Reports (MOE, 2009), rates for non-municipal water takings for the Tier 3 Assessments should be representative of the "study period" (i.e., the period during which data are available and are considered representative for the drinking water systems under consideration). As will be discussed further on, daily pumping rates are available for the municipal wells and other permitted water takings from 2009 to 2014.

This section of the report describes the compilation of water use data, results of efforts to reconcile and integrate the various water taking data sources, and methods for obtaining reasonable estimates of consumptive groundwater and surface water use for both permitted and non-permitted takings within the model area.

Groundwater and surface water use information (both permitted and non-permitted use) were made available to Earthfx from provincial agencies, the GRCA, other conservation authorities, the counties, and municipalities. Supplementary data were obtained from on-line sources. A list of the key data sources is provided in Table 6.1.

Table 6.1: Data sources for the water use analysis.

Data Source	Data	Period
Province	MOE Permit to Take Water (PTTW) database	Current as of 1/2016
	MOE Water Taking Reporting System (WTRS)	Yearly for 2009 - 2014
	MOE Water Well Information System (WWIS)	Current as of 2015
GRCA/LPRCA	Various Water Use Reports Tier 2/Tier 3 Source Water Protection Studies	2005-2014
Oxford County/Brant County/RMOW	Municipal water takings for the Bright and Paris Wellfields.	2009-2014
	Municipal water takings for other wellfields in the study area.	2009-2014

6.1 *Previous Studies*

A number of studies have been undertaken in the GRCA and the Whitemans Creek area to estimate actual water takings and consumptive use. Because water use changes from year to year, the data tabulated in these studies may have been superseded; however, many of the methods developed and general observations from the earlier studies are still relevant. The most significant changes in the data are related to improvements in WTRS reporting.

The GRCA-wide studies generally break down usage by major catchments, with Whitemans Creek one of the few subwatersheds considered separately. The regional analysis of the Whitemans Creek data is useful but the GRCA-wide studies do not provide detailed spatial analysis within the subwatershed.

A report on water use in the Grand River watershed by Bellamy and Boyd (GRCA, 2005) was a foundational study. This study analyzed water use for municipal supply and non-municipal, non-agricultural water use from PTTW data. It used 1996 Agricultural Census data and the methods of

Kreutzwiser and de Loë (1999) to estimate livestock watering and other non-irrigation farm use. It estimated actual crop irrigation use by determining the amount of land irrigated and the number of irrigation events per year. The number of irrigation events was determined using daily soil moisture information computed from continuous GAWSER model simulations (Schroeter *et al.*, 2001). Irrigation demand was split between groundwater and surface water based on the relative number of groundwater and surface water permits (61% and 39%, respectively). The lower part of Whitemans Creek and the McKenzie Creek subwatersheds had the highest irrigation water demand. The study used 1991 census data (latest available at the time) for estimating domestic water use in unserviced areas.

A water use assessment was conducted as part of the Tier 2 Subwatershed Stress Assessment for the GRCA under the Source Water Protection Program (AquaResource, 2009b). Most of the municipal water demand estimates were taken from GRCA (2005) along with more recent municipal pumping data from Waterloo Region. AquaResource (2009b) listed all the permits to take water in the GRCA as part of their integrated water budget assessment. They estimated the distribution of water use in the Grand River watershed to be about 53% for municipal water supply with industrial, commercial, agricultural, and dewatering ranging from 7 to and 9 percent each.

The distribution of water use varies by subwatershed. AquaResource (2009b) provided summary tables showing the numbers of surface water and groundwater permits on a subwatershed basis broken down by usage class. They also estimated municipal water supply, non-permitted agricultural demand (i.e., water takings below the 50,000 L/d threshold for obtaining a PTTW), and the un-serviced domestic water demand from private wells on a subwatershed basis. Source data for non-permitted agriculture was not determined, rather it was assumed to be half groundwater and half surface water. Their results, in litres per second (L/s), are provided in Table 6.2 for Whitemans Creek and the subwatersheds that fall partly within the study area.

Table 6.2: Permit information from the GRCA Tier 2 Subwatershed Stress Assessment.

Subwatershed	Municipal Groundwater Supply (L/s)	Municipal Surface Water Supply (L/s)	Permitted Groundwater (L/s)	Permitted Surface Water (L/s)	Non-permitted Agriculture (L/s)	Unserviced Domestic Water Supply (L/s)
Whitemans Creek	1	0	3543	1304	8	15
Grand above Brantford to Doon	274	0	5865	510	5	7
Grand above York to Brantford	476	547	1784	7947	11	17
Nith above Grand to New Hamburg	399	0	3293	409	14	21

The data used in their study predated the availability of self-reported water takings (WTRS data). Instead, they relied on data collected by GRCA through a program to gather actual pumping rate data from PTTW holders (discussed in GRCA, 2005). The program collected data from all municipalities, about 16% of agricultural permit holders, about 66% of other groundwater users, and 20% of other surface water users. Irrigation demand was estimated using the irrigation model developed in GRCA (2005). Reported takings data suggested that actual water use is approximately 60% of the permitted maximum pumping rate.

The Water Use Inventory Report for the Grand River Watershed (GRCA, 2011) by Amanda Wong is a comprehensive and expanded update of GRCA (2005) that included (1) actual takings data from an early (2008) release of the WTRS data and (2) more recent agricultural census and population data. The report examined municipal water use in detail; it broke down consumption by usage category, looked at differences between ‘total water supplied’ and ‘revenue water’ to estimate leakage and other water losses, and examined patterns of monthly water use and the effect of conservation measures.

GRCA (2011) included a detailed analysis of the PTTW data and assessed compliance for self-reporting (as noted earlier). Monthly adjustment factors to account for seasonality of water use were determined from the usage limits in the PTTW database and from the 2008 WTRS data. A separate analysis of water usage for aggregate washing was made to account for the recycling of pumped water in closed-loop systems. Updates to the estimates for non-permitted livestock watering and unserviced domestic water use were made based on more recent agricultural census and population data.

Irrigation crop demand was estimated from a combination of reported takings (where available), the previously-developed GAWSER-based crop irrigation model, and local knowledge. Where actual takings were not available, the other information was used to adjust maximum permitted values. Finally, all information was processed to determine water use by subwatershed. This included summarizing extractions from all sources as well as applying consumptive use factors to determine how much of the extracted water is returned to the original source.

Using similar methodology as GRCA (2005), Wong and Bellamy (2005) prepared a report on water use in the Long Point Region Conservation Authority area. They analyzed municipal water use, agricultural takings, unserviced domestic water use, and other takings.

The Long Point Tier 3 study (Matrix Solutions, 2013) assessed three areas within the LPRCA jurisdiction, of which Waterford, Delhi, and Tillsonburg were considered to have a moderate or significant potential for hydrologic stress for groundwater and surface water. The study focused on the lands immediately surrounding these communities (Focus Area on Figure 1-1 in their report), although the study included characterization of the entire LPRCA. The northernmost portion of Big Creek is within the Whitemans Creek study area but is not within any of the LPRCA Tier 3 focus areas.

A Tier 3 Water Quantity Risk Assessment was conducted on behalf of the Upper Thames River Source Protection Authority (AquaResource, 2012). Water use data, based on the PTTW database, were broken down for each subwatershed with respect to takings type (surface water or groundwater), and primary purpose. Non-permitted takings were also estimated. Subwatersheds 07T and 09T and parts of subwatersheds 03T and 08T fall within the current study area. Results are summarized below.

Table 6.3: Groundwater takings in the Upper Thames Source Protection Area.

Subwatershed	Agriculture (m^3/d)	Comm./ Indus./Misc. (m^3/d)	Dewatering /Remediation (m^3/d)	Water Supply (m^3/d)	Non-Permitted (m^3/d)	Total (m^3/d)
Black Creek/Avon River (03T)	0	0	0	147	1,249	1,396
Cedar Creek (07T)	0	953	0	22,243	315	23,511
Thames R. above Ingersoll (08T)	0	3,308	60,755	6,847	898	71,807
Middle Thames River (09T)	115	37,540	2,882	518	1,576	13,462

Table 6.4: Surface water takings in the Upper Thames Source Protection Area.

Subwatershed	Agriculture (m^3/d)	Comm. (m^3/d)	Indus./Misc. (m^3/d)	Non-Permitted (m^3/d)	Total (m^3/d)
Black Creek/Avon River (03T)	10	199	0	930	11,139
Cedar Creek (07T)	0	532	0	195	727
Reynolds Creek/Thames R. above Ingersoll (08T)	158	86	3,392	898	4,469
Middle Thames River (09T)	200	88	115	959	1,362

6.2 *Provincial Permitting and Water Use Data*

6.2.1 MOE PTTW Database - Active Permits as of January 2016

The MOECC maintains a database of Permits to Take Water (PTTW) issued under the Ontario Water Resources Act for water takings larger than 50,000 litres per day (L/d). The PTTW database includes information on the maximum permitted water taking rates along with the maximum number of hours per day and days per year of permitted operation. The permits are classified by primary and secondary purposes (e.g., water supply/municipal or agriculture/tobacco). GRCA (2011) provides an excellent description of the categories and how patterns of water use can be inferred from this information. While PTTW holders are required to report water use, actual water use information is not part of this database.

Other reporting or operational limits are sometimes included in comment fields in the database records. These are generally not captured but can sometimes be extracted from the issued permit documents. Copies of the permits for some municipal wells were found in reports provided by the GRCA or municipalities and counties. Copies of a small percentage of the non-municipal permits were found on the MOE environmental registry (http://www.ebr.gov.on.ca/ERS-WEB-External/) and retrieved.

A complete copy of the MOECC PTTW database was downloaded from the Land Information Ontario (LIO) website in October of 2015. The last permit entered in the database had a date of December 2015. Each permit may have multiple sources (e.g., more than one well), with multiple purposes (e.g., a golf course can have one source for irrigation and another for drinking water at the clubhouse), and may include both groundwater and surface water taking sources (e.g., a well source and a pond source). The database was filtered to select only permits within the vicinity of the study area, resulting in a database extract of 3897 records, each representing a single water taking identified under a Source ID and belonging to a permit number.

A key unknown is whether water takings are continuing for expired permits; that is, are there some users unaware that their permits have expired? To account for these takers in this study, any permit with an expiration date after January 1st, 2009 that has also not been amended by another permit between 2009 and 2016 has been included as an active permit in the Tier 3 Assessment. For example, a water taking permit issued in 2008 with an expiration date in 2012 would be considered still active; however, if that permit was subsequently amended by a permit in 2011, then the original permit would become inactive, and its replacement would become the active permit. The 2009 cut-off was selected because this corresponds to what is considered to be the first reliable year within the Water Taking Report System (WTRS) database, discussed in the following section.

Of the 3897 source records, 557 sources have been included in the Tier 3 Assessment based on the criteria discussed above. The sources included represent 401 unique permits in the model area and 144 unique permits within the Whitemans Creek subwatershed. Permitted surface water and groundwater sources included in the study are listed in Appendix A and Appendix B, respectively.

6.2.2 MOE WTRS Database - Database Extract for 2009 to 2014

Under the Ontario Water Resources Act, all PTTW holders are now required to report actual daily water takings to the MOECC for each source listed in the permit. To facilitate compliance, the MOECC developed the Water Taking Reporting System (WTRS) to accept self-reporting information electronically over the Internet. Submission of data by e-mail or paper reporting forms is also acceptable.

The GRCA provided a copy of the yearly WTRS data for the Whitemans Creek area spanning 2009 to 2012 in June 2015, as well as WTRS data for 2013 and 2014 in May 2016. In other studies, Earthfx found data prior to 2009 to be incomplete because (1) the requirement to report was phased in over time (2005 to 2008) for different classes of users and (2) all the non-electronic reporting may not have been processed at the time of the release of earlier versions of the WTRS data.

GRCA (2011) also noted that, in 2008, reporting for some sources (e.g., municipal and several commercial/industrial subcategories) was 100% compliant, while agricultural pumping had poor compliance reporting. Daily reported rates of agricultural takings amounted to 34% of all sources in the Grand River watershed. It was further noted that (1) 2008 was the first year for agricultural reporting and many agricultural takers could have been late entering their information; (2) many glitches were experienced in entering the proper data into the online database; (3) many users lacked the Internet connection required for data input; and (4) 2008 was a wet year, which had little irrigation requirements. Some confusion may exist among permit holders as to whether it is necessary to report zero values (or a nothing/null entry) if water is not used on a particular day.

A key difficulty in analyzing the WTRS data from 2009 to 2012 is that no location coordinates or client name are provided in the WTRS extract. Matching can only be done based on the PTTW permit numbers and the source description. Permit numbers are often changed when the permit is renewed or when it is reissued with changes to conditions or water use rates. Source descriptions are very brief and often generic (e.g., “well” or “pond”) making it more difficult to re-link new permit numbers to older ones. Some (24) of the source descriptions for permits with multiple sources are indistinguishable (e.g., two or more occurrences of the SourceID “pond” for the same permit) making it impossible to determine which source is being reported. It should be noted that there appear to be improvements in recently issued permits which tend to have more descriptive SourceIDs. In 2013, the MOECC started providing location coordinates with the WTRS data, making it easier to match reported takings with a permitted source from the PTTW data.

Of the 413 PTTW sources active in the study area for part of 2014, 299 matches were found in the 2014 WTRS data (after some corrections were made to data entries). These findings are summarized in Table 6.5. Furthermore, 117 matches were found to the 151 PTTW permits within the Whitemans Creek subwatershed. Match results for other years are also reported in Table 6.5. Active surface water permits in the model area and Whitemans Creek subwatershed with reported WTRS data dating back to 2009 are listed in Appendix A. Active groundwater and mixed groundwater/surface water permits dating back to 2009 are listed in Appendix B. Results for previous years (2009 to 2013) are also shown in Table 6.5. Compliance with water use reporting was about 72% in 2014. The rate of compliance has improved considerably since 2009, the year after mandatory reporting for all private takings went into effect.

Table 6.5: Sources in the PTTW database matching WTRS reported data.

WTRS Data (Year)	Matches to PTTW Data	Active Sources	Matches in Whitemans Creek	Active Sources
2009	110	519	21	190
2010	282	473	76	162
2011	316	443	89	153
2012	300	411	104	138
2013	283	426	104	143
2014	299	413	117	151

6.2.3 MOE WWIS Database - Database Current as of 2015

The third key source of provincial information is the MOECC Water Well Information System (WWIS). This database summarizes well construction information reported by well drillers for water wells drilled in the province. The WWIS provides valuable information on the well location, well depth, screen setting, static water level, specific capacity, well yield and pump capacity, and well purpose. Each well is assigned a unique alphanumeric Well ID. The well information can be used to determine the aquifer from which the groundwater takings are drawn. Digital copies of the paper records (for data verification and location sketches) can be obtained from the MOECC website.

There is no direct link between the information in the WWIS and the PTTW databases although *occasionally* there is a reference to a specific Well ID in the PTTW Source description. Coordinates supplied for the permit location usually do not match exactly with those in the WWIS database. WWIS owner names and PTTW client names, which frequently change, also do not match exactly. The well purpose code categories used in the WWIS are similar but not identical to the PTTW records, and there are purpose codes in the PTTW database that are not represented in the WWIS data. However, using GIS techniques, it is sometimes possible to visually link the source location with a well record. A significant effort was made in this study to link the PTTW sources to the appropriate well records and thereby determine which hydrostratigraphic unit was being pumped.

6.2.4 Methodology for Compiling Provincial Water Use Data

The PTTW and WTRS databases described in Section 6.2 were used as the primary sources of groundwater and surface water use estimates. Some initial screening and reconciliation of the data was required, including:

- Water takings in the MOECC PTTW database are classified as "ground water", "surface water", or "surface and ground water". An example of the latter would be a shallow dug-out pond, where the pond is assumed to be excavated into the shallow water table. According to the MOECC PTTW database, 416 of the active permit sources were classified as groundwater, 99 as surface water, and the remaining 42 were classified as surface and groundwater. For the groundwater sources, more than half of them listed "pond", "dugout", or other surface water source as their Source ID. To rectify inaccuracies in the permit source classifications, a search was conducted on all "surface water" and "surface and groundwater" locations for Source IDs with key words implying a groundwater source (e.g., "well", "pw", "sand point"). Any inconsistencies were corrected by reassigning the source to the "groundwater" classification. Similarly, all groundwater sources were filtered for key words relating to surface water sources, including "Grand", "Nith", "River", "Creek", "tributary", and "on-stream"; any such occurrences in the database were reviewed and reassigned as "surface water" takings.

- Reported takings within the WTRS datasets were linked to the sources in the PTTW database using a combination of the permit number and the Source ID. Coordinates (northings and eastings) were also provided in the 2013 and 2014 WTRS datasets allowing for more certain matching of PTTW sources to their WTRS datasets.

- As noted earlier, expired permits (as of January 2016) were kept in the current database and used when assessing compliance with reporting documented in the 2009 to 2014 WTRS datasets. All permits active as of January 1st, 2009 were included in the Tier 3 Assessment, unless they were amended (replaced) by a newer permit.

- Of the active sources, many can be considered to be non-consumptive water uses. This includes permits with the primary or secondary purpose listed as conservation, dams and reservoirs, dredging, pipeline testing, pumping tests, and wildlife recreation. These have been flagged in the permit tables and omitted from the following water use estimation and other analyses for the Tier 3 Assessment.

6.2.5 Spatial Distribution of Water Takings

The locations of active groundwater and mixed surface and groundwater permit sources, based on the PTTW records, are shown in Figure 6.3. The majority of the permit sources are located in the lower portion of the Whitemans subwatershed, with a similar density of permit sources immediately to the south. Active surface water permit sources are shown in Figure 6.4.

6.2.6 Water Use by Category

As noted above, permit sources are categorized by primary and secondary use. The largest primary category is agriculture with 458 groundwater sources and 99 surface water sources in the study area. A breakdown of permitted water takings by primary and secondary use is provided in Table 6.6. Locations of groundwater and surface water permits by primary class are shown on Figure 6.3 and Figure 6.4, respectively. Further breakdowns of agricultural permits by secondary purpose are shown on Figure 6.5 and Figure 6.6, respectively.

Table 6.6: Active permitted sources categorized by primary and secondary purpose.

Primary Purpose	Secondary Purpose	Study Area		Whitemans Creek	
		Groundwater	***Surface Water***	***Groundwater***	***Surface Water***
Agricultural	Field/Pasture Crops	173	35	59	19
	Fruit Orchards	3	2	0	0
	Mkt. Garden/Flowers	2	0	0	0
	Nursery	3	0	2	0
	Other Agricultural	79	19	28	9
	Sod Farm	11	1	10	1
	Tender Fruit	2	0	1	0
	Tobacco	96	33	37	23
Commercial	Aquaculture/Other	2	3	0	0
	Golf Courses	10	6	4	0
	Other	1	0	0	0
Construction/	Construction	2	0	0	0
Dewatering	Pits and Quarries	0	0	0	0
Industrial	Aggregate Washing	11	0	0	0
	All Other	4	0	0	0
Miscellaneous	All	4	0	0	0
Recreational	All	0	0	0	0
Remediation	All	0	0	0	0
Water Supply	Municipal	41	0	7	0
	All Other	14	0	0	0
Totals		**458**	**99**	**149**	**52**

Table 6.7 provides a summary of the number of total permits versus the number of reporting permits by primary use category within the study area. While reporting has improved in recent years, agriculture, the largest primary use category, had only 74% compliance. When assessing the remaining percentage of permits that did not report, it is important to determine whether the permits are either (1) not taking water and failing to report zero usage, (2) taking water and failing to report, or (3) a combination of both. To be conservative, takings for non-reporting users were estimated from the maximum permitted takings for the source and statistics for reported usage.

Table 6.7: Number of sources reporting to WTRS in 2014 by primary use category.

Primary Purpose	Number Reporting to WTRS (Study Area)	PTTW Sources	Number Reporting to WTRS (Whitemans)	PTTW Sources
Agricultural	254	344	108	140
Commercial	7	14	2	3
Construction	1	1	0	0
Industrial	8	10	0	0
Recreational	0	0	0	0
Remediation	0	0	0	0
Water Supply	27	41	7	7
Miscellaneous	2	3	0	0

Figure 6.7, Figure 6.8, and Figure 6.9 show the location of reported sources as well as scaled dots showing average annual takings for 2012, 2013 and 2014, respectively. A similar set of figures for reported surface water takings is provided in Figure 6.10, Figure 6.11, and Figure 6.12. As can be seen, most of the takings are relatively small and similar in scale. A smaller number of larger takings, primarily for water supply (discussed further on), can also be seen.

Table 6.8 compares maximum permitted takings and reported water use within the Whitemans Creek subwatershed by source and specific use. The values are summarized in the pie charts below (Figure 6.1), which show that agricultural use - primarily for field and pasture crops, tobacco and sod farms - dominate both permitted and reported takings. Total maximum permitted takings are about 82,000 m^3/d while total reported takings are only about 4,400 m^3/d. While it is understood that irrigation needs can vary widely from year to year, there appears a general tendency to have permitted maximum takings far in excess of actual needs. It is our understanding that the MOECC has been attempting in recent years to re-issue permits with lower, more realistic limits. The comparison also shows the importance of using the WTRS data in assessing water use rather than the PTTW values, which were used in many of the previous studies and are likely to significantly over-estimate actual water use. Figure 6.13 presents the distribution and magnitude of average reported agricultural takings within the Whitemans Creek subwatershed for 2014.

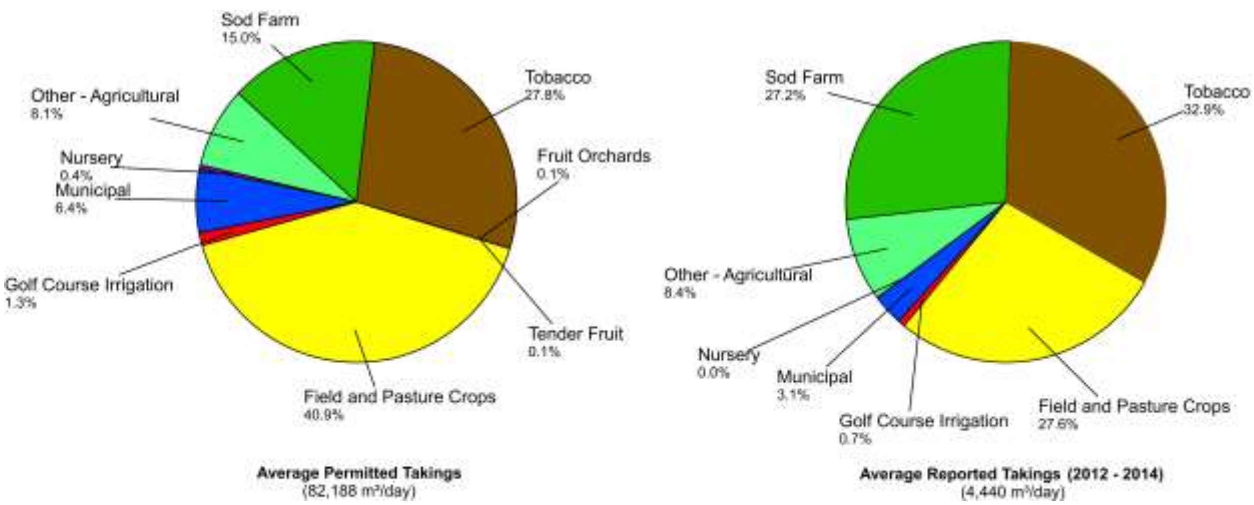


Figure 6.1: Total average permitted takings and average reported takings (2012 to 2014) in the Whitemans Creek subwatershed by specific use.

The water use analyses discussed above are based on average takings. Model simulations, however, use actual daily takings based on information in the WTRS database. No seasonal correction factors, such as those used in other Tier 3 studies, were needed.

Table 6.8: Permitted and reported water use within the Whitemans Creek subwatershed by primary and secondary use for 2012 to 2014.

Source	Purpose	Specific Use	Mean Annual Permitted Taking (m³/d)	Reported 2012 Average Demand (m³/d)	Reported 2013 Average Demand (m³/d)	Reported 2014 Average Demand (m³/d)	Average Reported Demand (m³/d)
Groundwater	*Agricultural*	Field and Pasture Crops	28,861	993	1431	747	1057
		Fruit Orchards	60	0	0	0	0
		Nursery	333	0	5	1	2
		Other - Agricultural	4,709	320	375	333	343
		Sod Farm	9,215	1303	1027	225	852
		Tender Fruit	42	0	0	0	0
		Tobacco	18,376	1520	1700	506	1242
	Commercial	Golf Course Irrigation	1,067	33	34	29	32
		Other	131	0	0	0	0
	Water Supply	Municipal	5,251	111	139	166	139
	Total		**68,045**	**4,280**	**4,711**	**2,007**	**3,666**
Mixed GW/SW	*Agricultural*	Field and Pasture Crops	2,108	16	305	93	138
		Fruit Orchards	6	0	0	0	0
		Market Gardens / Flowers	4	0	0	0	0
		Other - Agricultural	1,001	14	0	0	5
		Sod Farm	2,597	575	432	60	356
		Tobacco	199	65	0	0	22
	Total		**5,915**	**670**	**737**	**153**	**520**
Surface Water	*Agricultural*	Field and Pasture Crops	2,582	38	25	30	31
		Other - Agricultural	948	0	0	81	27
		Sod Farm	487	0	0	1	0
		Tobacco	4,212	272	242	74	196
	Total		**8,228**	**309**	**267**	**186**	**254**
Grand Total			***82,188***	***5,259***	***5,714***	***2,345***	**4,440**

Despite the significant improvements in the number of agricultural water users reporting their water usage to the WTRS database, there is still considerable uncertainty regarding non-reporting users and potential non-permitted users. These sources of uncertainty highlight the need for a specific irrigation demand tool that can estimate water use based on various hydrological parameters such as soil moisture deficit rather than relying solely on the reporting system.

6.2.7 Water Use by Aquifer

Neither the PTTW data nor the WTRS data provide any information linking a specific groundwater source to a known hydrostratigraphic unit. Information regarding details of well construction is available within the MOECC WWIS. However, these data, as previously discussed, lack explicit linkages to the PTTW and WTRS datasets. A significant effort was made to link these data in order to assign each pumping well to a specific hydrostratigraphic unit within the model. To accomplish this, a process was developed to jointly process the PTTW and WWIS databases, along with the hydrostratigraphic model layers within the Tier 3 Assessment model area. The approach relied upon a hierarchical approach, with increasing uncertainty, to assign groundwater permit sources to hydrostratigraphic units.

As illustrated in Figure 6.2, the highest level of certainty occurred where a perfect match could be made between a PTTW Source ID and a pumping well location. This was the case for the municipal wells with a number of years of detailed reporting and wellfield studies available to confirm the details.

The second best match occurred when the PTTW Source ID could be linked to a specific WWIS well record number; however, without corroborating supplemental information such as a wellfield report, the location was based on PTTW and WWIS database locations. This method has a slightly higher level of location uncertainty.

The third best match occurred when the PTTW Source ID was matched to the closest WWIS well within a 100 m radius. Finally, a fourth level of permit assignment was made when no well was located within 100 m. In this final case, the PTTW Source was assigned to the aquifer most commonly used within an 800 m radius of the source.

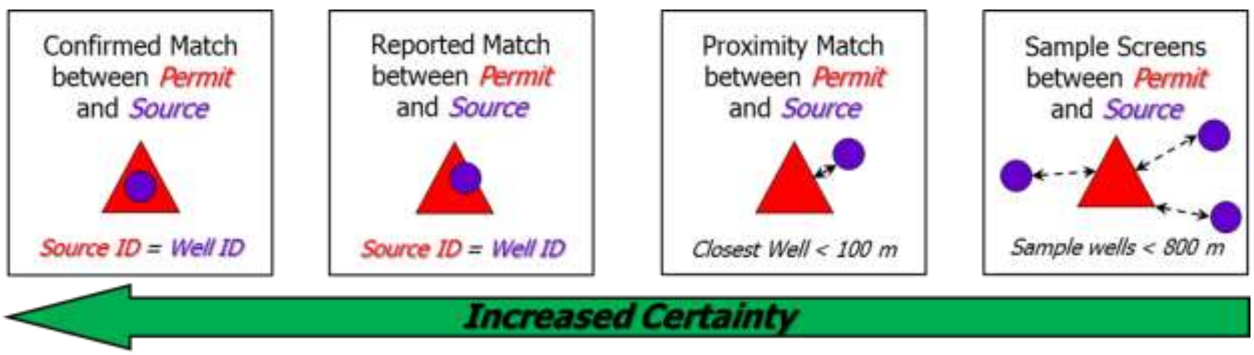


Figure 6.2: Schematic of hierarchical approach used to link groundwater permit sources to water well records, and relative levels of certainty.

The distribution of groundwater sources, along with their interpreted source-type (bedrock, overburden, or shallow water table source) are presented in Figure 6.14. Table 6.9 contains reported average takings from individual hydrostratigraphic layers within the model area and the Whitemans Creek subwatershed. The values in Table 6.9 include both groundwater and shallow water-table sources (i.e., dugout ponds). A review of the shallow overburden stratigraphic layers below each of the dugout ponds was undertaken so that these ponds could be assigned to the shallowest significant aquifer unit. This was most frequently identified as the Sand Plain-Outwash Aquifer that occurs in the Norfolk Sand Plain.

The majority of the reported water takings for agricultural use are from the Sand Plain-Outwash and the Waterloo Moraine aquifers. These are generally shallow units making them economical options for irrigation. The volumes taken vary significantly from year-to-year based on irrigation demand. The deeper Weathered Bedrock and Onondaga Escarpment aquifers also have relatively large reported takings, and are typically used for municipal water supply.

Table 6.9: Reported average water use by aquifer for 2012 to 2014

Hydrostratigraphic Unit	WTRS Average Reported Taking within Model Area (m^3/d)			WTRS Average Reported Taking within Whitemans Creek Subwatershed (m^3/d)		
Year	2012	2013	2014	2012	2013	2014
Whittlesey Sands	343	27	44	--	--	--
Wentworth Aquitard	--	--	--	--	--	--
Sand Plain – Outwash Aquifer	10,007	9,136	7,861	2,723	2,605	1,860
Port Stanley Till Aquitard	75	31	86	34	31	86
Tavistock Till Aquitard	12	10	19	--	--	--
Waterloo Moraine Aquifer	16,765	12,407	13,517	661	1,129	404
Maryhill Till Aquitard	--	--	--	--	--	--
Post Catfish Aquifer	447	87	87	25	25	27
Catfish Creek Till	3	3	3	3	3	3
Pre-Catfish Aquifer	319	--	275	--	--	--
Canning Till Aquitard	--	--	--	--	--	--
Weathered Bedrock Aquifer	4,527	4,370	3,860	610	453	5
Onondaga Escarpment Aquifer	2,151	1,513	2,003	--	--	--
Salina Poor Aquifer	--	--	--	--	--	--

6.3 *Municipal Water Supply Systems*

The assessment of the sustainability of the Bright and Bethel municipal water supply systems is a primary goal of this Tier 3 Assessment. Only those two municipal supplies in the Whitemans Creek subwatershed will be assessed under the Tier 3 rules; however other municipal water takings are included in the numerical simulations to insure that cumulative effects of pumping are represented. Figure 6.15 shows the locations of municipal wellfields in the Tier 3 Assessment area and, in particular, the Community of Bright and the Paris Bethel Road municipal wellfields located in the Whitemans Creek subwatershed.

Data on municipal takings were provided by the GRCA, and the Counties of Oxford and Brant which operate the municipal systems, in June 2015. Background information on well locations, well depths, and well capacities were found in earlier studies although some data have been updated. Annual reports by the wellfield operators are published online. The annual reports focus on water quality; however, the County of Oxford also supplies data on monthly and annual water takings. Daily data were extracted from the WTRS database for 2009 to 2014. Figure 6.16 presents the annual average groundwater takings for the municipal wells within the Tier 3 Assessment area. Descriptions of the municipal water supply systems are provided in the following sections.

6.3.1 Community of Bright Municipal Wellfield

The Bright Drinking Water System, operated by the County of Oxford, is located in the upper part of Whitemans Creek subwatershed and provides water from two wells, 27 m and 38 m deep, under PTTW No. 7467-84BQEE. The wells serve a population of approximately 409 residents. Maximum permitted takings are 327 m^3/d. Annual reports are available at the Oxford County website (www.oxfordcounty.ca/drinkingwater). Daily takings were provided by Oxford County and were also found in the WTRS database. Table 6.10 provides a summary of the 2011 to 2014 production rates and water takings from the Bright wellfield.

Table 6.10: Annual production rates and water taking summary from the Bright wellfield.

Annual Report (Year)	Average Daily Flow (m^3/d)	Maximum Daily Flow (m^3/d)	Total Annual Production (m^3)	Total Well 4 (m^3)	Total Well 4A (m^3)	Total Well 5 (m^3)
2011	87	177	31,609	-	31,602	7
2012	96	200	35,150	-	35,138	12
2013	94	195	34,266	-	34,264	1
2014	96	213	35,217	-	32,764	2,453

Note: [1] Annual reported takings for Bright municipal wells 4A and 5 were not available for 2015.

Well 4A is used as the main production well. Well 4 is no longer used and Well 5 was idle most of 2011, 2012, and 2013. The annual report for 2015 noted that the wells are not capable of producing at the maximum permitted rate and a more realistic estimate of maximum capacity of the system is 286 m^3/d. At the time of this study, the County was undertaking exploratory investigations to identify an additional groundwater source. They were not yet able to locate a nearby aquifer with acceptable water quantity and quality.

Figure 6.17 and Figure 6.18 present the well characterization plots for the two Bright municipal wells. These plots show the response of groundwater levels, both in the supply well and in nearby monitoring wells, to pumping at Bright municipal Wells 4A and 5, respectively. These characterisation plots indicate that the impact of pumping from the municipal wells is limited to the immediate vicinity of the supply wells, with little to no observable impact to water levels in the neighboring monitoring wells MW-1D and MW-1S.

The impact of increased pumping at Well 4A, in 2010, (when wellfield production was shifted entirely to this well) can be seen by a significant decline in the in-well water levels (shown in orange; Figure 6.17). The problems with well efficiency in Well 5 can also be seen in Figure 6.18. Well 5 pumping through 2010 depressed water levels (orange line in Figure 6.18) to the well screen, after which pumping was shifted to Well 4A. After 2010, water levels in Well 5 recovered with the cessation of pumping and levels can be seen to fluctuate in a similar manner as nearby monitor MW-1D.

6.3.2 Bethel Road (Town of Paris) Municipal Wellfield

The Paris water system is owned and operated by the County of Brant and serves about 11,400 people (4,335 residential and 320 industrial/commercial/institutional connections). There are three wellfields; the Gilbert wellfield, which is the primary source of water, the Telfer wellfield, and the Bethel Road site. The Bethel Road site is located at the eastern end of the Whitemans Creek subwatershed and provides water to the Brant 403 business park and the south end of the city of Paris, as described on the County's website. Four wells were drilled near Bethel Road west of the intersection with Rest Acres Road. The wells are completed in the intermediate to deep overburden sediments (depths ranging from 22.3 to 33 m). A study by International Water Consultants (2012) concluded that the wells are not considered GUDI (groundwater under direct influence of surface water) although earlier studies had provisionally designated the wells as GUDI with effective filtration due to the unconfined nature of the aquifer (IWC, 2008). The Bethel wellfield was officially put into production in May 2013.

Pumping at the Bethel Road site is governed under PTTW No. 8545-A48Q8C (which replaced PTTW 1823-9X6HYC in November 2015). The permit allows pumping from TW1/05 at a maximum rate of 15 L/s; while PW1/12, PW2/12 and PW4/12 can all pump at maximum individual rates of 15.2 L/s. Daily taking from TW1/05 cannot exceed 1,296 m^3/d, while PW1/12, PW2/12 and PW4/12 each have individual total daily limits of 1,311 m^3/d. The total combined daily taking from the wellfield cannot exceed 3,240 m^3/d. The permit allows combined peaking rates of 50 L/s (or 4,320 m^3/d daily taking) for a 30 day period. Table 6.11 provides a summary of the 2012 to 2015 production rates and water takings from the Bethel Road wellfield. Production at the wellfield increased in 2015 compared to the preceding years as all four wells came into operation, with a combined an annual production of 76,000 m^3.

Table 6.11: Annual production rates and water taking summary from the Bethel Road wellfield.

Annual Report (Year)	Average Daily Flow (m^3/d)	Maximum Daily Flow (m^3/d)	Total Annual Production (m^3)	Total TW 1/05 (m^3)	Total PW 1/12 (m^3)	Total PW 2/12 (m^3)	Total PW 4/12 (m^3)
2012	15.3	744	5,590	5,590	0	0	0
2013	44.7	442	16,308	16,308	0	0	0
2014	68.1	485	24,857	24,857	0	0	0
2015	208.3	1,741	76,033	21,587	18,316	19,130	17,000

The well characterization plots for Bethel Road wells PW1/12, PW2/12, TW1/05 and PW4/12 are provided in Figure 6.19 through Figure 6.22, respectively. Pumping from TW1/05 (Figure 6.21) has been ongoing since October 2012. This well has been interpreted as being screened across a deeper confined to semi-confined sand aquifer. Water levels from the nearby monitoring well SMW6/12 seem to support this, as the drawdowns due to nearby pumping are apparently absent in the adjacent monitoring well. PW1/12 and PW2/12 entered into operation in July of 2015 and pumping at PW4/12 began in August of 2015; however, water level data for the nearby municipal monitoring wells were not available for this period at the time of this study, making it difficult to evaluate the impacts of municipal pumping on the adjacent monitoring wells.

6.3.3 Municipal Wells outside of the Whitemans Tier 3 Assessment Watershed

The following is a summary of the municipal wells located within the model area but outside of the Whitemans Creek subwatershed. Pumping from these wells will be included in the simulations so as to reflect the cumulative water use during the Study Period; however these wells will not be included in the Tier 3 Risk Assessment.

6.3.3.1 County of Brant Municipal Supplies in the Model Area

The Paris water system includes two additional wellfields that are located immediately outside of the Whitemans Creek subwatershed (Figure 6.15). The Gilbert wellfield on Grand River Street North is the primary source of water. It consists of eight wells: two wells (P28 and P29) are drilled into bedrock and are capable of pumping 37.9 L/s each, the other six wells (P210, P211, P212, P213, P214, and P215) draw water from the overburden. Total capacity of the overburden wells is 50 L/s. The permitted maximum pumping is 3,024 m^3/d on a 7-day running average. A summary of water takings for the County of Brant municipal supplies is provided in Table 6.12. The active wells are referred to as TW3, TW4, TW, TW6, and TW8 in the PTTW database. The Telfer wellfield, on West River Road, has two wells (P31 and P32) which are used primarily during high demand periods or system maintenance. P31 is completed in the overburden and P32 is completed in the bedrock. Each well is capable of pumping 37.8 L/s. A well, referred to as P36, is listed in the PTTW database but was not active. The Fairview Heights wellfield on Schuyler Street was decommissioned in May 2014.

Other Brant County operations in the model area include the Airport Road and Mount Pleasant water supplies. The Mount Pleasant water supply system is located on Ellis Avenue and consists of two drilled wells completed in the overburden, each equipped with a vertical turbine pump capable of pumping 26.5 L/s each. The PTTW restricts combined pumping from the wells to a maximum of 26.5 L/s. The distribution system services 581 residences and 25 commercial accounts.

The Airport water supply system consists of one drilled well completed in the overburden equipped with a vertical turbine pump capable of pumping 26.5 L/s. The Airport municipal system operates under PTTW number 4487-6YPSAM, which expires October 31st, 2016. This permit is expected to be amended to reflect the addition of a new municipal water supply well completed in 2014. The distribution system services about 248 residences and 26 commercial accounts near the Brantford Airport.

Table 6.12: Water takings for County of Brant municipal systems for 2012, 2013, and 2014 (inside model area).

Wellfield	Permit Number	Source ID	2012 Average Pumping (m^3/d)	2013 Average Pumping (m^3/d)	2014 Average Pumping (m^3/d)	Average Annual Production (m^3)
County of Brant						
Bethel	8545-A48Q8C	TW 1/05	0	161.5	134.4	20,582
		PW 1/12	0	0	0	0
		PW 2/12	0	0	0	0
		PW 4/12	NA	NA	0	0
Mount Pleasant	4008-6YUQ6G	Mt. Pleasant Well #1	115.0	NA	NA	41,987
		Mt. Pleasant Well #2	647.0	NA	NA	236,328
Brantford Airport	4487-6YPSAM	Airport Municipal Well	219.2	206.6	214.2	77,937

6.3.3.2 County of Oxford Municipal Supplies in the Model Area

The County of Oxford operates the Beachville, Bright, Drumbo-Princeton, Hickson, Ingersol, Innerkip, Norwich, Plattsville, Tavistok, and Woodstock water supply systems in the study area. The Bright system was discussed earlier. Data on well construction and water use were obtained from County of Oxford annual reports, ARL Groundwater Resources Limited (2010), and the Tier 3 Water Budget Assessment for Oxford County (Matrix Solutions, 2014). Water takings for the Oxford County municipal supplies are provided in Table 6.13.

The Beachville–Loweville Subdivision Water System is a small municipal water system that serves a population of about 181. The system has a 91 m deep bedrock well which pumped at 16,183 m^3 in 2012, 13,868 m^3 in 2013, 13,850 m^3 in 2014, and 17,746 in 2015. The maximum permitted taking is 657 m^3/d.

The Drumbo-Princeton system consists of three deep overburden wells located in Drumbo and serves a population of about 1300. Well 1 is about 37 m deep, Well 2A is about 44 m deep, and Well 3 is 32 m deep. In June 2012, a transmission line was completed to supply the town of Princeton. The permit for the local Princeton wells expired in 2006. Combined pumping was 90,956 m^3 in 2012, 103,631 m^3 in 2013, 109,984 m^3 in 2014, and 106,622 m^3 in 2015. The maximum permitted taking is 1329 m^3/d.

The Hickson water system is a small municipal water system that serves approximately 102 people. The system has a 53 m deep bedrock well which pumped at 8,014 m^3 in 2012, 8,500 m^3 in 2013, 8,625 m^3 in 2014, and 9,225 m^3 in 2015. The maximum permitted taking is 300 m^3/d.

The Ingersoll water system is located at the western extreme of the study area and serves a population of approximately 13,100. The system consists of seven bedrock wells, two of which were listed as unused (Well 7 and Well 11) in the 2014 and 2015 reports. One well, Well 5, is located inside the model boundary. Well depths range from 109 to 148 m. The wellfield was issued a new permit in August 2012 and the WTRS database has no reported takings (except for Well 2) prior to that time. The maximum permitted taking is 26,367 m^3/d.

Table 6.13: Water takings for Oxford County municipal systems for 2012, 2013 and 2014 (inside model area).

Wellfield	Permit Number	Source ID	2012 Average Pumping Rate (m³/d)	2013 Average Pumping Rate (m³/d)	2014 Average Pumping Rate (m³/d)	Average Annual Production (m³)
County of Oxford						
Bright	7467-84BQEE	Well 4	0	0	0	0
		Well 4A	96.0	94.1	89.8	34,078
		Well 5	0	1.5	6.7	831
Beachville	2531-9KTQ2U	Well #1	44.2	NA	NA	16,150
Drumbo - Princeton	3760-8KDJB9	Well 1	0	54.3	56.9	14,608
		Well 2A	71.9	81.8	76.9	28,069
		Well 3	177.1	182.5	172.7	64,814
Ingersoll	0282-8XER2W	Well 5	1504.2	1643.8[1]	1369.8[1]	550,050[1]
Innerkip	2268-7MKSAR	Well 1	198.1	217.9	227.6	78,364
		Well 2	195.4	206.4	216.8	75,327
Norwich	1101-7HJQ9C	Well No. 2	389.1	377.9	258.4	124,845
		Well No. 4	107.7	154.2	102.5	44,368
		Well No. 5	246.5	239.2	162.9	78,959
Tavistock	0352-8SFKQF	Park Well #1	74.5	72.3	69.6	21,833
		Park Well #2A	139.6	45.6	609.9	36,829
		Park Well #3	1137.9	1174.9	1220.4	381,248
Woodstock	7546-8C6SS5	Southside Well 6	867.9	1216.4	1420.2	394,629
		Sutherland Park Well 7	590.1	621.6	451.2	189,459
		Hart Springs Well 9	0.8	3.0	1.5	332
		Thornton Well 1	18.8	125.3	87.4	18,054
		Thornton Well 3	151.3	160.1	0.9	24,382
		Thornton Well 5	157.8	1044.4	4.9	132,176
		Thornton Well 8	1330.5	1216.8	1194.6	450,035
		Thornton Well 11	1838.1	1464.9	1545.2	590,273
		Tabor Well 2	5295.0	4776.9	4688.5	1,797,084
		Tabor Well 4	4723.1	4493.0	4391.3	1,656,692

Note: [1] 2013 and 2014 daily reported values not available for the Ingersoll municipal system. Averages were inferred from 2013 and 2014 Annual Drinking Water System Summary Reports prepared by Oxford County.

The Innerkip water system serves a population of approximately 935. The system consists of two bedrock wells located 1.8 km southwest of the town. Well 1 has a depth of approximately 34.4 m and Well 2 has a depth of 35 m. Combined pumping was 144,036 m³ in 2012, 124,323 m³ in 2013, 154,842 m³ in 2014, and 120,411 m³ in 2015. The maximum permitted taking is 1,728 m³/d.

The Norwich water system consists of three wells which serve about 3,200 residents as well as commercial, institutional and industrial customers. Wells 2 and 5 are about 34 m deep. Well 4 is about 26 m deep. Combined pumping was 272,046 m³ in 2012 and 294,962 m³ in 2013. In 2014, Norwich started reporting combined takings with Otterville and Springford which are outside the study area. The maximum permitted taking is 4,743 m³/d. The location for Norwich Well No. 2 was incorrect in the PTTW database and has been updated.

The Tavistock water system services a population of approximately 2,690 people. The system consists of three groundwater wells: Park Well #1 is in the overburden to a depth of 19.5 m, while Park Well #2A and

Park Well #3 are bedrock wells with depths of 62 m and 48 m, respectively. The bedrock wells are the primary suppliers. The wellfield was issued a new permit (0352-8SFKQF) in February 2012. The WTRS database has some takings reported under the old permit (6217-7JHMTQ) and the rest under the new permit although about 36 days of reporting is missing. Combined pumping is estimated at 484,653 m^3 in 2012, 454,404 m^3 in 2013, 481,364 m^3 in 2014, and 486,555 m^3 in 2015. The maximum permitted taking is 5,616 m^3/d.

The Woodstock water system serves 38,000 residents in the City of Woodstock and the community of Sweaburg to the south. There are three bedrock wells within the City to the north of Highway 401 and two major wellfields with multiple overburden wells southwest of the city. The three bedrock wells are Southside Park (Well 6), Sutherland Park (Well 7), and Hart Springs (Well 9) and are between 20 and 63 m deep. The Thornton wellfield has five wells (Wells 1, 3, 5, 8, and 11) with screen settings ranging from approximately 13 to 32 m deep. The Tabor wellfield has two wells (Wells 2 and 4) with screen settings from 15 to 23 m below surface. There is also a planned well, referred to as the Bond Well (Well 12), located to the west of the Tabor wellfield. Combined pumping was 5,480,246 m^3 in 2012, 5,239,938, m^3 in 2013, 5,425,686 m^3 in 2014, and 5,314,616 m^3. The maximum permitted taking is 57,775 m^3/d.

6.3.3.3 Township of Perth Municipal Supplies in the Model Area

The Shakespeare water system is a small municipal water system operated by the Township of Perth under PTTW number 3714-7BCMU5, and serves approximately 260 people. The system consists of an 85 m deep bedrock well. The total annual pumped volume for the Shakespeare wellfield was 22,184 m^3 in 2012, 20,736 m^3 in 2013, and 20,982 m^3 in 2014. The maximum permitted taking is 546 m^3/d. Water takings for the Township of Perth municipal supplies are provided in Table 6.14.

Table 6.14: Water takings for Township of Perth municipal systems for 2012, 2013 and 2014 (inside study area).

Wellfield	Permit Number	Source ID	2012 Average Pumping Rate (m^3/d)	2013 Average Pumping Rate (m^3/d)	2014 Average Pumping Rate (m^3/d)	Average Annual Production (m^3)
Township of Perth						
Shakespeare	3714-7BCMU5	Well	60.5	56.8	57.5	21,290

6.3.3.4 Regional Municipality of Waterloo Municipal Supplies in the Model Area

The New Hamburg municipal water supply system is operated by the Regional Municipality of Waterloo. It consists of a single well, NH3, which is located just inside of the study area, on the south side of the Nith River. The wellfield is operated under MOECC Permit No. 8556-8M5QAL, which has a maximum permitted taking of 3,543 m^3/d. The system supplies an estimated 13,287 residents. Total pumping for 2012 was reported at 514,331 m^3, 592,898 m^3 in 2013, and 577,357 m^3 in 2014. Municipal water takings for New Hamburg are provided in Table 6.15.

Table 6.15: Water takings for Regional Municipality of Waterloo municipal systems for 2012, 2013 and 2014 (inside study area).

Wellfield	Permit Number	Source ID	2012 Average Pumping Rate (m³/d)	2013 Average Pumping Rate (m³/d)	2014 Average Pumping Rate (m³/d)	Average Annual Production (m³)
Regional Municipality of Waterloo						
New Hamburg	8556-8M5QAL	NH3-6507832	1405.3	1684.3	1581.8	561,144

6.4 *Private Domestic Wells*

According to the MOE WWIS database, there are 1,247 wells with primary or secondary purpose designated as “domestic water supply” located in the model area (Figure 6.23). Assuming a private domestic daily water use rate of 1.2 m³/d with a consumptive use factor of 0.2, the private domestic wells in the model area represent a mean daily consumptive taking of approximately 300 m³/d.

6.5 *Livestock Watering*

Unlike water takings for irrigation purposes, livestock watering does not require a permit. In addition, the demand for livestock watering is generally year-round rather than seasonal. With no permitting or reporting system in place, estimating livestock water requirements is more difficult and requires many assumptions. There have been several studies within southern Ontario that estimated regional-scale livestock water use (e.g., AquaResource Inc., 2009a; de Loë *et al*., 2001; GRCA, 2005; and Wong, 2013). These assigned water use coefficients to different livestock categories and then applying these values to the Canadian agricultural census data. AquaResource Inc. (2009a) and Wong (2013) provided estimates for the Whitemans Creek subwatershed of approximately 690 and 1,200 m³/d, respectively. The source of the discrepancy between the two estimates is unclear. Water use coefficients are available from OMAFRA and from Agriculture and Agri-Food Canada (AAFC).

A total of 1,178 WWIS wells with primary or secondary purpose designated as “livestock” are located in the model area (Figure 6.24). These were represented explicitly in the model. Water takings for livestock were estimated using an improved approach based on Municipal Property Assessment Corporation (MPAC) data for Oxford and Brant counties, as described below.

For this study, the average daily livestock water use on a per-farm basis was calculated by multiplying the average number of animals per farm by their average water requirement. A breakdown of the different livestock types and their water requirements are presented in Table 6.16. For cattle, swine, and sheep, the average water requirement was assumed to be a weighted average based on population breakdowns from Statistics Canada (2012a, b, and c). Swine were given special consideration as some farms were classified as “large-scale” operations. These farms were estimated to have 2,500 pigs based on an assumed holding area of 50,000 square feet and 20 square feet allotted per pig as per Bond *et al.* (1962). For poultry, horses, and other livestock, an unweighted average was used due to lack of available data. The majority of the livestock water use data were obtained from OMAFRA (2007); however, in some cases, data were obtained from AAFC (2009) when it provided a better match to the census data.

Table 6.16: Water use by animal and by farm.

Animal Type		Water Use Range (L/d)[1]	Average Daily Water Use per Animal (L/d)[1]	Average Number[2]	Average Daily Water Use per Farm (L/d)
Dairy Cattle	Calves	4.9 - 13.2	9	86	4,836
	Heifers	14.4 - 36.3	25		
	Milking cows	68 - 155	115		
	Dry cows	34 - 49	41		
Beef Cattle	Cows	22 - 54	28	86	4,996
	Calves	18 - 27[3]	22.5[3]		
	Heifers	22 - 55	38		
	Bulls/Steers	22 - 56	38		
Swine	Breeding Stock	13.6 - 22.7	17.5	1,208/2,500	10,268/21,250
	Growing Pigs	5.0 - 10[3]	7.5[3]		
Sheep	Rams	4.4 - 7.1	5.75	99	518
	Ewes	4.4 - 7.1	5.75		
	Lambs	3.6 - 5.2[3]	4.4[3]		
Poultry	Laying Hens	0.18 - 0.32	0.25	6,458	1,302
	Pullets	0.03 - 0.18	0.105		
	Broiler breeders	0.18 - 0.32	0.25		
	Turkey (Fall/Winter/Spring)	0.296 - 0.513	0.41	3,762	1,862
	Turkey (Summer)	0.402 - 0.723	0.58		
Horse	Small (500 lb)	13 - 20	16.5	8	261
	Medium (1000 lb)	26 - 39	32.5		
	Large (1500 lb)	39 - 59	49		
Other	Rabbits	0.3 - 1.02	0.7	unknown	unknown
	Mink	0.19 - 0.39	0.3	1,970	591
	Goats	3.0 - 15[3]	9[3]	54	486

[1] Range and average data obtained from OMAFRA (2007) unless stated otherwise
[2] From 2011 Canadian Agricultural Census
[3] Range from AAFC (2009), average calculated

For Oxford and Brant counties, MPAC-based estimated water takings were assigned to parcels of land known to contain specific types of livestock. Missing data from Perth County were filled in by hand using air photo analysis within the Whitemans Creek subwatershed boundary. The land parcels with known livestock operations are shown in Figure 6.25, and estimated daily livestock water takings for these farms are shown in Figure 6.26. In total, the livestock water requirements are estimated to be approximately 4,870 m³/d and 1,470 m³/d for the model area and the Whitemans Creek subwatershed, respectively.

6.6 *Data Limitations*

The compilation of water use data from various sources represents a reasonable snapshot of actual water use in the Whitemans Tier 3 model area during the 2009 through 2014 study period. These data, provided in the report tables and appendices, represent water use estimates for both model calibration and threats assessment. As noted, it was very challenging to reconcile and match permit numbers used in the different data sources. It was even more challenging to match a groundwater source with a particular WWIS well log and thereby determine information on well screen settings and the aquifer from which water is taken.

The water use compilation, reconciliation and assessment must be analyzed over an appropriate time period. The primary control over the selection of the time period was the availability of the three primary data sources (PTTW, WTRS and WWIS). The quality (including reporting compliance) and climatic conditions (representing typical water use) over the period was also considered.

Under ideal conditions, the three MOECC data sources would be linked by unique identifiers and all fields would be complete, historically accurate, up to date, and spanning several overlapping years. Unfortunately that was not the case. The WWIS database used in the analysis was downloaded from the MOECC web site in 2015 and is considered up to date. The PTTW database provided was dated June 2014, but it is difficult to determine whether permits that were to expire between 2014 and 2015 have been renewed or revised in the interim.

Finally, the WTRS database covered the 2009 to 2014 period. Assessment of water use in 2008 and earlier would require considerable estimation (as in the previous studies cited earlier). Accordingly, our efforts focused on reconciling the WWIS, PTTW and WTRS databases to the end of 2014. The reconciled data and assessment are considered representative of the 2012 through 2014 time period, and moderately representative of the 2009 to 2011 time period.

The GRCA and other agencies have recognized the importance of tracking actual water use, so progress will be made over time. It is recommended that the GRCA request that the MOECC begin a general program of reconciliation and synchronization of their three primary databases (i.e., the MOECC Water Well Information System, the PTTW database, and the WTRS database). The reconciliation and synchronization of the databases will make it easier to maintain and update critical water use information in the study area and across the province.

6.7 *Figures*

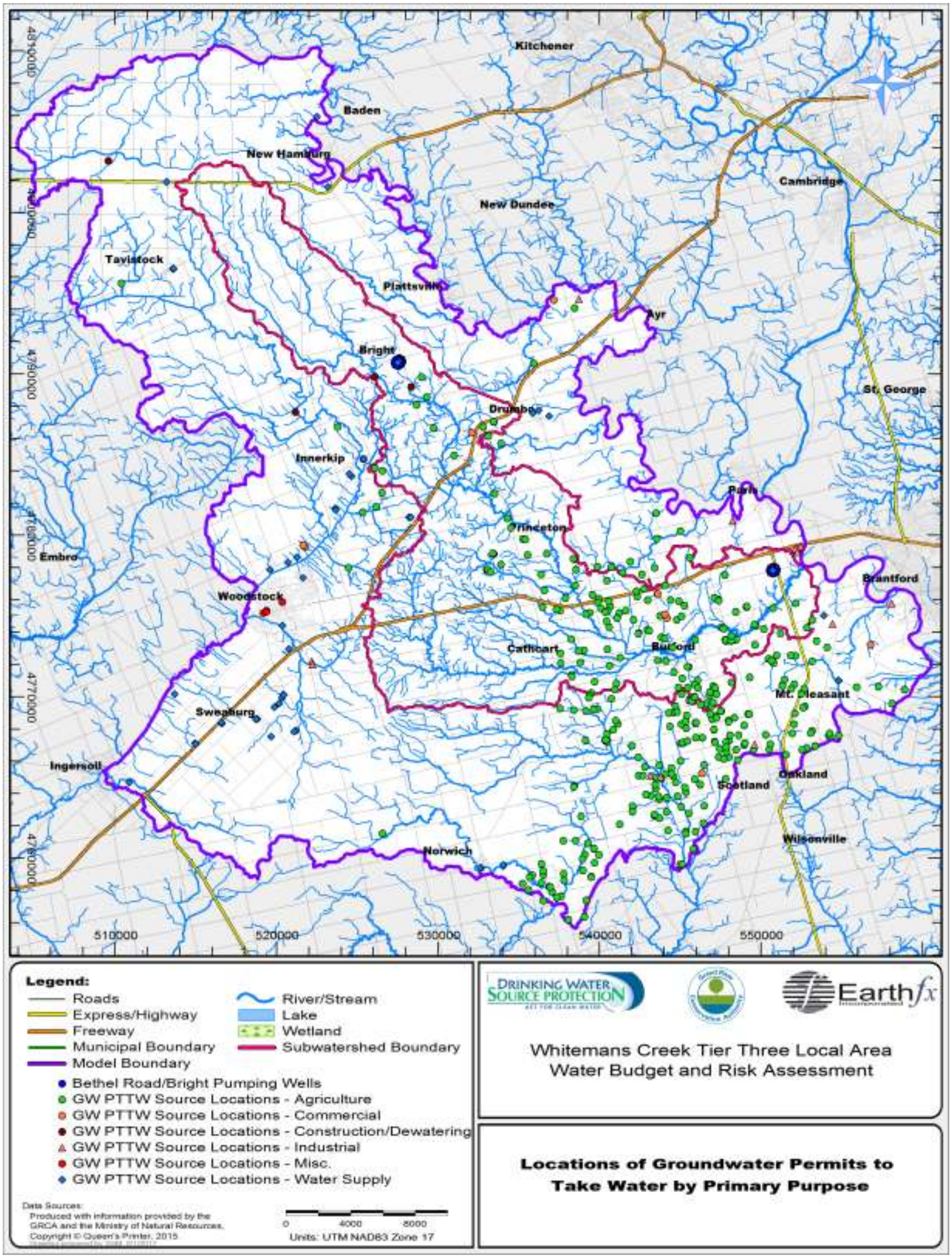


Figure 6.3: Location of groundwater permits to take water (PTTW) categorized by primary purpose, active as of January 2016.

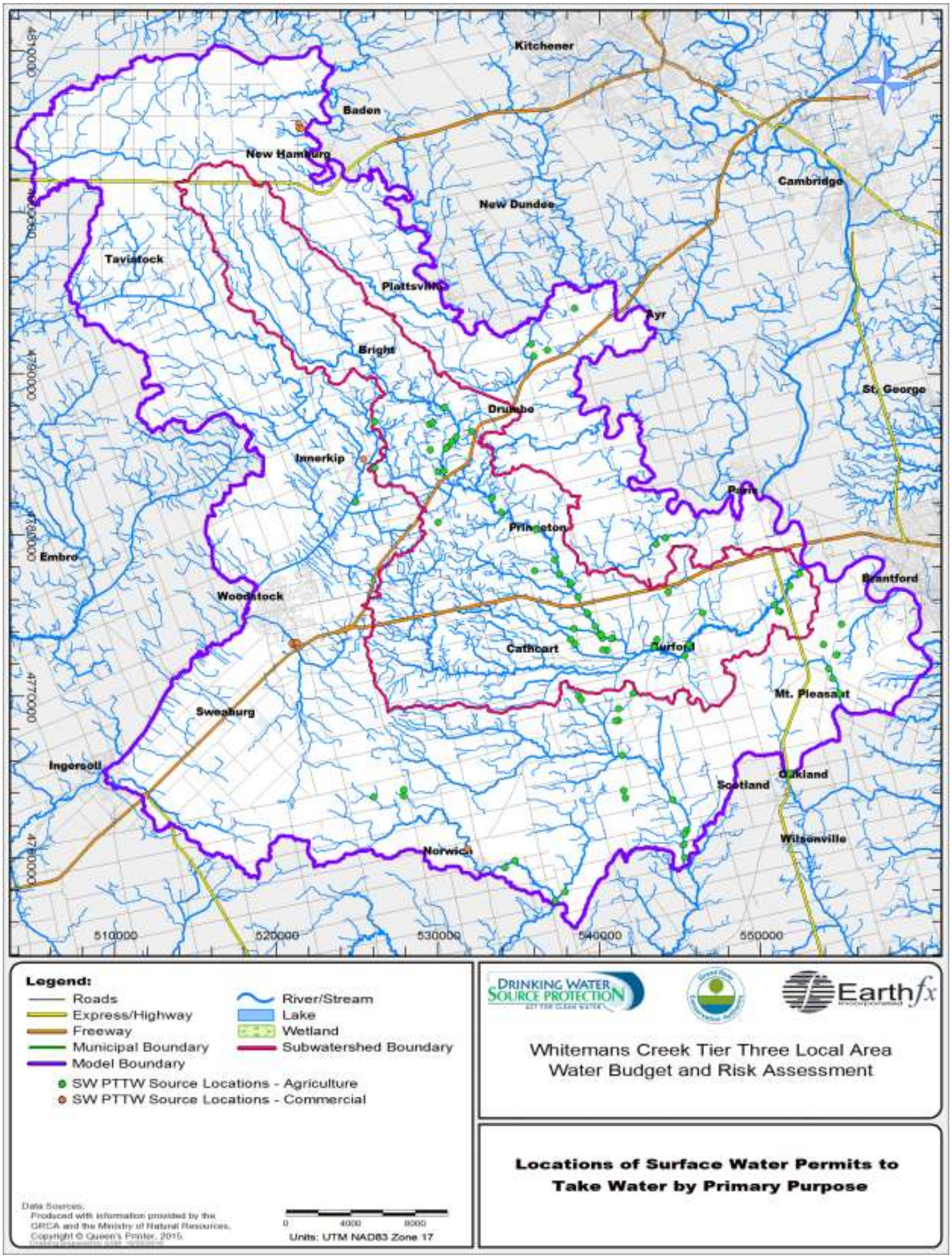


Figure 6.4: Location of surface water permits to take water (PTTW) categorized by primary purpose, active as of January 2016.

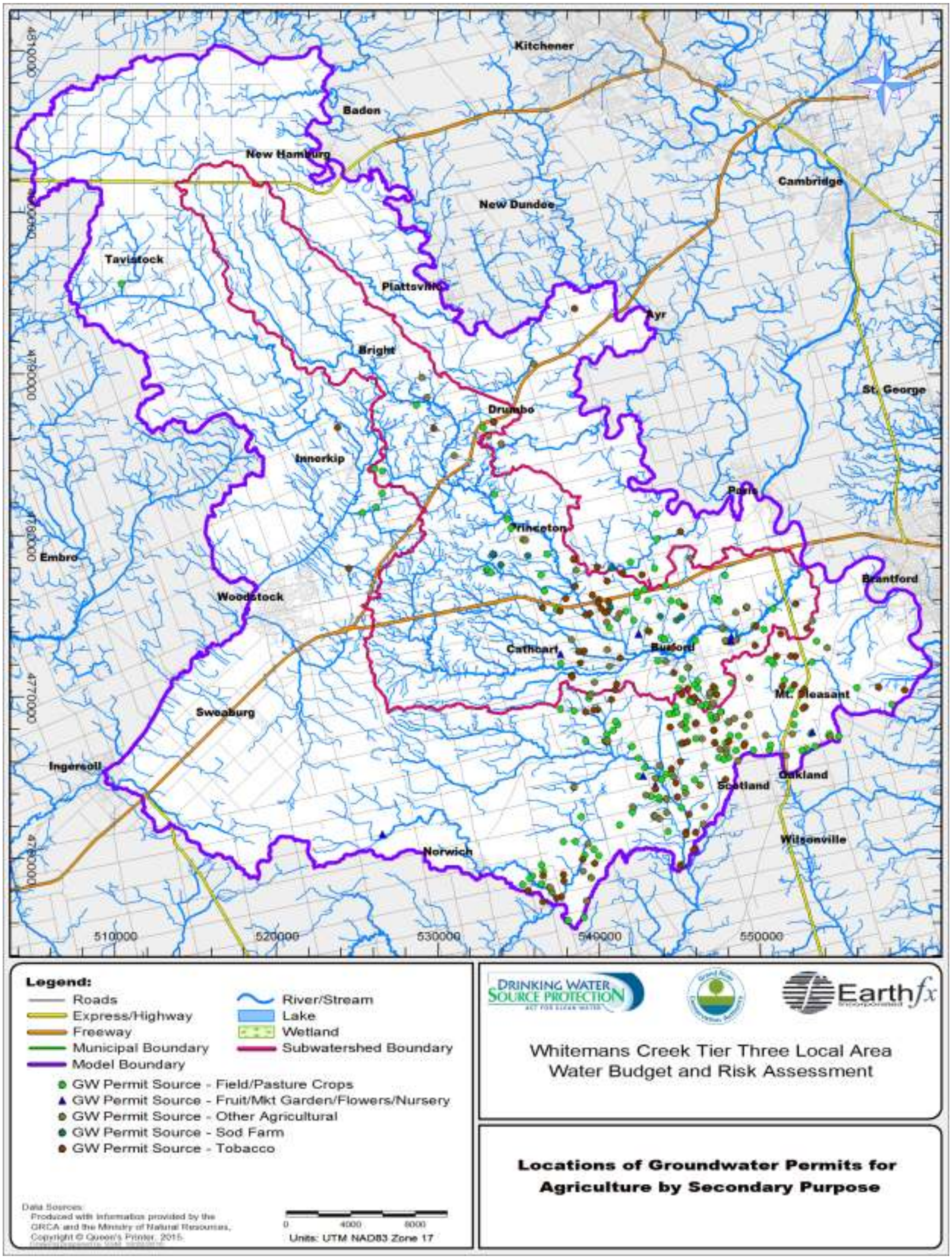


Figure 6.5: Location of groundwater permits for agriculture categorized by secondary purpose.

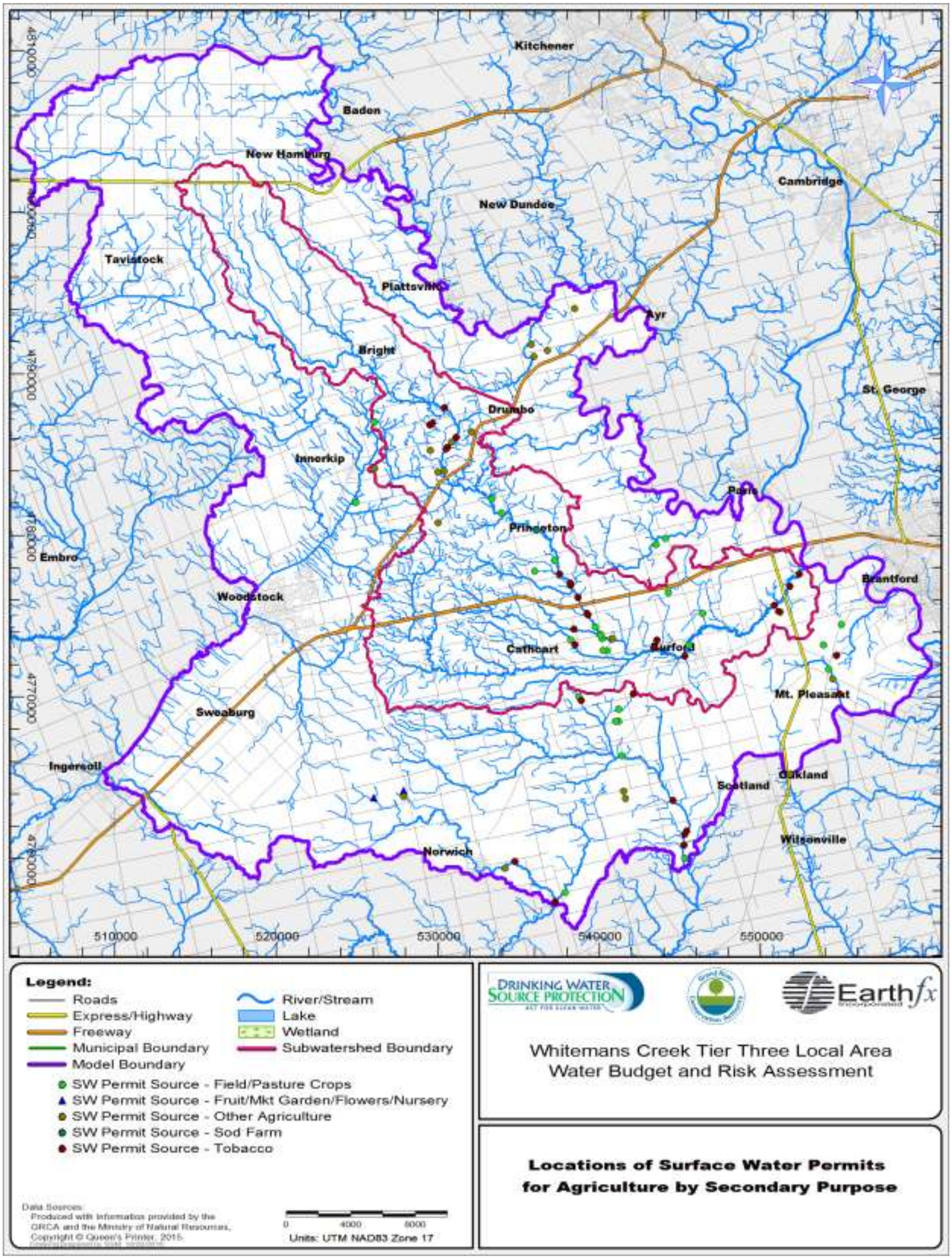


Figure 6.6: Location of surface water permits for agriculture categorized by secondary purpose.

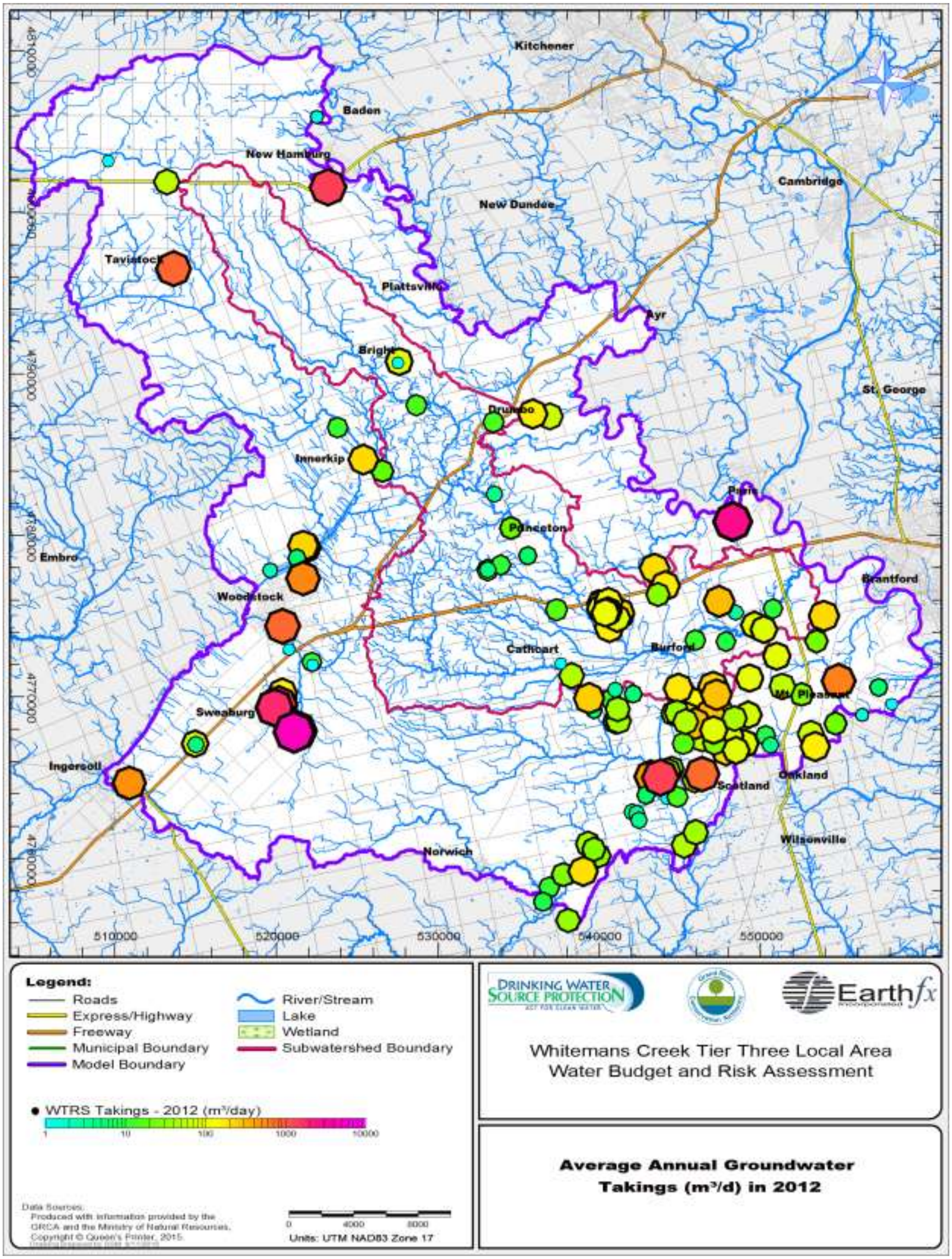


Figure 6.7: Average annual groundwater takings, in m³/d, based on 2012 WTRS self-reported data.

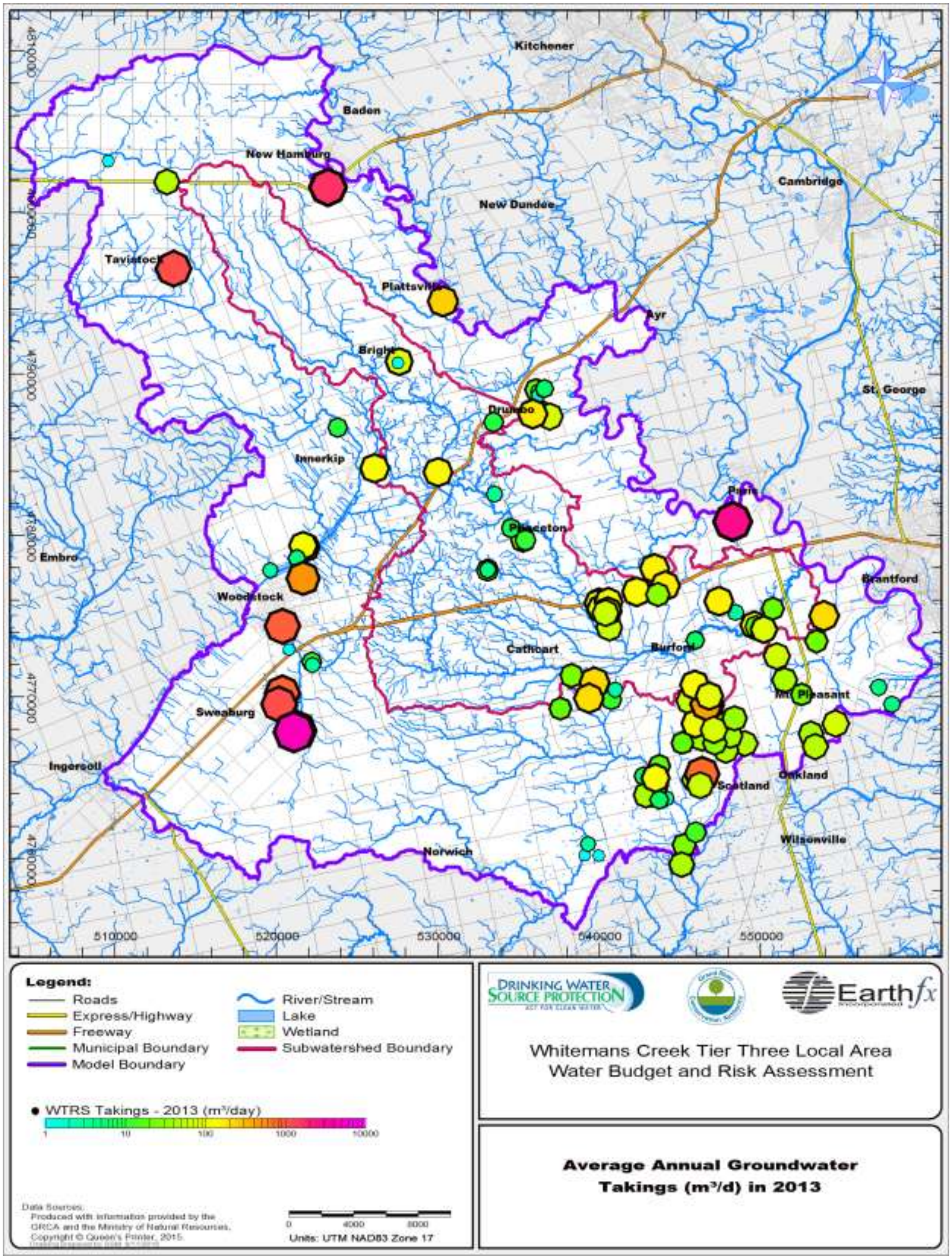


Figure 6.8: Average annual groundwater takings, in m³/d, based on 2013 WTRS self-reported data.

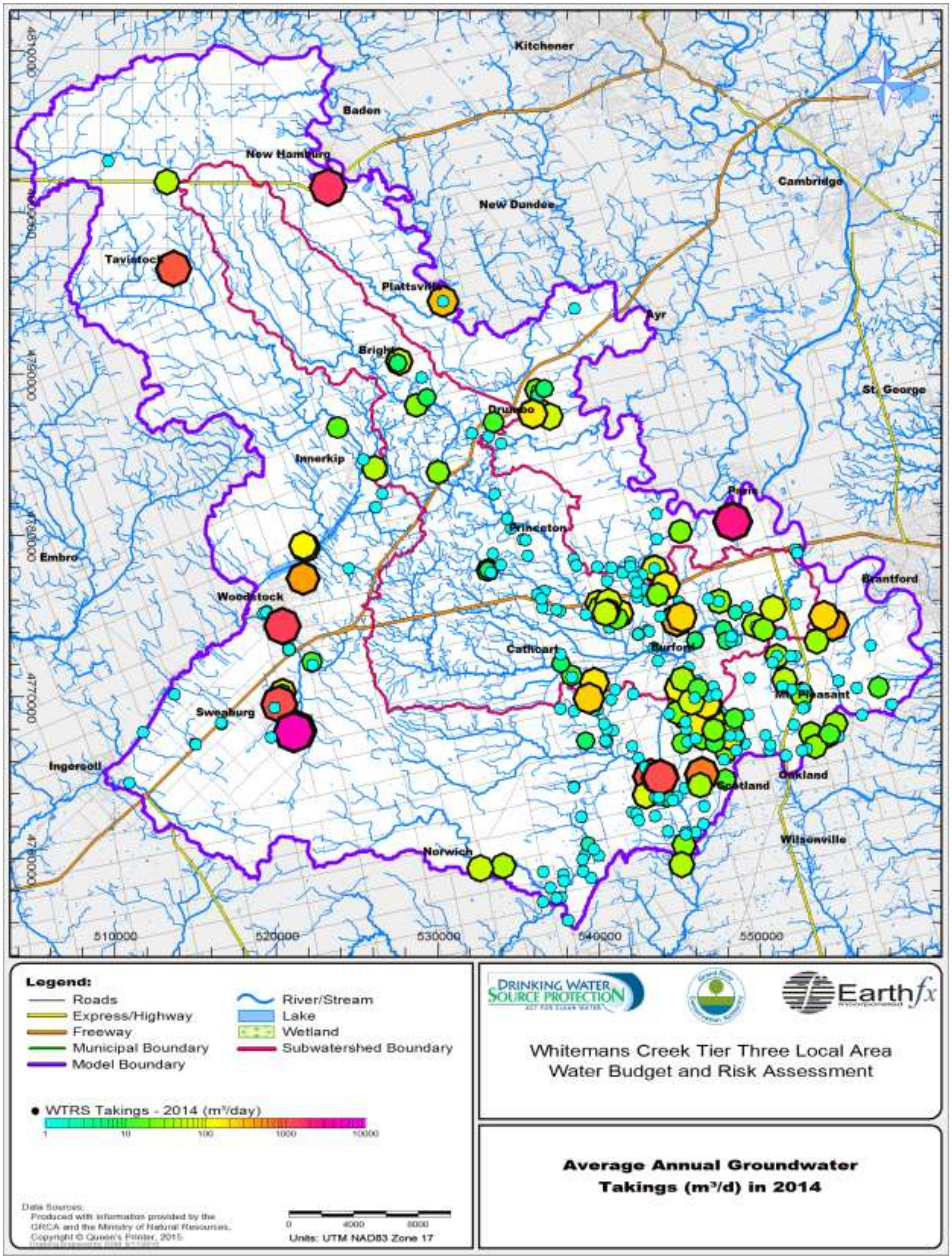


Figure 6.9: Average annual groundwater takings, in m^3/d, based on 2014 WTRS self-reported data.

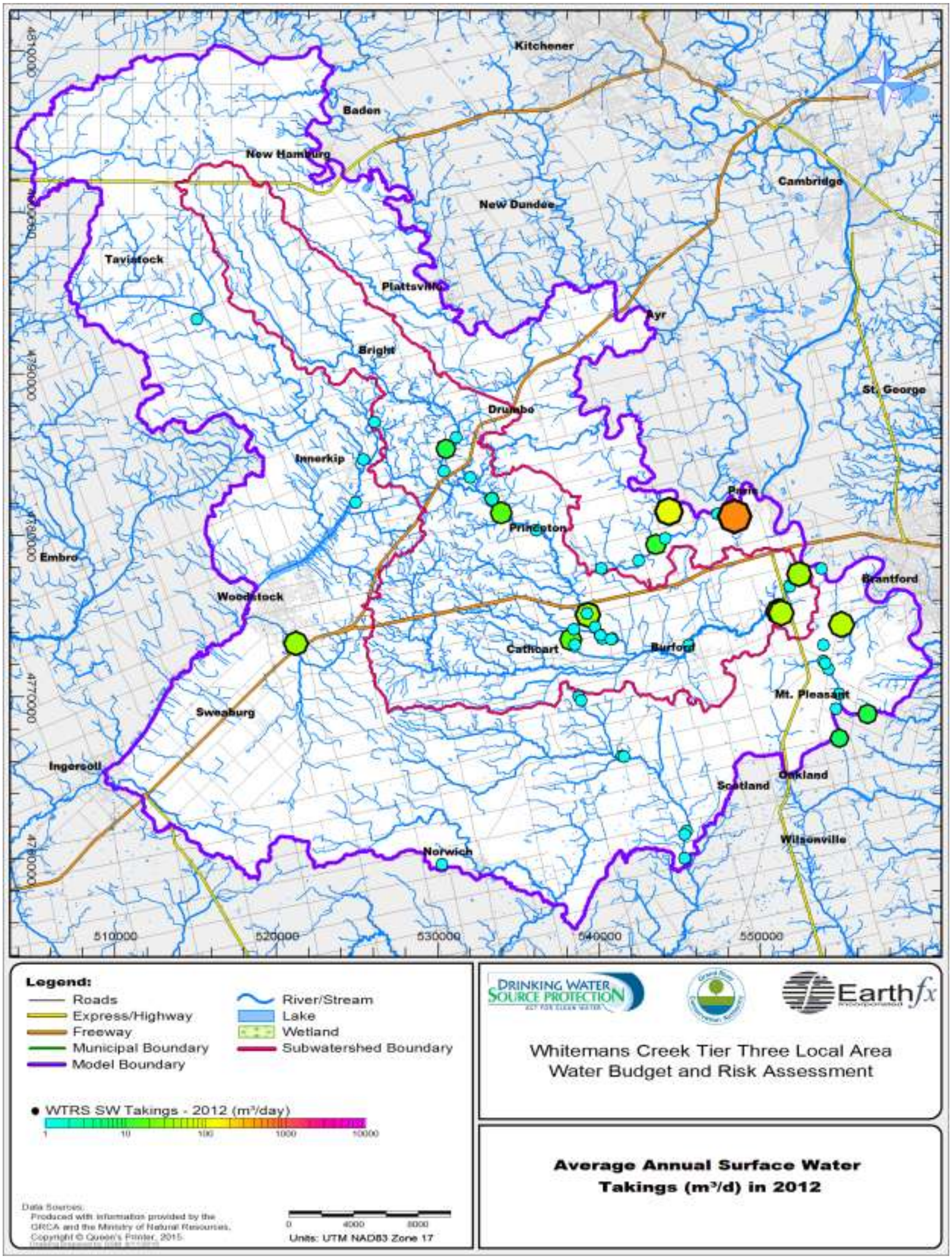


Figure 6.10: Average annual surface water takings, in m^3/d, based on 2012 WTRS self-reported data.

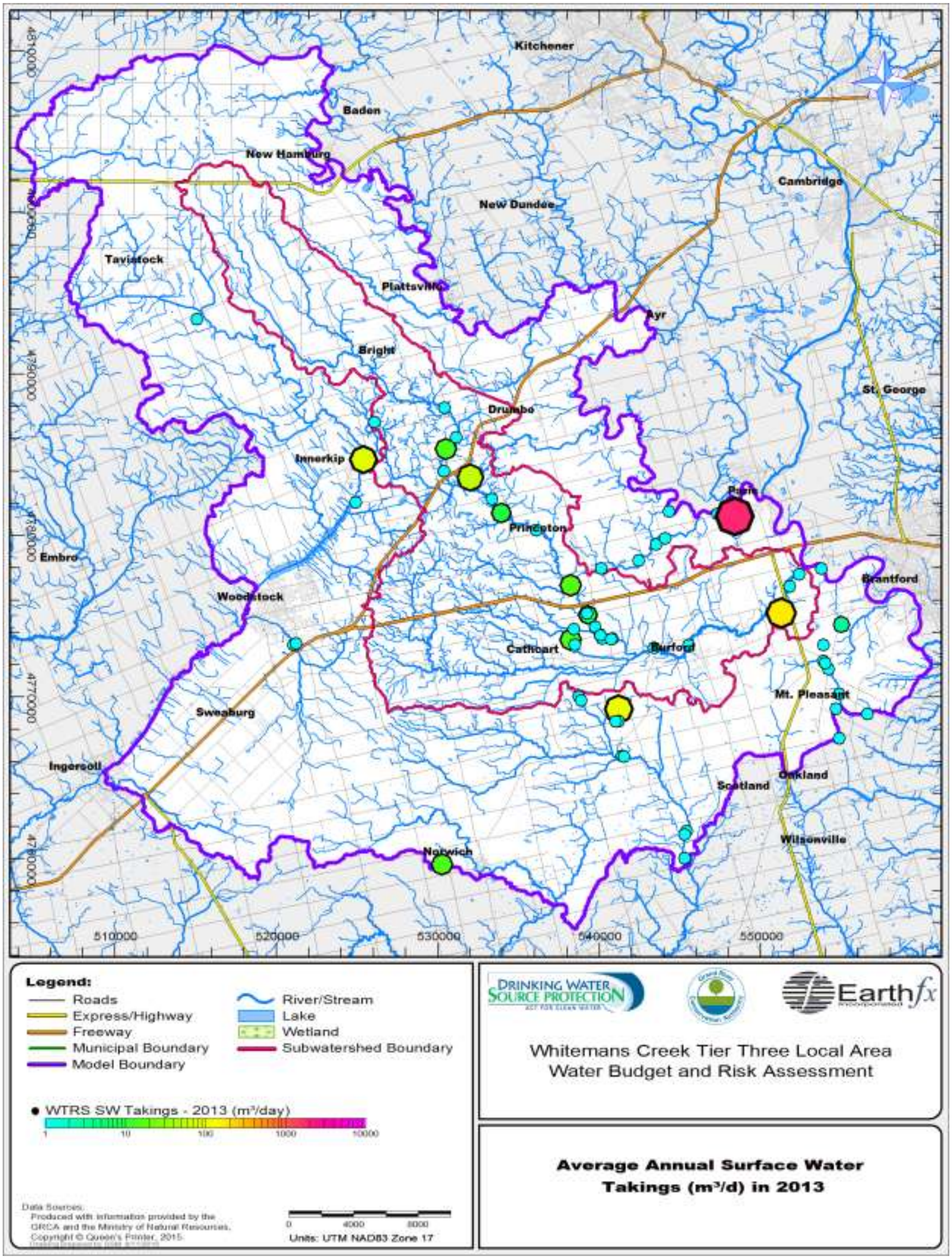


Figure 6.11: Average annual surface water takings, in m^3/d, based on 2013 WTRS self-reported data.

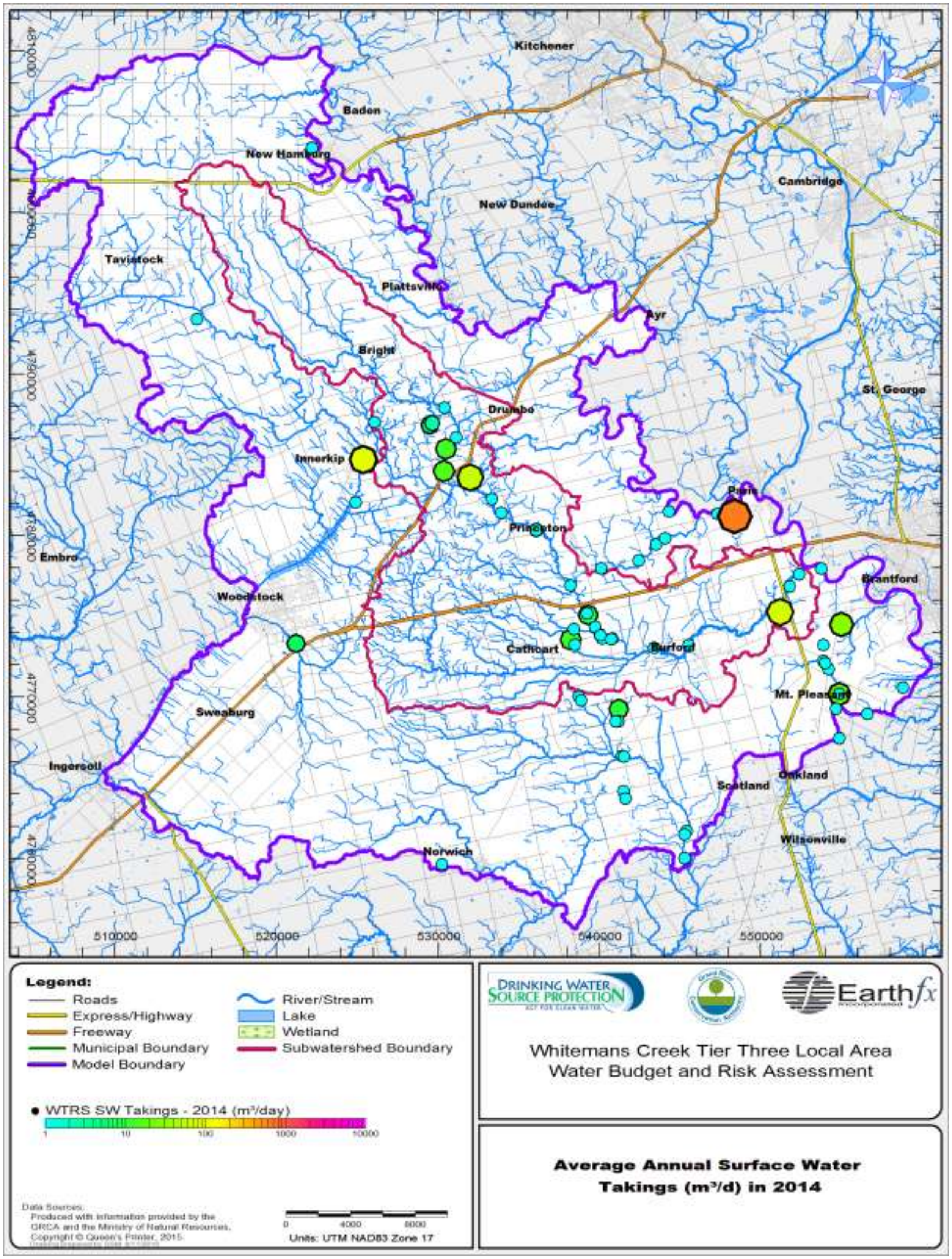


Figure 6.12: Average annual surface water takings, in m³/d, based on 2014 WTRS self-reported data.

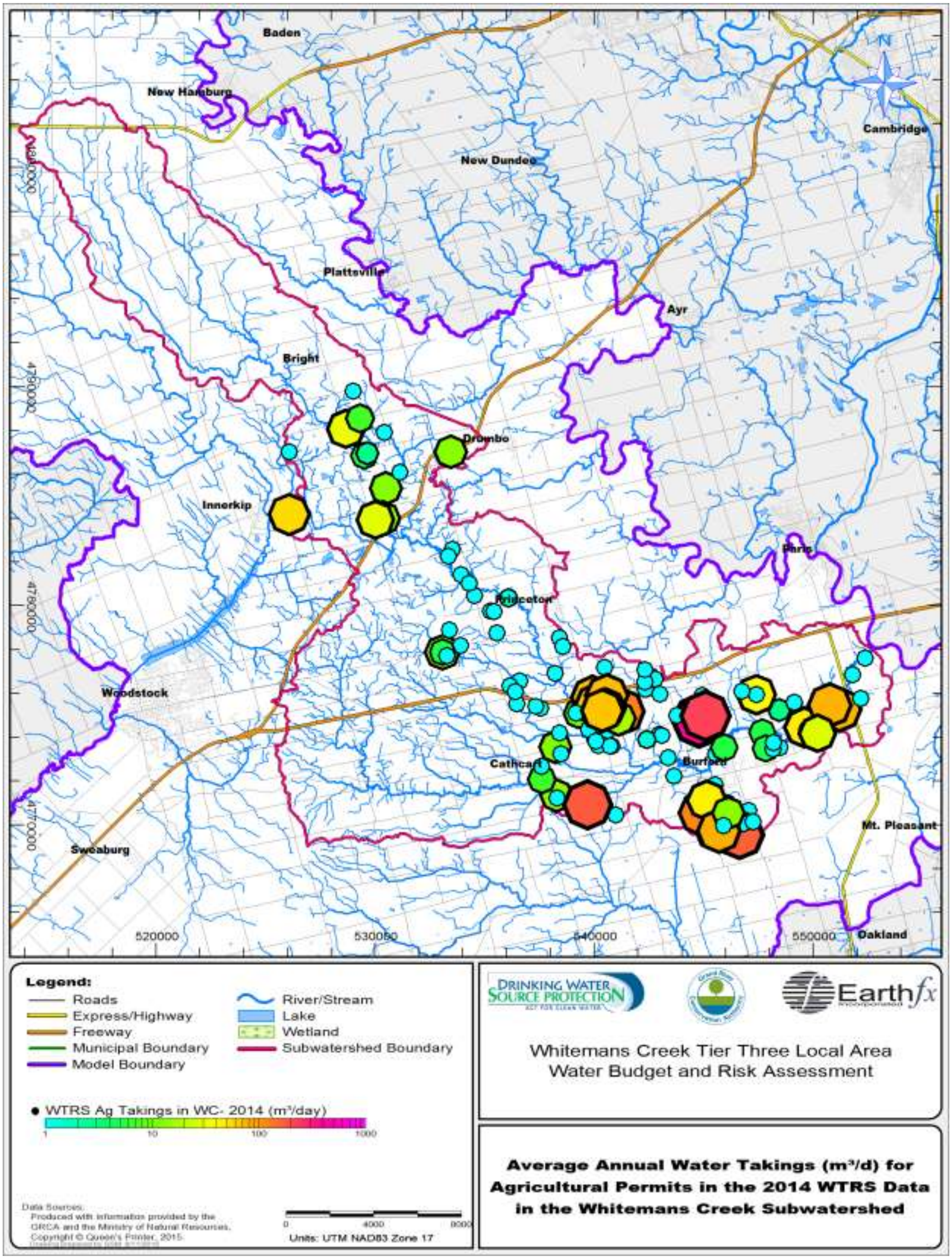


Figure 6.13: Average annual water takings, in m³/d, for agriculture based on 2014 WTRS data in the Whitemans Creek subwatershed.

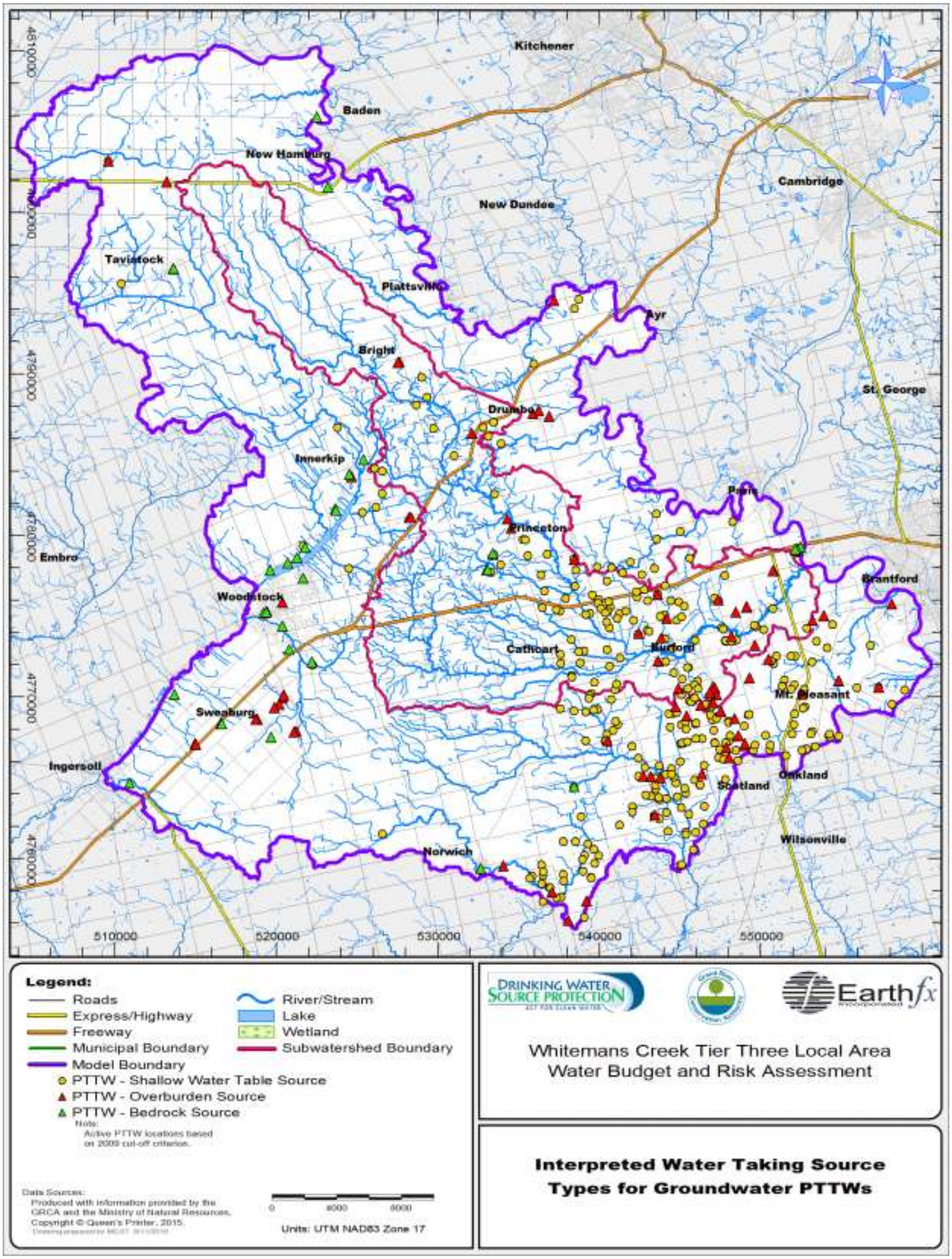


Figure 6.14: Interpreted water taking source types for groundwater PTTWs in the study area.

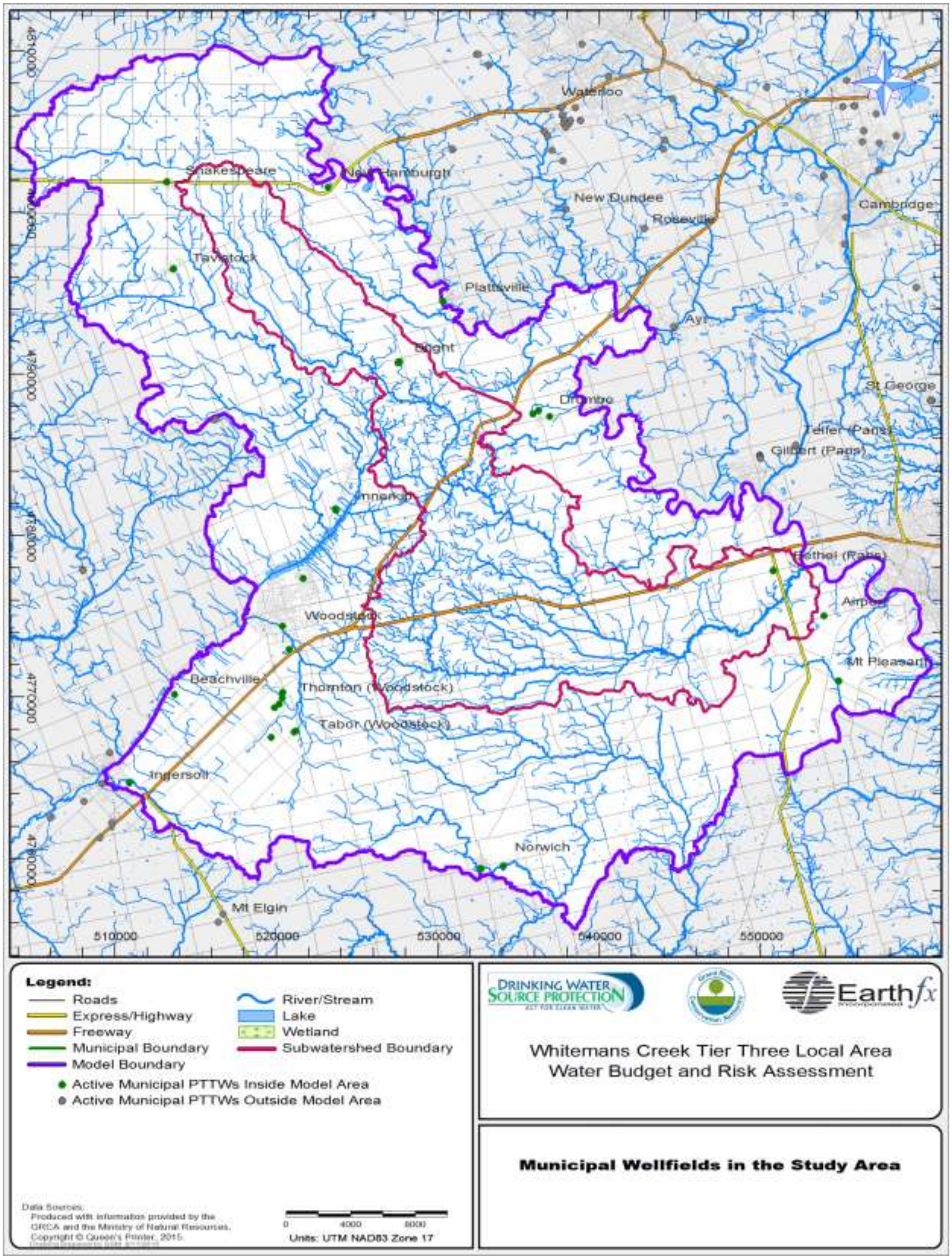


Figure 6.15: Location of municipal wellfields in the study area.

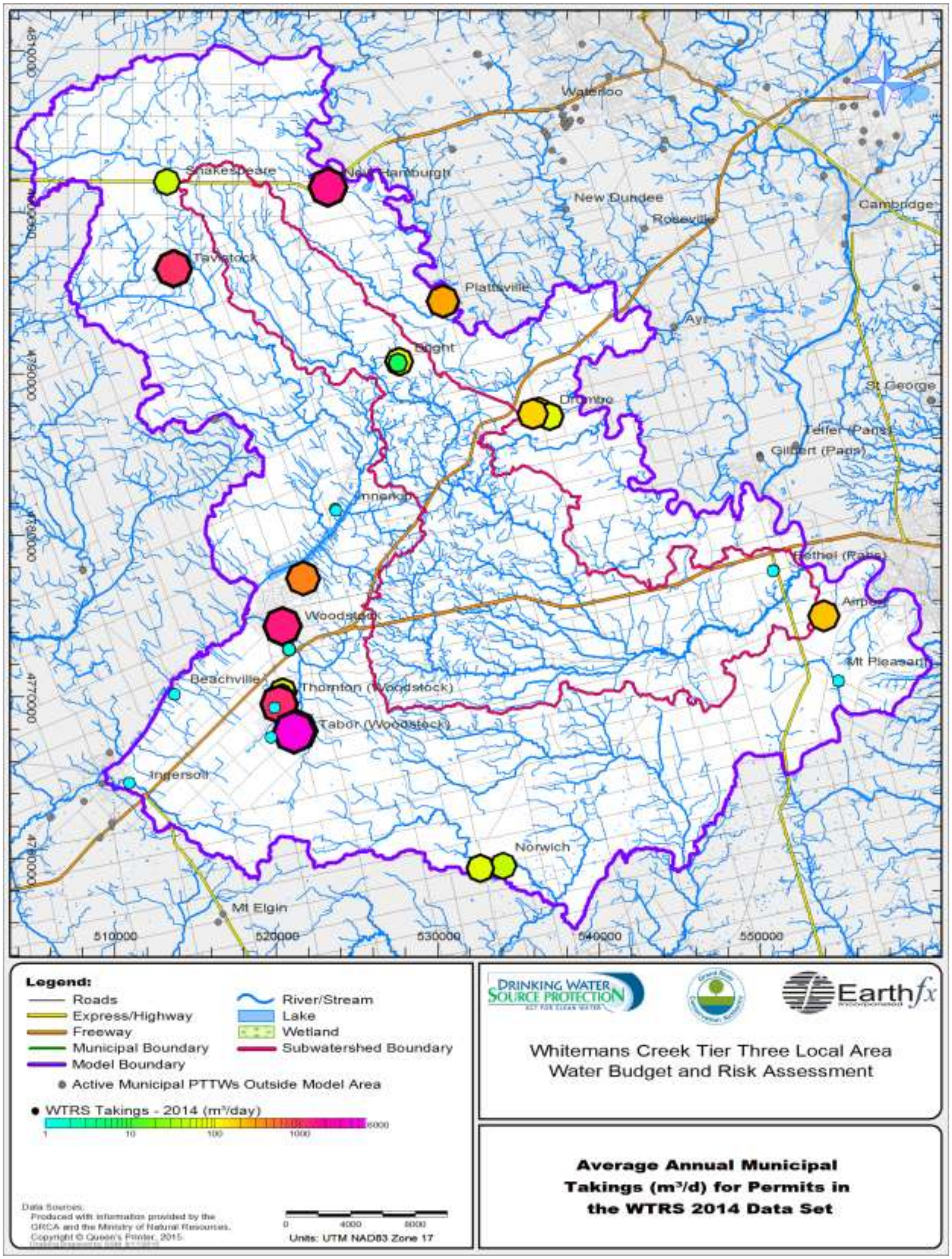


Figure 6.16: Annual average groundwater takings (m^3/d) for municipal wells in the study area from 2014 WTRS data.

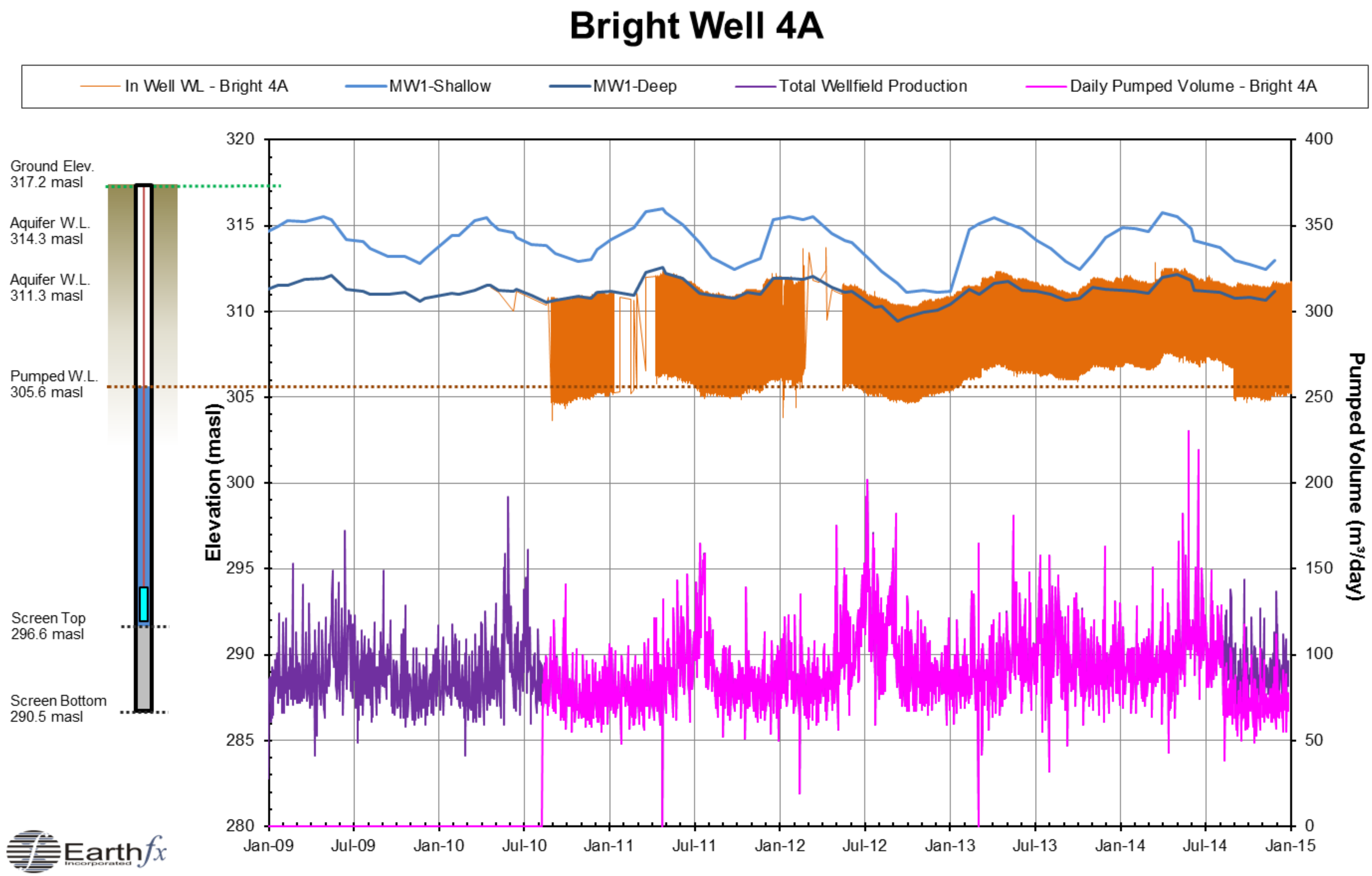


Figure 6.17: Daily water levels and pumped volumes at Bright Well 4A with observed water levels at adjacent monitors.

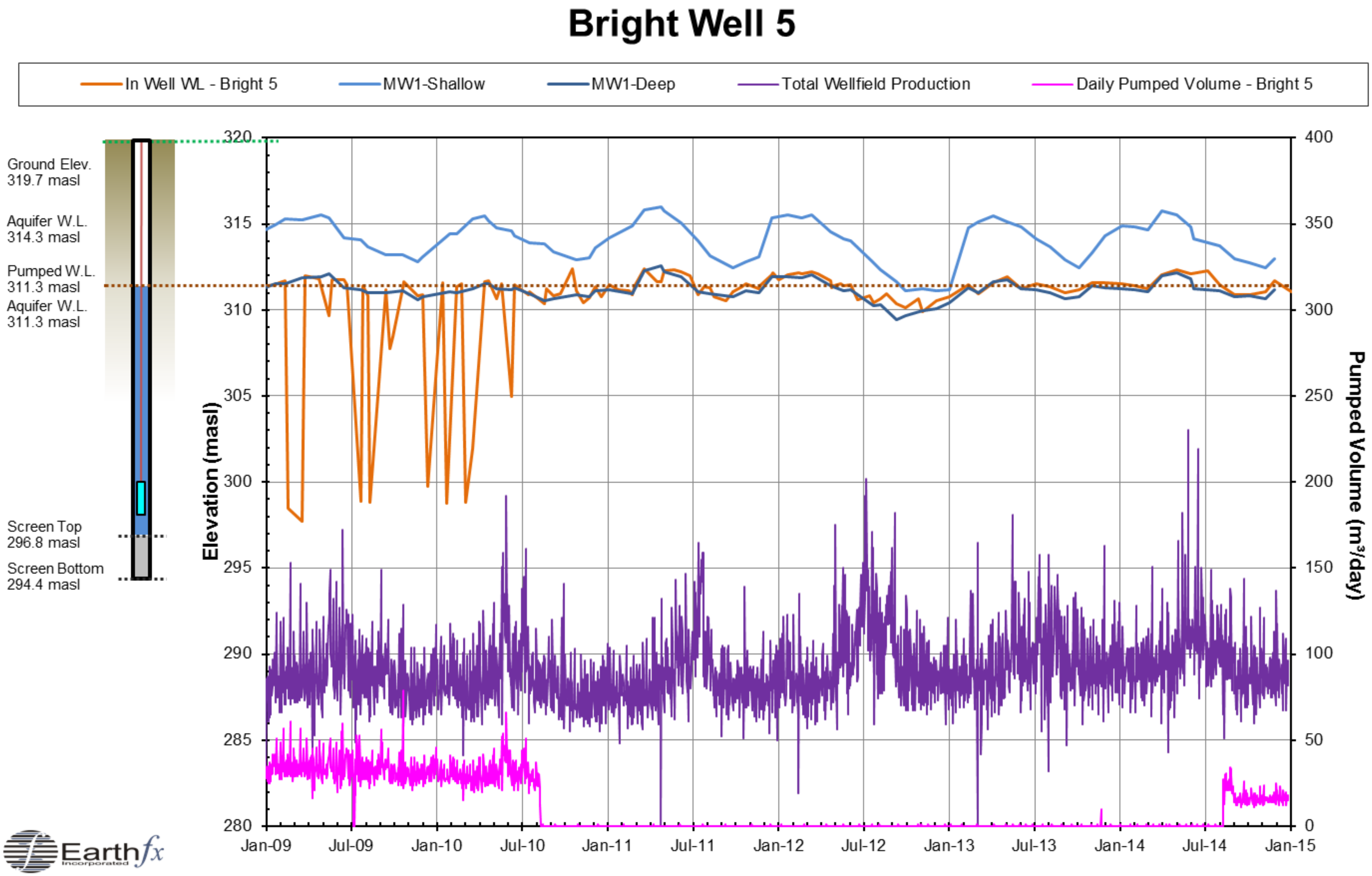


Figure 6.18: Daily water levels and pumped volumes at Bright Well 5 with observed water levels at adjacent monitors.

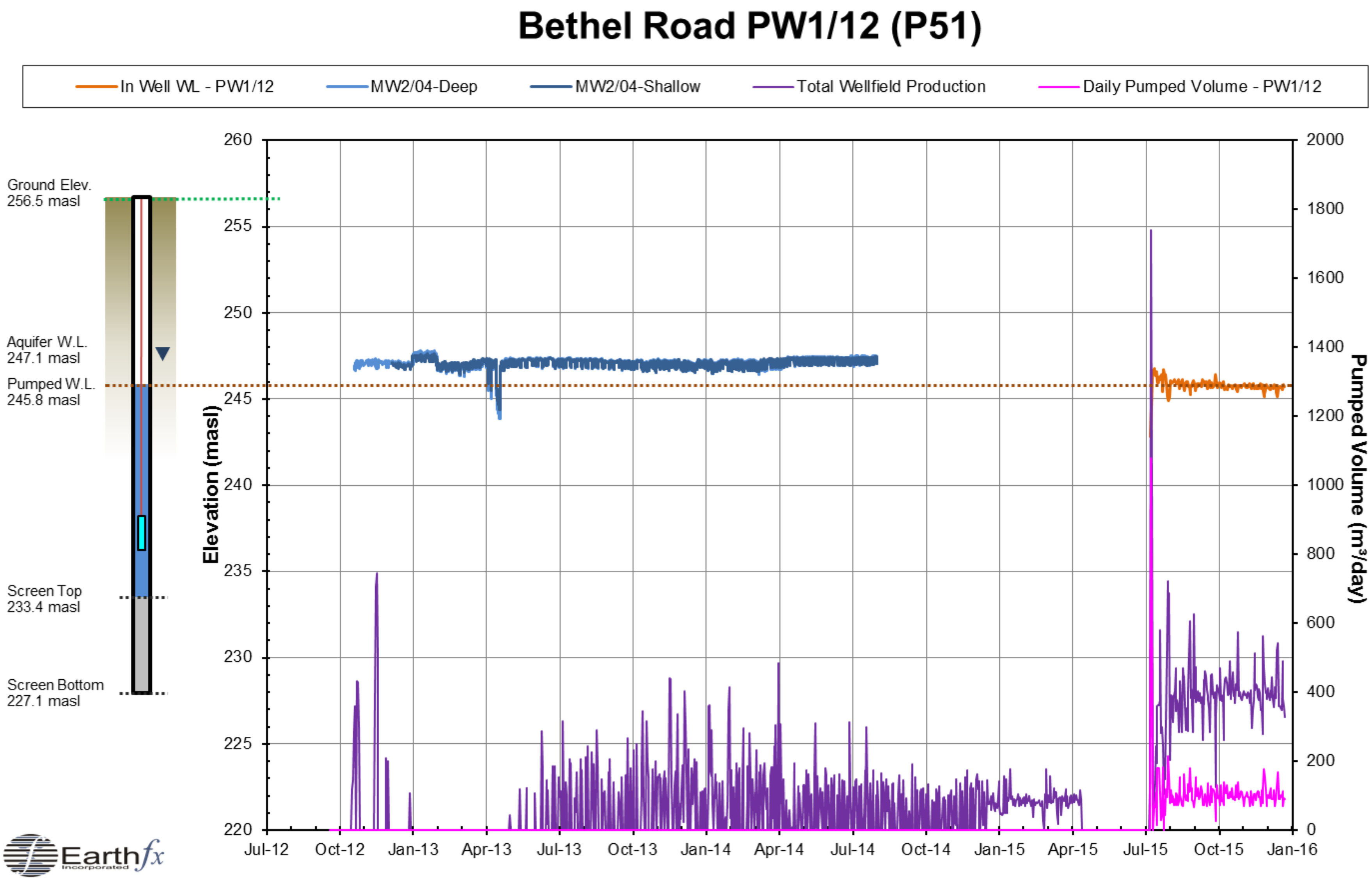


Figure 6.19: Daily water levels and pumped volumes at Bethel Road PW1/12 with observed water levels at adjacent monitors.

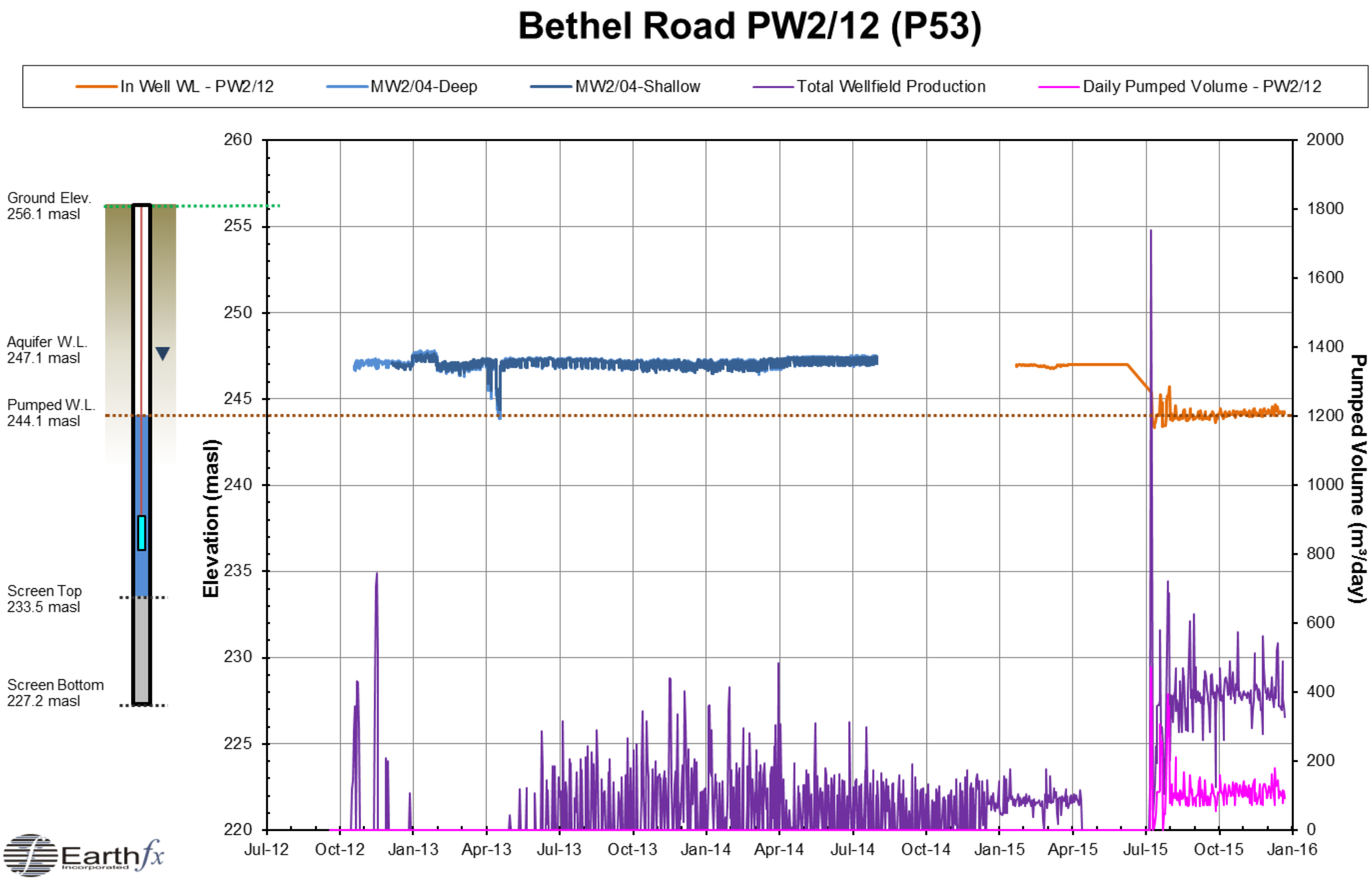


Figure 6.20: Daily water levels and pumped volumes at Bethel Road PW2/12 with observed water levels at adjacent monitors.

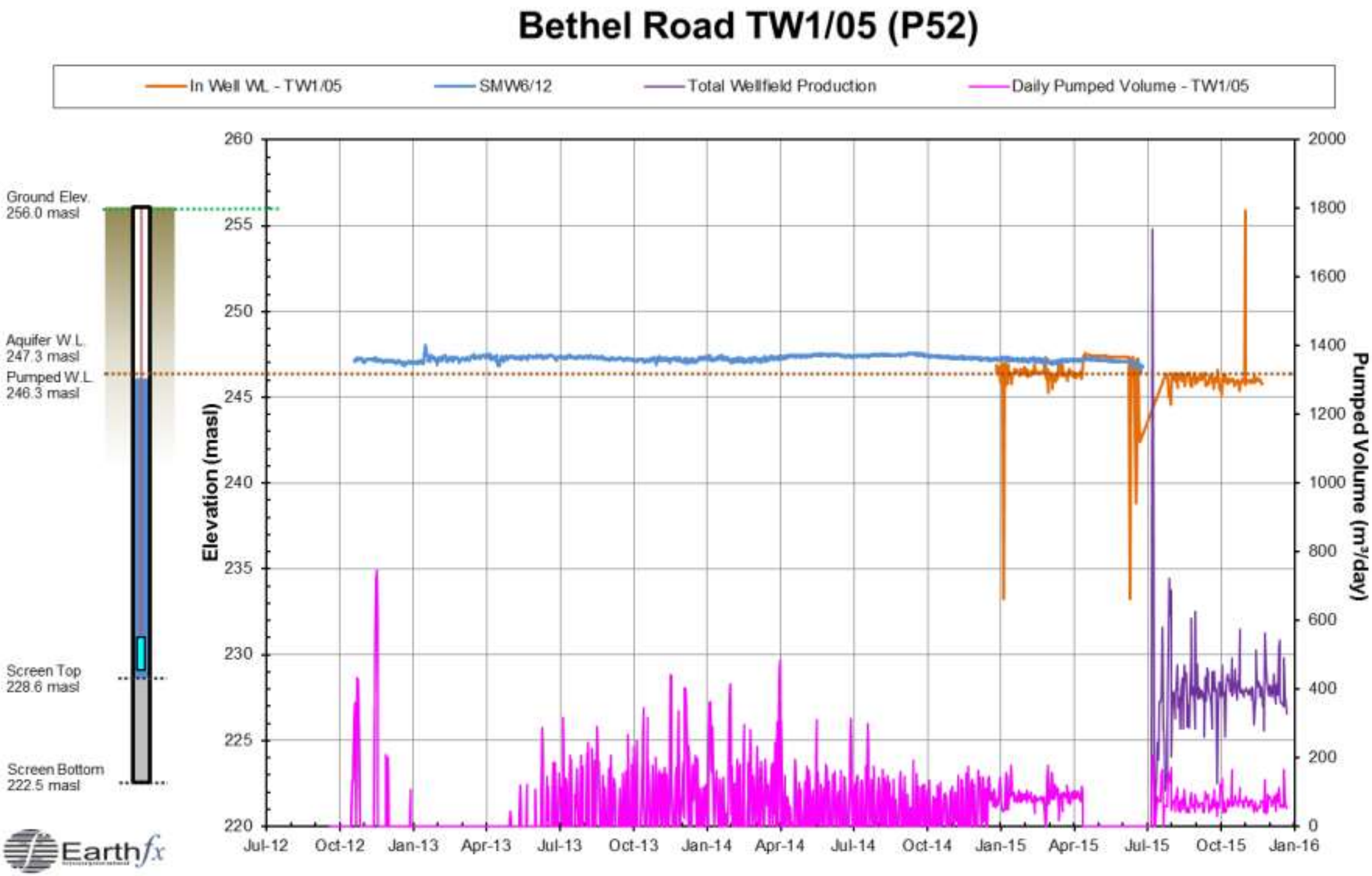


Figure 6.21: Daily water levels and pumped volumes at Bethel Road TW1/05 with observed water levels at adjacent monitors.

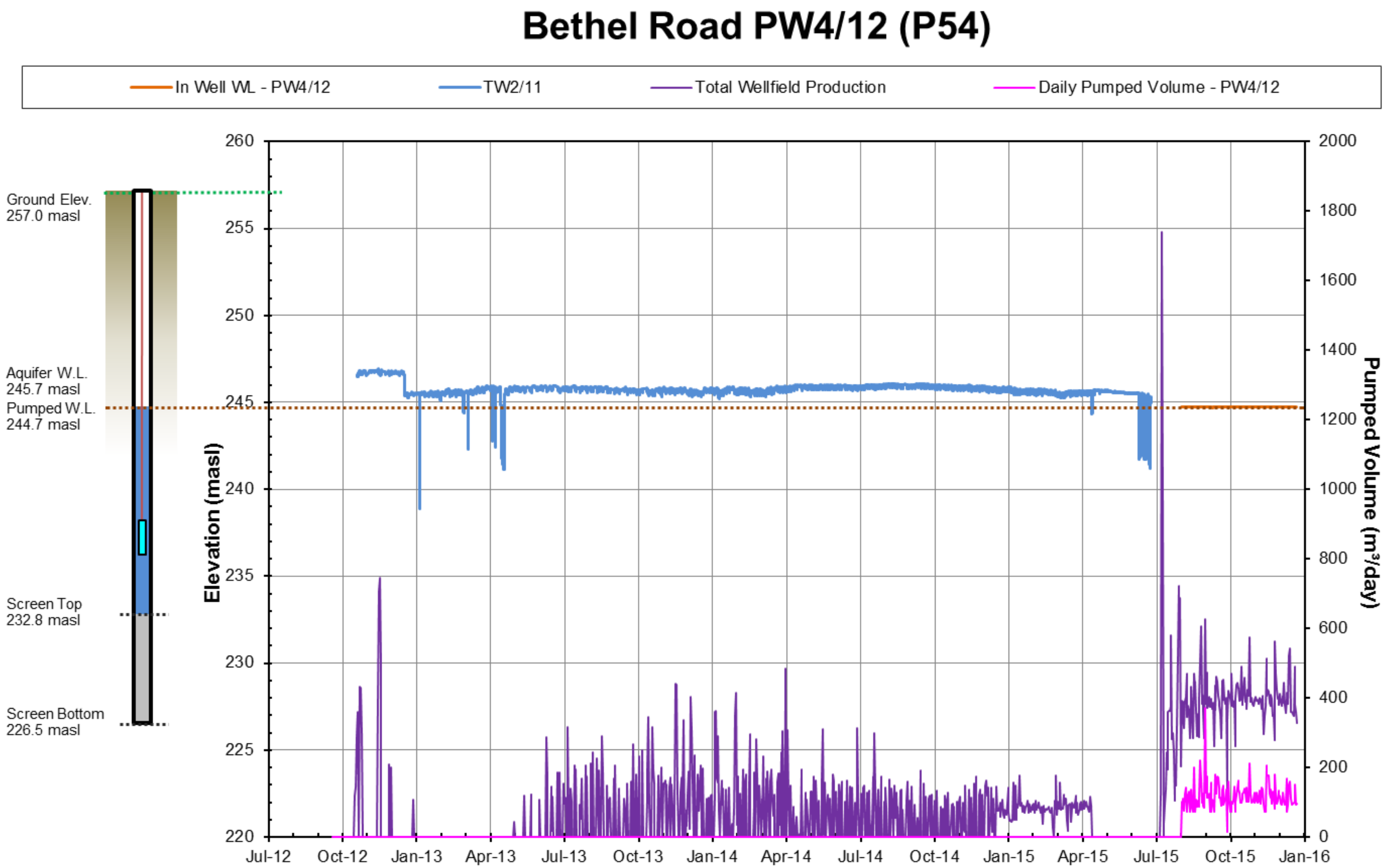


Figure 6.22: Daily water levels and pumped volumes at Bethel Road PW4/12 with observed water levels at adjacent monitors.

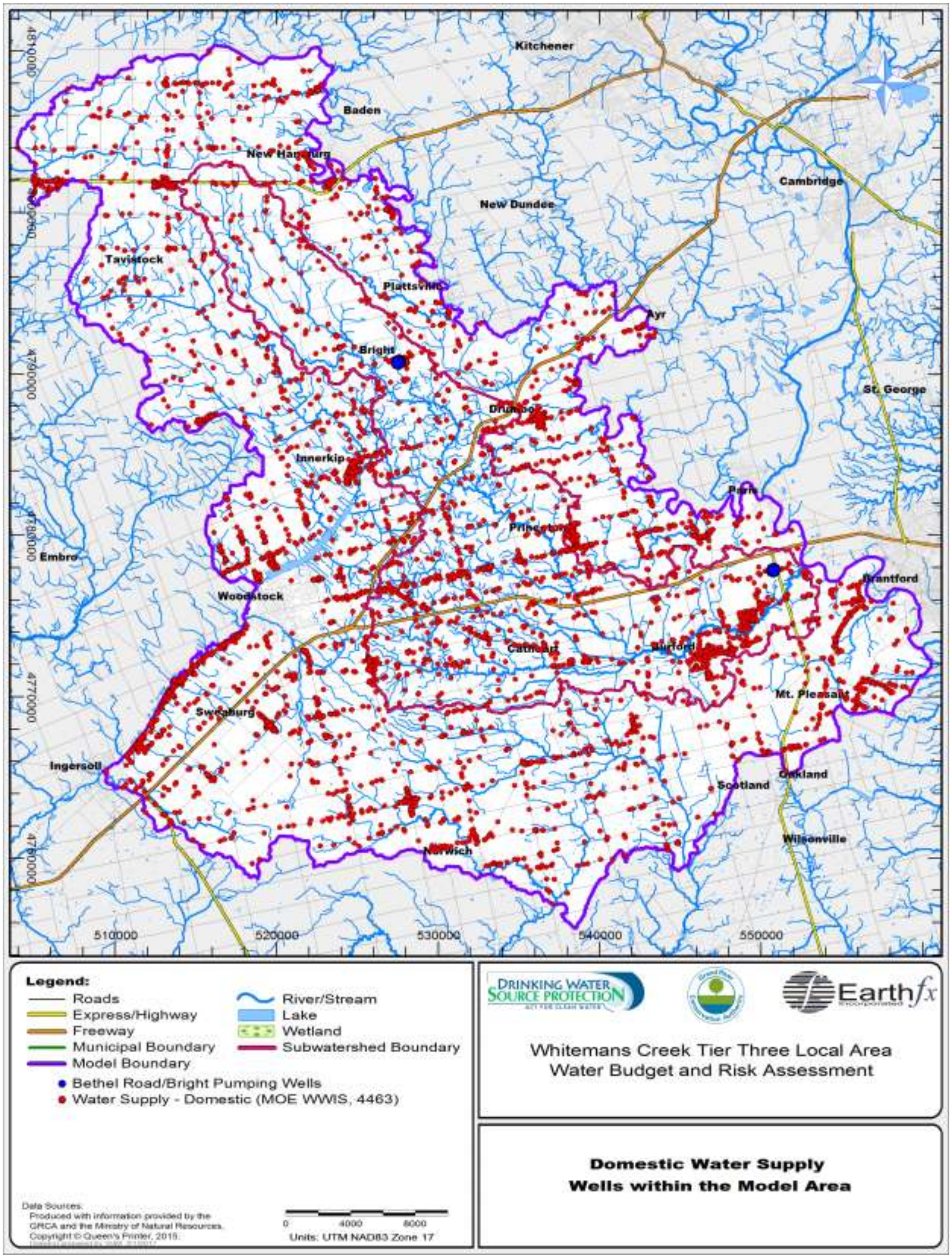


Figure 6.23: Location of domestic water supply wells in the Whitemans Creek subwatershed.

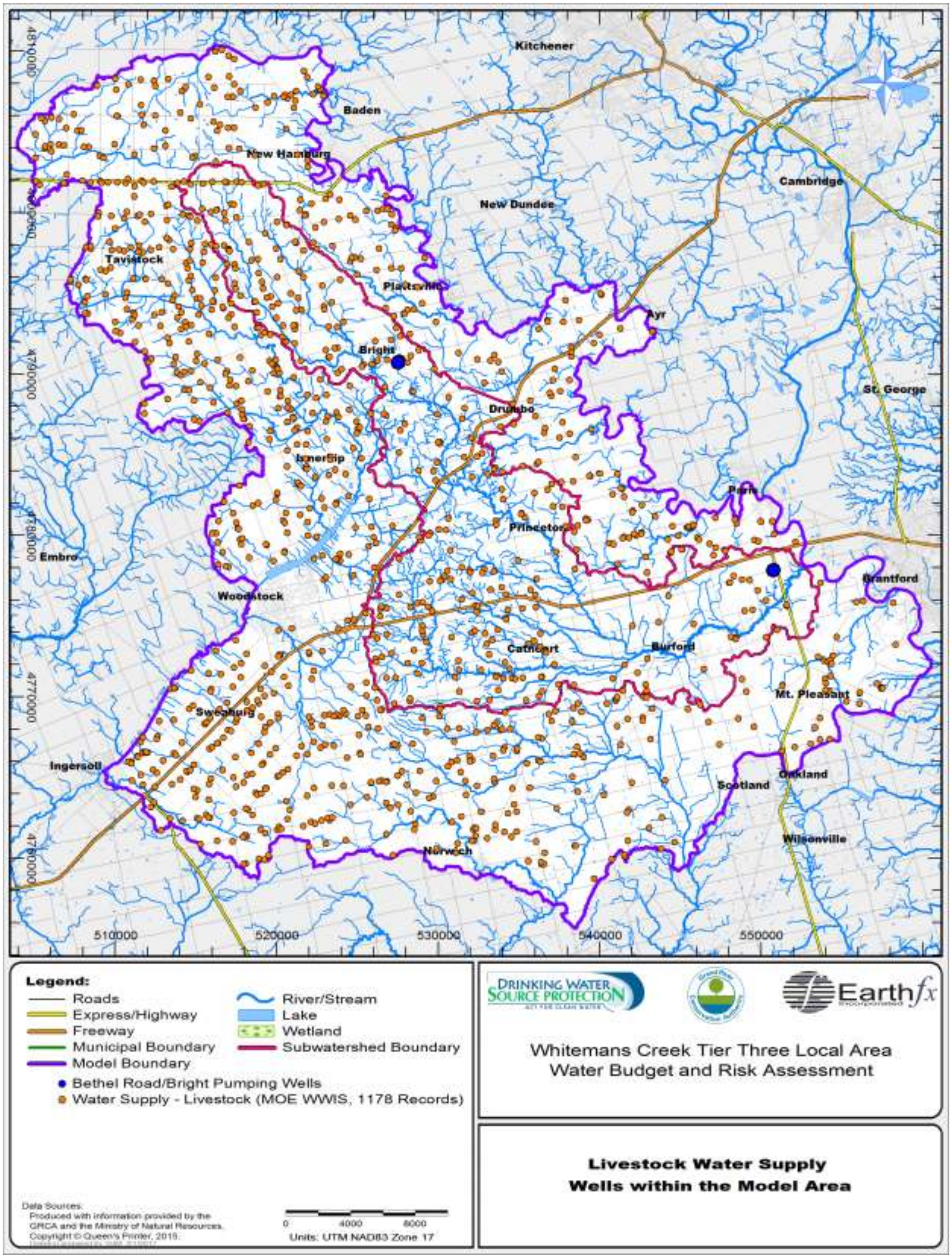


Figure 6.24: Location of livestock water supply wells in the Whitemans Creek subwatershed.

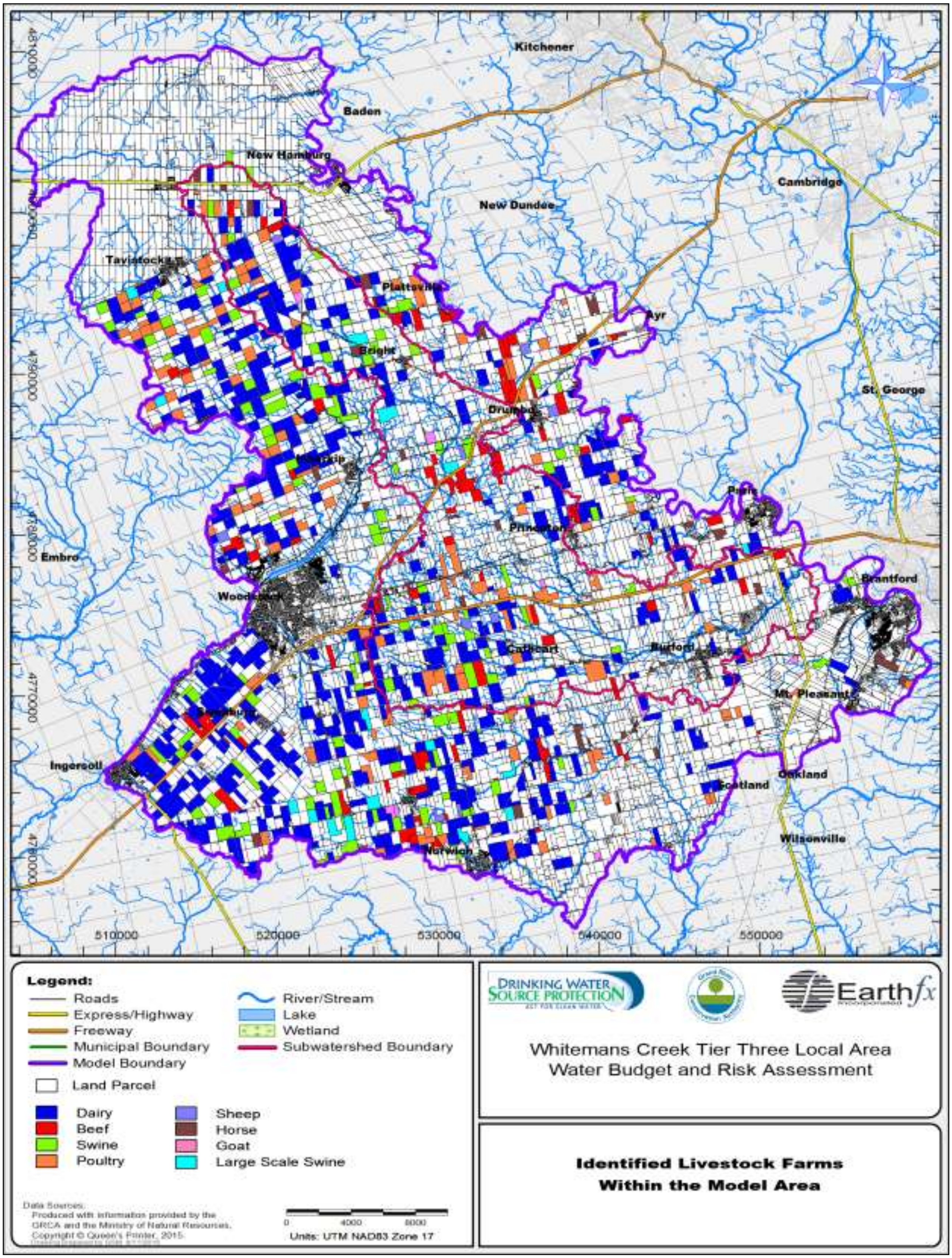


Figure 6.25: Distribution of livestock farms within the model boundary.

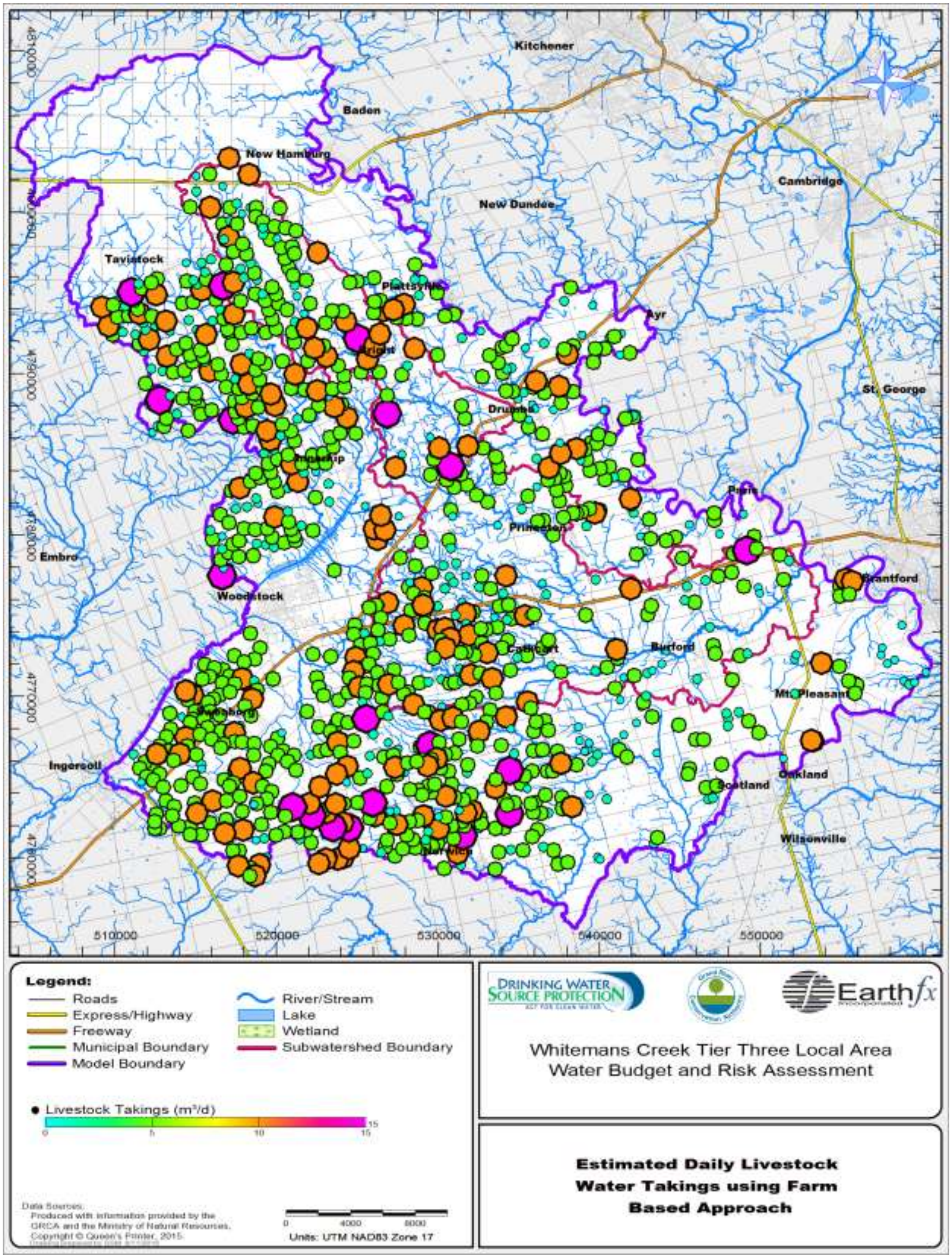


Figure 6.26: Daily estimated livestock water takings in the model area.

7 Integrated Model Development Overview

7.1 Introduction

Many of the technical readers of this report will be familiar with the concepts of surface water and groundwater modelling. As integrated modelling is less commonly applied, the purpose of this chapter is to address the following:

1. What is integrated modelling?
2. What are the benefits and possible disadvantages of integrated modelling as it applies to the objectives of this study and the unique features of this watershed?
3. How is the movement of water between the surface and groundwater systems (dynamic feedback) represented in the integrated model?
4. What is the overall approach to the development and calibration of the integrated model?

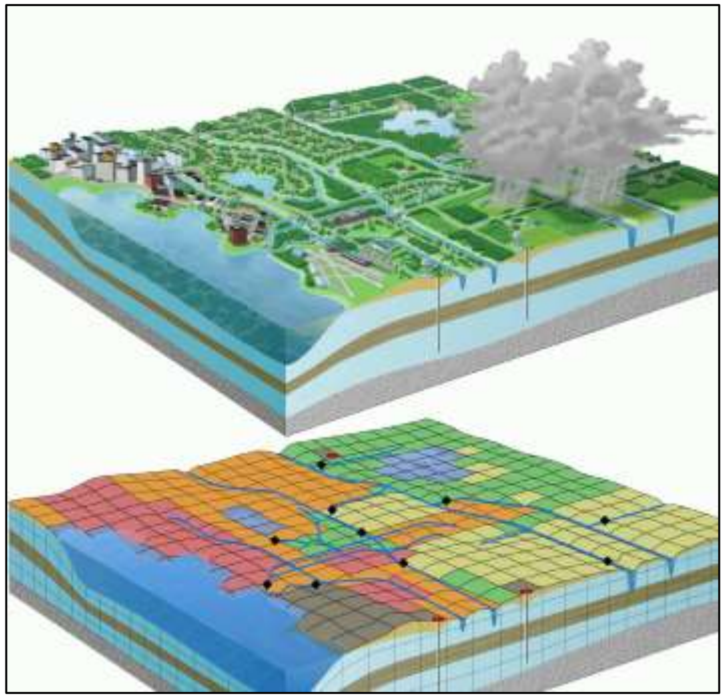


Figure 7.1: The physical system (upper image) and a numerical model representation in a fully distributed, cell-based, integrated model (lower image).

The final part of this chapter provides the reader with an overview of the process of developing and calibrating the integrated model. This overview will help the reader understand how each of the sub-model components are developed, pre-calibrated, and then coupled and "final calibrated". With this high-level overview of the model development process, the reader will better understand the technical details presented in subsequent model construction chapters.

7.2 Integrated Modelling - Overview

7.2.1 Integrated Modelling

The basic definition of an integrated model is one that represents the entire hydrologic cycle in a comprehensive and coupled manner. The hydrologic cycle, as depicted in Figure 7.1, includes:

- Hydrologic processes (e.g., precipitation, interception snowpack, runoff, evapotranspiration (ET), and other soil zone processes)
- Hydraulic processes (e.g., streamflow, wetland water balance, lakes, reservoir operations)
- Groundwater processes (i.e., saturated and unsaturated subsurface flow)

A *comprehensive representation* of the hydrologic cycle is one in which the overall water budget is tracked through both the surface water and groundwater domain and where water cannot be created or lost within the simulation (full accounting).

The terms *integrated* or *coupled* are used to describe how the transfer of water between the hydrologic, hydraulic and groundwater domains is simulated in a manner that reflects the dynamic nature of the system and the variable feedback that can occur between the surface water and groundwater domains. Some model developers have made distinctions between integrated and coupled models based on whether the governing equations are solved simultaneously or in an iterative manner. Our experience indicates that ensuring that the domains are coupled in a physically consistent manner that preserves mass is the most important aspect of an integrated model, not the solution method.

7.2.2 Project Objectives and the Whitemans Subwatershed

Two objectives were identified for this study. The primary objective was to complete a Tier 3 Water Budget Risk Assessment for the Bright and Bethel Road municipal wells. This *water quantity* risk assessment evaluated the effects of increased municipal water demand, changes in land development, drought conditions, and the cumulative effect of all surface water and groundwater takings on the wells. An integrated model was the most effective way to simulate all of these processes with a single tool and quantitatively assess the effects of future change as well as represent how surface and groundwater processes and storage may affect the sustainability of the wells through an extended (10-year) drought.

While the first objective focussed on specific municipal wells, a secondary objective was to improve the overall understanding of the watershed function under low-water response conditions and changing water demand and irrigation patterns. In the highly variable and complex Whitemans Creek subwatershed, storage in the wetlands and shallow aquifers in the central portion of the watershed can help sustain ecological flows in the lower portion of the watershed. Further, irrigation affects the watershed behaviour in a complex manner, providing additional ET losses and some return flow to the groundwater system, while also potentially enhancing runoff and recharge during post-irrigation rainfall events.

An integrated approach also provides some additional benefits that are related to the development and calibration of the model. When independent surface and groundwater models are developed, simplifying assumptions must be made in each model to account for the processes that occur in the other model domain. For example, groundwater recharge must be independently estimated and applied to a groundwater model. Similarly, multi-aquifer systems with complex hydrostratigraphy are often represented as simple linear reservoirs accepting excess water and whose discharge to streams must be estimated and incorporated in the calibration of a surface water model. Little dynamic feedback is provided between the systems. These simplified estimates can particularly difficult to evaluate under dynamic and variable climate and water use conditions. With an integrated model, the sub-models are “pre-calibrated” using a traditional model development processes, but final calibration is undertaken without the need to rely on simplifying assumptions and estimates.

7.3 *USGS GSFLOW Overview*

The U.S. Geological Survey (USGS) GSFLOW code (Markstrom *et al*., 2008) was selected for use in developing the integrated surface water/groundwater model of the study area. GSFLOW is an open-source, well-documented code that can be obtained at no cost from the USGS. The code is well-tested and has been used to investigate surface water/groundwater interaction in a number of recent peer-reviewed studies (e.g., Huntington and Niswonger, 2012; Hunt *et al*., 2013; Woolfenden and Nishikawa, 2014; Tanvir Hassan *et al*., 2014; and Niswonger *et al*., 2014).

7.3.1 GSFLOW Submodels

GSFLOW was developed from two widely-recognized USGS submodels: the Precipitation Runoff Modelling System (PRMS, Leavesly *et al*., 1986), the modular groundwater flow model MODFLOW-NWT (Niswonger *et al*., 2011) with the USGS UZF unsaturated flow module (Niswonger *et al*., 2006) and the SFR2 and LAK3 surface water modules (Niswonger and Prudic, 2005 and Merritt and Konikow, 2000). The different processes and submodels in GSFLOW are listed in Table 7.1 and are shown schematically in Figure 7.2. The submodels include numerical representations of the complete physical system and the processes that occur within each submodel domain.

A flowchart showing the interaction between the regions is provided in Figure 7.4. The individual submodels are described briefly below with respect to their main processes and interconnections.

Table 7.1: Processes and GSFLOW submodels.

Region	Process Component	GSFLOW Submodel
1	Hydrology – (Soil Water Processes)	Hydrologic Submodel (PRMS)
2	Unsaturated Flow	UZF module for MODFLOW
2	Streamflow, lakes and wetlands	SFR2 and LAK3 modules for MODFLOW
3	Groundwater flow	Groundwater Submodel (MODFLOW-NWT)

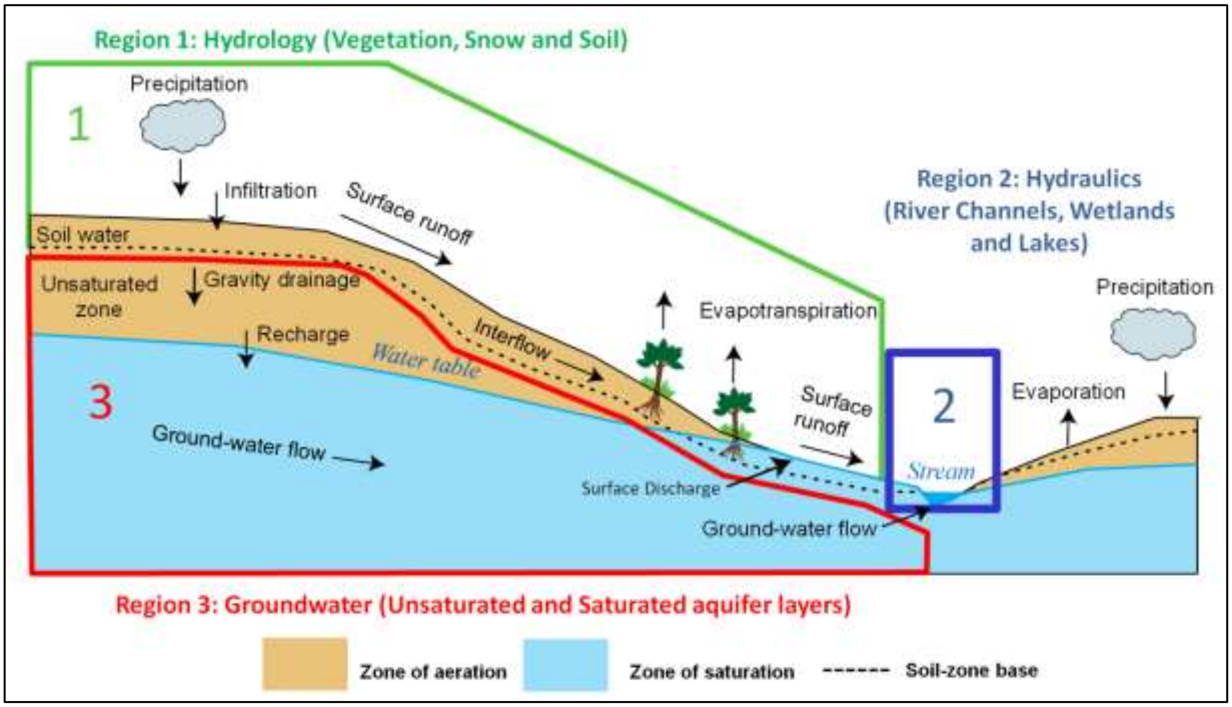


Figure 7.2: Schematic diagram of the GSFLOW process regions.

7.3.2 Spatial Representation

The MODFLOW groundwater flow submodel in GSFLOW is fully-distributed model, meaning that groundwater processes are simulated using a cell-based representation of the study area, as shown schematically in the lower portion of Figure 7.1. The PRMS hydrology sub-model can be run using either subcatchments (lumped-parameter mode) or in a fully-distributed manner where the hydrologic response units (HRUs) are small cells rather than subcatchments, with each cell having unique physical properties. During model construction each cell is assigned spatially variable soil and land cover properties, and during a simulation receives unique, spatially-variable inputs, such as daily rainfall, snowfall, temperature, and solar radiation. Overland runoff and interflow are routed between cells and, ultimately, to streams or lakes by a topographically-drive cascade flow system.

The spatial representation in GSFLOW is particularly flexible. Three different grid resolutions can be used for the climate, surface hydrology, and subsurface groundwater processes (Figure 7.3). This allows for different levels of refinement in each of the three regions to meet the accuracy requirements associated with those processes and the type and spatial distribution of property and observation data available in the study area.

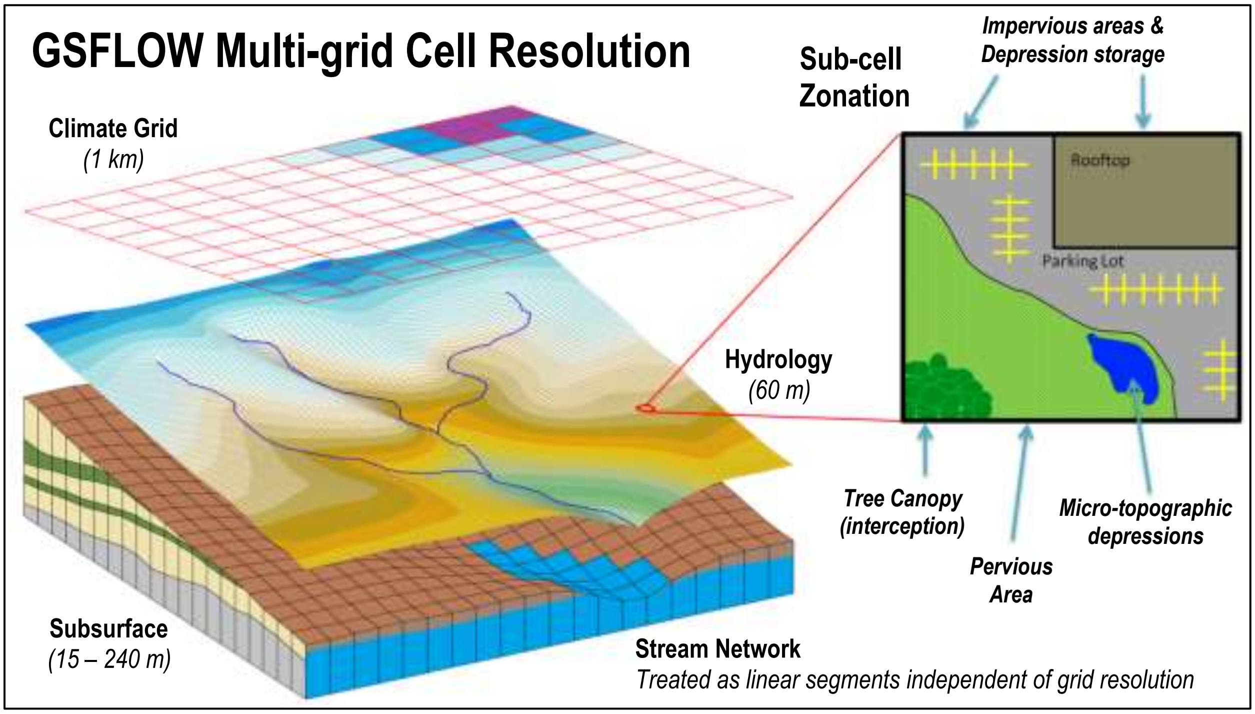


Figure 7.3: Different grid resolutions are available for each process region within GSFLOW.

7.3.2.1 Hydrology

Topography, soil properties, and land use can vary widely across the study area, so a fine resolution is typically used to represent local-scale natural features and anthropogenic modifications such as agricultural land use and urban development (Figure 7.3).

A second useful feature of the GSFLOW cell-based HRU representation is that sub-cell hydrologic processes can be represented. Each cell in the PRMS submodel can be divided into pervious (grass or soil) and impervious (roads, parking lots, buildings) zones (Figure 7.3, right side enlargement), with different processes, storage properties, and interactions simulated in each sub-cell zone.

7.3.2.2 Hydraulics

Rivers and streams in GSFLOW are represented as a network of one-dimensional line elements with open-channel flow routing through the network. The storage associated with small wetlands can be represented in the PRMS soil zone, while larger lakes and wetlands are represented with the LAK3 module and can be incised into one or more groundwater layers.

7.3.2.3 Groundwater

Groundwater flow processes can generally be represented at a coarser scale and aquifer/aquitard property data and groundwater level data are often limited. GSFLOW allows a variable cell size grid to represent variation in aquifer/aquitard thickness and the grid can be locally refined in the vicinity of wells, excavations, lakes, and streams.

7.3.2.4 Climate

Finally, climate inputs, such as climate station or NEXRAD rainfall data, are typically only available on a coarser resolution. GSFLOW allows a specific grid resolution optimised for climate inputs, such as a 1 or 2-km cell size, to be used to represent spatially variable temperature and precipitation.

7.3.3 GSFLOW Process and Region Integration

While a complete description of the GSFLOW code can be found in Markstrom *et al*. (2008), the following simplified overview touches on key aspects of how the model represents the physical systems and how the surface water and groundwater systems interact.

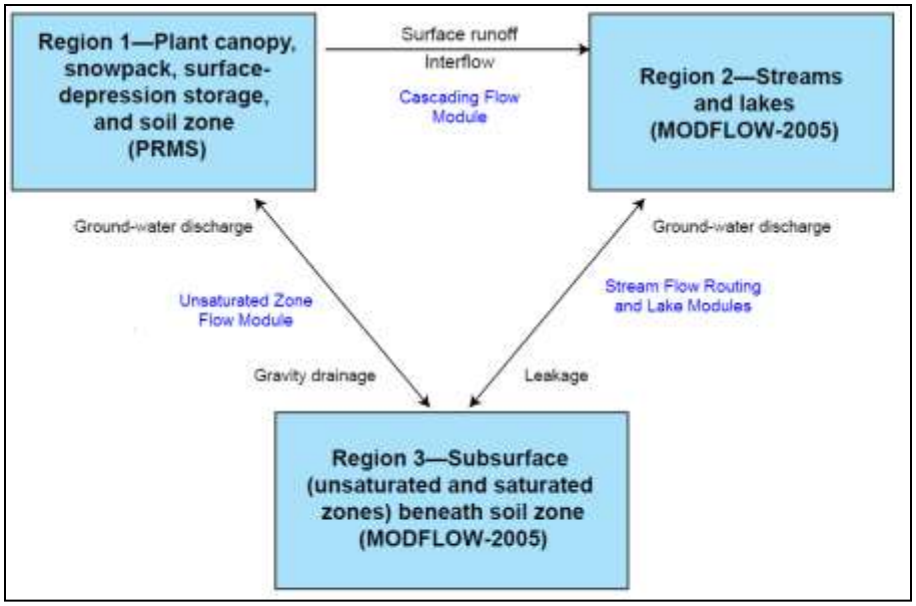


Figure 7.4: GSFLOW process flowchart.

7.3.4 Inter-Region Movement of Water

A key aspect of the integrated model is the representation of processes that move water between the three main model domains shown in Figure 7.4. The following is a brief description of the key inter-region processes.

Canopy interception and surface processes represent storage and losses that occur above or at land surface prior to infiltration and runoff. Vegetation can intercept rainfall at rates dependent on the plant type and per-cent of vegetative cover under winter and summer conditions. Intercepted water is subject to evaporation. Depression storage accounts for water that is intercepted on impervious surfaces and also subject to evaporation. Water in excess of canopy interception capacity is passed to land surface or the snow pack (if present) as “throughfall” or net precipitation. Water in excess of depression storage is routed as overland runoff.

The PRMS model includes an energy balance submodel to calculate the accumulation, compaction, melting, and refreezing of the snowpack during winter months. Snowmelt is added to net precipitation. Groundwater percolation rates are reduced by a user-specified value when snowpack is present because the underlying soil is assumed to be frozen near surface.

Topography-driven cascading overland flow and interflow represent the numerous processes that together enhance the movement of water downslope, such as by micro-channelization (rills) and/or sheet flow. Overland runoff can be generated by Hortonian processes when rainfall exceeds the infiltration rate for the soil. There are a number of methods to partition rainfall and runoff available in the PRMS code. Runoff can also be generated by Dunnian (saturation excess) processes discussed below.

Soil zone processes are controlled by the amount of moisture in the soil zone as shown schematically in Figure 7.5. Evapotranspiration can occur only when the moisture content is above the wilting point. Water can be retained against gravity drainage when the moisture content is between field capacity and wilting point. ET rates increase as the ratio of the available moisture content (i.e. moisture content minus the wilting point) to the maximum available moisture (field capacity minus the wilting point) increases.

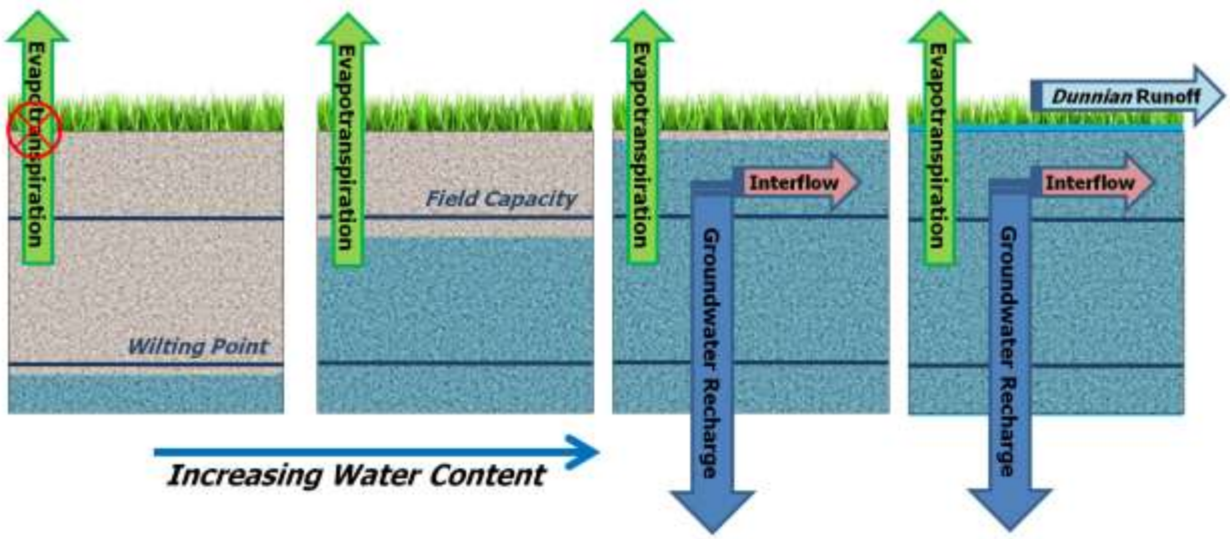


Figure 7.5: Influence of soil zone moisture on recharge, interflow, and runoff processes.

Gravity drainage is the principle process driving groundwater recharge. Gravity drainage occurs when infiltration raises the moisture content in the soil zone above field capacity (third picture in in Figure 7.5). Gravity drainage is directed to the unsaturated zone where deep root zone ET (groundwater ET) and downward percolation to the water table can occur. Feedback can occur if the hydraulic conductivity of the unsaturated zone is low enough that the total volume of gravity drainage cannot pass through. Water will then be retained in the soil zone and the moisture content may build up to reach saturation. Additional rain falling on the area will run off as saturation-excess Dunnian flow. No feedback occurs when the unsaturated zone is sufficiently permeable and the water table is located well below the soil zone. A portion of excess soil moisture can also leave the cell as interflow and will move to a downslope cell via the cascade flow network.

Groundwater discharge to the soil zone occurs when the water table rises to intersect the base of the soil zone. The discharging groundwater is added to the soil zone to raise the soil moisture content. Excess soil moisture (above saturation) and any rain falling on the cell will discharge as another form of Dunnian runoff. Surface runoff moves downslope via the cascade flow network where it can re-infiltrate into a downslope cell or discharge to a lake or stream. As above, a portion of excess soil moisture can leave the cell as interflow and move to a downslope cell.

The portion of the model area where feedback from the groundwater system occurs can change with seasonal fluctuations in the water table or in response to rainfall events. The portion of the watershed where the water table is near surface and contributes to Dunnian runoff has been referred to as the “contributing area” (Dickinson and Whiteley, 1970). Figure 7.6 shows a schematic drawing illustrating the change in contributing area due to the shift in the position of the water table between spring and summer.

Rainfall and snowmelt events generate more runoff during the spring because the “contributing area” is larger and saturation excess (Dunnian runoff) is more prevalent. Frozen soils can also contribute to saturation excess runoff by limiting the available space within the soil zone for moisture storage.

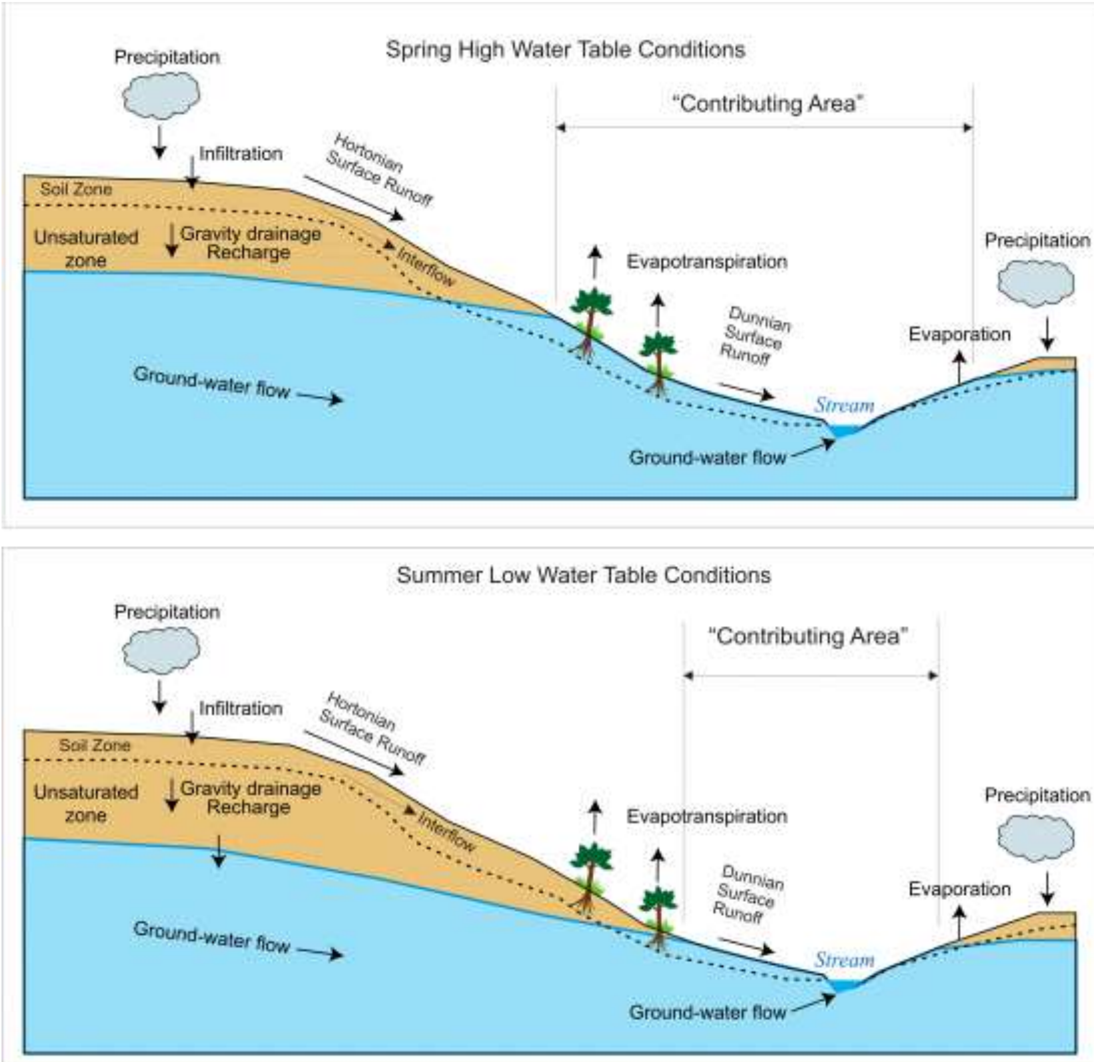


Figure 7.6: Changes in the spring and summer position of the water table increasing Dunnian runoff and the size of the "Contributing Area" (from Markstrom *et al*., 2008).

Stream/aquifer interaction occurs in the hyporheic zone where water is exchanged between the stream and the groundwater system. This exchange is represented in the GSFLOW model as head-dependent discharge or leakage with the assumption that the rate of water movement between the aquifer system and the stream is proportional to (1) the difference between the head in the aquifer and the stream stage, and (2) the permeability of the intervening streambed. The exchange of water can occur in either direction as shown in Figure 7.7. Similar exchange can occur between a lake and the aquifer across the lake bed materials as lake levels or groundwater heads change over time.

In older groundwater models, only the exchange of water across the stream bed was represented. Other Tier 2 and Tier 3 studies with the GSFLOW have shown that considerable amounts of water are exchanged as groundwater discharge to the soil zone which subsequently emergences as Dunnian overland runoff in the riparian areas. At the same time, groundwater discharge across the streambed is locally supressed or even reversed as simulated stream stage rises as a result of precipitation events. Groundwater then seeps back out to the stream as the stage subsides (bank storage). While the representation of the groundwater discharge to streams in GSFLOW is more physically correct, it has become more problematic to separate the surface water components and groundwater components of discharge to streams on a cell-by-cell basis.

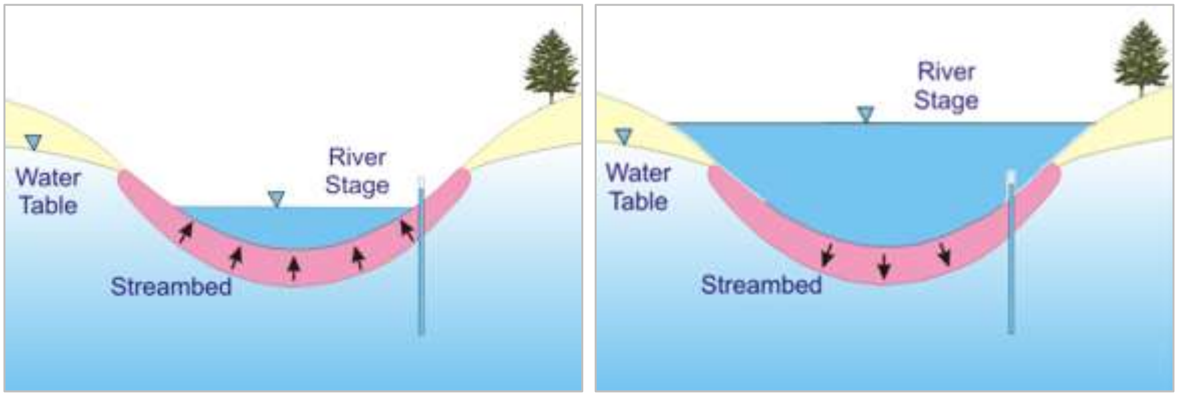


Figure 7.7: Head-dependant groundwater discharge to streams (left) and leakage from streams (right).

7.3.5 Temporal Discretization and Submodel Coupling

During a GSFLOW simulation, each submodel receives a set of input “stresses”, such as daily climate data for PRMS and changes in pumping for MODFLOW. The PRMS submodel calculates a new water balance for each cell in response to the climate inputs and passes updated estimates of groundwater recharge, overland runoff to streams, and residual ET demand to the MODFLOW submodel. In turn, the MODFLOW submodel solves the groundwater flow equations to compute new groundwater levels, changes in storage, groundwater ET, and groundwater discharge to the soil zone, lakes, and streams in response to the new recharge rates and pumping. The MODFLOW submodel also routes surface water flows and calculates new stage values in lakes and streams using the SFR2 and LAK3 modules. The process is repeated in an iterative manner until the exchange of water calculated by the two submodels converges. The final soil water balance, groundwater recharge rates, change in discharge to streams, stream flows, lake stages, groundwater heads (including the updated water table position) are then computed and saved and the model progresses to the next daily time step. A schematic showing the iterative computations executed as the model progresses through time is presented in Figure 7.8.

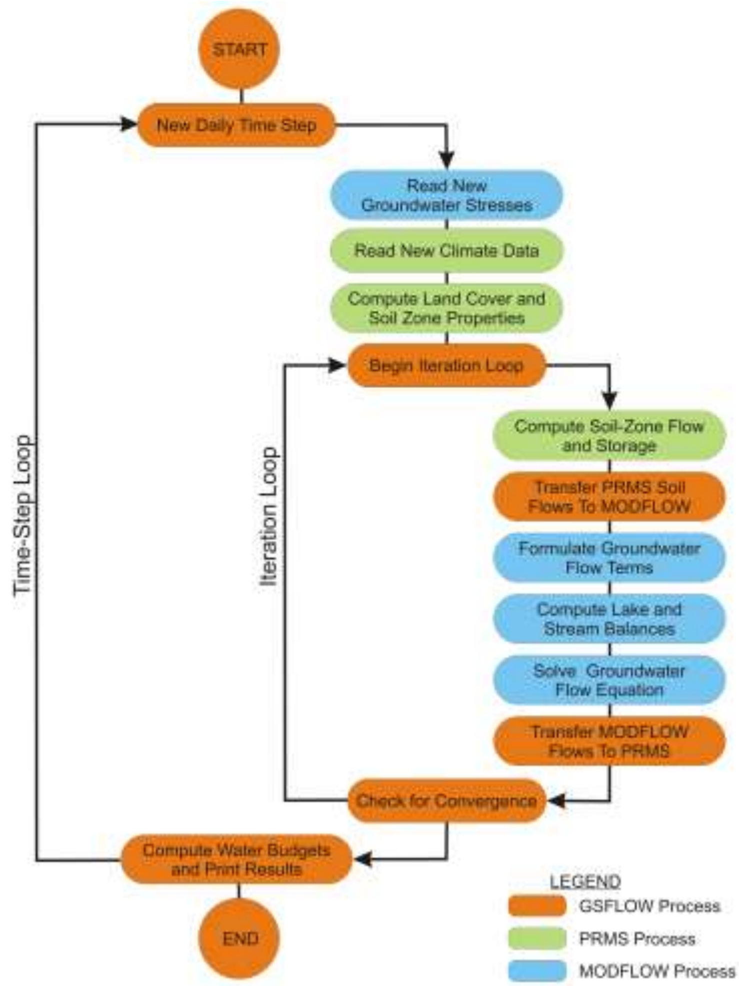


Figure 7.8: Computational sequence for an integrated PRMS/MODFLOW simulation in GSFLOW (modified from Markstrom *et al.* (2008)).

7.4 *GSFLOW Model Extensions*

As an open-source model, GSFLOW continues to be developed by both the USGS and the modelling community. Earthfx has supported several modifications to the GSFLOW code to improve performance, add additional input and output functions, to improve the methods for simulating overland flow and interflow and finally, for this study, add an irrigation demand module. Some of these extensions include:

7.4.1 Green and Ampt Infiltration Equation

The original PRMS code included a “contributing area” (or “partial-area”) method (Dickinson and Whiteley, 1970) to partition flows between infiltration and overland runoff on a daily basis. Earthfx added the Green and Ampt method into the PRMS submodel to calculate infiltration using hourly precipitation data. In this module, infiltration is computed with the Green and Ampt (1911) equation after Dawdy *et al.* (1972) using information on the saturated hydraulic conductivity of the soil, the volume of water in the soil (i.e., antecedent conditions), the capillary drive (capillary drive is equal to the product of the initial capillary potential (at the start of infiltration), and the antecedent moisture deficit (field capacity minus the initial moisture content)). Water not infiltrating the soil is added to overland runoff and routed down the cascade flow network. The Green and Ampt equation was included in an earlier version of PRMS and is well documented in Leavesley *et al*. (1983).

7.4.2 Brooks-Corey Percolation

The PRMS model assumes that all excess soil moisture - water above field capacity - leaves the cell as either interflow or gravity drainage within the same day. In reality, the rates of gravity drainage and interflow would depend on the unsaturated hydraulic conductivity of the cell. As a simple approximation, unsaturated hydraulic conductivities were adjusted on a daily basis using a Brooks-Corey relationship (Equation 1) that depends on the moisture content and saturated hydraulic conductivity. Water in excess of the amount that can be passed to interflow or gravity drainage is retained in the soil zone.

$$K_{unsat} = K_{sat} \cdot \theta^{3.0} \qquad \text{Equation 1}$$

where θ is the volumetric soil water content.

7.4.3 Darcy-based Interflow and Rate Limited Direct Runoff

The cascade flow algorithm in the PRMS model assumes that all overland flow and interflow can pass through the network within the same day as the rainfall or snowmelt event. This can lead to high overland flow and interflow to streams on the first day, with little flow on subsequent days. The revised model allows overland flow to be limited based on a Mannings “n” roughness coefficient and interflow to be limited based on the unsaturated hydraulic conductivity of the soil. Water in excess of the amount that can be discharged within the day is retained within the cell.

7.4.4 Irrigation Demand Module

To calculate irrigation requirements on a daily basis, Earthfx modified the GSFLOW code and added an Irrigation Demand module. The module first prepares input data describing farm properties and crop types and then uses the simulated daily soil moisture conditions and crop tolerances to trigger irrigation events on a parcel-by-parcel basis. The volumes taken in an irrigation event, as pumped groundwater or diverted streamflow, are determined based on a series of rules related to crop needs, pump capacity, and permit restrictions; the rules can be varied on an annual basis. Irrigation water is applied to portions of each farm by adding the pumped volume above or below the plant canopy based on the irrigation method (spray or drip). The added water is subject to interception, runoff, and “losses” to groundwater recharge as calculated by the PRMS submodel. Volumes of water taken and the applied water are tracked on a daily basis. Runoff or groundwater recharge due to excess application (irrigation return flow) is tracked. Oher changes to the water balance, such as higher groundwater recharge rates or runoff over irrigated areas during subsequent rainfall events, can be calculated by comparing simulations with and without the Irrigation Demand module. This module is discussed in more detail in Section 10.

7.5 *GSFLOW Model Development Process*

Developing an integrated watershed model is more complicated than building a “stand-alone” hydrologic model or groundwater model. However, many of the basic model development steps and procedures are similar. The key steps in the integrated model development process are presented schematically in Figure 7.9.

7.5.1.1 Task 1: Data Compilation and Synthesis

Model development begins with the collection of available data and reports to capture observations as well as insights from the work of others. Earthfx follows a data-driven approach where all available climate, hydrologic, geologic, and hydrogeologic information was synthesized and stored in a central database that was shared and analyzed by all disciplines. Centralizing the data makes it easier to observe patterns and feedback between the systems. For example, analyzing the dependence of streamflow and shallow groundwater response on rainfall and temperature provided useful information to calibrate the snowmelt process in PRMS.

7.5.1.2 Task 2: Data Review and Conceptual Model Development

The next steps, as documented in the Report Sections 2 through 6, include describing and assessing the features and critical processes active in the study area. Information on the topographic, physiographic, hydrologic, geologic, and hydrogeologic settings is synthesized and used to formulate conceptual models of the soil zone, surface water flow system (lakes, wetlands, and streams), stratigraphy, and hydrostratigraphy.

While each of these conceptual models focusses on a particular discipline, there is also a need for considering the interaction between these systems. For example, it was important to focus on the shallow subsurface (which controls the interaction with streams and wetlands) when developing the conceptual stratigraphic and hydrostratigraphic models for the Whitemans Creek subwatershed and surrounding areas.

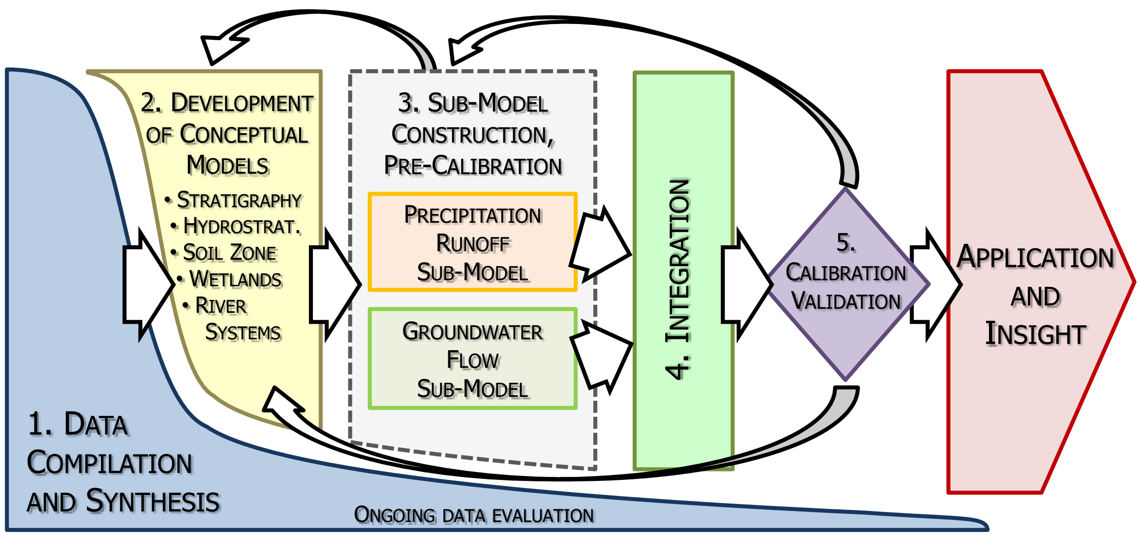


Figure 7.9: The integrated model construction process

7.5.1.3 Task 3: Submodel Development and Pre-calibration

With data compilation and conceptualization completed, the next step involved converting the conceptual model and data into input data and parameter values for the PRMS and MODFLOW submodels. This translation is described in Sections 8 through 10. The submodels were tested and “pre-calibrated”. For example, steady state groundwater simulations were undertaken to demonstrate that the groundwater submodel was functioning in a reasonable manner.

7.5.1.4 Task 4 and 5: Integrated Model Development and Calibration

Because of the complexity of the integrated model, an iterative integrated model development and calibration approach was followed, as described in Section 11. It is important to note that the overall process of data assimilation, conceptual model development, and integrated model calibration is also iterative. Analysis of preliminary model results can often point to gaps in the previous analyses. The gaps are addressed by obtaining additional data or re-evaluating the data analysis and assumptions made in the conceptualization phases.

8 Hydrologic Submodel Development

8.1 *Introduction*

Hydrological processes in the integrated model were simulated using the USGS Precipitation-Runoff Modeling System (PRMS) code. The original version of the code is documented in Leavesley *et al.* (1983); a modified version of the code was implemented as a submodel in GSFLOW (Markstrom *et al.*, 2008). The PRMS submodel in GSFLOW can run in a stand-alone mode or in a fully-integrated manner, which links the PRMS submodel with the MODFLOW-NWT groundwater submodel. The following section presents a brief description of the PRMS submodel, a summary of the climate inputs required to drive the model, an outline of the parameterization process employed in this study, and a brief discussion of the preliminary hydrologic submodel calibration.

During PRMS-only simulations, percolation from the soil zone is directed to a series of linear groundwater reservoirs. This simplification allows the PRMS submodel to be run quickly. However, feedback from the groundwater flow system is not represented. Because of the lack of feedback, a second stage of calibration is required when the submodel is linked back in with MODFLOW-NWT (see Figure 8.1). The bulk of calibration occurs during the first stage, because many of the hydrologic processes can be calibrated in the stand-alone submodel. For example, processes like snowpack accumulation or calculation of potential evapotranspiration proceed in a similar manner whether the submodels are linked or not.

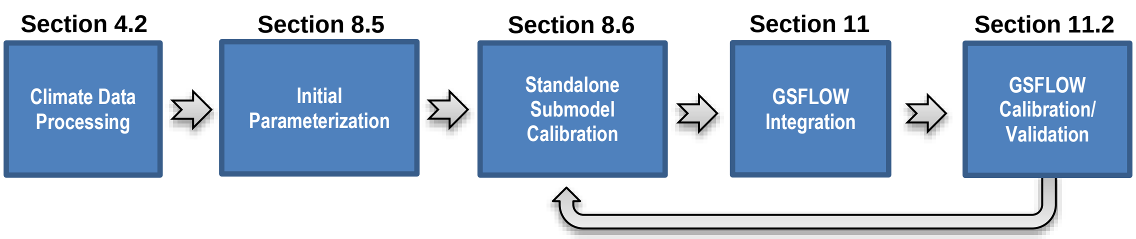


Figure 8.1: Hydrologic submodel (PRMS) development workflow.

Integration into GSFLOW and final model calibration can often result in changes to how the overall model functions. The changes can be dramatic if groundwater feedback is significant within the watershed. For example, if the stand-alone model is calibrated with parameters that create a large amount of Hortonian runoff, the parameters may need to be adjusted considerably if the integrated model produces a large amount of Dunnian runoff due to groundwater feedback. Therefore, it was important to keep the stand-alone PRMS submodel assumptions as consistent as possible with those of the final model. This was accomplished through an iterative approach to model development and calibration, where preliminary groundwater submodel results provided insight into the stand-alone PRMS calibration. In this way, the final calibration focussed on variables associated with groundwater recharge, such as percolation rates and interflow parameters.

It should be noted that the ultimate goal of the PRMS submodel development and calibration is not to produce the best stand-alone PRMS model possible. Rather, the goal is to produce a model of sufficient predictive capability that GSFLOW model development can begin. Outputs from the final stand-alone PRMS submodel are considered interim, and were not used in the final Tier 3 Risk Assessment and other analyses.

8.2 *Submodel Description*

PRMS is an open-source code for calculating all components of the hydrologic cycle at a watershed, subwatershed, or cell-based scale. PRMS is a modular, deterministic, physically-based, fully-distributed model developed to evaluate the impacts of various combinations of precipitation, other climate inputs, topography, soil properties, and land cover on streamflow and groundwater recharge. The modular design provides a flexible framework for model enhancement. The PRMS code has been used recently in many applications across the US, in Europe (Barth, 2005; Ely, 2006; Yeung, 2005), and in Canadian watersheds (such as Earthfx (2010, 2012, 2013, 2014a, 2014b, 2015)). Version 1.1.6 of GSFLOW was employed in this study which integrates PRMS version 3.0.5 and MODFLOW-NWT version 1.0.7. Modifications to the model code made by Earthfx for this project were discussed in Section 7.4.

8.2.1 Spatial Discretization

To use PRMS as a fully-distributed model, the study area was first discretized into a grid of square cells. Each cell was then assigned a unique set of hydrologic properties. Property values and methods for assigning properties are discussed further on. The PRMS cell size does not need to correspond to the area of the MODFLOW cells, allowing for finer representation of the shallow soil zone processes including overland runoff and interflow across the study area (see Figure 7.3).

For this study, square cells, 60 m on a side, were found to adequately represent the distribution of land cover, topography, and soil properties within the model boundary while minimizing the number of model cells. This cell size is a multiple of the 15 m SOLRIS mapping (Figure 2.11) which was used to parameterize the model. The PRMS grid contained 920 rows and 952 columns with 422,592 active cells covering an area of 1,521 km². Cells that covered areas outside of the MODFLOW submodel boundaries were designated as inactive and were not included in the water balance computations. The origin of the PRMS grid was aligned with the groundwater submodel grid.

8.2.2 Temporal Discretization

The PRMS submodel in GSFLOW and the groundwater submodel are integrated on a daily time step basis. Select rainfall-related processes within the PRMS submodel such as infiltration can be calculated on an hourly time step, however, daily outputs were deemed adequate for this phase of the study. As previously discussed in Section 4.2, daily climate data - precipitation and minimum/maximum temperature - from multiple stations were interpolated to the study area using an inverse-squared-distance weighting scheme. Solar radiation was adjusted for slope and slope aspect for each cell. Using the distributed climate inputs, PRMS computes individual water and energy balances for every cell on a daily basis.

8.3 *Hydrologic Processes*

A flow chart describing the physical processes simulated by the PRMS code is shown in Figure 8.2. A more complete description of the program code and underlying theory can be found in Leavesley *et al.* (1983), Markstrom *et al.* (2008), and Markstrom *et al.* (2015). The PRMS model tracks volumes of water for each cell in multiple storage reservoirs. These include interception storage, depression storage, snowpack storage, capillary soil moisture zone storage, gravity soil moisture zone storage (water in excess of field capacity), preferential flow storage, and groundwater storage (when GSFLOW is run in the PRMS-only mode).

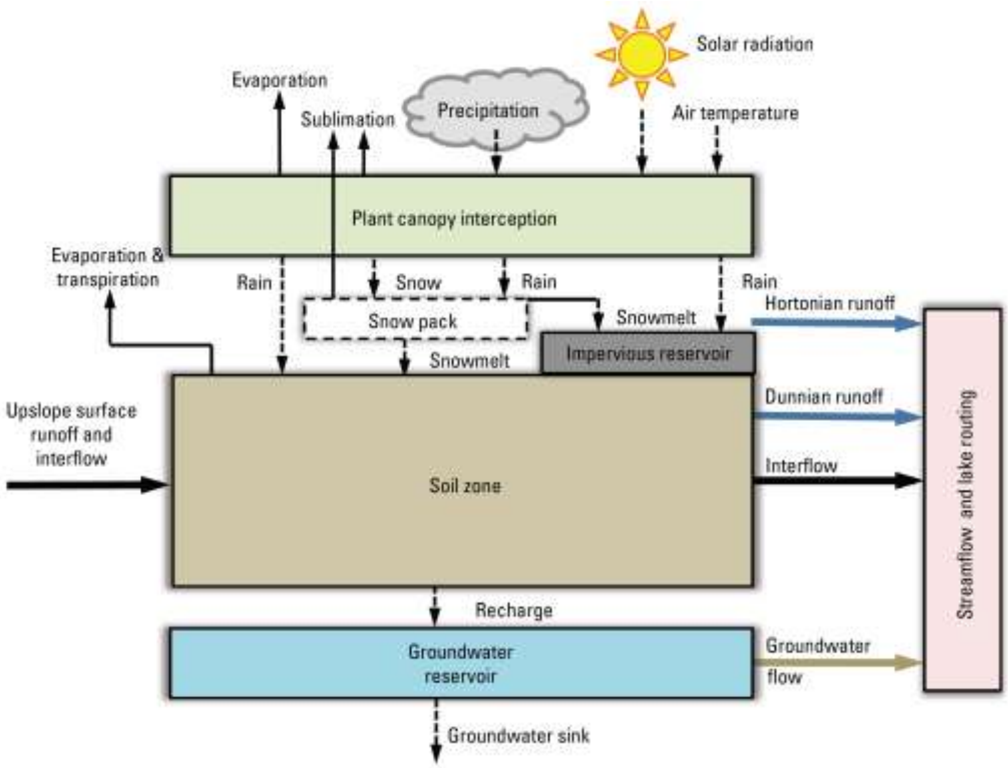


Figure 8.2: Hydrological processes simulated by the Precipitation-Runoff Modeling System (from Markstrom *et al.*, 2015)

8.3.1 Cascade Runoff, Interflow, and Imperviousness

The routing of overland runoff and interflow between cells is defined by a cascade flow network created based on basin topography. The cascade directs outflows (overland runoff and interflow) of one or many upslope cells to downslope cells. Overland runoff onto a cell from upstream (also referred to as run-on) is factored into the water budget for the downstream cell, thereby allowing the run-on to re-infiltrate and/or contribute to the runoff to the next cell. Interflow from upstream cells is added directly to the soil water budget for the downstream cell where it can contribute to groundwater recharge, interflow, and/or Dunnian runoff. Overland runoff and interflow are eventually directed either to the catchment outlet or to streams and lakes.

Each cell can contain both pervious and impervious sub-areas. Separate water balance computations are done for each sub-area at every daily time step. For both subareas, the model first computes interception by vegetation. The amount intercepted depends on vegetation type, precipitation type (rain, snow, or mixed) and winter/summer vegetation cover density. When interception storage capacity is exceeded, the surplus is allowed to fall through onto the snowpack, if present, or directly onto the ground surface, a process termed throughfall or net rainfall. In impervious areas, the model computes the capture of precipitation by depression storage. When depression storage capacity is exceeded, the surplus is discharged as overland runoff. Water is removed from the depression storage reservoir in each cell by evaporation.

8.3.2 Snow Pack

A two-layer, energy-balance model for the snowpack, shown schematically in Figure 8.3, computes snowpack depth, density, albedo, temperature, sublimation, and snowmelt on a daily basis using maximum and minimum air temperature, solar radiation, and precipitation data. The linear, energy-balance snowpack model is combined with an areal snow depletion curve to simulate the sub-cell spatial distribution of snowmelt at shallow snowpack depths (DeWalle and Rango, 2008).

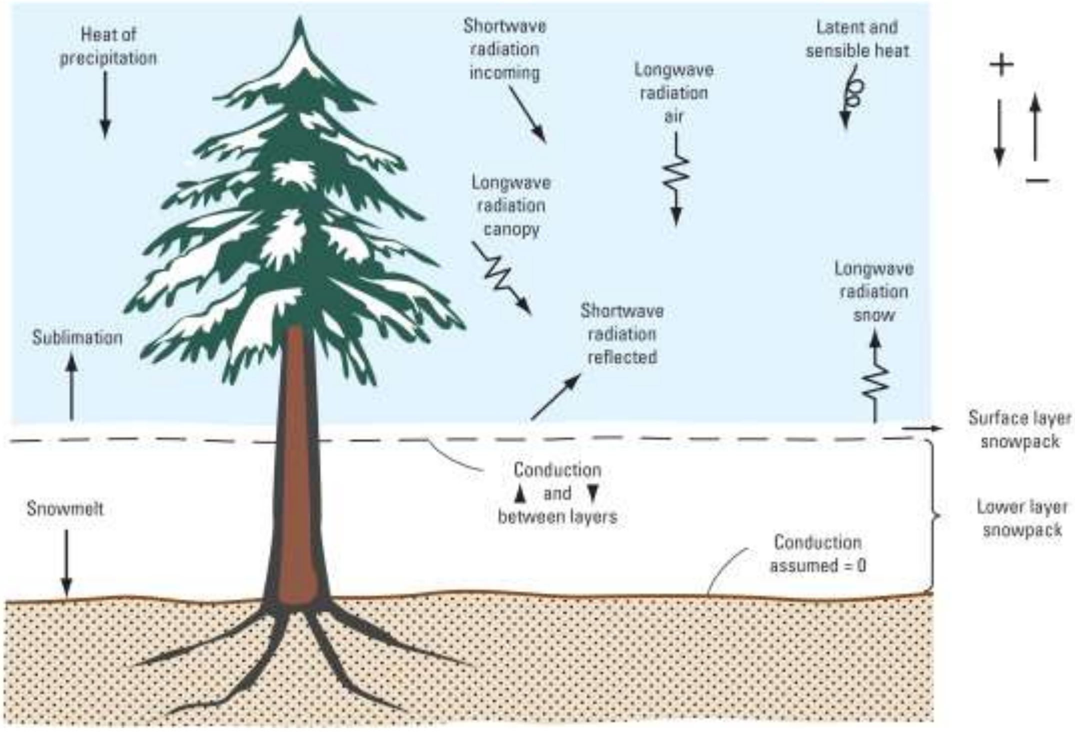


Figure 8.3: PRMS two-layer snowpack conceptualization and the components of the snowpack energy balance, accumulation, snowmelt, and sublimation algorithms (from Markstrom *et al*., 2015).

The snowpack energy balance model is used to determine the amount of snowmelt on pervious and impervious areas on a sub-daily basis to account for differences in the night and day energy flux. Detailed descriptions of the energy balance model can be found in Anderson (1968), Obled and Rosse (1977), and Leavesley *et al*. (1983). The snowpack is treated as a porous medium, where liquid water can be stored and potentially re-freeze.

During precipitation events, the model first checks whether a snowpack exists. If the temperature is below a user-defined base (or critical) temperature (T_c), all throughfall (i.e., precipitation in excess of interception storage) is added to the snowpack as new snow. If the temperature is higher, the throughfall is added as rain to the snowpack and is used to raise the temperature of the snowpack through sensible and latent heat exchange. If the energy input is high enough and the snowpack has become isothermal, all or part of the snowpack can melt. Recharge is limited by scaling the maximum daily percolation rate during periods when a snowpack is present to simulate the effect of partially frozen ground.

Water remaining in the snowpack can refreeze based on air temperature change. The albedo (reflectivity) of the snow decreases over time allowing the snowpack to absorb more energy as it ages. The albedo is reset every time there is a new snowfall event. The snowpack is also subject to sublimation.

8.3.3 Overland Runoff, Infiltration, and Evapotranspiration

Throughfall in the absence of a snowpack is partitioned between infiltration and runoff. The original PRMS code included a “contributing area” (or “partial-area”) method (Dickinson and Whiteley, 1970) to partition flows on a daily basis. Because the Source Water Protection Program Technical Rules (OMOE, 2011) require infiltration to be simulated on an hourly time step, Earthfx added the Green and Ampt method used in the original PRMS code (see Leavesly *et al.,* 1983) back into the PRMS submodel to calculate infiltration using hourly precipitation data. In this code, infiltration is computed with the Green and Ampt (1911) equation as modified by Dawdy *et al*. (1972) using information on the saturated hydraulic conductivity of the soil, the volume of water in the soil, the capillary drive (capillary drive is equal to the product of the initial capillary potential (at the start of infiltration), and the antecedent moisture deficit (field capacity minus the initial moisture content)). Runoff generated is calculated as the excess over the infiltration capacity. Infiltration excess runoff is termed “Hortonian” runoff.

Water entering the soil in pervious areas is held in the capillary zone reservoir where it is subject to evapotranspiration (ET). The PRMS code has several methods for calculating potential evapotranspiration (PET). The Priestly and Taylor (1972) method was used in this study to estimate daily PET and only requires values for daily temperature, incoming global radiation, and a few other climate variables. The methodology implemented within the GSFLOW code follows the approach described by Irmak *et al*. (2012). Actual evapotranspiration (AET) depends on available moisture and is assumed to follow a hierarchy whereby ET is first extracted from interception storage and then depression storage. If there is insufficient water to meet the total PET demand, the deficit is extracted from the capillary zone (the upper soil zone) at a rate based on soil type and the ratio of the current volume of water stored in the capillary zone to its maximum storage capacity. If PET demand is still not met, moisture is extracted indirectly from the gravity soil zone reservoir which is used to replenish the capillary deficit (Markstrom *et al.*, 2008). Once below a specified evaporation extinction depth, transpiration can continue at a rate dependent on canopy coverage, vegetation type, soil type, and the ratio of the current volume of water stored in the capillary soil zone to its maximum storage capacity. Soil zone depth is defined by the average rooting depth of the dominant vegetation and was adjusted during model calibration. Initial upper soil zone storage was set to 20% of soil zone capacity. When running GSFLOW in integrated model mode, any remaining PET demand is passed from PRMS to MODFLOW where it can be extracted as groundwater ET from the saturated zone (GWET) at a rate dependent on the depth to the water table.

8.3.4 Gravity Drainage, Interflow, and Groundwater Discharge

PRMS directs any soil water above field capacity to the gravity reservoir where it is partitioned between interflow and gravity drainage (percolation) to the groundwater reservoir. Percolation is limited to a daily maximum value based on the vertical hydraulic conductivity of the surficial soils (assuming a unit gradient). Earthfx added the ability to adjust the vertical hydraulic conductivity based on the soil moisture content using the Brooks and Corey equation (1964). This provided a better representation of unsaturated soil zone behaviour on a distributed basis. Excess moisture above the percolation limit is held within the soil zone but can discharge as overland runoff when the gravity and capillary storage reservoirs reach capacity. This form of saturation-excess runoff is termed “Dunnian” runoff within the GSFLOW modelling framework (Markstrom *et al.,* 2008). The volume of water held in the gravity reservoir is updated every day and can be depleted by evapotranspiration, discharge to downslope cells as interflow, or percolation to the groundwater reservoir as gravity drainage.

During PRMS-only simulations, percolation is fed to a linear groundwater reservoir associated with every cell. Lateral groundwater movement can be approximated using a separate groundwater reservoir cascade algorithm or it can be treated as a single groundwater reservoir that contributes to a gauged subbasin. The latter option was used in this preliminary phase of the calibration. Discharge from the groundwater reservoirs to streams occurs at a rate dependent on the volume of water stored in the groundwater reservoir and a linear decay coefficient that can be determined using gauge discharge records (Linsley *et al.*, 1975). When combined with MODFLOW (GSFLOW mode), groundwater recharge is directed to the underlying MODFLOW cell and MODFLOW simulates the groundwater flow processes. In addition, MODFLOW calculates the volume of water transferred back to the soil reservoirs when the water table intersects the soil zone. This water can fill the soil reservoirs and contribute to Dunnian runoff. This feedback mechanism is significant in low-lying areas such as stream valleys and wetlands.

8.4 *Climate Inputs*

As discussed in Section 4.2, data were obtained at Environment Canada and GRCA climate stations proximal to the study area. Locations of the 79 stations used in creating the time-series data were shown in Figure 4.6. Over 624,256 daily records were added to the database and analyzed in this task. A partial record exists dating back to 1866 for some stations; however, significant gaps exist in these data. A complete climate record is available within the model area for the period spanning water WY1868 to WY2016 (October 1, 1867 to September 30, 2016). Data from this 149-year period were employed to generate inputs for the PRMS submodel and to select the 10-year drought period. The early data were not needed for the modelling scenarios planned for the Tier 3 Risk Assessment, but they are available for use in future studies.

Climate inputs required for the hydrologic submodel include daily precipitation, maximum and minimum air temperature, rainfall intensity, and solar radiation. The daily precipitation and temperature data from multiple stations were interpolated over the study area using an inverse-distance weighting method. The development of the solar radiation input dataset and the hourly intensities are discussed below.

8.4.1 Solar Radiation

Solar radiation observations serve as one of the primary drivers of the ET module within the hydrologic submodel. Incoming solar radiation is controlled primarily by the number of possible hours of sunshine per day and the percent cloud cover. Solar radiation data are collected at few stations in Ontario; therefore, data had to be compiled from a variety of sources (Table 8.9). Through linear regression analysis, it was shown (Earthfx, 2010) that the southern Ontario solar radiation stations exhibited good inter-station correlation. The stations with available data are within 100 km of each other; Sucking and Hay (1976) suggest that stations within 250 km should demonstrate good correlation. Accordingly, a continuous dataset for 1956 through 2015 was created by averaging and infilling daily solar radiation information from eight southern Ontario stations. Data provided in sub-daily increments were summed to daily energy gains and converted to langleys per day (one ly/d = 1 cal/cm²/d or 41.84 kJ/m²-day), the input units required by the hydrologic model.

The incoming solar radiation dataset was based primarily on the average of measurements from four climate stations maintained by EC between 1956 and 2005. These stations include: 611KBE0 (Egbert CARE); 6142285 (Elora Research Station); 6158350 (Toronto); and 6158740 (Toronto MET Research Station). Unfortunately, the period of record of these four sites does not extend beyond August 31, 2003; therefore the remaining data up to 2015 had to be infilled using measurements from the University of Waterloo, York University, University of Toronto Mississauga campus, and the Burford Tree Farm (GRCA). The properties of the climate stations used to create the composite solar radiation dataset are summarized in Table 8.9. A portion of the available incoming solar radiation record is provided on Figure 8.5. A histogram of monthly observed solar radiation is provided on Figure 8.6.

8.4.1.1 Infilling Solar Radiation Dataset

Where direct observations were unavailable, solar radiation was estimated by the Hargreaves and Samani (1982) method which uses daily minimum and maximum temperatures to correct incidental extraterrestrial radiation to match observed local conditions. A complete daily temperature record was created for the watershed for the period spanning WY1872 through WY2016 (Section 4.2.2). This dataset was used to generate a complete solar radiation time series. The constants in the Hargreaves and Samani method were calibrated against the observed solar radiation time series (Figure 8.7). A correction factor (KT) of 0.151 was found to best fit the data; this compares well to the value of 0.162 recommended for “interior” regions. Adequate correlation was found between the calculated and observed solar radiation values on a daily basis ($r^2 = 0.73$) as shown on Figure 8.8a. Although more scatter is present in the daily dataset calculated with the Hargreaves and Samani method, an excellent match was achieved ($r^2 = 0.96$) on a monthly basis (Figure 8.8b). The estimated data, while not as good as actual field observations, were sufficient for the objectives of this study.

8.4.2 Synthetic Hourly Rainfall Intensities

The Source Water Protection Program Technical Rules (OMOE, 2011) require infiltration to be simulated on an hourly time step. Accordingly, the Green and Ampt method is applied in this study on an hourly basis. Daily rainfall volumes were applied as determined by the gridded inverse-distance weighting technique (Section 4.2). Hourly intensity curves were synthesized after the method outlined by Schroeter *et al*. (2001) (discussed further in AquaResource (2008)). Hourly precipitation data from Brantford MOE (Figure 8.9), Stratford MOE (Figure 8.10), and Woodstock (Figure 8.11) were obtained from Environment Canada for this task. Hourly data from Brantford MOE were used to derive the synthetic hourly intensities as this station has the most complete hourly record.

While it would be ideal to apply observed hourly precipitation measurements directly into the model, the density of hourly stations is significantly less than primary and ordinary climate stations with daily data. There is a high degree of monthly variation during the summer months (see Section 4.2.1) across the study area and increasing the number of available stations improves the spatial quality of the precipitation inputs. The use of significantly more climate stations, with daily data, may be a preferable modelling strategy over using fewer stations with hourly data from disparate sources. Past projects have demonstrated that synthetic hourly rainfall intensities produce similar runoff volumes and timing as using observed data (Schroeter *et al*., 2001).

8.5 *Parameter Assignment for the Hydrologic Submodel*

Initial estimates of model parameters were defined prior to starting PRMS submodel runs and the calibration process. For parsimony, consistent assumptions and parameter values were applied across all subwatersheds within the study area, where possible. Discussion of model parameters is grouped into five sub-sections, including:

1. topography-related parameters
2. land-cover related parameters;
3. soil parameters derived from agricultural soils mapping;
4. recharge parameters derived from surficial geology mapping; and,
5. other parameters related to hydrological processes such as snowmelt.

The software package VIEWLOG (Kassenaar, 2013) was used to create or interpolate gridded data (such as slopes and elevations) and to assign parameters using lookups for tabulated values and cell-based indices. It should be noted that for the sake of clarity, model parameters presented in this section of the report refer to values used in the final, calibrated GSFLOW model. Table 2.1 presents the data sources employed to derive the hydrologic submodel parameters.

Table 8.1: Summary of hydrologic submodel parameterization data sources.

Model Parameters	Data Source
Topography-related properties • (e.g., slope, aspect, and the cascade network)	• LIDAR digital elevation mapping provided by GRCA • 10-m DEM (OMNRF) • Canadian Digital Surface Model (CDSM) (Natural Resources Canada)
• Stream network (for overland runoff routing)	• Water Resources Information Program (WRIP) Enhanced Watercourse mapping (OMNRF)
Soil and recharge parameters • Soil-type, field capacity, wilting point, porosity, and interflow parameters.	• Agricultural soils mapping for the study area (OMAFRA)
• Maximum daily percolation rates.	• Surficial geological mapping for the study area (OGS/MNDM)
• Interflow and surface runoff parameters	• Tile Drainage and Constructed Drain Mapping (OMAFRA)
Vegetation and land-cover related properties • (e.g., cover density, percent imperviousness, and rooting depth)	• Southern Ontario Land Resource Information System (SOLRIS) land cover mapping (15-m resolution upscaled to 60 m)
Hydrologic process parameters • (relating to snowpack/melt and potential ET model processes)	• Pan Evaporation data (EC) • Snow Courses (GRCA/UTCA)

8.5.1 Topography-related Parameters

Topographic data for the model area (obtained in 2014; as discussed in Section 2) were re-sampled to each 60 m PRMS cell (Figure 8.12). Slope (Figure 8.13) and slope aspect (Figure 8.14) values were calculated from the DEM using a nine-point planar regression technique that fits a plane to every cell and its eight surrounding cells (*see* Moore *et al.,* 1991). Slope and slope aspect affect the amount of shortwave solar radiation arriving at land surface. For example, a north-facing valley slope will get less solar radiation than the south-facing slope and will therefore have lower potential ET rates and a longer-persisting snowpack. PRMS corrects the solar radiation inputs for each cell, based on its slope and slope aspect as well as for time of year, before these data are used in snowmelt and ET calculations.

As noted earlier, the PRMS code incorporates a cascading flow algorithm that routes overland flow and interflow from one cell to adjacent cells (Markstrom *et al.*, 2008). In many catchment models, runoff generated at a point in the model is routed directly to stream channels, without having the possibility of infiltrating somewhere along the pathway. The cascading algorithm transfers runoff from one cell and adds it as run-on to the total volume of water available for infiltration and/or runoff to the downslope cell. Interflow is also routed down the cascade network. Accumulation of runoff from upstream cells and the convergence of the generally dendritic flow network results in more realistic patterns of ET, runoff to streams, and enhanced recharge in the downslope areas.

Topographic data and terrain analysis techniques were used to define the cascade overland flow routing network. An 8-direction steepest-descent method was selected because it generates an efficient many-to-one cascade network (i.e., only one outflow path per cell is defined) and it avoids undesirable upslope numerical dispersion (*see* Seibert and McGlynn, 2007). A small portion of the cascade flow within the lower Whitemans Creek valley is shown in detail on Figure 8.15 along with the resampled land surface topography. A cascade pathline goes from cell to cell until a stream reach, lake, or a closed depression (“swale”) is encountered. Runoff generation and overflow are controlled by a series of variables related to land cover and soil type as discussed below.

8.5.2 Land Cover Related Parameters

The SOLRIS v2 land cover mapping (Figure 2.11) played a large role in assigning key land cover parameters in the hydrologic model. For the sake of parsimony and to simplify property assignment, these were assigned to model cells using a look-up table with parameter values for each classification category. An underlying assumption was that properties for a particular land-use class, such as “Treed Swamp”, were the same in one part of the model area as another. The SOLRIS parameterization grid is presented on Figure 8.16. Values were assigned to a 15 m raster then upscaled to the final 60 m grid to preserve fidelity. The hydrological properties that were spatially distributed based on the SOLRIS mapping included:

- ***Vegetation index:*** dominant vegetation type (bare, grass, shrub, or trees) in the cell.
- ***Vegetative cover density:*** the fraction of pervious area covered by vegetation and/or tree canopy. Two values are provided: one for the growing season (Figure 8.17) and one for winter (Figure 8.18). Values were taken from book values (Chang, 2006) and previous studies.
- ***Interception storage:*** the amount of precipitation retained on vegetative surfaces and/or tree canopy. Three values are provided: interception storage for summer rain (Figure 8.19), winter rain (Figure 8.20), and winter snow (Figure 8.21). Values were estimated for each category from book values (Chang, 2006; Winkler *et al*., 2009; Komatsu *et al*., 2011) and for conifers by the method described by Ellis *et al*. (2010). Effective interception capacity is the product of vegetative cover density and interception storage.
- ***Soil Depth:*** soil depths (Figure 8.22) are typically represented as mean vegetation rooting depths and were derived from book values (Strong and Roi, 1983; Van Rees, 1997; Kohzu *et al.*, 2003; Chang, 2006) based on the land cover classification.
- ***Evaporation extinction depth:*** the depth below the soil surface where evaporative loss becomes negligible. Note that transpiration losses may still occur below this depth.
- ***Overland Runoff Roughness:*** Overland flow down the cascade network is limited by the hydraulic gradient between the upgradient and downgradient cells and the cell roughness. This

parameter lacks direct physical meaning; it is an empirical combination of cell roughness and characteristic length. Values were arrived at through submodel calibration (Figure 8.23).

- ***Percent Imperviousness:*** the proportion of the cell area assumed to be impervious (Figure 8.24).

The PRMS code expects inputs in a mix of imperial and metric units. Conversions were applied to the tabulated values in the data pre-processors. Parameters were refined as needed during model calibration to improve the match between observed and simulated flows. A lookup table of final model hydrological parameters by land cover class is provided in Table 8.10.

8.5.3 Soils Mapping Related Parameters

Soil properties have a significant influence on hydrological processes and water budget because they control the amount of water that can infiltrate and be transmitted to the water table, as well as the amount of water lost to evaporation and transpiration by plants (actual ET). In PRMS, the soil zone is divided into two main reservoirs: the capillary reservoir and the gravity reservoir (Figure 8.4). The capillary reservoir represents the tension storage between field capacity and wilting point. This reservoir can be depleted by ET. The gravity reservoir represents the remaining available storage within the soils column above field capacity where water can drain freely to recharge the groundwater system. Infiltration is controlled by two main factors: (i) the ability of the soil to transmit water (hydraulic conductivity); and (ii) the gravity and suction forces acting on the soil water. For PRMS-only simulations, all water above field capacity - remaining after ET - is available to percolate to the water table or to discharge to adjacent cells as interflow. If the soil permeability is low, water will be retained in the gravity reservoir and gradually percolate or discharge over a period of days. Soil water-holding capacity in the capillary and gravity reservoirs (*see* Markstrom *et al*., 2008) were input as model parameters that were assumed to be functions of soil zone thickness, porosity, field capacity, and wilting point. Parameters that control the partitioning of flow between interflow and percolation were also specified as soil-type properties.

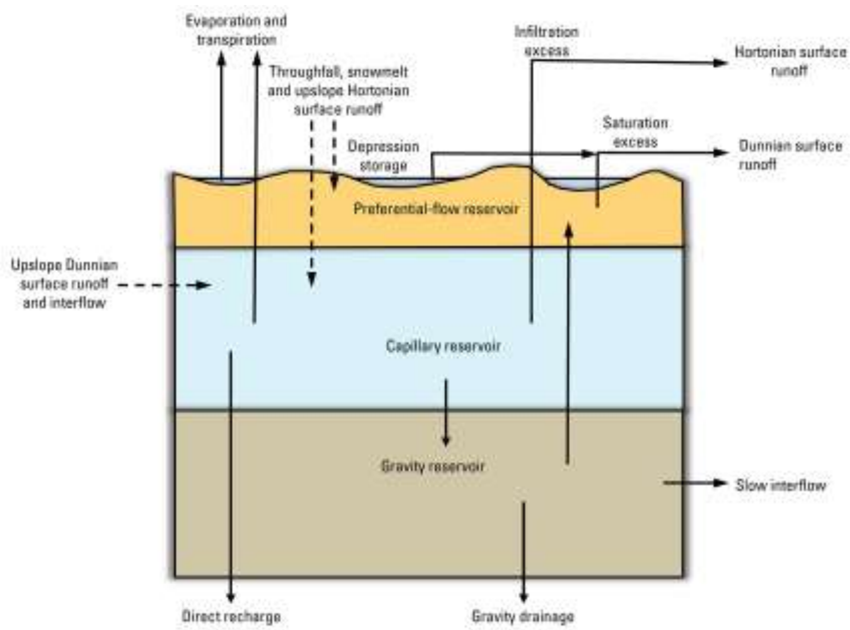


Figure 8.4: Soil water zones in PRMS and GSFLOW (modified from Markstrom *et al*., 2015).

Agricultural soils mapping produced by the Ontario Ministry of Agriculture and Food, Ontario Ministry of Rural Affairs (2003) was used to distribute the several soil zone parameters. The mapped textural class of the surface (or 'A' horizon) shown on Figure 8.25 was used to define the wilting point, field capacity, and porosity across the region using relationships developed by Saxton and Rawls (2006). While some mismatching of soil textures is observed between the various agricultural soil maps, good edge fitting is observed in the distributed model inputs presented below. The soil zone properties which were spatially distributed based on the agricultural soils mapping included:

- ***Specific soil zone properties:*** Porosity (Figure 8.26), field capacity (Figure 8.27), and wilting point (Figure 8.28) were determined based on soil texture as per Saxton and Rawls (2006). These are not input directly, instead are employed to calculate the following model parameters:
    - ***Soil moisture reservoir capacity:*** This is the product of soil depth and the difference between field capacity and wilting point, also known as Plant Available Water (Figure 8.29).
    - ***Subsurface reservoir capacity:*** This is the volume of drainable storage in the soil column (the product of soil depth and the difference between porosity and field capacity). Markstrom *et al.* (2015) refer to this term as *Saturation Threshold*;
- ***PRMS soil types:*** Soils were classified as one of the three types: sand, loam and clay (Figure 8.30). Separate moisture profiles are included within PRMS for these soil types to control ET rates when soil moisture levels approach the wilting point.
- ***Green and Ampt Infiltration Rates:*** These specify the rate at which water enters the soil at surface (Figure 8.31) as determined by Saxton and Rawls (2006) based on soil texture. Controls the generation of infiltration-excess (Hortonian) runoff

A lookup table of final soil zone parameters distributed by agricultural soil type is provided in Table 8.11. The soil zone parameters described above were not modified during calibration.

8.5.4 Surficial Geology Related Parameters

OGS (2010) surficial geology maps (see Section 3.2.4, Figure 3.11) were used to assign groundwater seepage rates and interflow properties within the study area. Parameters which were spatially distributed based on the surficial geology mapping included:

- ***Maximum Daily Percolation Rates:*** These values (Figure 8.32) limit the rate water can move out of the soil zone downward as recharge to groundwater. Values were estimated initially from previous PRMS models (such as Earthfx, 2014b) or the available literature (for example Chow, 1964; Linsley *et al*., 1975; Fetter, 1980; Todd, 1980; and DeWalle and Rango, 2008) and refined during submodel calibration. When snow cover is present, “winter” percolation rates were set as the maximum daily percolation rates divided by 20.
- ***Lateral hydraulic conductivities:*** These hydraulic conductivity values control the lateral movement of water in the shallow subsurface (Figure 8.33). These rates were based on the above maximum daily percolation rates and estimates of anisotropy in the shallow subsurface. Areas mapped as tile drained fields (Figure 8.34) based on OMAFRA records (OMAFRA. 2015b) were subject to higher interflow rates to increase the speed at which available water above field capacity leaves the soil zone laterally.

The surficial geology classes and associated final parameter values used by the PRMS submodel are listed in Table 8.12. The lateral hydraulic conductivities were modified during submodel and GSFLOW model calibration.

8.5.5 Hydrologic Process Parameters

The PRMS model contains several submodels, such as the Green and Ampt infiltration submodel, the energy balance snowmelt model, and the PET submodels. These submodels have numerous parameters, of which many can be assigned on a cell-by-cell basis. For simplicity and consistency, global values were used where appropriate. Where possible, independent testing of the submodels was done to determine optimal values for these parameters.

8.5.5.1 Snow Pack Parameters

The GSFLOW model employs a snowpack model that estimates the rate of snow accumulation and snowmelt using an energy balance (Section 8.3.2). There are 14 parameters that need to be defined, each with varying degrees of sensitivity.

The performance of the snowpack model was evaluated against snow course data collected at several locations in and around the study area by GRCA and the Upper Thames Conservation Authority (Figure 8.35). Snow monitoring involves the use of a calibrated sampler, (West Montrose/ Federal Sampler) which is a hollow tube equipped with a cutting edge which is rotated into the snow pack to cut a core of snow down to ground level. Each core is measured for depth and then weighed to determine its water equivalent. The average of each of these snow core readings over the ten locations at each site is recorded as the average depth and water equivalent. The sampler is calibrated to allow for the direct conversion of weight to snow water equivalence. Snow depth and snow water equivalent (SWE) is directly measured and qualitative observations are taken of the snow surface and soil condition. Manual snow course data are collected near Burford (1961-present), Cambridge (1972- present), and Tavistock (1961- present), with historical data available near Woodstock (1957-1998). The dataset is relatively complete, with biweekly measurements spanning the observation period. The data are used by GRCA to estimate the snowpack conditions across the watershed and to forecast runoff events. Figure 8.36 summarizes the available snowpack measurements at the four stations for the period spanning WY 1975 to WY 2015. The extreme snowpack conditions observed in WY1983 and WY2012 correlate well to the snowfall values interpolated from study area climate stations (Figure 4.20).

A four-cell PRMS model was built for the sole purpose of calibrating the snowpack model at locations where snow data are available. Using a Monte Carlo approach, a total of 150,000 models runs for the period 1970 through 2014 were performed to obtain an optimized snowpack model parameter set. Many of the 14 parameters were found either to be un-identifiable (i.e., insensitive) or demonstrated good performance with the default values. Four identifiable parameters were found; the optimal values are presented in Table 8.2. Figure 8.37a plots the simulated snow depth against the observed values at the Burford monitoring site. While some positive bias is present in the upper range of the observations, the fit (r^2 = 0.81) was deemed adequate given the extremely long period over which the model was tested. Figure 8.37b shows that the optimized model was able to produce a very good match to observed snowpack depth at the Burford snow course. Figure 8.38a plots the simulated snow depth against the observed values at the Tavistock monitoring site. Some negative bias is present in the upper range of the observations (r^2 = 0.76). Figure 8.38b shows that the optimized model was also able to produce a very good match to observed snowpack depth at the Tavistock snow course.

Table 8.2: Energy-balance snowpack model parameters for the GSFLOW model.

Parameter	Description	Default Range	Calibrated Value
cecn_coef	Convection-condensation energy coefficient [calories per degree C above 0]	0 - 60	22.7
den_init	Average density of new-fallen snow [gm/cm³3]	0.01 - 0.5	0.1
freeh2o_cap	Water-holding capacity of snowpack (relative to proportion of frozen water)	0.01 - 0.2	0.01
potet_sublim	Decimal fraction of PET sublimated from snow surface	0 - 1	0.21

Note: Snowpack parameters are defined in Leavesley *et al*. (1983) and Markstrom *et al*. (2008))
Parameters not included in this list were kept at their default values.

8.5.5.2 Estimates of Precipitation Form

Precipitation form is an important input to the snowmelt and snow accumulation submodel within the hydrologic submodel. Form is required to accurately simulate rain-on-snow events which generally correspond to annual streamflow peaks in rural catchments (Dickinson *et al*., 1992). With EC stations moving away from collecting manual snow measurements, precipitation form data are often not available. A combined total precipitation value is reported rather than separate rain or snow values. At stations equipped with tipping buckets without manual observations, snow data are not collected at all.

Rain versus snow fractions can be estimated from the daily observed precipitation based on the daily maximum and minimum temperatures. Two critical temperatures are defined, the maximum daily temperature above which all precipitation is rain ($T_{max\_all\_rain}$) and the minimum daily temperature below which all precipitation is snow ($T_{max\_all\_snow}$). Precipitation is all snow when the maximum daily air temperature is less than or equal to $T_{max\_all\_snow}$. Precipitation is all rain when the minimum air temperature is greater than $T_{max\_all\_snow}$ and when the maximum air temperature is greater than or equal to $T_{max\_all\_rain}$. When the maximum daily air temperature is between $T_{max\_all\_snow}$ and $T_{max\_all\_rain}$ and the minimum daily air temperature is less than or equal to $T_{max\_all\_snow}$, precipitation is assumed to be a mixture of rain and snow. $T_{max\_all\_snow}$ and $T_{max\_all\_rain}$ can be estimated for the study area from climate stations where both snow and rain data are available.

Figure 8.39 and Figure 8.40 present daily precipitation form observations plotted against daily maximum and minimum temperatures respectively. To avoid biasing this analysis with interpolated data, only observations from climate station where rain and snow measurements were both available in the record were used. While mixed form events occur across a 10°C range, precipitation generally falls as snow when the maximum daily air temperature is below 0°C. Similarly, when the maximum temperature is above approximately 6-7°C, all precipitation falls as rain. These critical temperatures were employed to modify precipitation inputs for the integrated model, where required.

8.5.5.3 Evapotranspiration (Priestley-Taylor Coefficient)

Potential evapotranspiration (PET) in the PRMS model is approximated using the Priestley-Taylor equation (Jensen *et al*., 1990). It is an empirical formulation of the theoretically-derived Penman equation which allows potential evaporation to be computed in terms of energy fluxes without an aerodynamic component (McMahon *et al*., 2013) as follows:

$$\text{Potential ET} = \alpha_{pt}\left[\frac{\Delta}{\Delta+\gamma}\frac{R_n}{\lambda} - \frac{G}{\lambda}\right] \qquad \text{(Equation 2)}$$

Where: α_{pt} = Priestley–Taylor constant.
Δ = slope of the vapour pressure curve (kPa C^{-1}) at air temperature
γ = psychrometric constant (kPa C^{-1})
R_n = net daily radiation at the evaporating surface (MJ m^{-2} day^{-1})
λ =latent heat of vaporization (MJ kg^{-1})
G =soil heat flux into the ground (MJ m^{-2} day^{-1})

Net daily radiation is estimated from incoming radiation and daily temperature within PRMS based on the approach outlined in Irmak *et al*. (2012) which follows from FAO-56 (Allen *et al*., 1999). Soil heat flux is assumed to be zero on when applying the Priestley-Taylor equation on a daily basis.

The α_{pt} factor represents an evaporative coefficient that corrects for wind effects and the degree of surface saturation. This value has been found to vary considerably depending on land cover and site conditions; reported values range from 0.6 to 1.5 (Cristea *et al*., 2013; McMahon *et al*., 2013) with a nominal value of 1.26 generally reported. Practitioners in southern Ontario have calculated values ranging from 0.80 to 1.17 in rural settings similar to the study area (Petrone *et al*., 2006; TRCA, 2014).

While it is possible to calibrate a local estimate of α_{pt} with a runoff model, this parameter competes with soil depth and recharge processes and can make identifying an optimal value difficult. To derive an estimate of α_{pt} appropriate for the study area and to evaluate the appropriateness of the Priestley-Taylor equation to the study area, historical pan evaporation data collected at EC climate stations were obtained. A value of α_{pt} was estimated by fitting the Priestley-Taylor equation to climate data and estimates of potential evapotranspiration demand at each location.

Pan Evaporation Data

Daily pan evaporation measurements were collected in the past at three climate stations in the study area; Delhi CDA (1970-1995), Simcoe (1965-1982), and Waterloo Wellington Airport (1984 to 1995). A sample of the pan data is presented in Figure 8.41, PET is inferred by assuming a pan correction coefficient of 0.70. Data are typically collected May through October, which represents approximately 75% of the annual demand. Monthly average pan evaporation was averaged over the three stations (Figure 8.42) where complete months were available. The maximum monthly pan evaporation value was observed in WY1988, which was also a period of lower than normal flow in Whitemans Creek (Figure 4.35). Monthly average pan evaporation varies considerably, a monthly histogram is provided on Figure 8.43. While the interquartile range is relatively small, extreme values can vary by 30-40% of the mean.

The mean monthly pan evaporation values are plotted against monthly global solar radiation and mean monthly basin averaged temperature on Figure 8.44. Despite the variability in the observations, monthly solar radiation measurements correlate well (r^2 = 0.90) to the pan evaporation averages. A weaker correlation (r^2 = 0.63) was found between the pan observations and the mean monthly temperature. This would suggest that an evapotranspiration model that incorporates direct solar radiation observations (such as the Priestley-Taylor equation) should prove sufficiently accurate to estimate demand.

Pan evaporation values typically overestimate daily potential evapotranspiration demand. Water in the shallow pan is subject to advection, resulting in higher heat fluxes. Additionally, evaporation from the pan is affected by the relative humidity of the air passing over the pan which can vary depending on the siting of the equipment relative to upwind vegetation. Daily pan evaporation values are corrected through the application of a pan coefficient. The pan coefficient incorporates a number of intrinsic parameters such as ground cover, average wind speed, average air moisture content, fetch, and the upwind topographic setting. A pan coefficient of 0.7 is often used across Canada (Environment Canada, 1999). To improve the local estimation of potential ET, pan coefficients were selected that incorporate local siting conditions. Table 8.3 summarizes the coefficients selected for the EC climate stations with pan evaporation data proximal to the study subwatershed based on the site factors presented in Allen *et al*. (1999)

Table 8.3: Site-specific pan coefficients selected for EC climate stations with pan evaporation data proximal to the study subwatershed.

Station	ID	Pan Coefficient	Rationale (Allen *et al*, 1999) (FAO-16)
Waterloo Wellington A	6149387	0.70	• Moderate winds (2-5 m/s) • 10 m distance from vegetation • medium relative humidity
Delhi CDA	6131982	0.80	• Light winds (<2 m/s) • 100 m distance from vegetation • medium relative humidity.
Simcoe	6137730	0.75	• Light winds (<2 m/s) • 100 m distance from vegetation • medium relative humidity.

Estimates of Priestly-Taylor Alpha

The Priestly-Taylor equation was fitted to the observed pan ET values with local climate data. Results are presented on Figure 8.45, Figure 8.46, and Figure 8.47. Because PRMS only applies ET demand on days without precipitation, only clear sky days were considered in this fitting analysis. Estimates of α_{pt} at the three locations were similar (0.812, 0.824, and 0.840), with little seasonal bias observed. A good fit with the method is observed on a monthly basis with r^2 values ranging from 0.88 to 0.95. Daily estimates demonstrate a poorer correlation with r^2 values ranging from 0.57 to 0.62, however, no bias was observed. Estimates of ET demand also appear to capture increased demand during most dry months, with an exception of one month over the 30-year period considered. The good daily, seasonal, monthly, and annual correlations generally suggest that the Priestly-Taylor equation is appropriate for use in the Whitemans Creek area.

An average α_{pt} of 0.825 was employed in the PRMS model. This value is very similar to preliminary values of α_{pt} achieved through calibration against streamflow volumes (0.75-0.85). It is also similar to values obtained at a rurally-sited Eddy-Covariance tower operated by TRCA (2014) of 0.80-0.85.

8.6 *PRMS Pre-Calibration Strategy and Results*

As noted, the PRMS submodel was calibrated independently to test the model's ability to represent the hydrological processes in the study area and to derive reasonable values for model parameters. Although the groundwater processes simulated were simplified and no feedback was allowed, care was taken that model results and parameter values were generally transferable to GSFLOW running as a fully-integrated groundwater/surface water model. The large difference in model run times between PRMS-only runs and GSFLOW runs precluded calibrating the fully-integrated model at the outset. The intent of the PRMS-only calibration was not to achieve a final calibration but rather to derive a set of reasonable parameter values that could be used in the GSFLOW model with a minimum of recalibration effort. Some adjustments of PRMS parameters were needed in the final calibration to account for transfer of flows through feedback mechanisms not fully represented in PRMS-only simulations, such as discharge from the shallow water table to the soil zone.

8.6.1 Calibration Targets

Rather than selecting just a single stream gauge for calibration, the calibration strategy attempted to regionalize as many of the input parameter values as possible across the model area and match flows at multiple gauges. Data from fourteen stream gauges operated by the Water Survey of Canada (WSC - a division of Meteorological Service of Canada, Environment Canada) were available. Six stations are now discontinued but the historic data are still useful. A summary of the gauge properties and streamflow characteristics for the available stations was provided in Section 4.3.

Of the fourteen gauges, five are unsuitable for calibration purposes. Unfortunately, the PRMS submodel in GSFLOW does not include a lake simulation package whereas the fully-integrated model can represent lakes. Accordingly, it was not possible to calibrate the hydrologic submodel against gauges with significant upstream water bodies. This precluded using Thames River at Woodstock (02GD012) which is downstream of the Pittock Reservoir as a calibration target. Thames River at Ingersoll (02GD016) is also downstream of this reservoir and additionally the contributing area to the gauge is not fully encompassed by the hydrologic submodel. Webber Drain at Highway No. 59 (Pittock Control) (02GD024) and Goring Drain at Concession No. 3 (Pittock Test) (02GD025) drain very small areas which have been further ditched and drained since these gauges were operated in the late-1980s. Changes in hydrography and land cover preclude these stations from the calibration dataset as well as Whitemans Creek near Burford (02GB003) which was operated between 1913 and 1916.

Of the remaining nine gauges, the contributing areas to three gauges are wholly contained within the study subwatershed with modern record. These gauges: Whitemans Creek near Mount Vernon (02GB008), Horner Creek near Princeton (02GB006), and Kenny Creek near Burford (02GB009) served as primary calibration targets. The gauges outside of the Whitemans Creek subwatershed served as validation gauges during calibration (no model parameters were modified based on the match to these gauges). The topographic catchments contributing to the nine monitoring locations boundaries were determined based on the 60-m DEM and are shown in Figure 8.48. Table 4.3 provides a summary of the gauges available for calibration.

Table 8.4: Gauged catchments contained within the model area employed for model validation and calibration.

WSC ID	Station Name	Drains To:	Available Period of Record	Record Length (years)	Status	Modelled Catchment Area* (km^2)
Calibration (Primary) Gauges						
02GB008	Whitemans Creek near Mount Vernon	--	1961 - 2015	55	Active	390
02GB006	Horner Creek near Princeton	02GB008	1953 - 2015	54	Active	164
02GB009	Kenny Creek near Burford	02GB008	1961 - 1991	31	Discontinued	87.0
Validation (Secondary) Gauges						
02GC011	Big Creek Near Kelvin	--	1963 - 2015	26	Active	147
02GC017	Big Otter Creek above Otterville	--	1964 - 2015	41	Active	101
02GD011	Cedar Creek at Woodstock	--	1951 - 2015	64	Active	91.7
02GD021	Thames River at Innerkip	--	1978 - 2015	38	Active	150
02GD023	Thames River near Tavistock	02GD021	1987 - 2000	13	Discontinued	34.8
02GD026	Avon River above Stratford	--	1993 - 2015	11	Active	53.4

* Watershed areas were derived from the 60-m DEM employed in the hydrologic submodel. These areas may not agree exactly with other delineations undertaken with different topographic data.

8.6.2 Pre-Calibration Strategy

The PRMS submodel was calibrated to two separate periods spanning WY1984 to WY1986 and WY2009 to WY2011, inclusive. The 3-year periods required shorter model run times and allowed for more model runs to be undertaken during calibration. All model parameter values were regionalized by the land cover, soils mapping, or surficial geology mapping. A Monte Carlo approach was undertaken to jointly measure model sensitivity and refine the model calibration. Maximum daily groundwater seepage rates, lateral interflow conductivities, and overland flow roughness were varied during calibration to improve the match between observed and simulated streamflow. Distributed parameters, such as seepage rates, conductivities, and roughness factors, were typically calibrated as a group, scaled against a single linear or logarithmic adjustment factor, and tested against multiple objective functions. Approximately 200,000 Monte Carlo runs were completed, varying single or multiple model parameters. As many parameters as possible were taken from book values or from physical descriptions of the study area. This was done to prevent the calibration process from over-parameterizing the model. A successful integration with GSFLOW required that the submodel is not over-constrained. The correct partitioning of recharge, interflow, and ET was essential. Table 8.5 presents the hydrologic submodel parameters that were modified during calibration.

Table 8.5: Hydrologic submodel parameters modified during calibration.

Parameter	Description	Initial Values	Distributed by	Final Values Shown on
ksat_lateral	Rates used to calculate interflow rates	Estimated from Surficial Geology and anisotropy values from the groundwater model (Section 9.5)	Surficial Geology Mapping	Figure 8.22
hru_rough	Cell roughness used to calculate overland runoff rates	Estimated from SOLRIS land cover mapping	SOLRIS mapping	Figure 8.23
Soil Depth	Value used by the model preprocessor to determine values of Saturation Threshold (*sat_threshold*: Soil saturation threshold above field-capacity threshold) and Maximum Soil Moisture(*soil_moist_max*)	Estimated from book values based on mapped SOLRIS vegetation type.	SOLRIS mapping	Figure 8.33

Three objective functions were used to drive the automated calibration of the model with respect to matching observed streamflow: Nash-Sutcliffe (1970) efficiency (NSE), log-transformed Nash-Sutcliffe efficiency (log NSE), and the observed percent volume difference between the observed and simulated streamflow. The NSE is given by:

$$\text{Nash Sutcliffe Efficiency} = 1 - \frac{\sum_{n=1}^{nobs} (Q_o - Q_s)^2}{\sum_{n=1}^{nobs} (Q_o - \overline{Q}_o)^2} \qquad \text{(Equation 3)}$$

where Qo is the observed flow and Qs is the simulated flow. The NSE can range from 1 to minus infinity, with 1 being a perfect fit. A Nash-Sutcliffe efficiency of 0.6 is considered a reasonable value (Chiew and McMahon, 1993). It must be recognized that the model simulates flow on a daily basis and would not be expected to achieve a perfect match to observed mean daily flows. Additionally, daily climate observations are made on a synoptic interval which ends at 0600Z rather than at midnight. Because of the importance of matching baseflow and low flows in this study, the Log NSE, which is considered a better measure of the model calibration to low flows (Krause *et al.*, 2005), was given particular emphasis. Percent volumetric difference or bias (Equation 4), normalized root mean difference, mean error, and r^2 statistics were also considered as secondary metrics during calibration.

$$\text{Volumetric Difference (Percent Bias)} = \frac{\sum (Q_s - Q_o)}{\sum Q_o} \times 100 \qquad \text{(Equation 4)}$$

8.6.3 Pre-Calibration Results

Figure 8.49 through Figure 8.57 present the results of the initial calibration efforts at the three primary calibration gauges for the period WY1984 to WY1986. Hydrographs, log-transformed hydrographs, and flow duration curves demonstrate the quality of the current calibration. Calibration statistics for the two calibration periods are listed in Table 8.6. The model achieved reasonable NSEs between 0.51 and 0.68 for daily values during Calibration Period 1. Daily results were aggregated over each month, and monthly NSEs ranged from 0.78 to 0.91, with Log NSEs generally showing slightly improved results compared to the non-transformed factors. As shown by the various flow duration curves, the model provides a good match to net streamflow volume (low model bias). Model performance appears to be consistent across the various gauged catchments.

Table 8.6: Preliminary calibration statistics for the PRMS submodel.

Gauged Basin	Daily		Monthly		Volumetric Difference
	Nash-Sutcliffe	*Log Nash-Sutcliffe*	*Nash-Sutcliffe*	*Log Nash-Sutcliffe*	
Calibration Period 1s	**(October 1983 – September 1986)**				
Horner Creek near Princeton	0.51	0.72	0.88	0.86	-2.4%
Whitemans Creek near Mount Vernon	0.61	0.72	0.91	0.83	-5.0%
Kenny Creek near Burford	0.68	0.68	0.87	0.77	-14.6%
Big Otter Creek above Otterville	0.55	0.72	0.78	0.83	-12.8%
Cedar Creek at Woodstock	0.65	0.60	0.81	0.77	0.1%
Thames River at Innerkip	0.69	0.68	0.88	0.83	0.6%
Calibration Period 2s	**(October 2008 – September 2011)**				
Horner Creek near Princeton	0.52	0.68	0.83	0.80	-11.1%
Whitemans Creek near Mount Vernon	0.55	0.62	0.84	0.71	-8.5%
Big Creek Near Kelvin	0.60	0.63	0.87	0.76	-6.1%
Big Otter Creek above Otterville	0.55	0.60	0.78	0.68	-12.0%
Cedar Creek at Woodstock	0.69	0.57	0.84	0.75	-1.5%
Thames River at Innerkip	0.61	0.61	0.75	0.68	-12.4%
Avon River above Stratford	0.62	0.64	0.85	0.84	-6.4%

Simulated streamflow was also validated against the long-term record. Calibration statistics are presented in Table 8.7. Model validation statistics are slightly reduced in quality relative to the model calibration runs shown on Table 8.6. Figure 8.58 through Figure 8.66 present daily, monthly, and daily flow duration curves for the 25-year validation run at Horner Creek near Princeton, Whitemans Creek near Mount Vernon, and Big Otter Creek above Otterville.

Table 8.7: Preliminary validation statistics for the PRMS submodel.

Gauged Basin	Daily		Monthly		Volumetric Difference
	Nash-Sutcliffe	*Log Nash-Sutcliffe*	*Nash-Sutcliffe*	*Log Nash-Sutcliffe*	
Long-Term Validation	**(October 1971 – September 2011)**				
Horner Creek near Princeton	0.48	0.66	0.78	0.77	-1.2%
Whitemans Creek near Mount Vernon	0.51	0.61	0.78	0.72	-0.9%
Kenny Creek near Burford	0.51	0.64	0.71	0.70	-12.1%
Big Creek Near Kelvin	0.54	0.66	0.76	0.78	2.7%
Big Otter Creek above Otterville	0.53	0.59	0.74	0.74	-1.1%
Cedar Creek at Woodstock	0.55	0.47	0.73	0.67	9.4%
Thames River at Innerkip	0.51	0.65	0.75	0.78	-8.8%
Thames River near Tavistock	0.51	0.64	0.74	0.77	-7.1%
Avon River above Stratford	0.56	0.56	0.82	0.74	-7.5%

As noted, PRMS was calibrated in stand-alone fashion to gain insight into the function of the model and the appropriateness of the parameterization. Integration with the groundwater submodel proceeded after an acceptable submodel calibration was achieved. In general, this corresponded to when the daily NSE factor was greater than 0.50 for the majority of the calibration period, and the volumetric percent difference was less than 10%. The PRMS submodel was not fully calibrated as a stand-alone model because the submodel itself has no major purpose in this study. The final GSFLOW calibration results with statistical analysis are presented in Section 11.2.

8.7 *Pre-Calibration Water Budget Assessment*

After preliminary calibration, the PRMS submodel was run from WY1976 through WY2010 to assess adequacy of the model calibration and to estimate components of the long-term average water budget. A secondary goal was to provide an initial estimate of long-term average annual groundwater recharge for use during the calibration of the groundwater submodel (to be superseded with GSFLOW model results after final calibration). Net precipitation over the model is presented in Figure 8.67. Values range from 900 mm/yr in the Grand River Valley to 1050 mm/yr around the topographic high at the north end of the model area.

Average annual evaporation from interception storage is shown in Figure 8.68. This term includes sublimation from snow intercepted by vegetation and ranges from a nominal value of 70 mm/yr over crop lands to over 200 mm/yr in the forested areas of the study area. Figure 8.69 shows simulated average annual potential evapotranspiration (PET). As discussed above, PET is calculated by PRMS with the Priestley-Taylor Equation and is sensitive to cell slope, aspect, and canopy cover. Initial estimates of annual PET values range from 1050 to 1150 mm/yr (averaging 1100 mm/yr). The simulated distribution of actual evapotranspiration (AET) is presented on Figure 8.70. As discussed above, AET is rate limited by the water available in interception, depression, and finally soil storage. Preliminary model results predict AET rates vary between 450 to 700 mm/yr (averaging 596 mm/yr) over the study area. The AET distribution is affected by runoff patterns where areas at the downstream end of the cascade network have more run-on and infiltration, and therefore, more soil water available for ET compared to uplands.

Figure 8.72 shows the average annual cascading flow. Cascading flow defines the average volume of water that is likely to pass a given location either as surface runoff or interflow. The cascading runoff map highlights the role topography and run-on have on the distribution of runoff. It can be seen that runoff in the study area follows a dendritic pattern, even within the relatively flat, permeable regions of the Norfolk Sand Plain. Figure 8.71 presents distribution of generated runoff across the model. The Norfolk Sand Plain and Grand River Outwash units generate very little Hortonian (infiltration-excess) runoff. The Port Stanley and Tavistock till units generate 150 to 200 mm/yr of runoff, while the urban areas generate 350 to 450 mm/yr of runoff controlled mainly by the degree of impervious cover.

Figure 8.73 shows average annual groundwater recharge which is affected by all the factors noted previously. The influence of surficial geology can be seen in the results. Higher recharge tends to occur in the Norfolk Sand Plain and Grand River Outwash units, with the till-covered areas contributing less recharge. The simulated long-term average recharge across the Whitemans Creek subwatershed was 248 mm/yr between WY1976 and WY2010.

8.8 *Comparison with the Grand River Hydrologic Model*

To provide an initial check on the magnitudes of the recharge values produced by the stand-alone PRMS submodel, subwatershed estimates were compared with outputs from the GRCA's Grand River Watershed Hydrologic Model (Table 8.8). The Hydrologic Model is a watershed-wide model based on the Guelph All-Weather Sequential-Events Runoff (GAWSER) code. Values shown in the table were based on modelled output from the Tier 3 version of the model averaged over the 1961 to 2002 time period. Estimates of distributed recharge produced by GRCA's Grand River Watershed Hydrologic Model are shown on Figure 8.74. Long-term averages across the study subwatershed produced by the two models compared favourably, with a simulated difference of 1%. Estimates within the gauged subcatchments compared somewhat less favourably. The PRMS hydrologic model incorporates tile drainage, and as such, produces a lower recharge estimate than the GAWSER model in the heavily-drained Kenny Creek. The PRMS model produces a higher recharge estimate in Horner Creek, with much of this additional recharge supporting shallow aquifers in the lower portion of Horner Creek.

Table 8.8: Comparison of simulated groundwater recharge between the Grand River Hydrologic Model and calibrated Hydrologic Submodel (PRMS).

WSC ID	Station Name	Gauged Area (km^2)	Baseflow Estimated from Gauged Streamflow		Simulated Groundwater Recharge (mm/yr)		Simulated Difference
			(m^3/s)	(mm/yr)	GAWSER Model	Hydrologic Submodel (PRMS)	
--	Whitemans Creek Subwatershed	401	--	--	243	240	-1.2%
02GB008	Whitemans Creek near Mount Vernon	386	2.37	194	239	240	0.4%
02GB006	Horner Creek near Princeton	150	0.938	197	199	258	29.6%
02GB009	Kenny Creek near Burford	91.9	0.324	111	178	151	-15.2%

8.9 *Limitations*

This section described the hydrologic submodel (PRMS) structure, input data sets, and preliminary results. The model and results presented were considered an interim step in the development of the final integrated GSFLOW model, discussed in Section 11. The main point of the exercise was to calibrate the PRMS submodel as best as possible prior to integrating it with MODFLOW to help expedite the calibration process.

As with all models, it must be recognized that there are inherent simplifications in the model conceptualisation of distributed hydrologic processes and in the simplified assignment of parameters. There are also limitations and uncertainty in the input and calibration target data. Accordingly, it is unlikely to achieve a perfect and/or unique surface water model. However, the results obtained with the PRMS-only model are reasonable and improvements were expected upon full integration.

8.10 *Tables*

Table 8.9: List of solar radiation stations available to compile study-area solar radiation estimates.

Station	Location	Coordinates	Sensor type(s)	Data Interval	Units	Available Period of Record
University of Waterloo Weather Station	North Campus	43°28'25.6" N, 80°33'27.5" W, 334.4 masl	Kipp & Zonen Model: CM11	15 minute	W/m²	1998-2014
University of Toronto Weather Station*	University of Toronto at Mississauga Meteorological Station (UTMMS)	43° 33' N, 79° 40' W	Kipp & Zonen model CM-5 and Kipp & Zonen CM-11 (from July 2007)	hourly	mv and W/m²	1999-*Present*
York University ESSE Meteorological Observation Station (EMOS)	York University (northwest gate)	43.7753N, 79.5100W, 196masl	Kipp & Zonen CNR1 Net Radiometer	5 minute	W/m²	2006-2015
GRCA Burford	Burford Tree Farm	556199m E, 4777329m N, 210 masl	unknown	5 minute	W/m²	2013-*Present*
Environment Canada**	611KBE0 Egbert Care	597434m E, 4898143m N	unknown	daily	MJ/m²	1988-2003
Environment Canada**	6142285 Elora Research Station	546774m E, 4833164m N	unknown	daily	MJ/m²	1970-2003
Environment Canada**	6143083 Guelph OAC	562230m E, 4818850m N	unknown	daily	MJ/m²	1962-1970
Environment Canada**	6158350 Toronto	628988m E, 4836465m N	unknown	daily	MJ/m²	1956-2000
Environment Canada**	6158740 Toronto Met Res Station	616643m E, 4850681m N	unknown	daily	MJ/m²	1967-1988
Environment Canada**	6158776 Toronto Scarborough	642575m E, 4842297m N	unknown	daily	MJ/m²	1959-1973

* mv to W/m² conversion factor was 93.63 W/m²/mv for the CM-5 and 77.276 W/m²/mv for the CM-11 (Ken Turner, Department of Geography, University of Toronto, Mississauga, pers. comm. 2010).

** All EC stations correlate well (Earthfx, 2010), having correlation coefficients greater that r^2>0.9 amongst all pairings with little systematic error.

Table 8.10: Hydrologic submodel lookup table for parameters based on land cover (SOLRIS v2.).

SOLRIS Index	Class Name	Percent coverage of model area	Vegetation Index	Percent Impervious	Summer Cover Density	Winter Cover Density	Summer Rain Interception Storage (mm)	Winter Rain Interception (mm)	Snow Interception Storage (mm)	Soil Depth (mm)	Calibrated Overland Flow Roughness Factor
193	Tilled	59%	Grasses	0	0.85	0.04	2	1	1	325	40
250	Undifferentiated	15%	Grasses	0	0.85	0.04	2	1	1	325	40
131	Treed Swamp	7.8%	Trees	0	1	0.85	3	2	3	300	60
203	Built-Up Area - Impervious	5.8%	Grasses	55%	0.5	0.2	2	1	2	200	5
93	Deciduous Forest	5.3%	Trees	0	1	0.4	2	1	5	600	100
202	Built-Up Area - Pervious	1.8%	Grasses	30%	0.85	0.4	2	1	2	300	15
160	Marsh	0.77%	Grasses	0	1	1	2	1	2	600	20
191	Plantations – Tree Cultivated	0.74%	Trees	0	0.85	0.35	2.5	2.5	5	600	60
204	Extraction -Aggregate	0.68%	Bare	5%	0	0	0	0	0	50	2
201	Transportation	0.63%	Grasses	65%	0.5	0.5	2	1	2	200	2
170	Open Water	0.54%	Bare	0	0	0	0	0	0	50	1
135	Thicket Swamp	0.49%	Trees	0	1	0.85	3	2	3	300	60
92	Mixed Forest	0.30%	Trees	0	1	0.6	3	3	5	600	100
91	Coniferous Forest	0.21%	Trees	0	1	1	4	4	10	600	100
192	Hedge Rows	0.051%	Shrubs	0	1	0.5	2.5	2.5	5	500	60
140	Fen	0.022%	Grasses	0	0.75	0.5	1.5	1	2	600	30
90	Forest	0.020%	Trees	0	1	0.85	3	3	5	600	100
83	Tallgrass Woodland	0.007%	Grasses	0	1	0.85	2	2	2	500	80

Table 8.11: Hydrologic submodel lookup table for parameters based on soils mapping.

"A" Horizon Texture	Description	Proportion	PRMS Soil Type	Wilting Point (wp)	Field Capacity (fc)	Porosity (n)	Plant Available Water (PAW)	Saturated Hydraulic Conductivity (mm/hr)
SIL	Silt Loam	27%	Loam	0.14	0.32	0.48	0.18	12.2
L	Loam	22%	Loam	0.13	0.27	0.46	0.14	18.6
SL	Sandy Loam	15%	Sand	0.08	0.18	0.45	0.10	50.3
CL	Clay Loam	11%	Clay	0.21	0.35	0.47	0.14	16.7
Unclassified	Unclassified	8.7%	Loam	0.13	0.26	0.40	0.13	9.3
LS	Loamy Sand	5.9%	Loam	0.06	0.12	0.46	0.06	91.3
FSL	Fine Sandy Loam	3.5%	Loam	0.09	0.21	0.45	0.12	42.0
ORG	Organic	3.3%	Clay	0.16	0.34	0.65	0.18	2.1
GL	Gravelly Loam	1.9%	Sand	0.05	0.11	0.42	0.05	12.4
SICL	Silty Clay Loam	0.51%	Loam	0.21	0.38	0.51	0.17	5.9
FS	Fine Sand	0.14%	Sand	0.03	0.08	0.46	0.05	110.0
LFS	Loamy Fine Sand	0.12%	Loam	0.07	0.14	0.45	0.07	72.5
GS	Gravelly Sand	0.11%	Sand	0.02	0.05	0.41	0.03	76.0
VFSL	Very Fine Sandy Loam	0.08%	Loam	0.13	0.25	0.45	0.12	19.5
GSL	Gravelly Sandy Loam	0.01%	Sand	0.00	0.00	0.43	0.00	33.5

Table 8.12: Hydrologic submodel lookup table for parameters based on surficial geology.

Geologic Description	Material Description	Percent coverage of model area	Maximum Daily Percolation Rate (m/s)	Maximum Daily Percolation Rate (mm/yr)
Port Stanley Till	Silt to sandy silt till	22%	1.0×10^{-08}	316
Tavistock Till	Clayey silt till	21%	1.0×10^{-08}	316
Glaciolacustrine sand	Sand	16%	3.5×10^{-05}	1104516
Glaciofluvial sand	Sand	10%	3.5×10^{-05}	1104516
Ice-contact sand	Poorly to well sorted, fine sand and/or gravel to coarse sand and/or gravel textured	5.3%	1.0×10^{-06}	31558
Stream deposits	Gravel, sand, silt and clay	5.0%	5.0×10^{-07}	15779
Outwash gravel	Gravel	4.9%	2.5×10^{-05}	788940
Tavistock Till	Clayey silt till	2.6%	1.0×10^{-08}	316
Stratford Till	Sandy silt till	2.5%	5.0×10^{-09}	158
Lacustrine deposits	Silt and clay	2.3%	5.0×10^{-08}	1578
Bog and swamp deposits	Peat, muck and marl	2.0%	5.0×10^{-09}	158
Catfish Creek Till	Sandy to silty, stoney till	1.8%	1.0×10^{-08}	316
Wentworth Till	Stoney, sandy silt till	1.2%	1.0×10^{-07}	3156
Port Stanley Till	Silt to sandy silt till	0.91%	1.0×10^{-08}	316
Outwash gravel	Gravel	0.88%	1.0×10^{-05}	315576
Older alluvium	Sand or gravel	0.85%	5.0×10^{-07}	15779
Maryhill Till	Clay till	0.76%	1.0×10^{-08}	316
Undifferentiated till	Sandy to clayey tills	0.63%	1.0×10^{-08}	316
River or stream section	May include stratified sediments.	0.10%	5.0×10^{-09}	158
Mornington Till	Silty clay till	0.06%	5.0×10^{-08}	1578
Bedrock	Shale and dolomite	0.03%	4.0×10^{-07}	12623
Canning till	Clayey silt till	0.01%	1.0×10^{-08}	316
Beach gravel	Gravel	0.01%	1.0×10^{-05}	315576

8.11 *Figures*

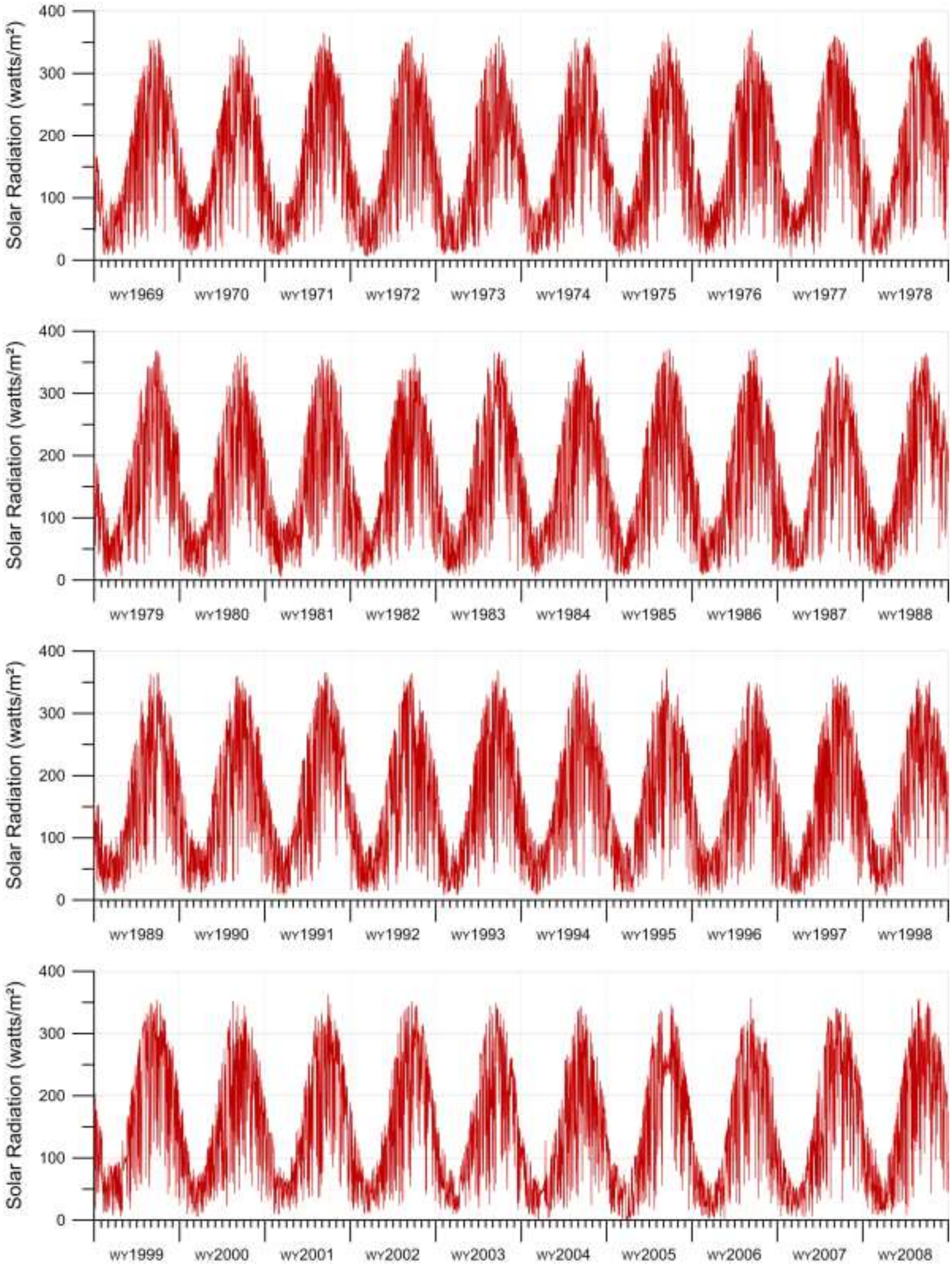


Figure 8.5: Observed daily global incoming radiation data derived from stations in southern Ontario.

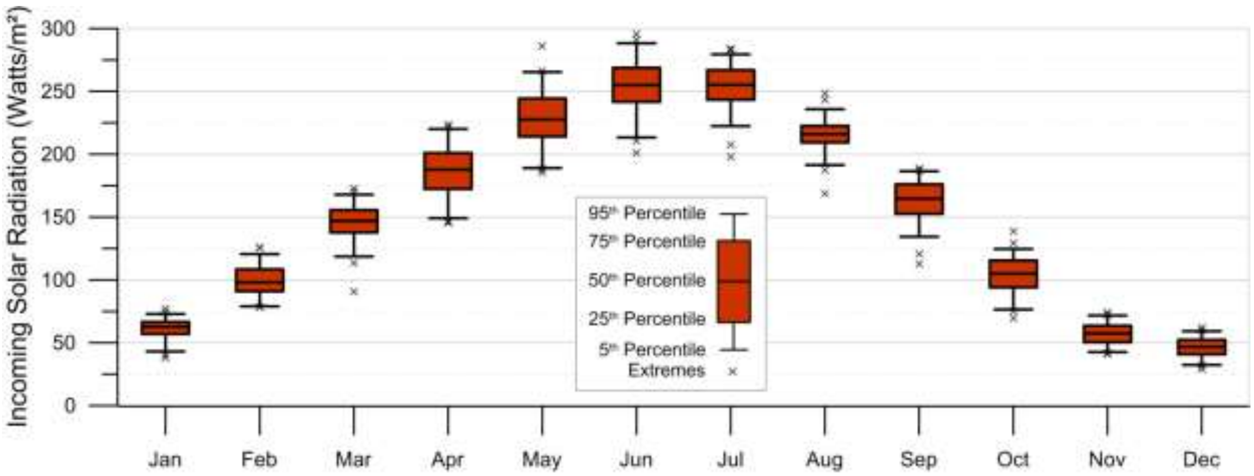


Figure 8.6: Monthly histogram of observed incoming solar radiation.

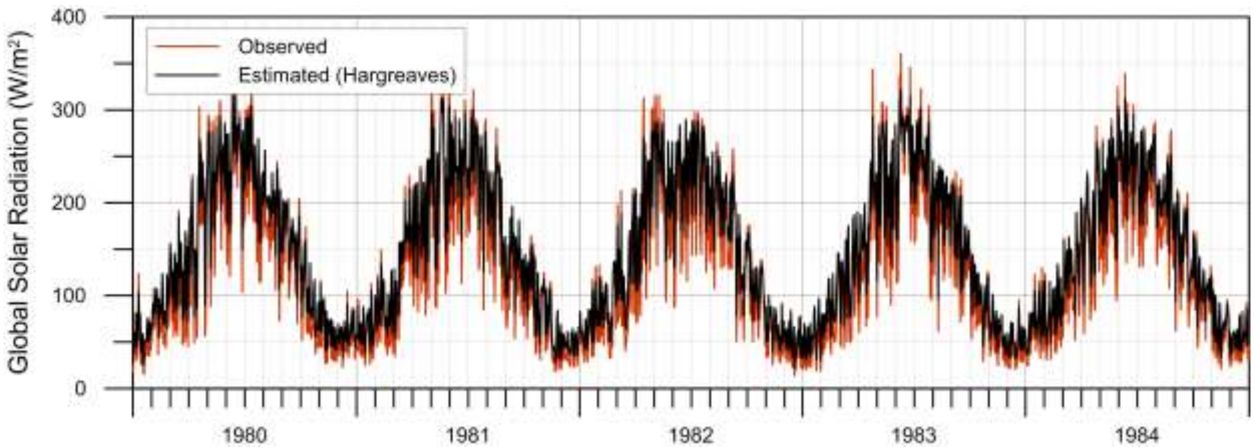


Figure 8.7: Observed versus estimated daily solar radiation time series.

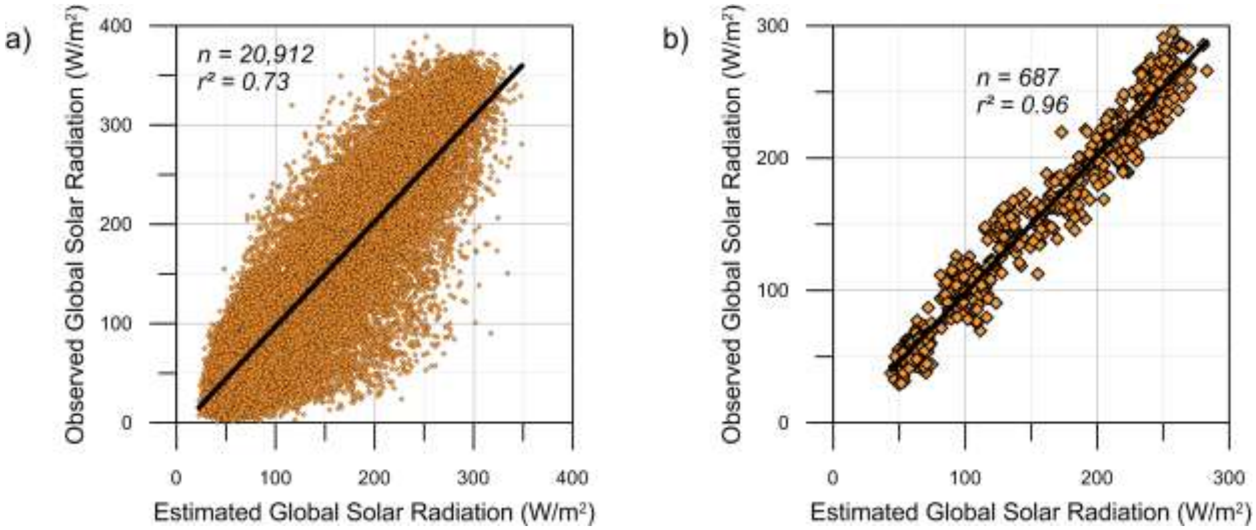


Figure 8.8: Observed versus estimated (Hargreaves and Samani) (a) daily and (b) monthly average solar radiation.

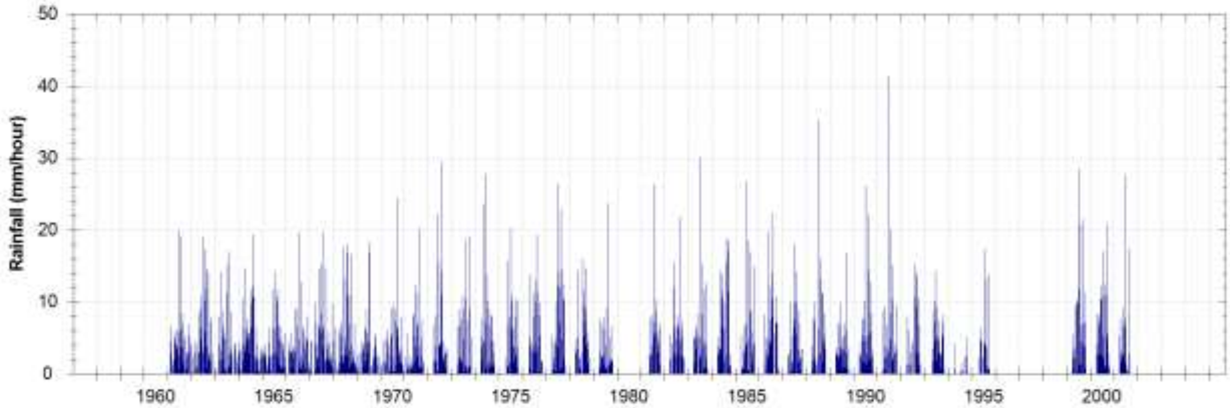


Figure 8.9: Hourly rainfall measured by tipping bucket (HLY03-123) at EC Climate Station BRANTFORD MOE.

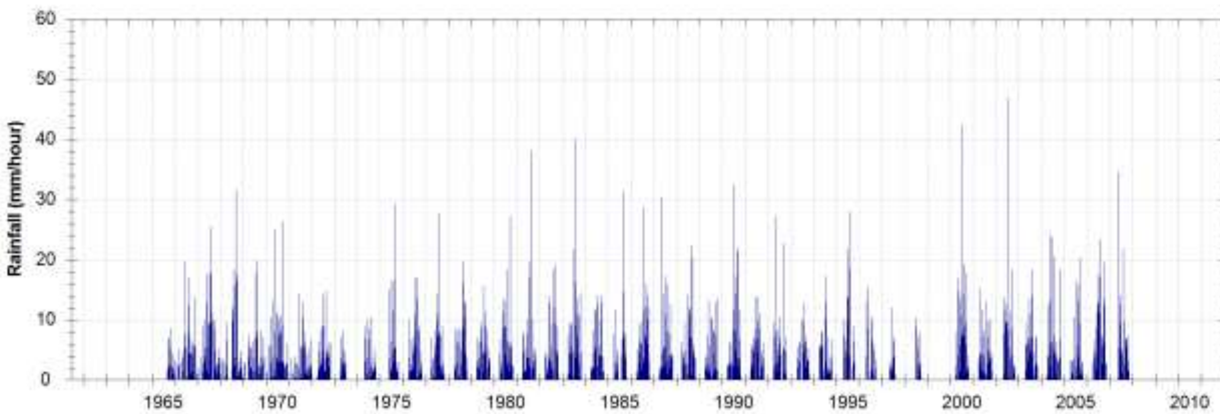


Figure 8.10: Hourly rainfall measured by tipping bucket (HLY03-123) at EC Climate Station STRATFORD WWTP.

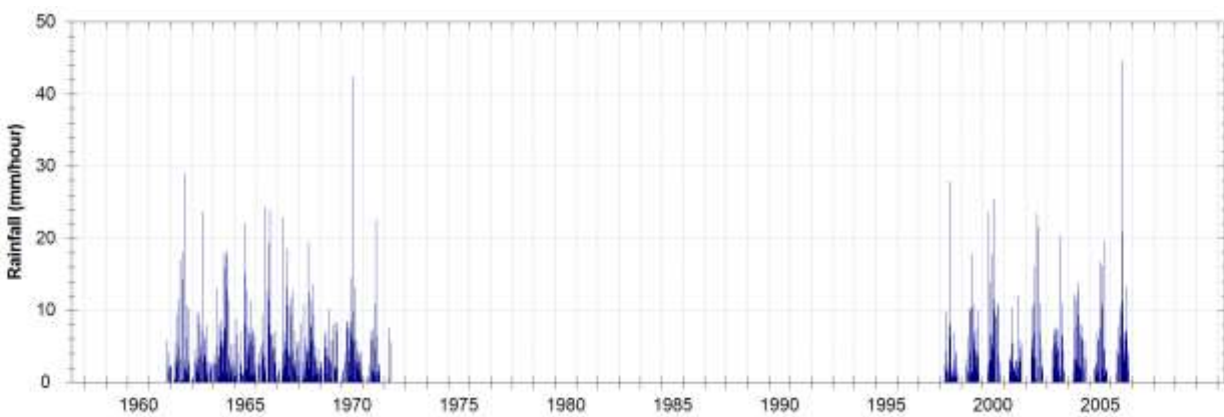


Figure 8.11: Hourly rainfall measured by tipping bucket (HLY03-123) at EC Climate Station WOODSTOCK.

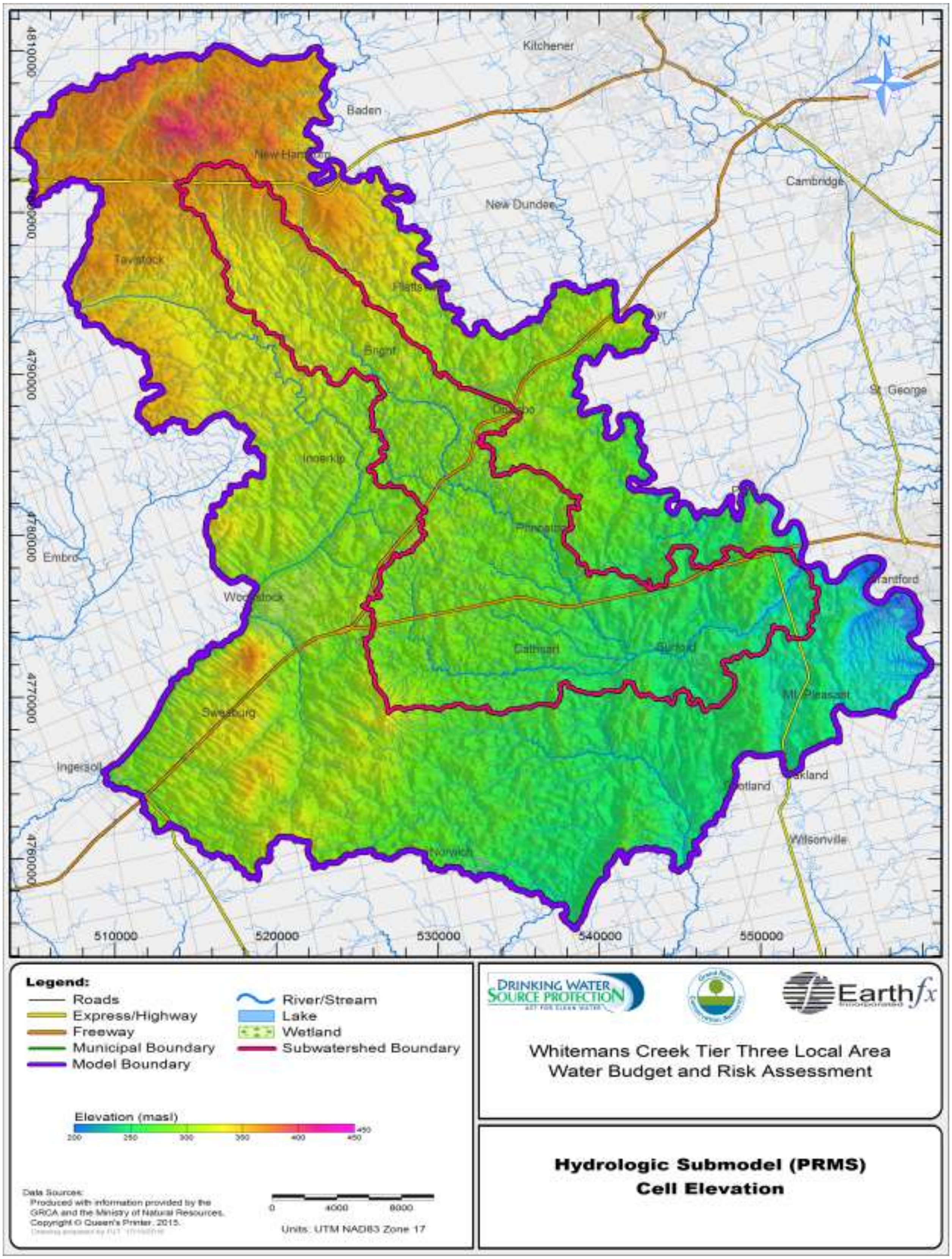


Figure 8.12: Topographic data used to develop the PRMS submodel.

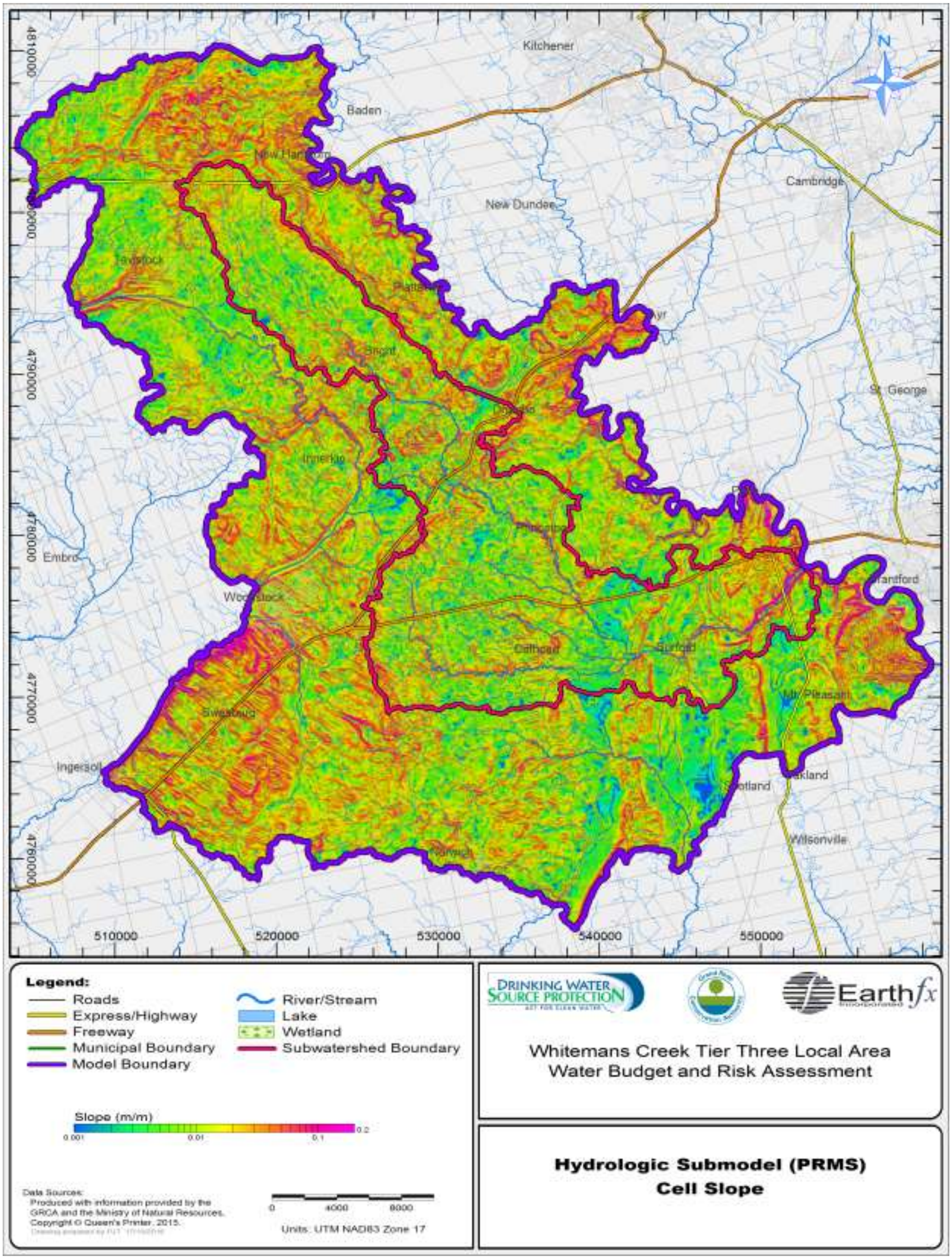


Figure 8.13: Distribution of slope (in m/m).

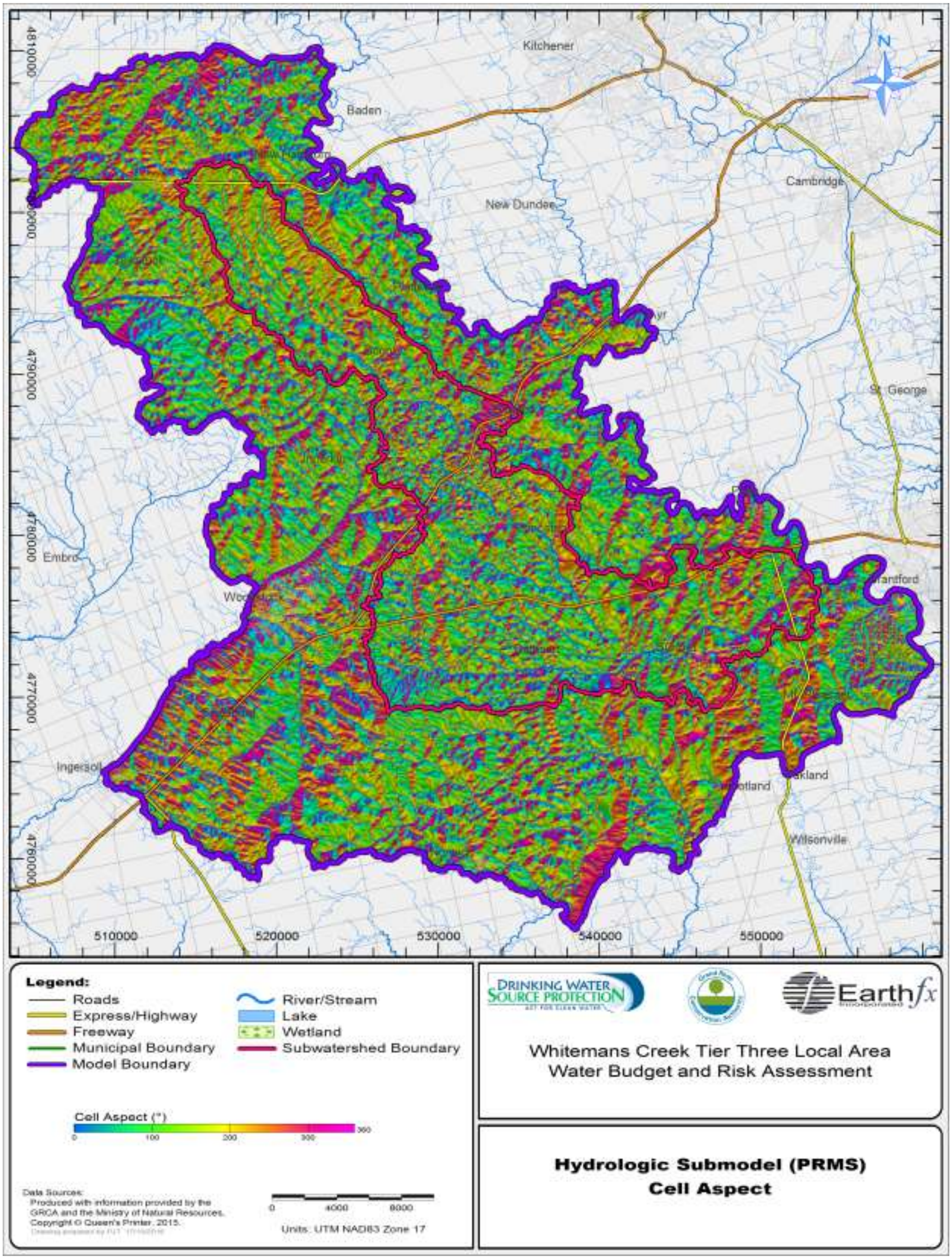


Figure 8.14: Distribution of slope aspect (value of 0 or 360 indicates cell is facing due north).

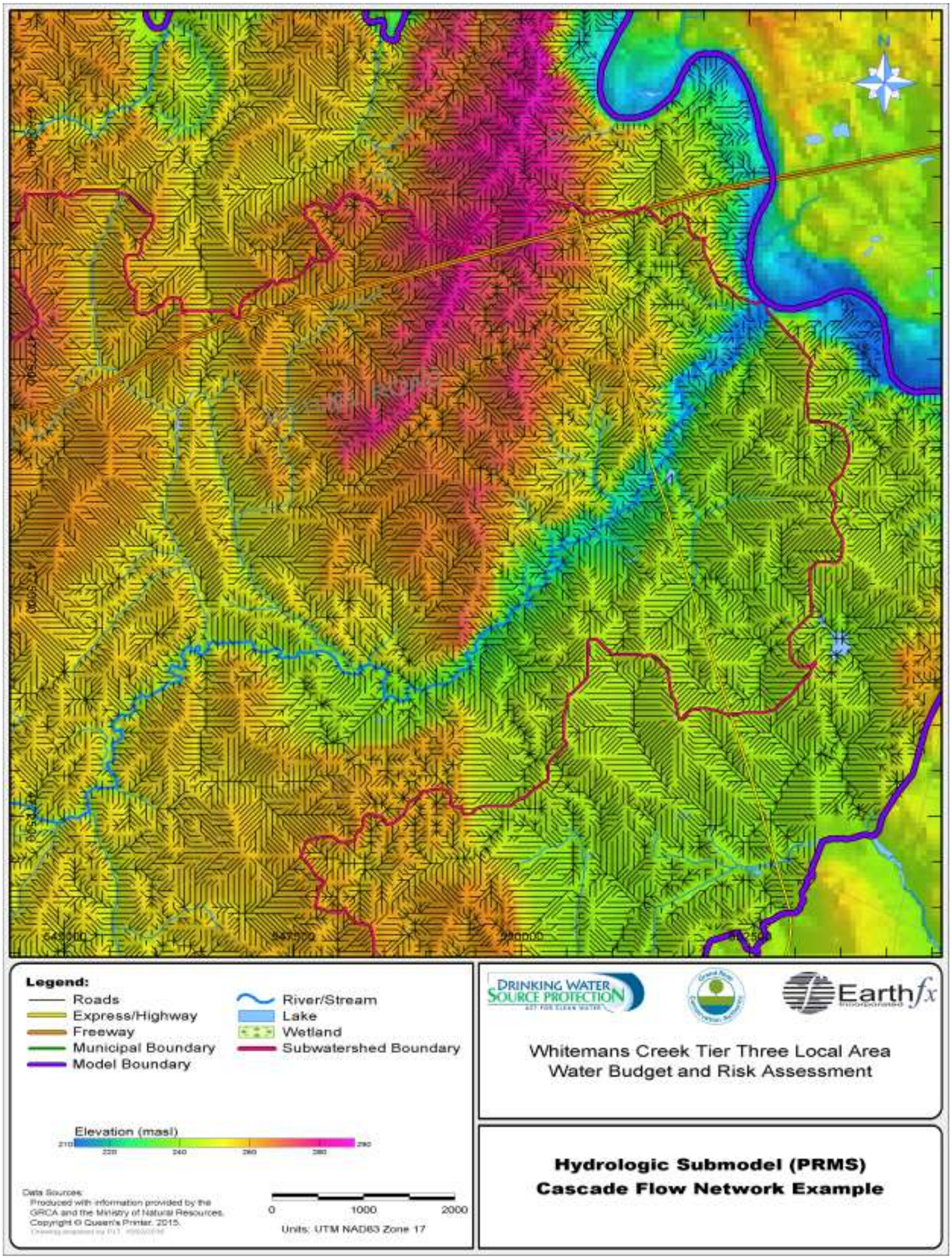


Figure 8.15: Topography and resulting cascade flow network in the lower Whitemans Creek area.

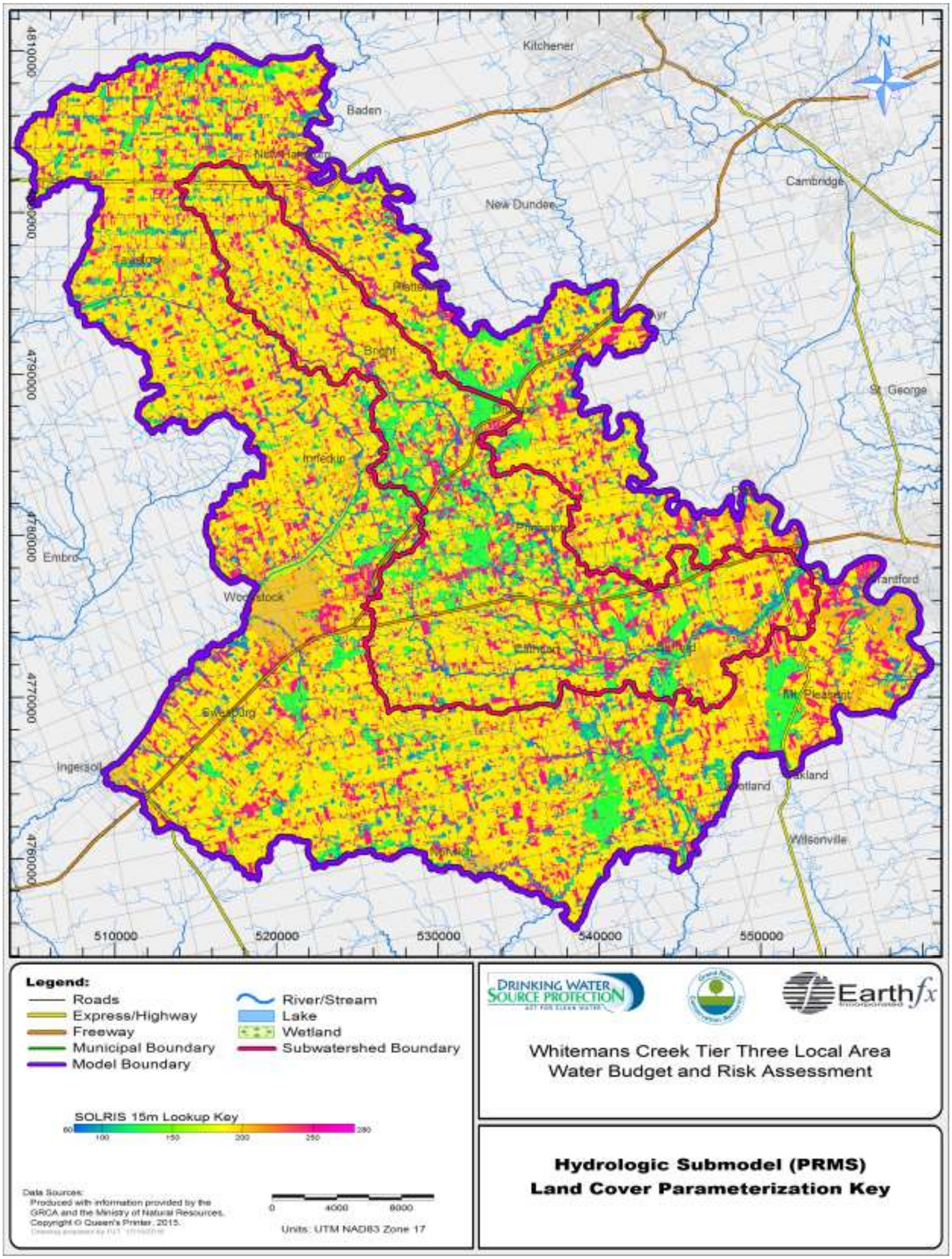


Figure 8.16: SOLRIS-based (OMNRF, 2014) parameterization grid.

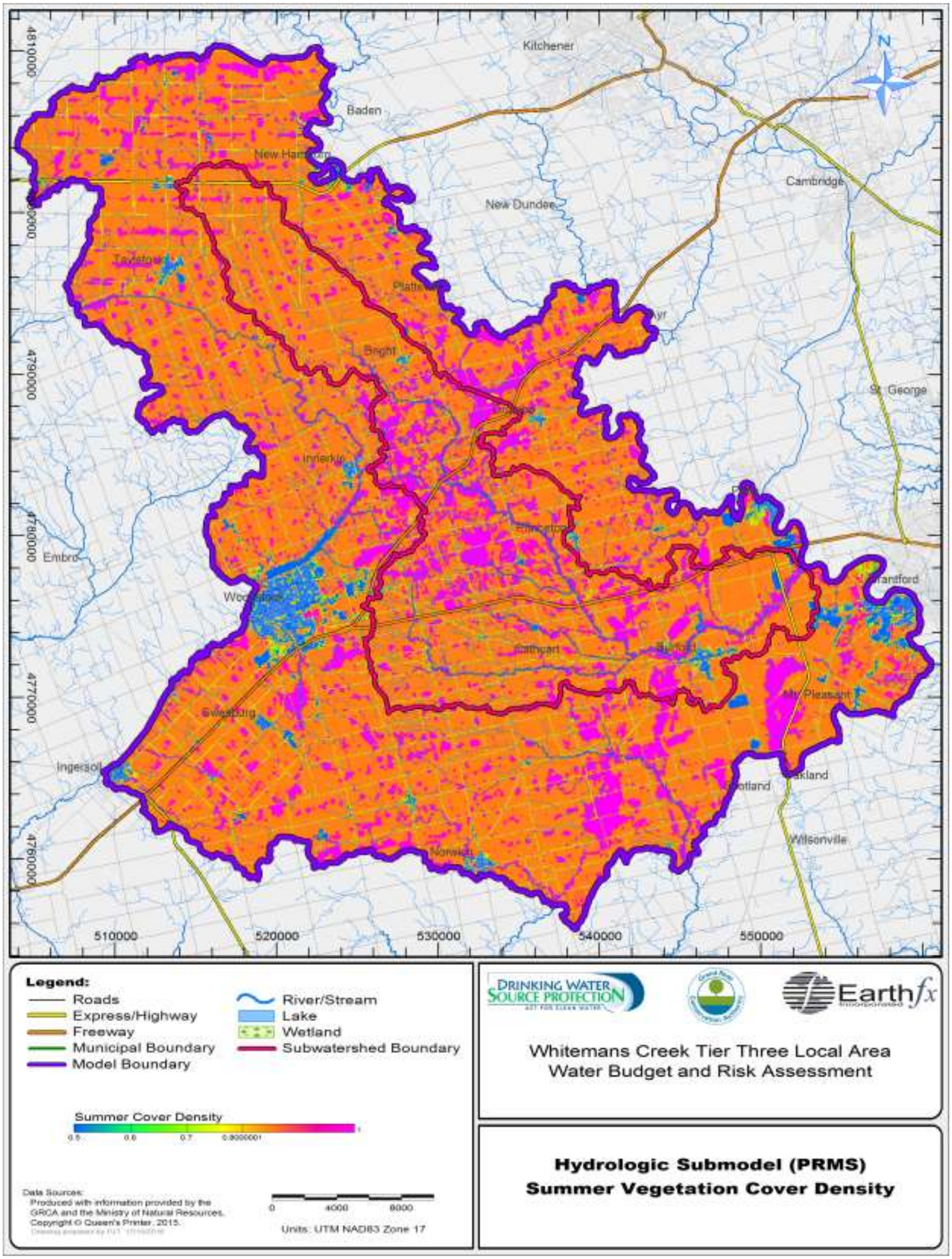


Figure 8.17: Distribution of summer vegetation cover density.

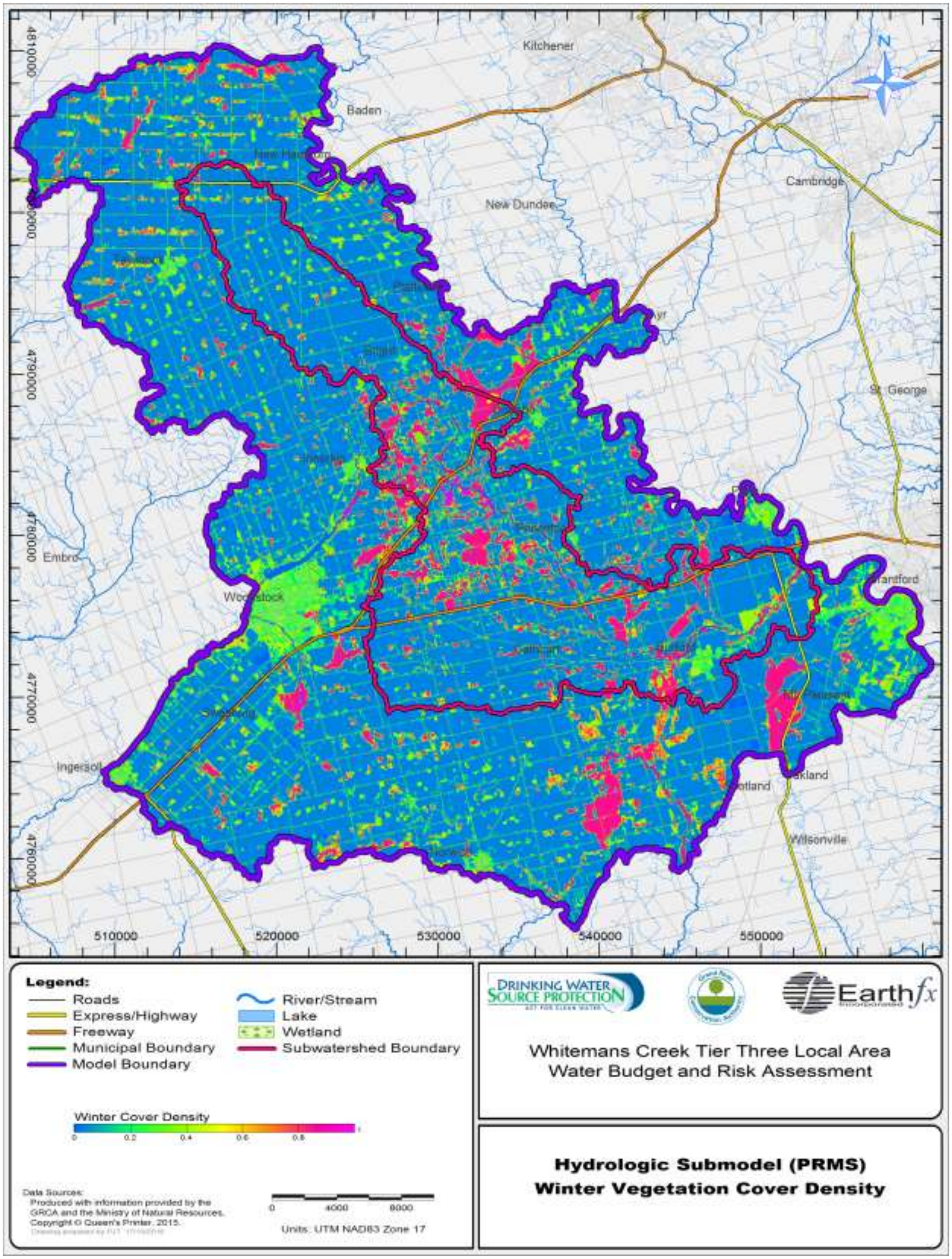


Figure 8.18: Distribution of winter vegetation cover density.

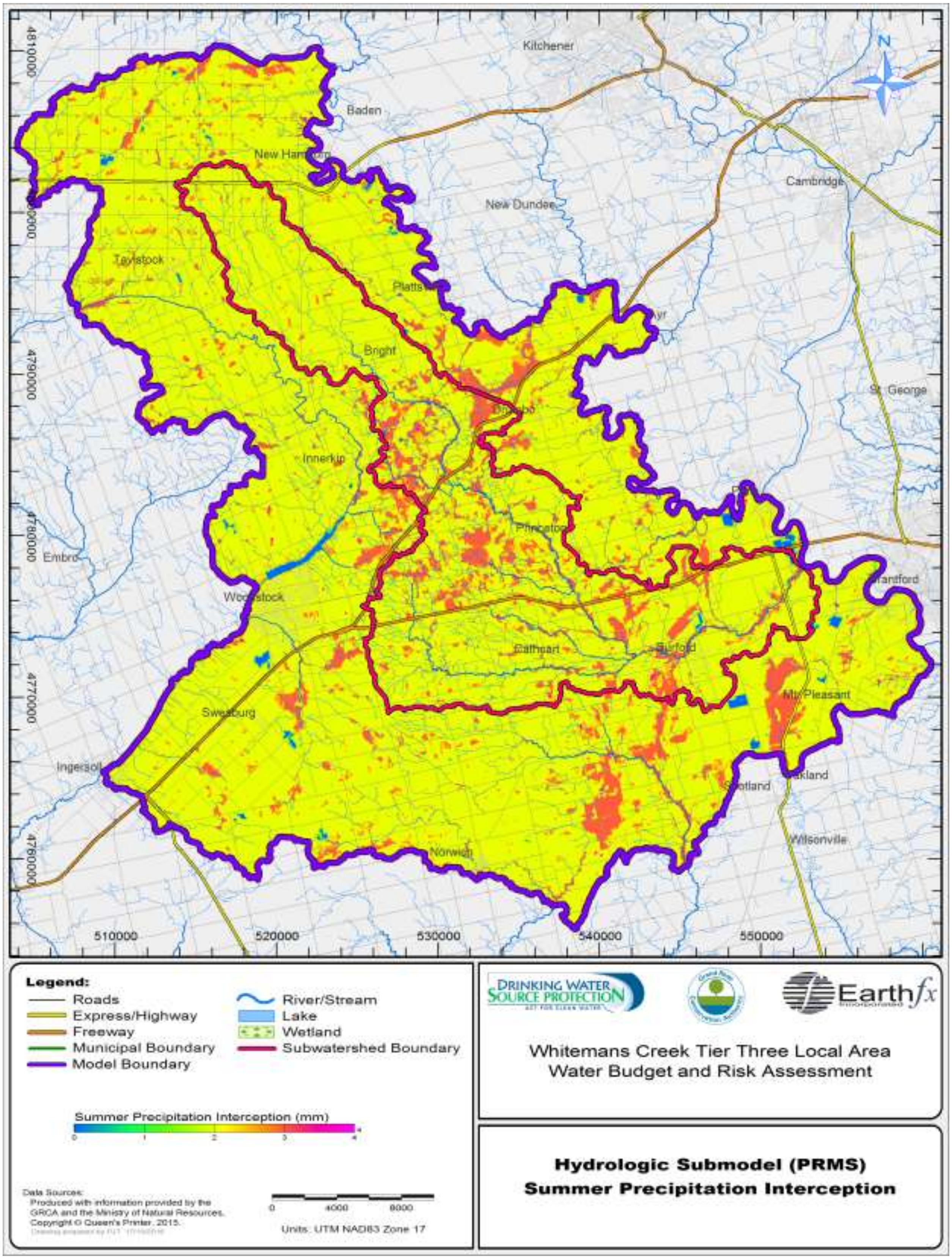


Figure 8.19: Distribution of summer precipitation interception storage.

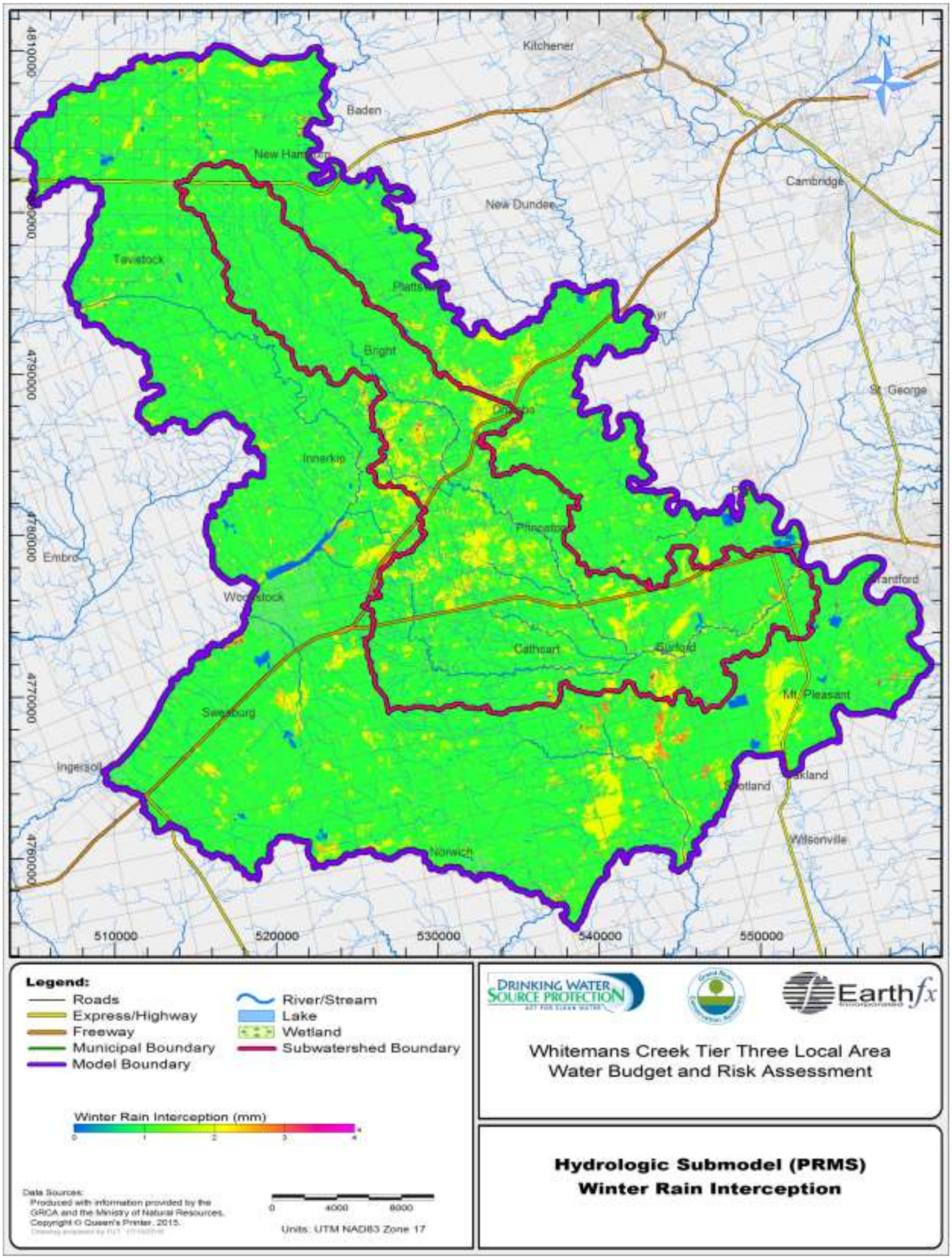


Figure 8.20: Distribution of winter rain interception storage.

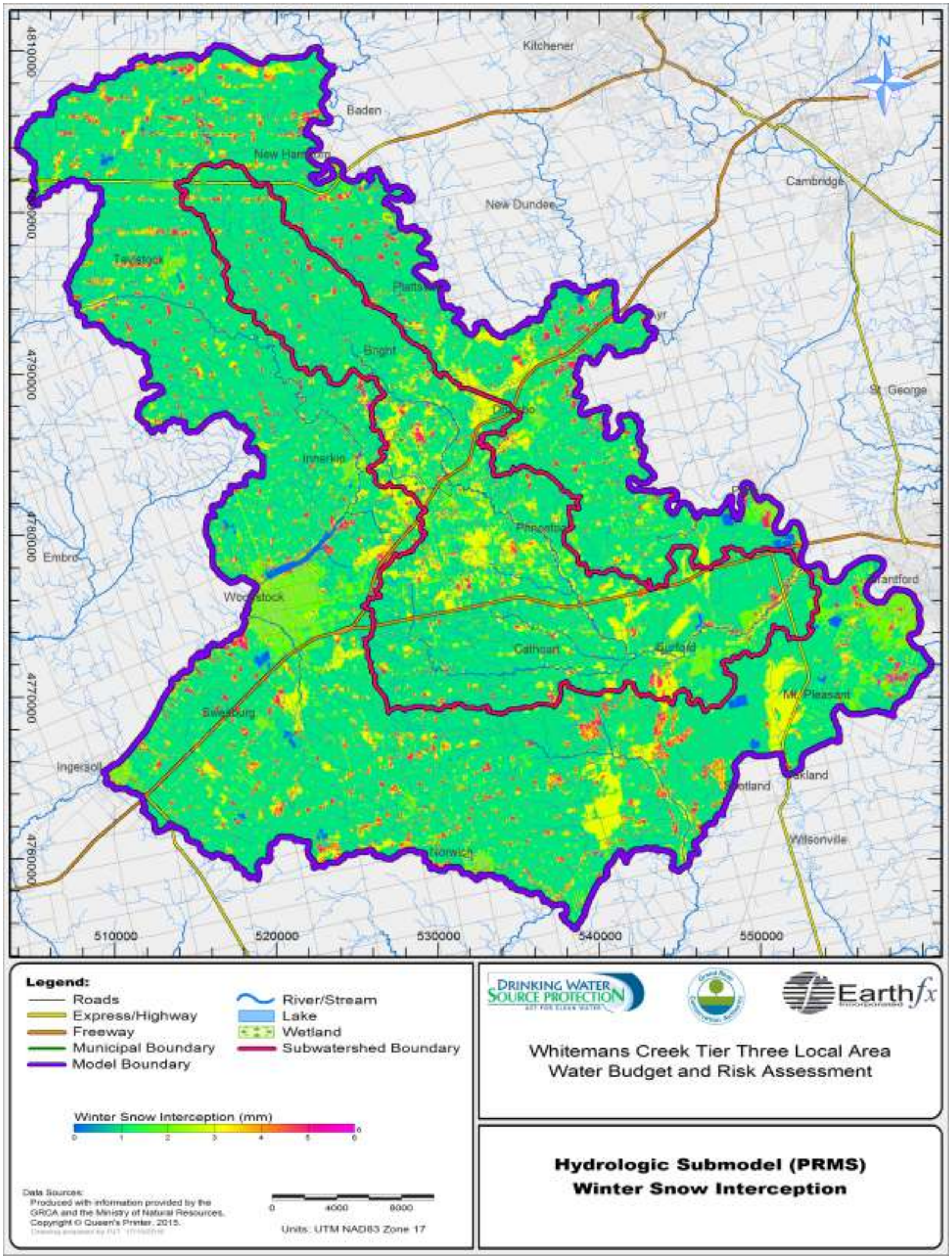


Figure 8.21: Distribution of winter snow interception storage.

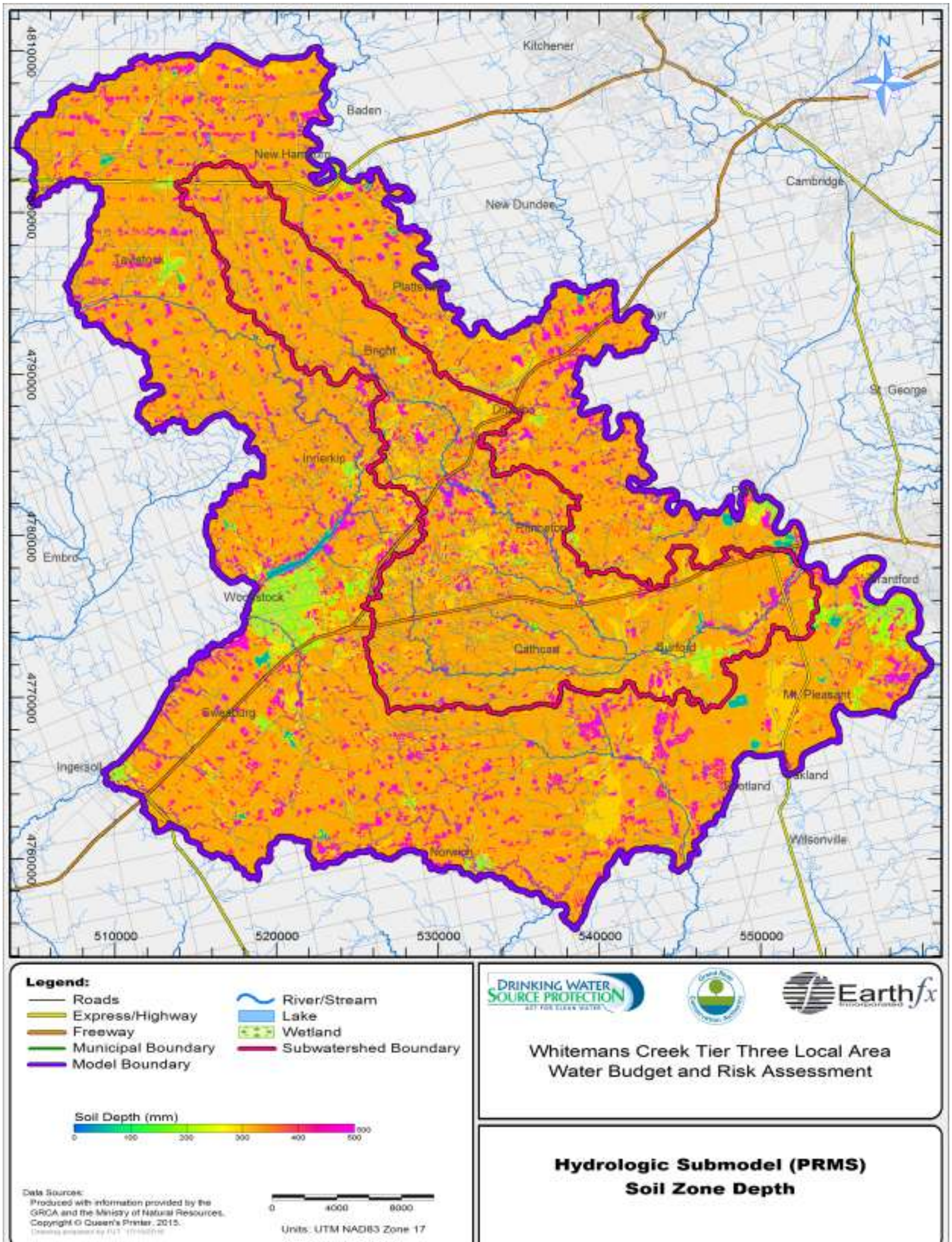


Figure 8.22: Distribution of soil zone thickness.

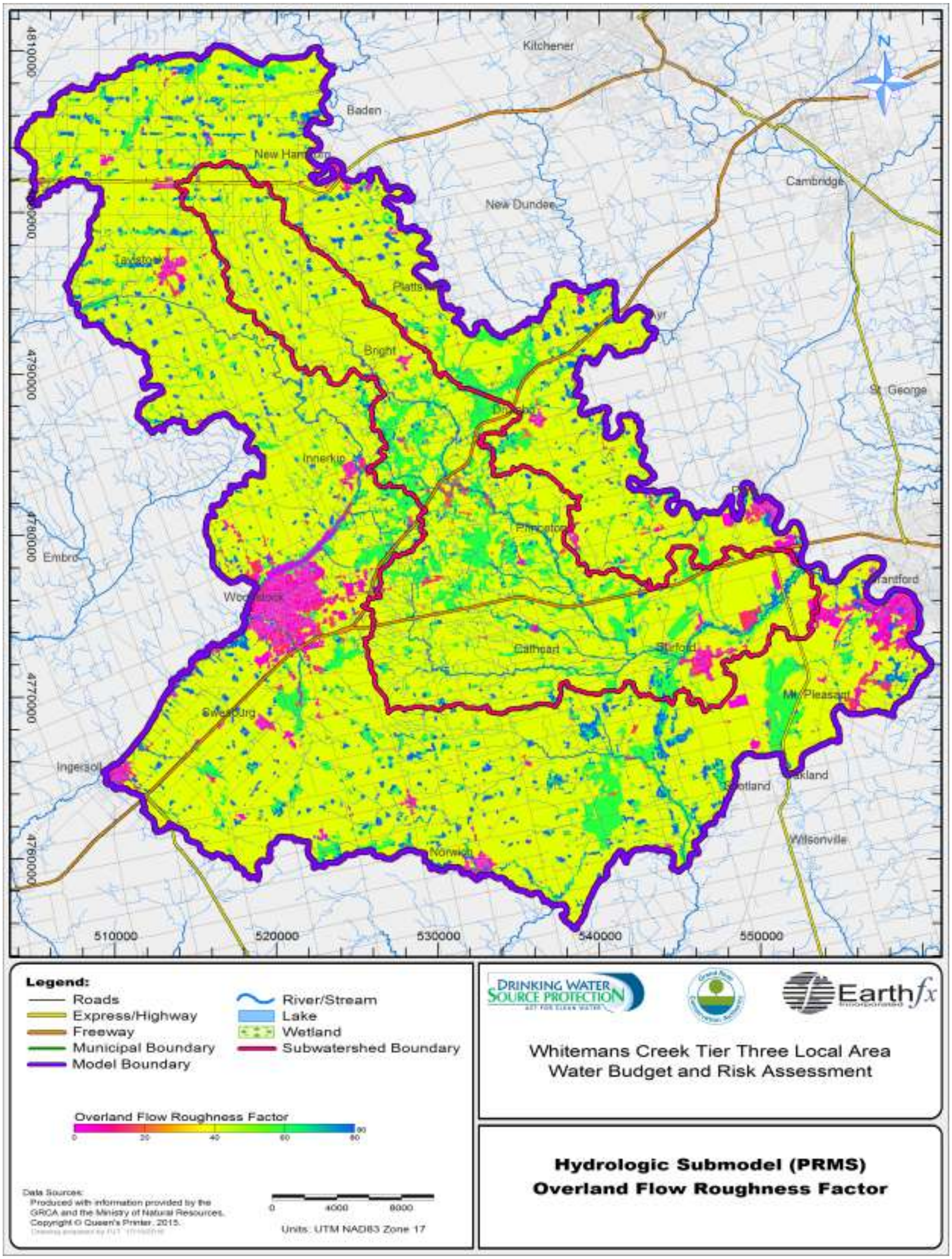


Figure 8.23: Distribution of overland flow roughness factors.

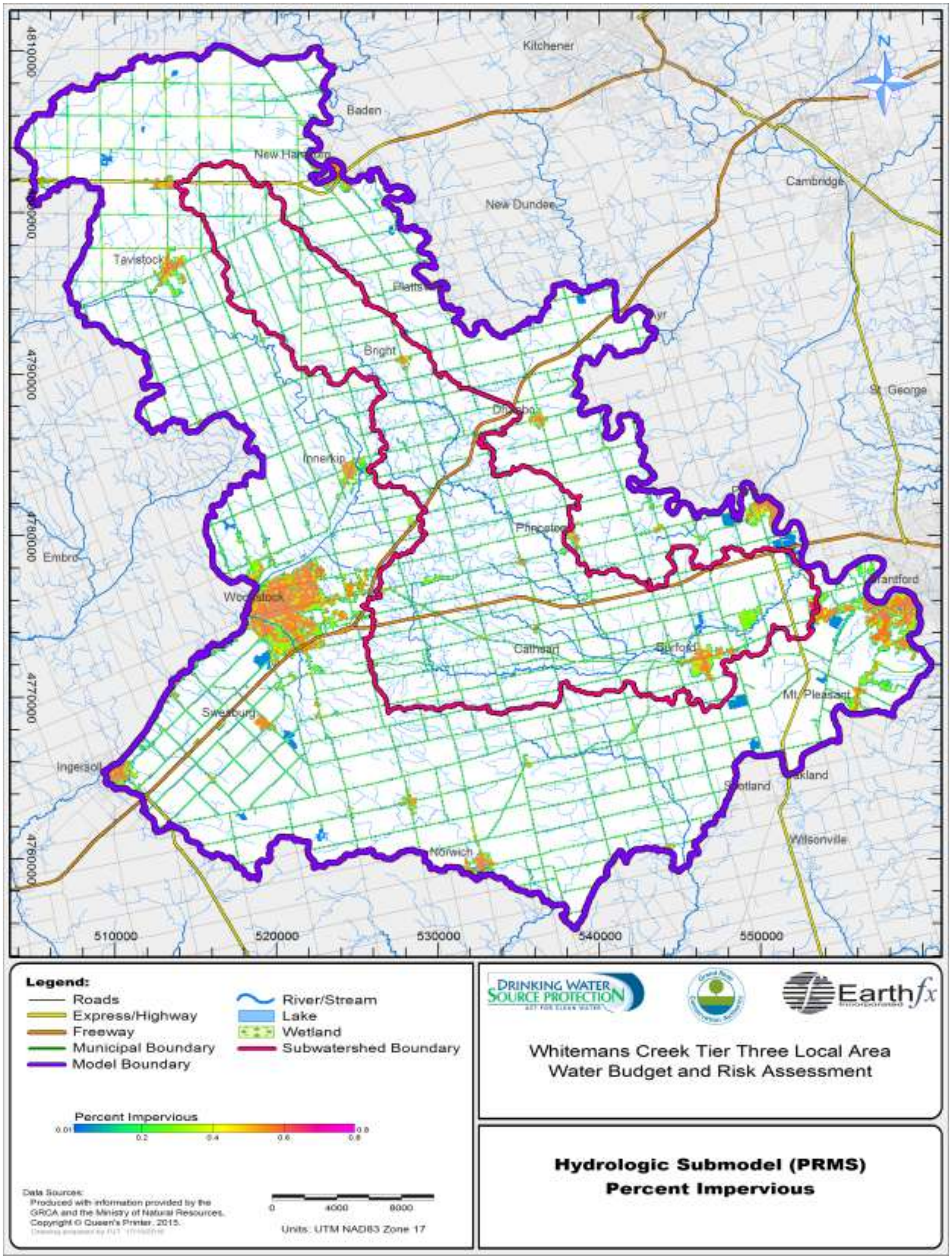


Figure 8.24: Distribution of imperviousness (0 to 1).

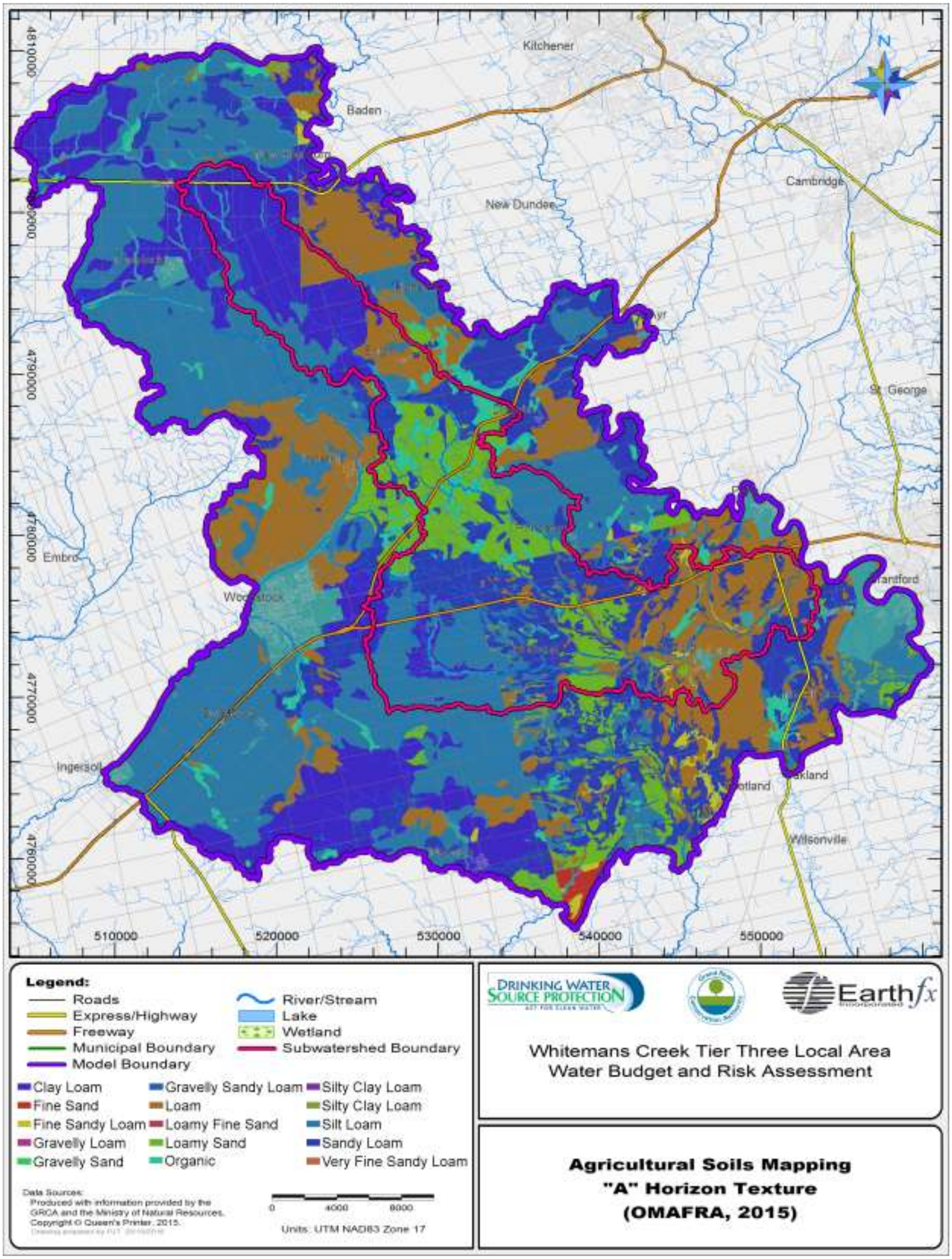


Figure 8.25: Textural agricultural soils mapping (OMAFRA, 2003).

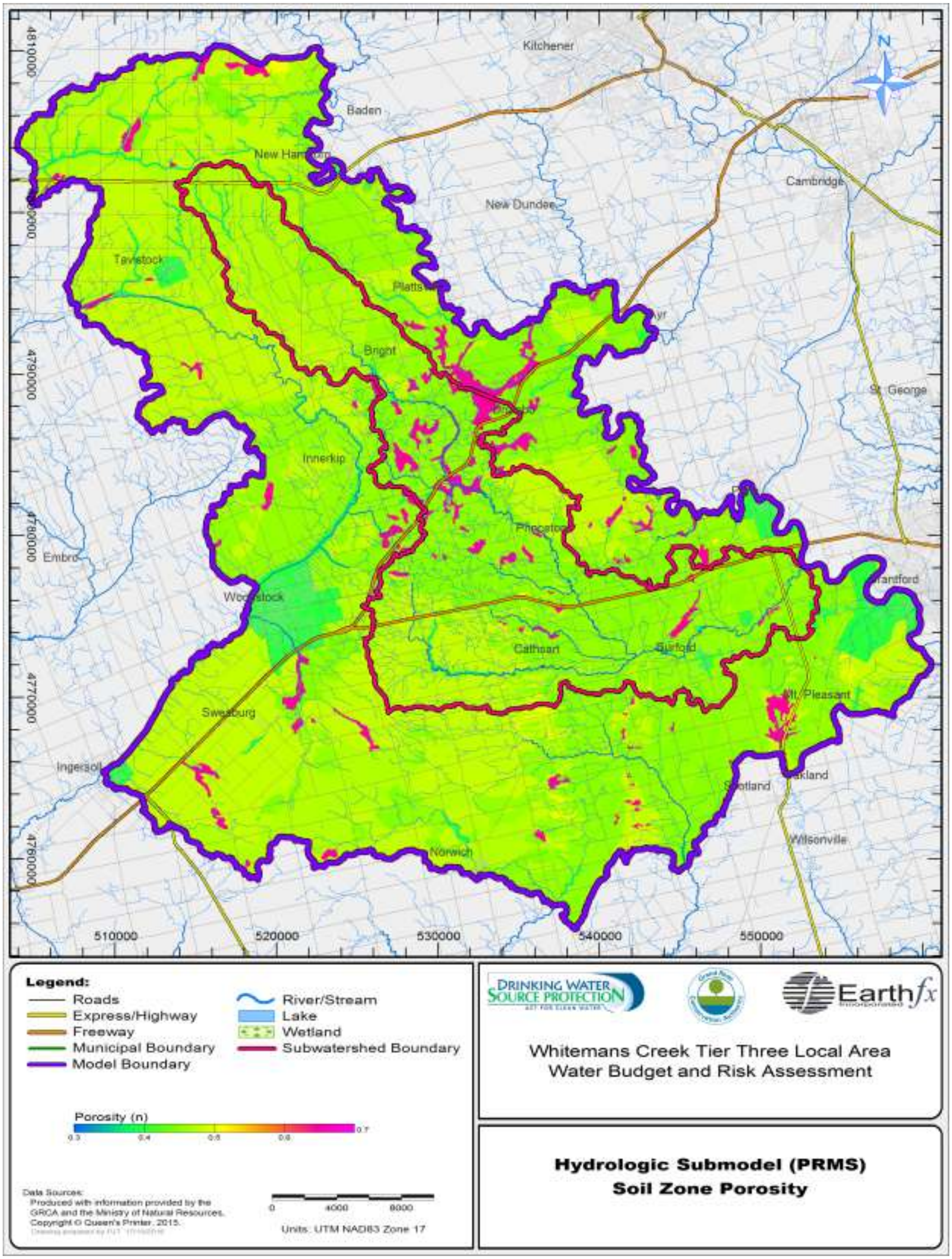


Figure 8.26: Distribution of soil zone porosity.

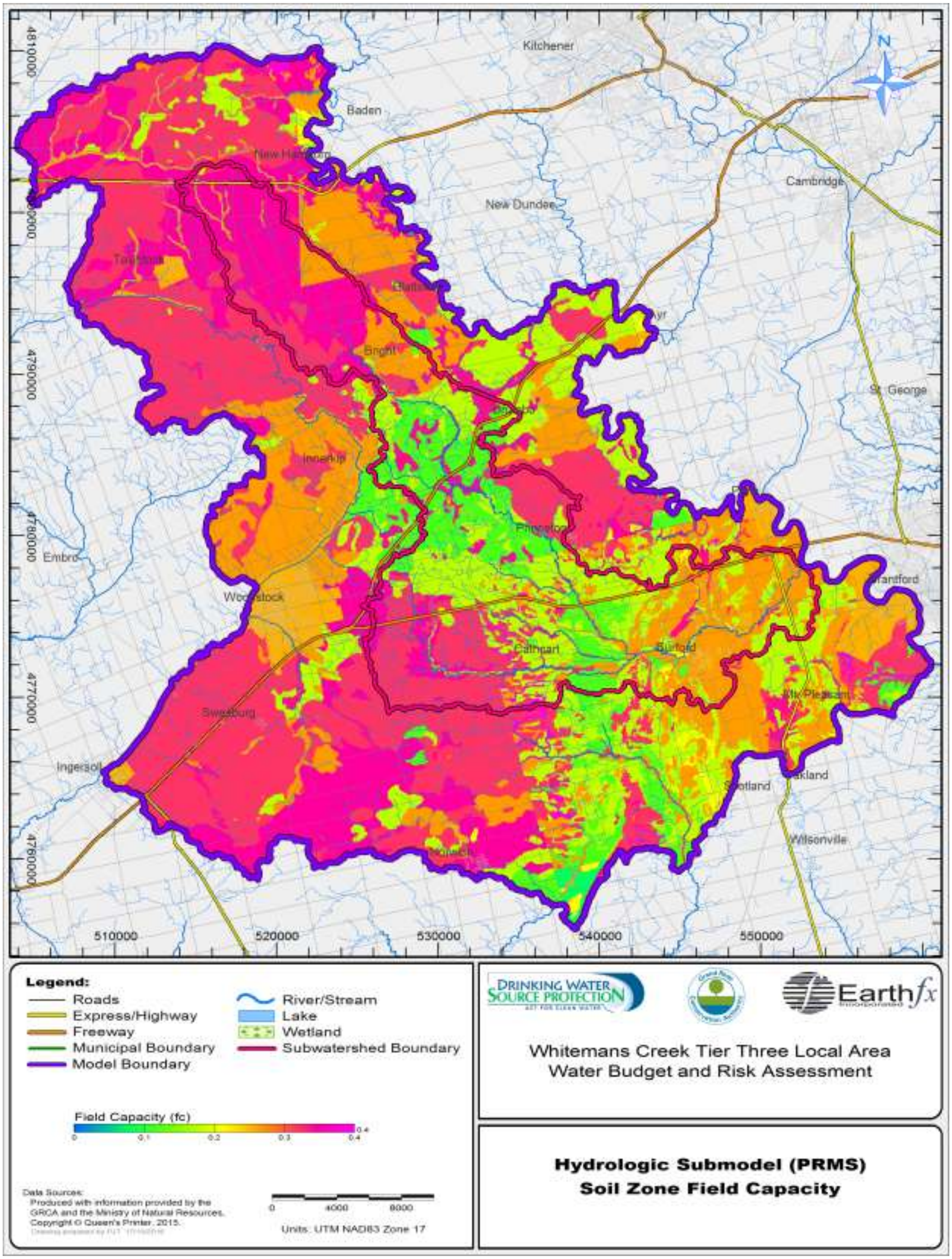


Figure 8.27: Distribution of soil zone field capacity.

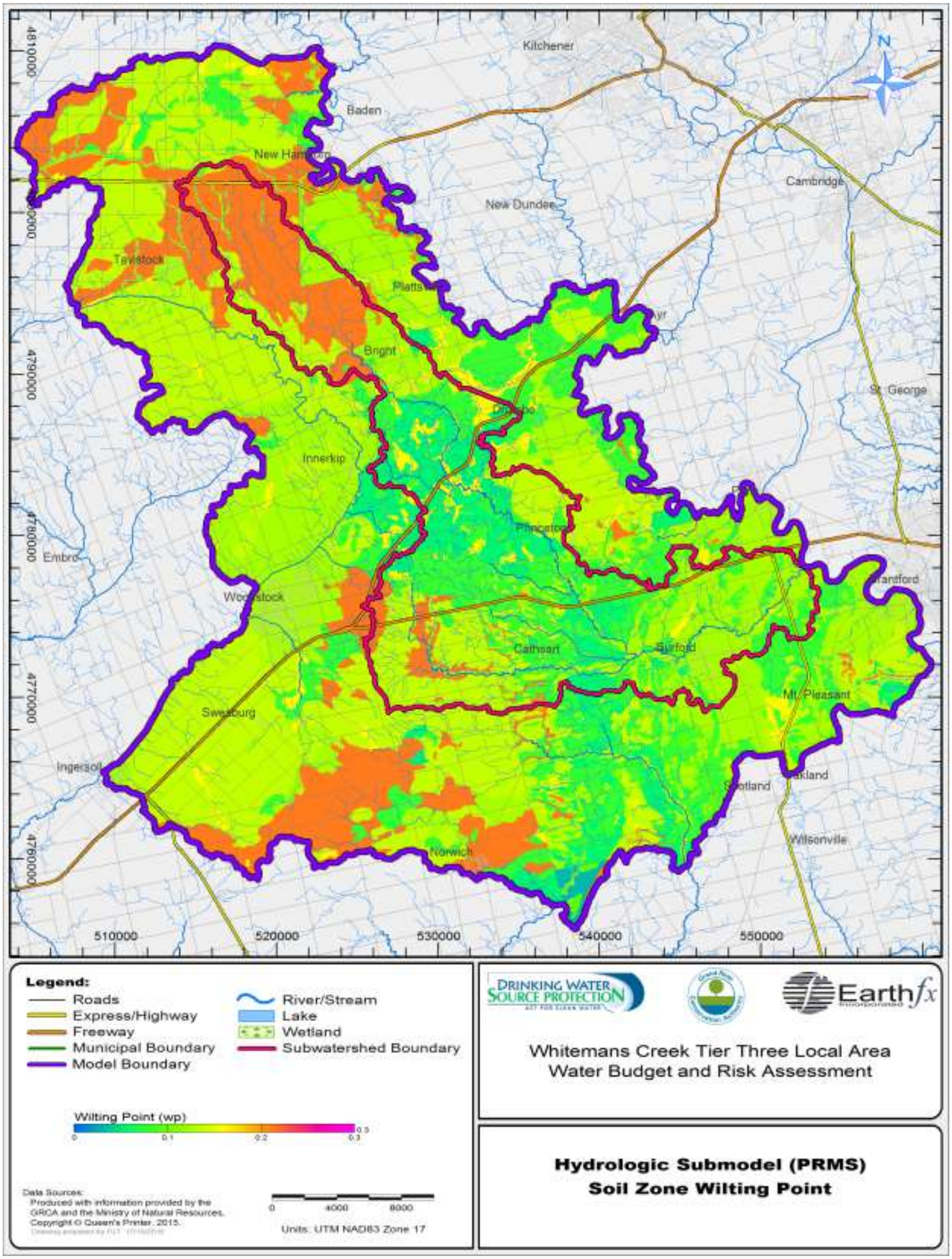


Figure 8.28: Distribution of soil zone wilting point.

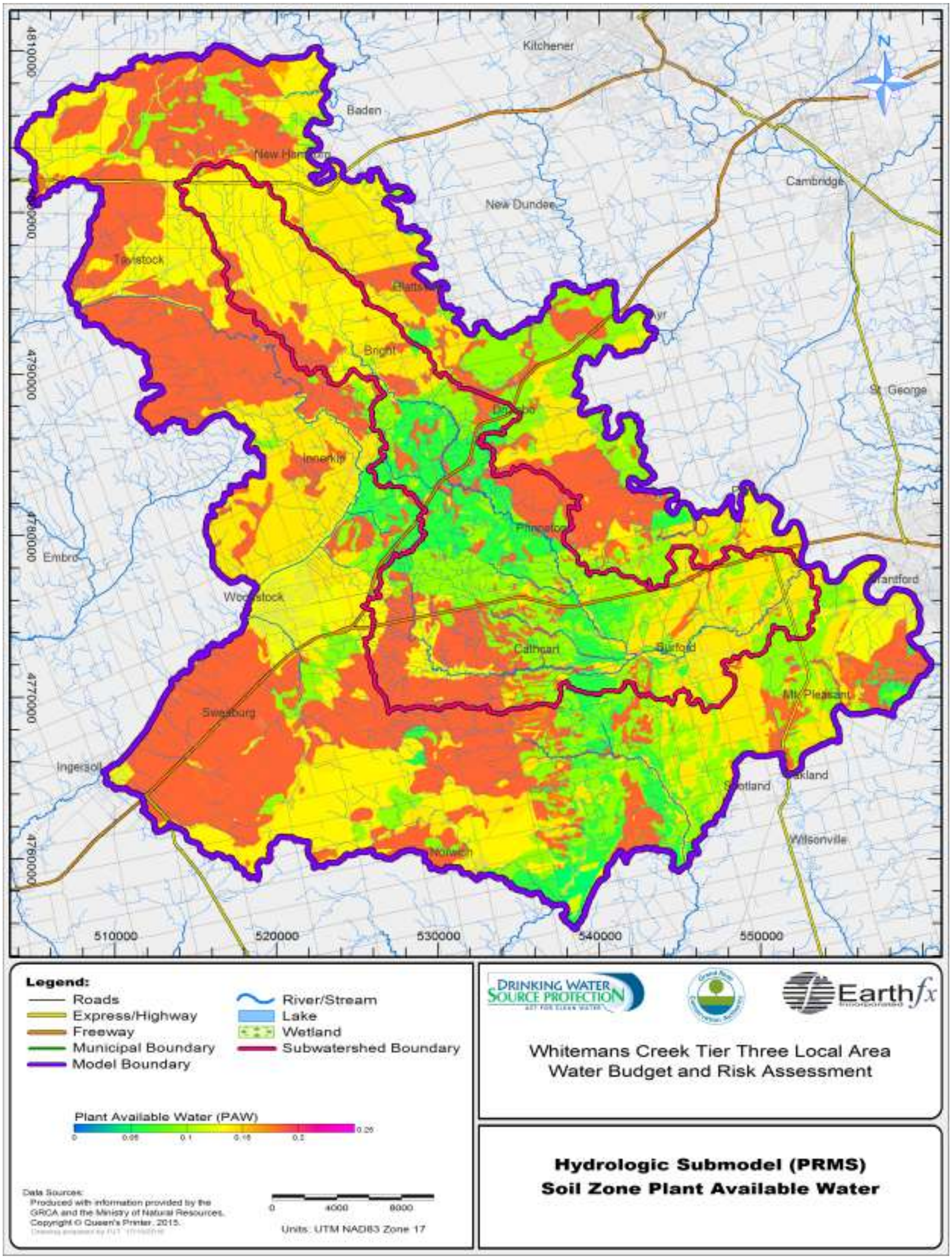


Figure 8.29: Distribution of plant available water (PAW).

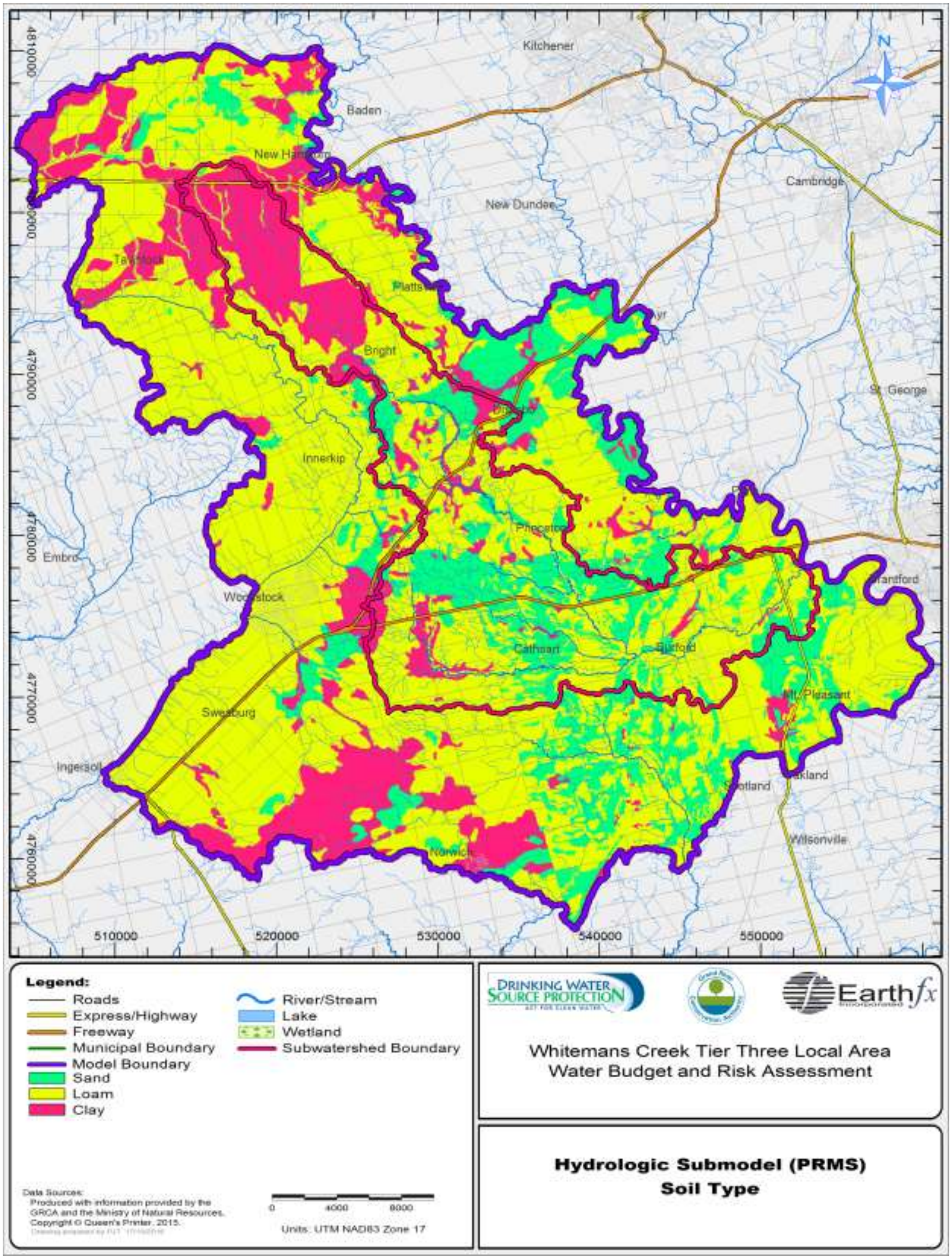


Figure 8.30: Distribution of soil type.

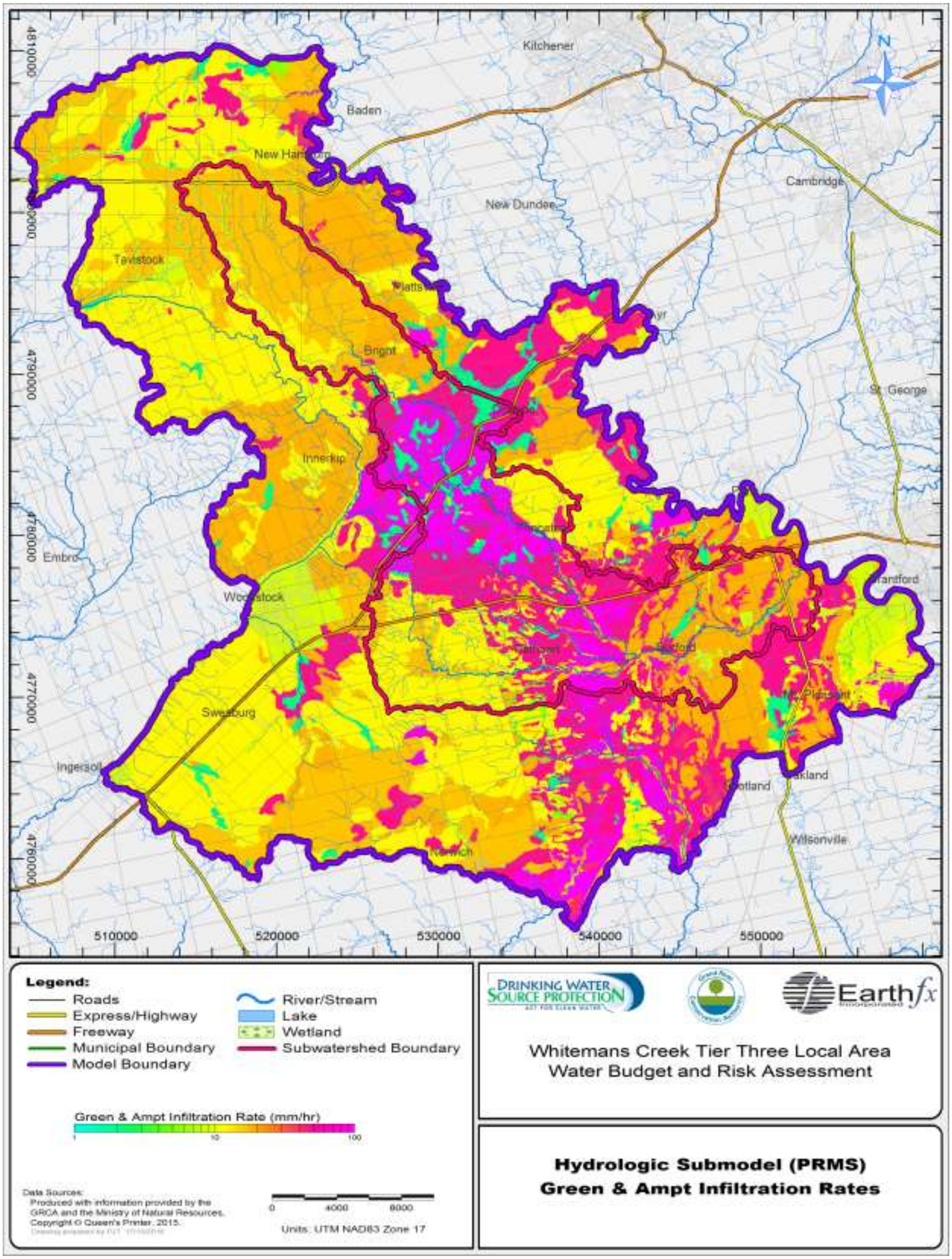


Figure 8.31: Distribution of Green and Ampt infiltration rates.

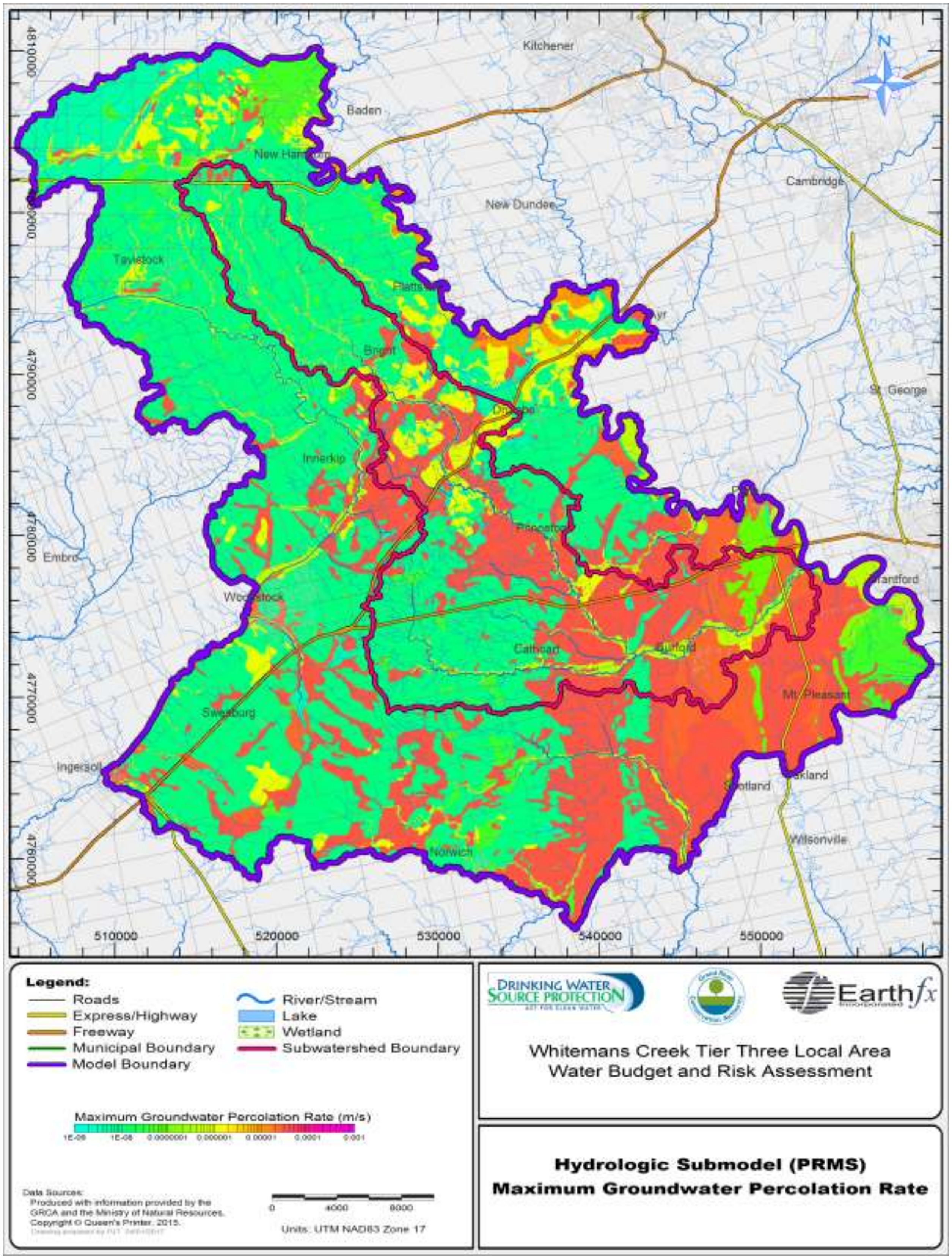


Figure 8.32: Distribution of the maximum daily soil zone percolation rates.

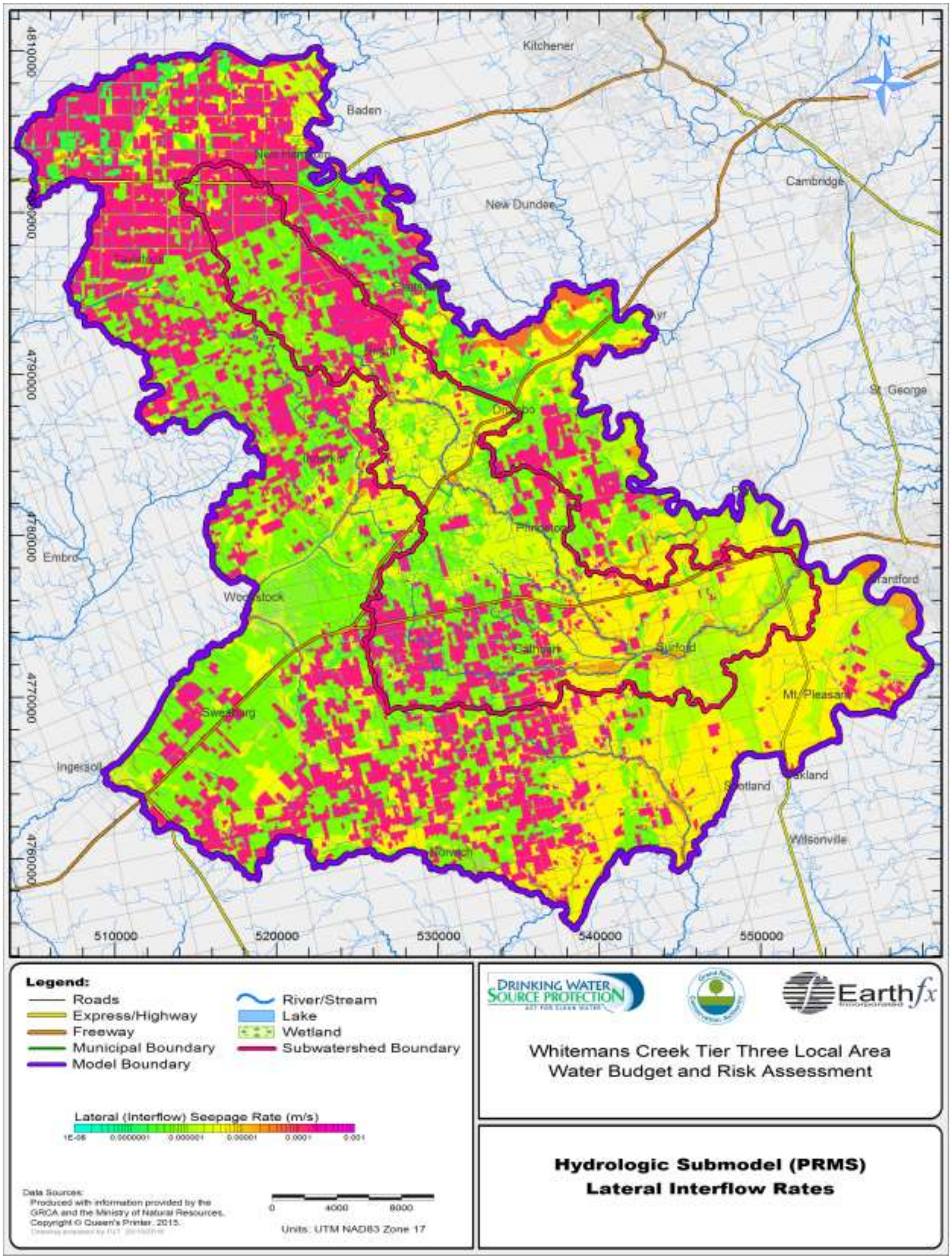


Figure 8.33: Distribution of lateral interflow seepage rates.

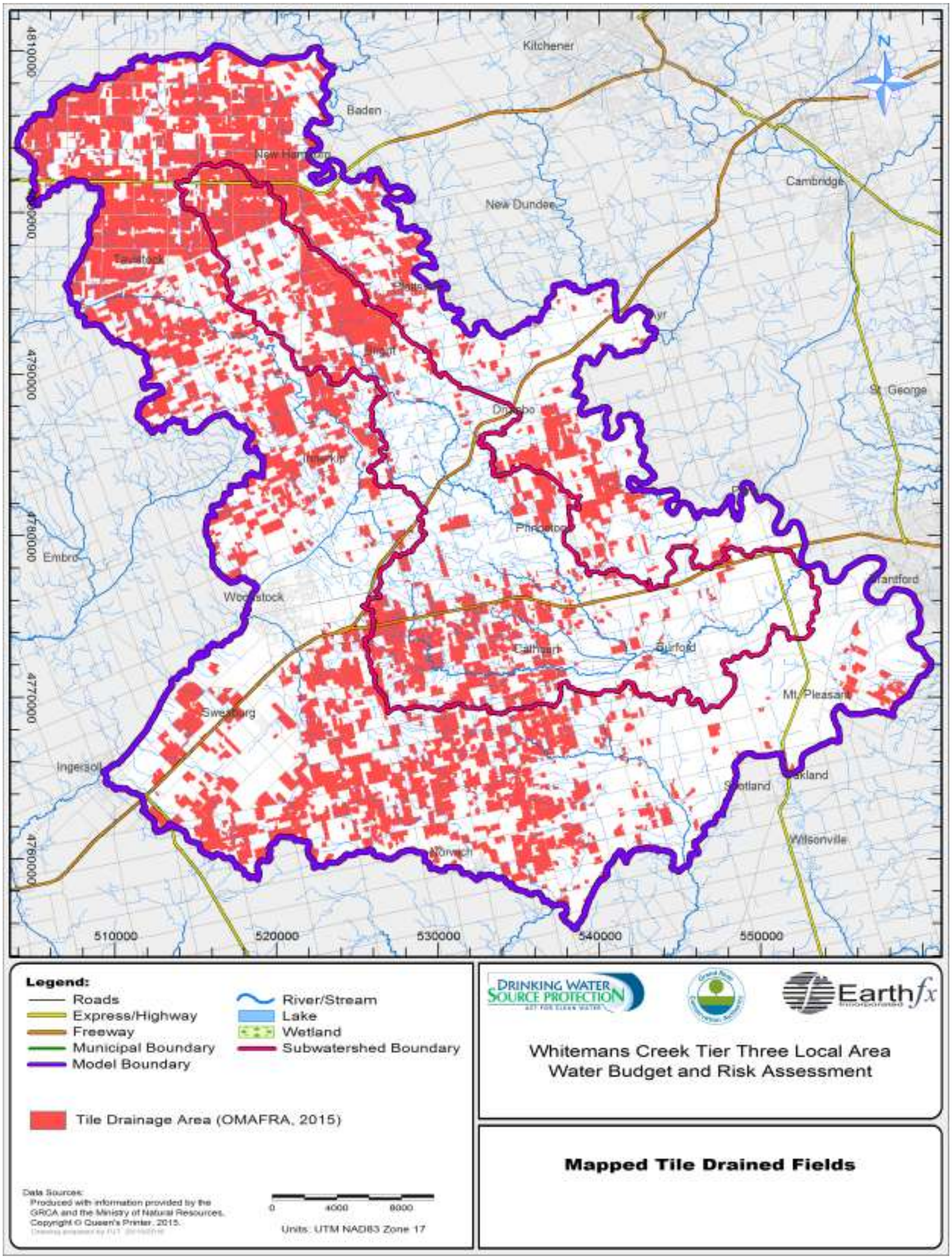


Figure 8.34: Tile drained fields (from OMAFRA, 2015b).

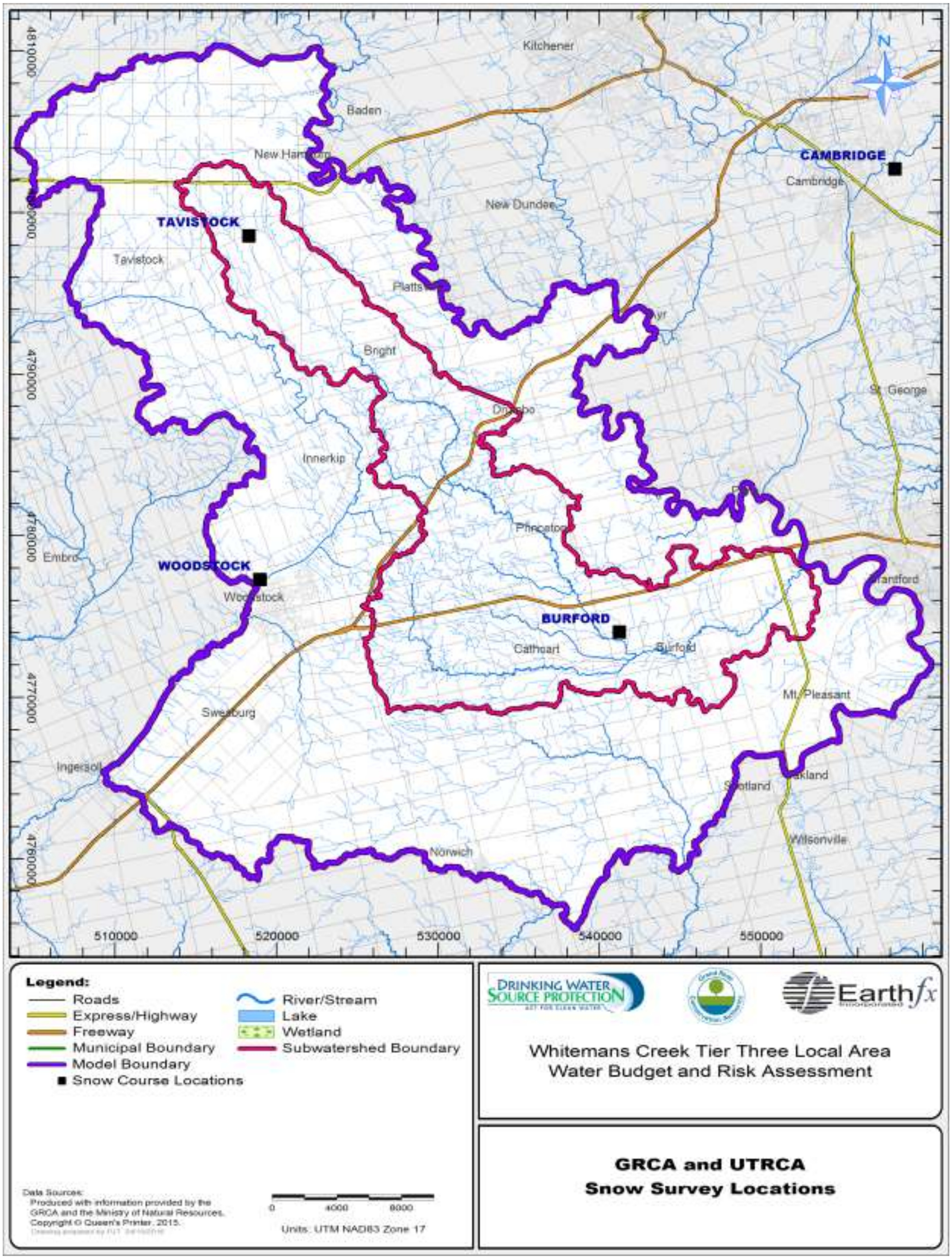


Figure 8.35: Snow course survey locations within the study area.

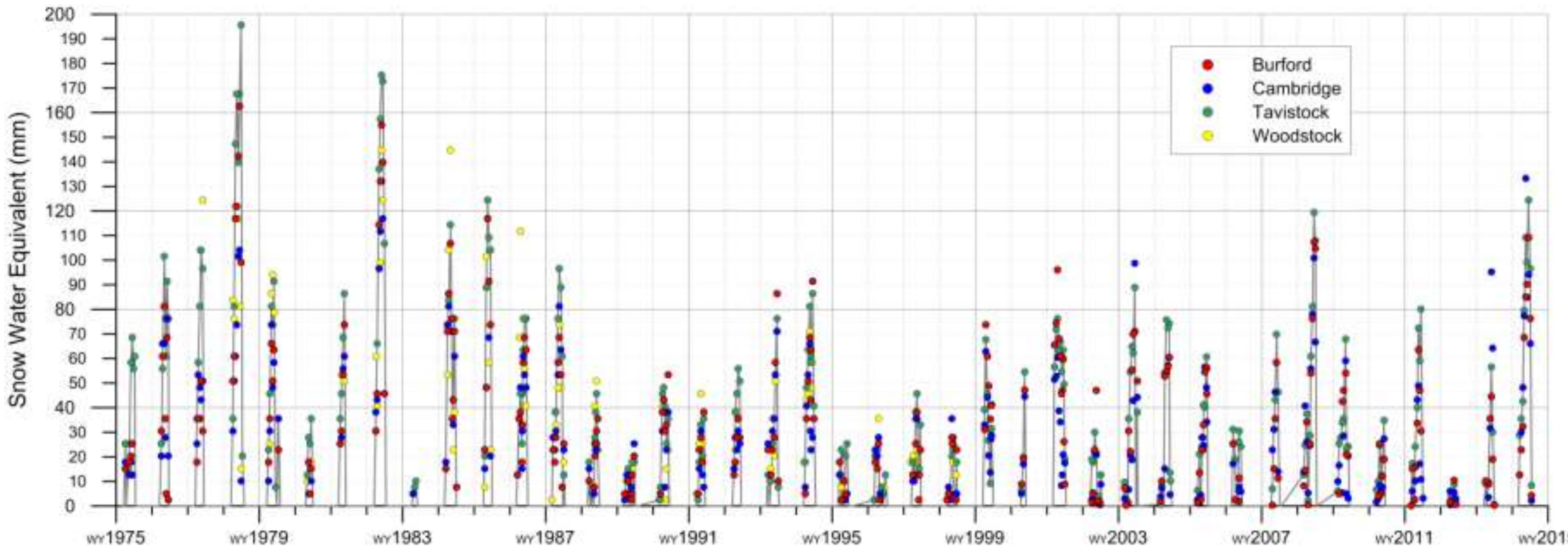


Figure 8.36: Observed snowpack measurements at snow courses within the study area.

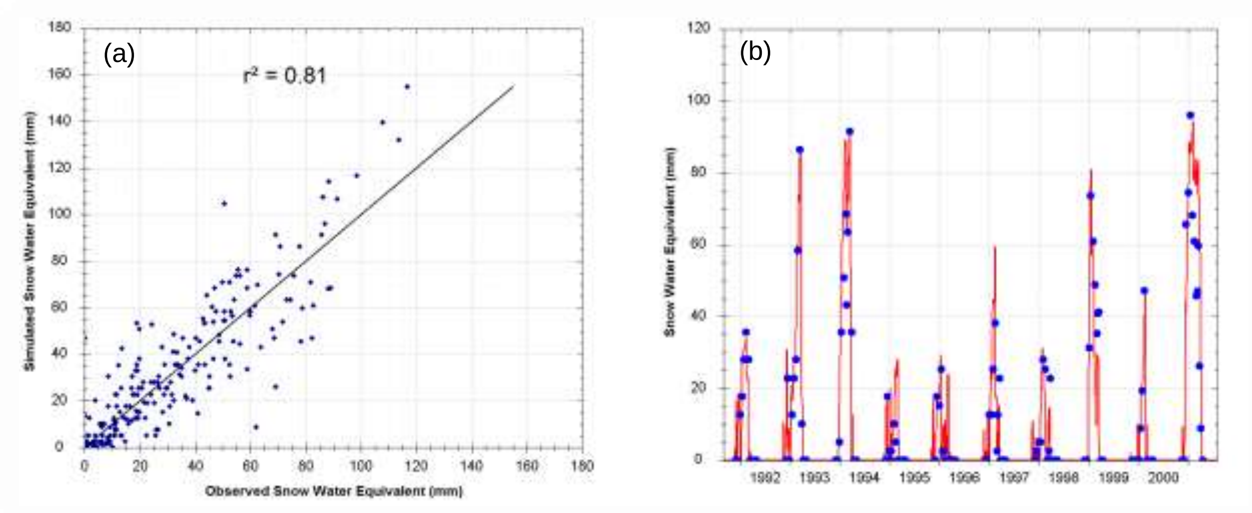


Figure 8.37: Simulated snowpack water equivalencies versus field observations taken near Burford; (a) scatter plot, (b) time series

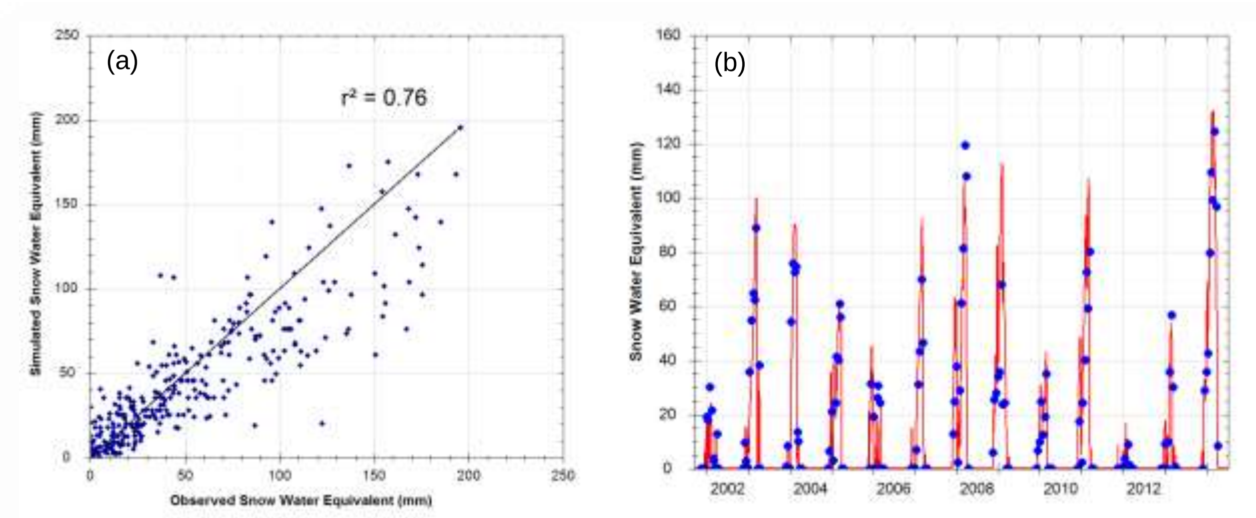


Figure 8.38: Simulated snowpack water equivalencies versus field observations taken near Tavistock; (a) scatter plot, (b) time series.

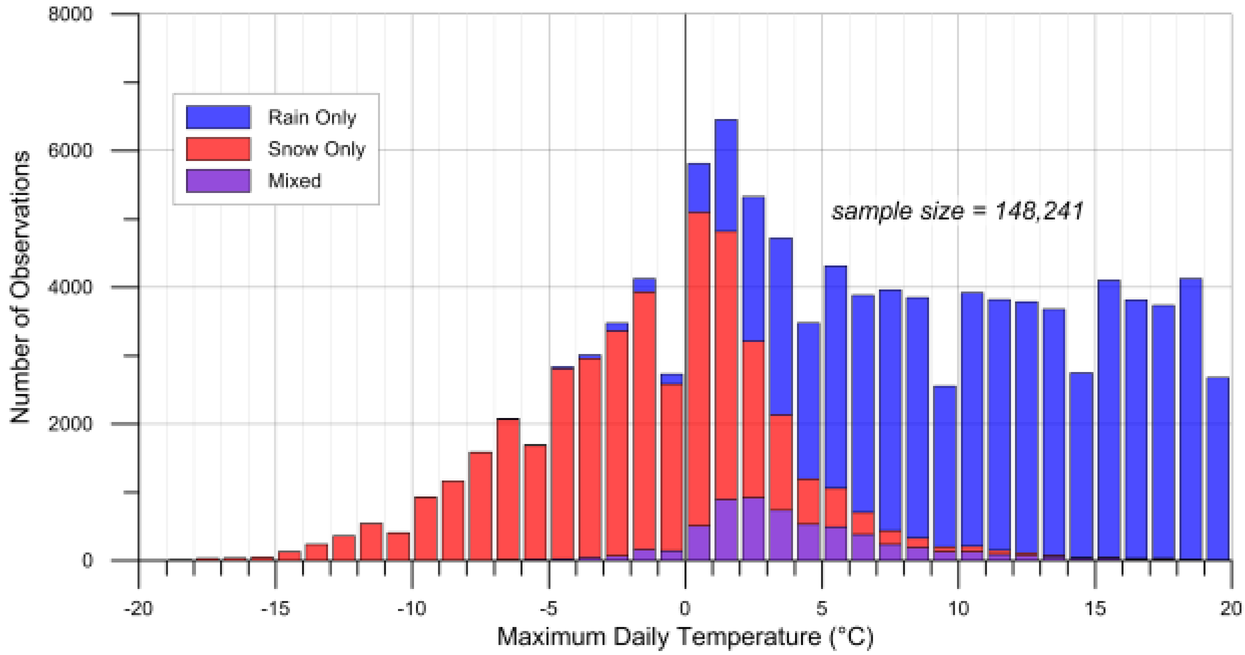


Figure 8.39: Frequency of precipitation form with observed maximum daily temperature at all climate stations proximal to the study area.

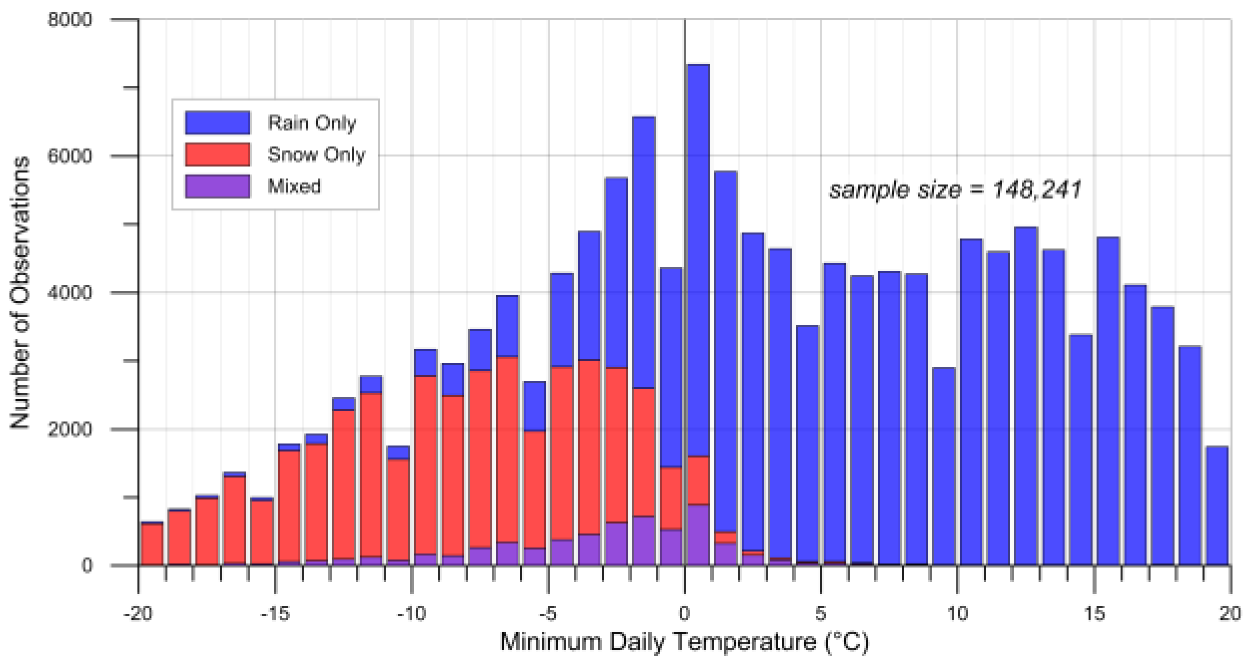


Figure 8.40: Frequency of precipitation form with observed minimum daily temperature at all climate stations proximal to the study area.

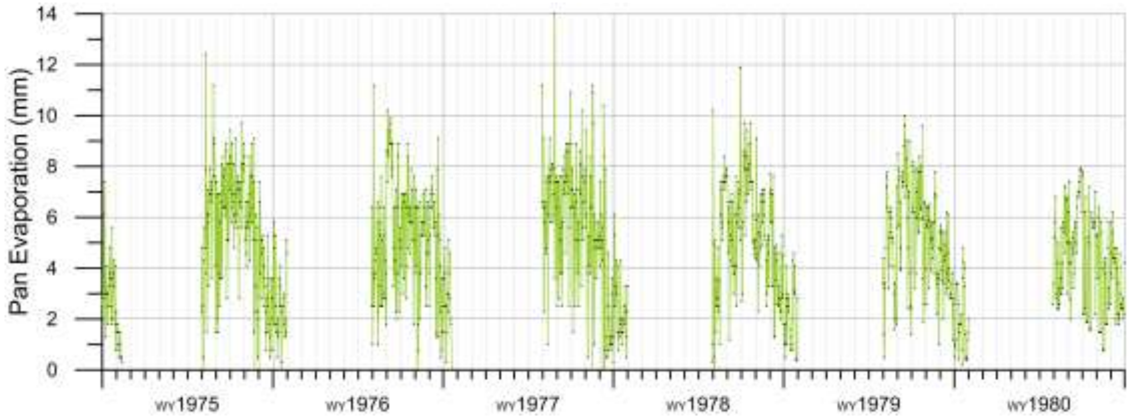


Figure 8.41: Daily pan evaporation observed at EC climate station Delhi CDA (6131982).

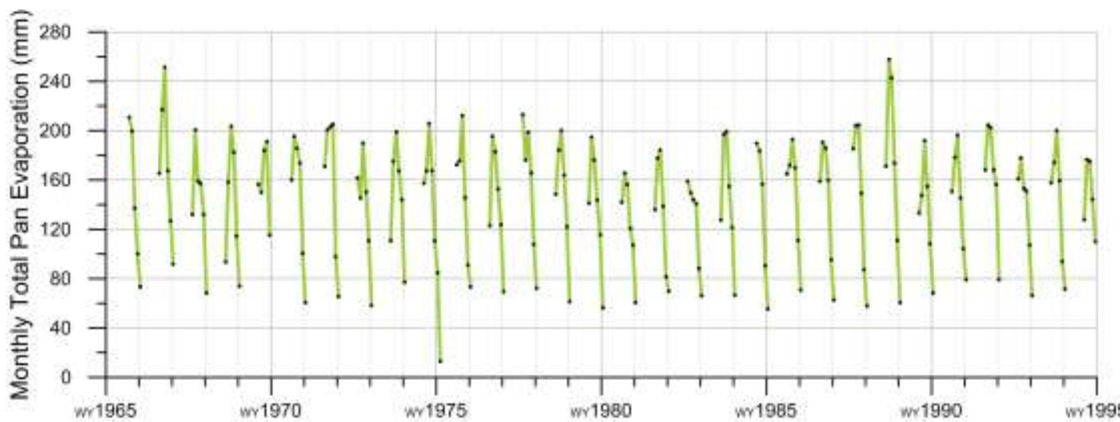


Figure 8.42: Monthly average pan evaporation observed at study area climate stations.

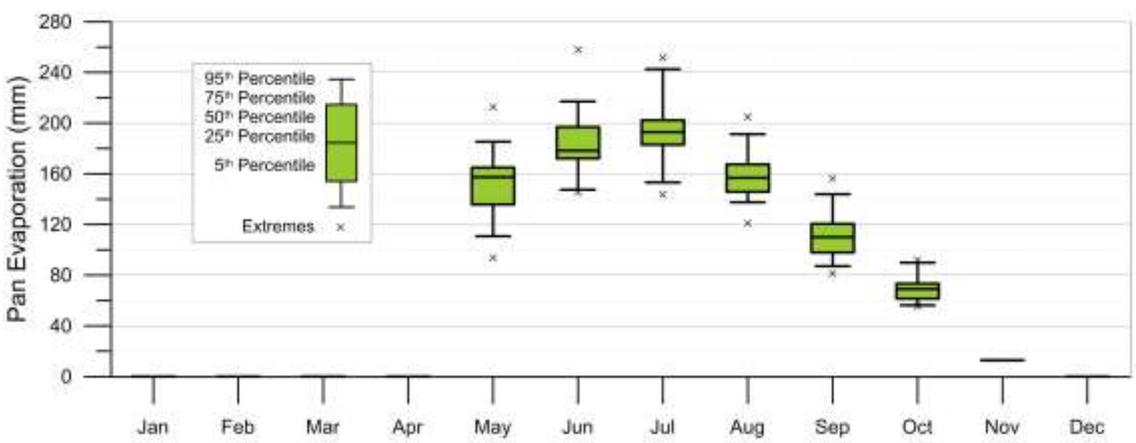


Figure 8.43: Monthly histogram of mean pan evaporation observations from study area climate stations.

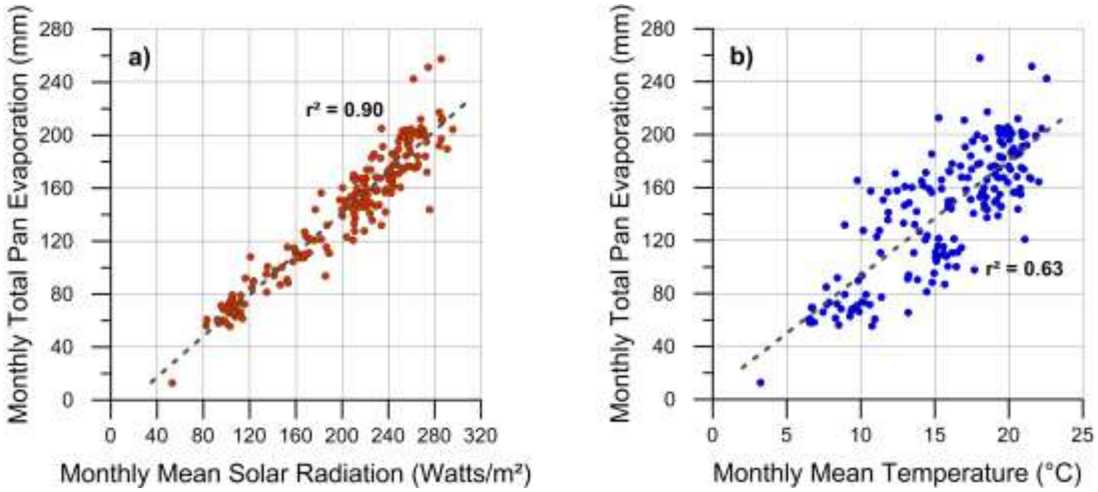


Figure 8.44: Monthly averaged pan evaporation observations versus monthly (a) solar radiation and (b) basin-averaged mean temperature.

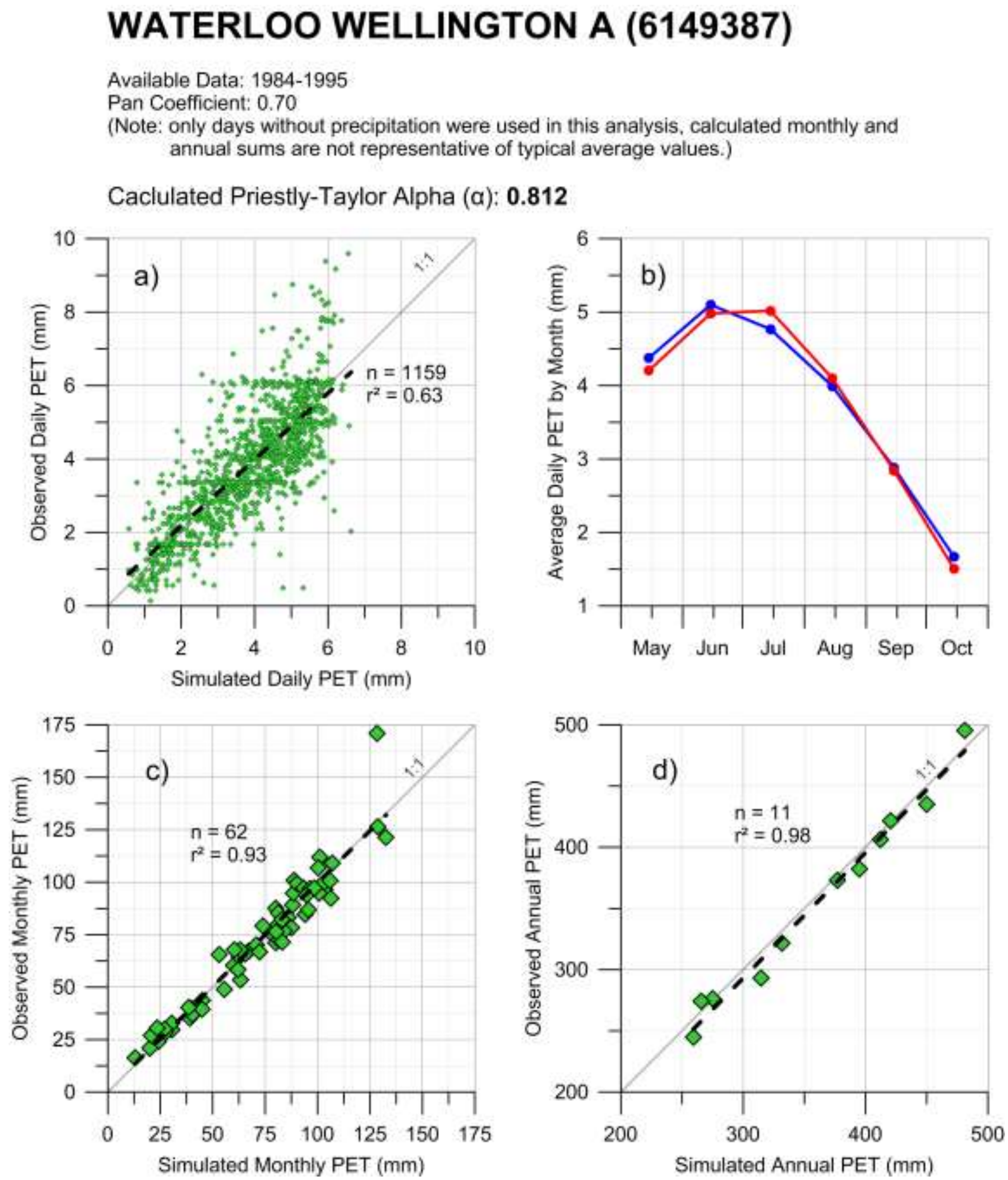


Figure 8.45: Calculated potential evapotranspiration via the Priestly-Taylor equation versus: (a) daily, (b) seasonal, (c) monthly, and (d) annual historical observed clear sky potential evapotranspiration at ECCC climate station WATERLOO WELLINGTON A.

DELHI CDA (6131982)

Available Data: 1984-1995
Pan Coefficient: 0.8
(Note: only days without precipitation were used in this analysis, calculated monthly and annual sums are not representative of typical average values.)

Caclulated Priestly-Taylor Alpha (α): **0.824**

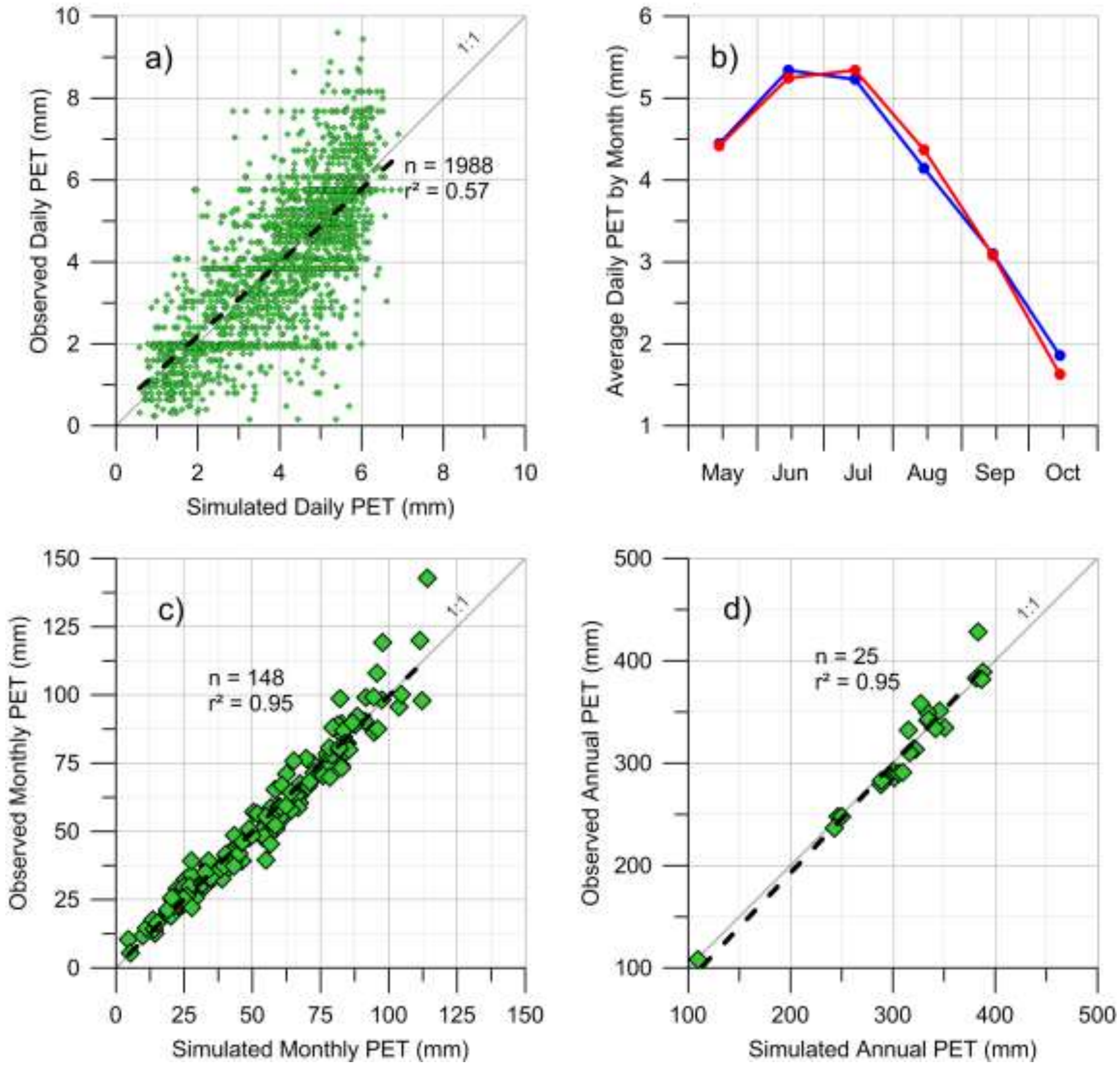


Figure 8.46: Calculated potential evapotranspiration via the Priestly-Taylor equation versus: (a) daily, (b) seasonal, (c) monthly, and (d) annual historical observed clear sky potential evapotranspiration at ECCC climate station DELHI CDA.

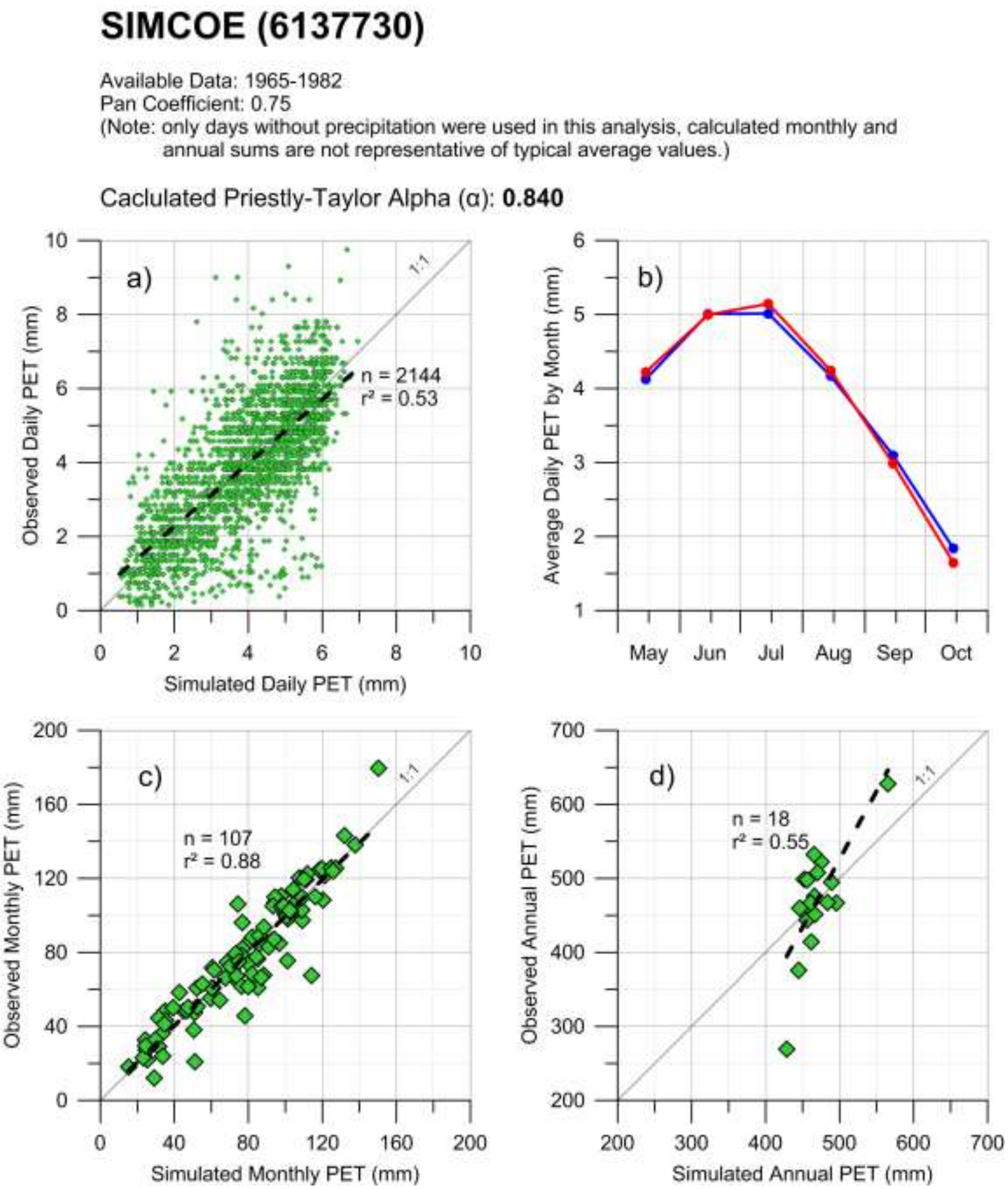


Figure 8.47: Calculated potential evapotranspiration via the Priestly-Taylor equation versus: (a) daily, (b) seasonal, (c) monthly, and (d) annual historical observed clear sky potential evapotranspiration at ECCC climate station Simcoe.

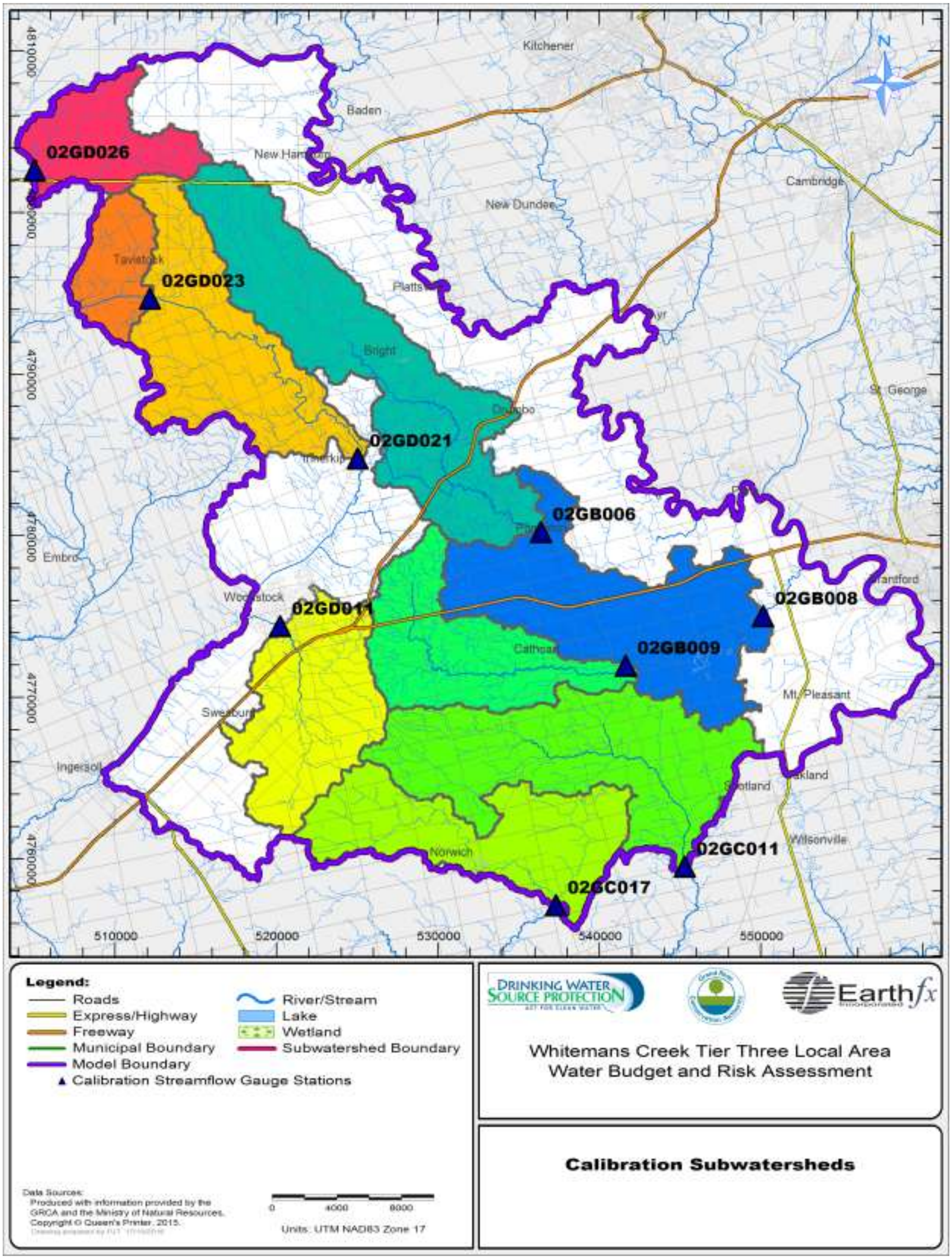


Figure 8.48: Historically gauged subcatchments contained within the model area available for calibration.

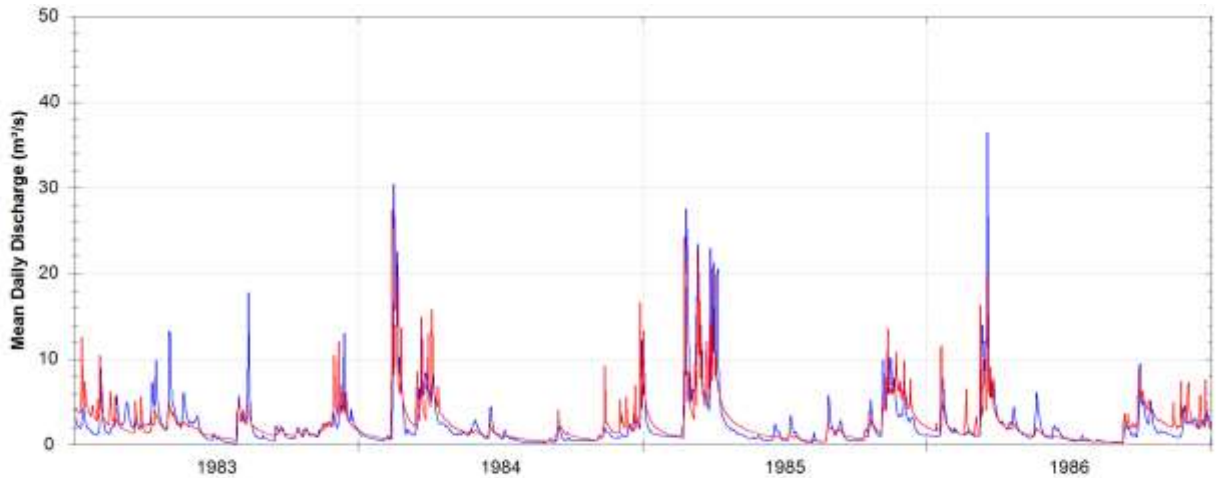


Figure 8.49: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) streamflow at Horner Creek near Princeton (02GB006) 1983-1986.

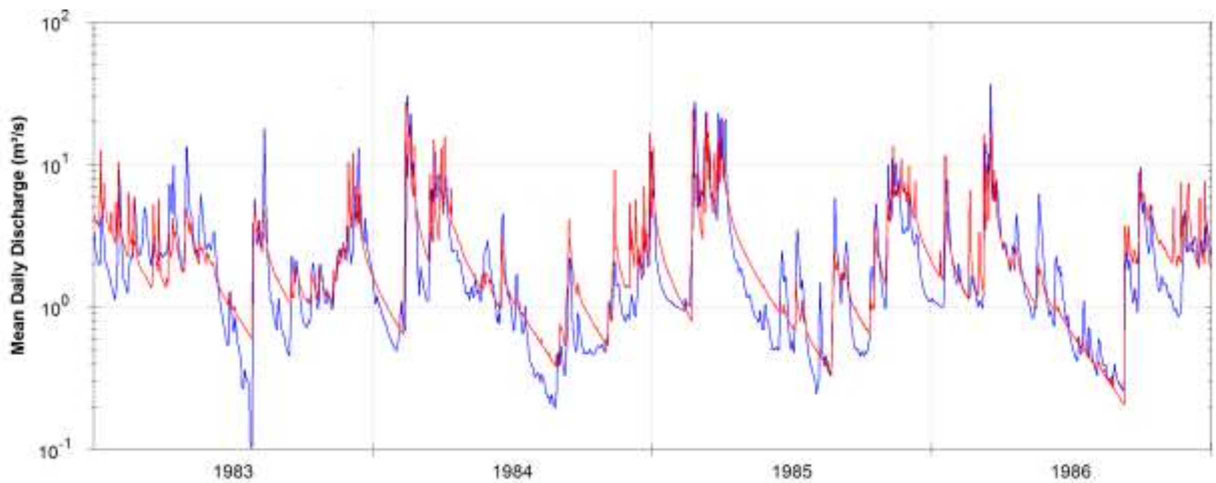


Figure 8.50: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) log-transformed streamflow at Horner Creek near Princeton (02GB006) 1983-1986.

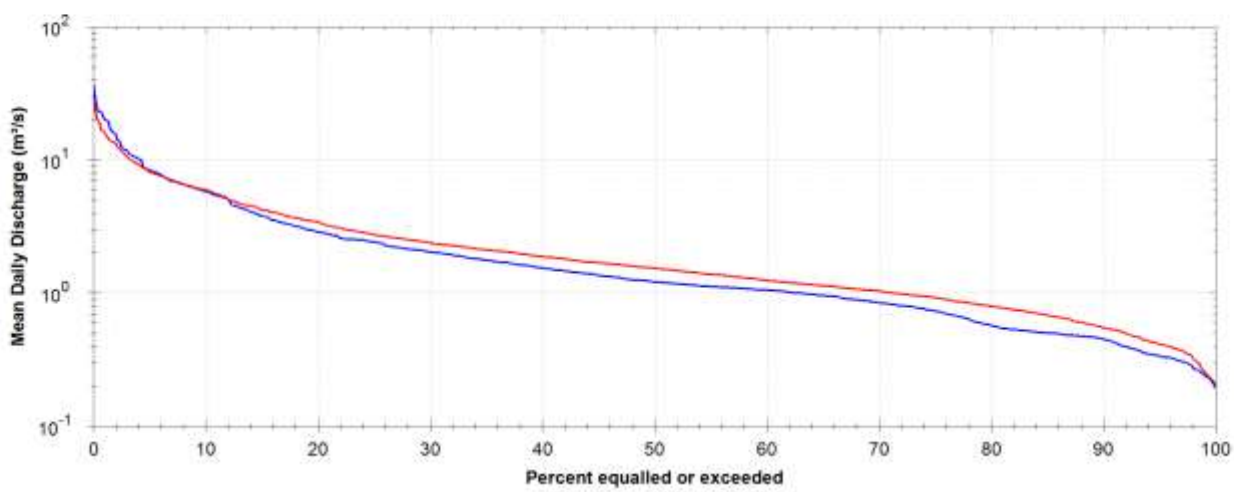


Figure 8.51: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) flow duration curves at Horner Creek near Princeton (02GB006) WY1983- WY1986.

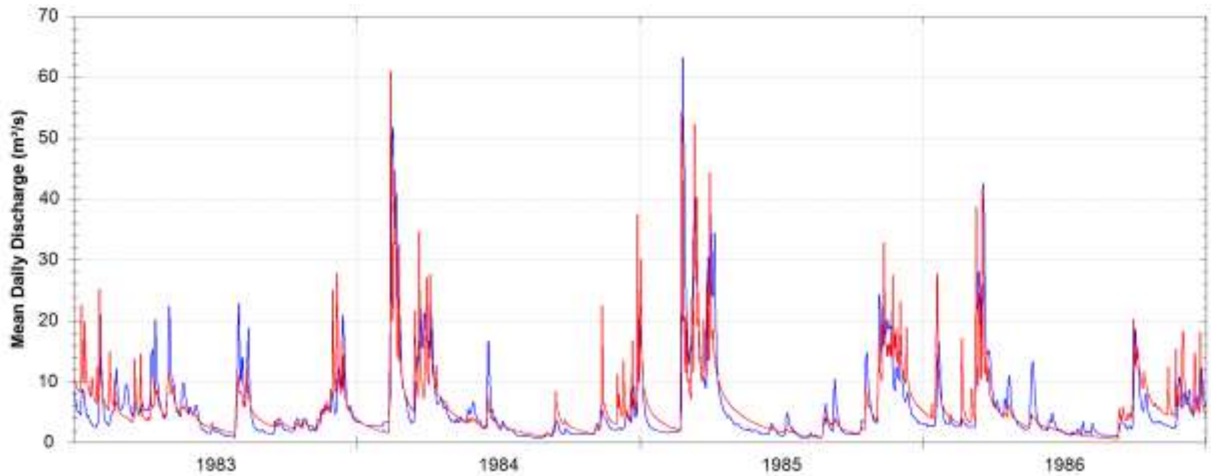


Figure 8.52: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) streamflow at Whitemans Creek near Mount Vernon (02GB008) 1983-1986.

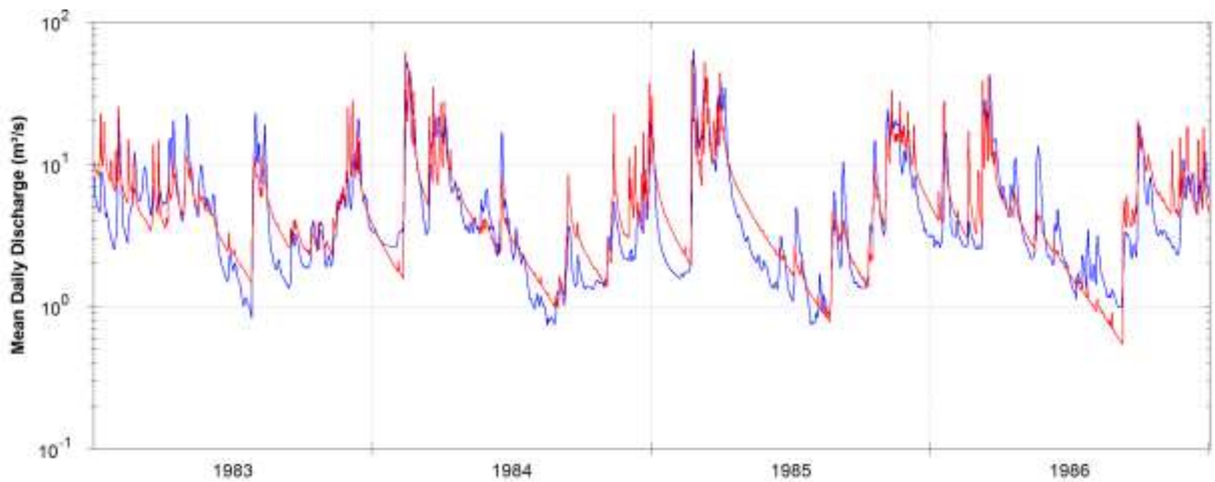


Figure 8.53: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) log-transformed streamflow at Whitemans Creek near Mount Vernon (02GB008) 1983-1986.

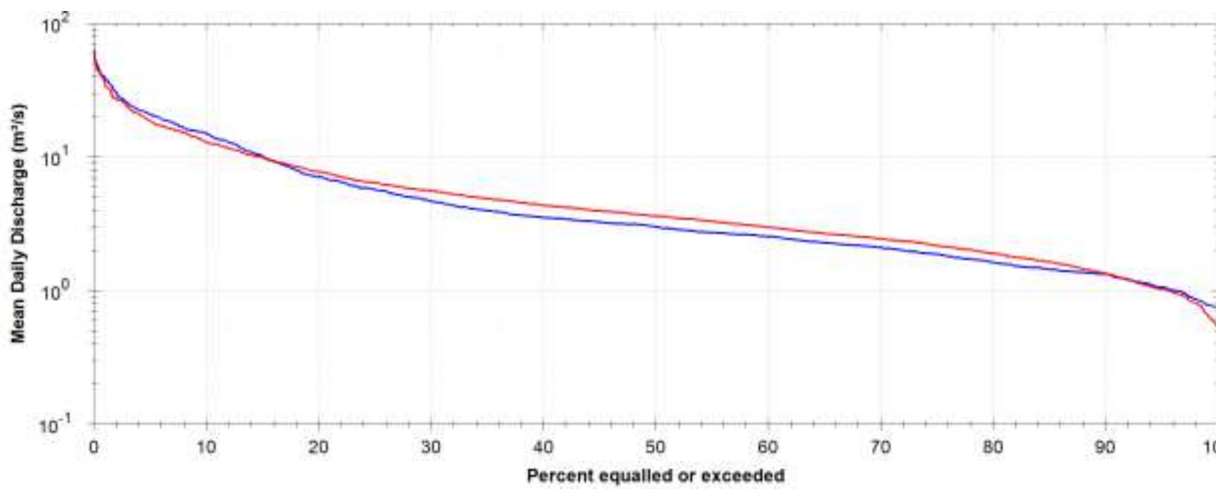


Figure 8.54: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) flow duration curves at Whitemans Creek near Mount Vernon (02GB008) $_{WY}$1983-$_{WY}$1986.

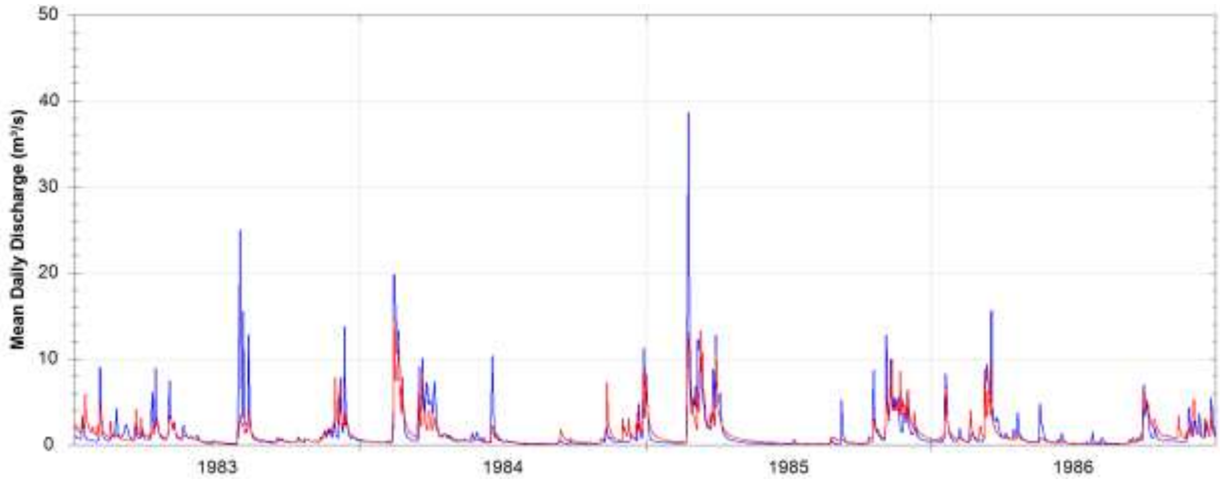


Figure 8.55: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) streamflow at Kenny Creek near Burford (02GB009) 1983-1986.

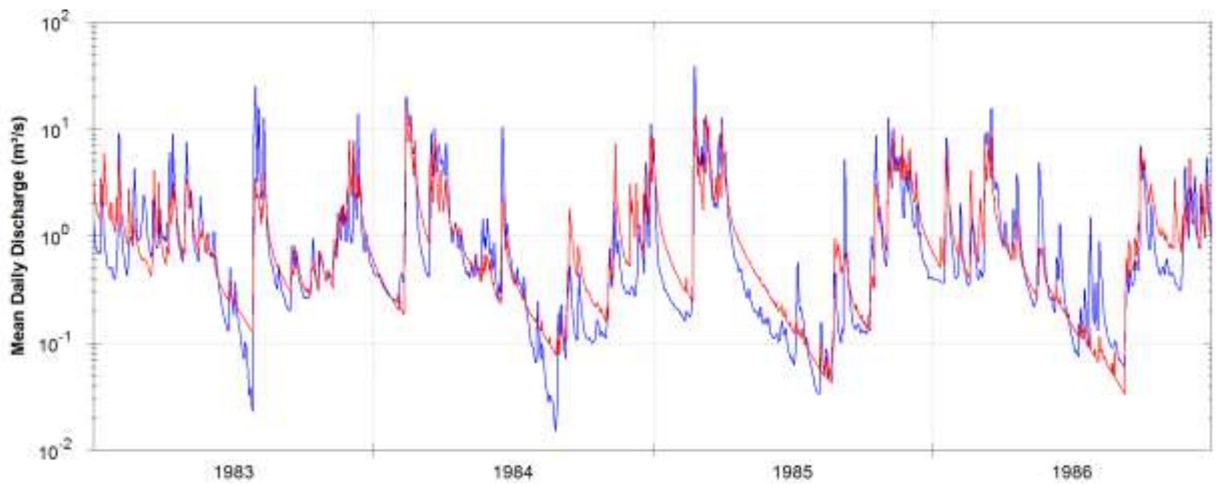


Figure 8.56: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) log-transformed streamflow at Kenny Creek near Burford (02GB009) 1983-1986.

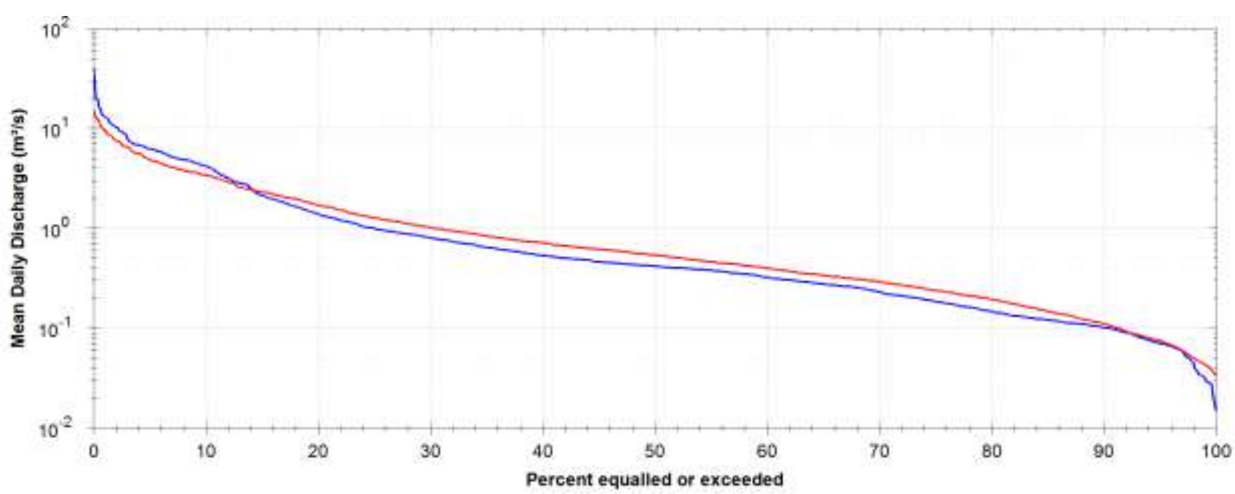


Figure 8.57: Preliminary hydrologic submodel calibration; daily simulated (red) versus observed (blue) flow duration curves at Kenny Creek near Burford (02GB009) WY1983- WY1986.

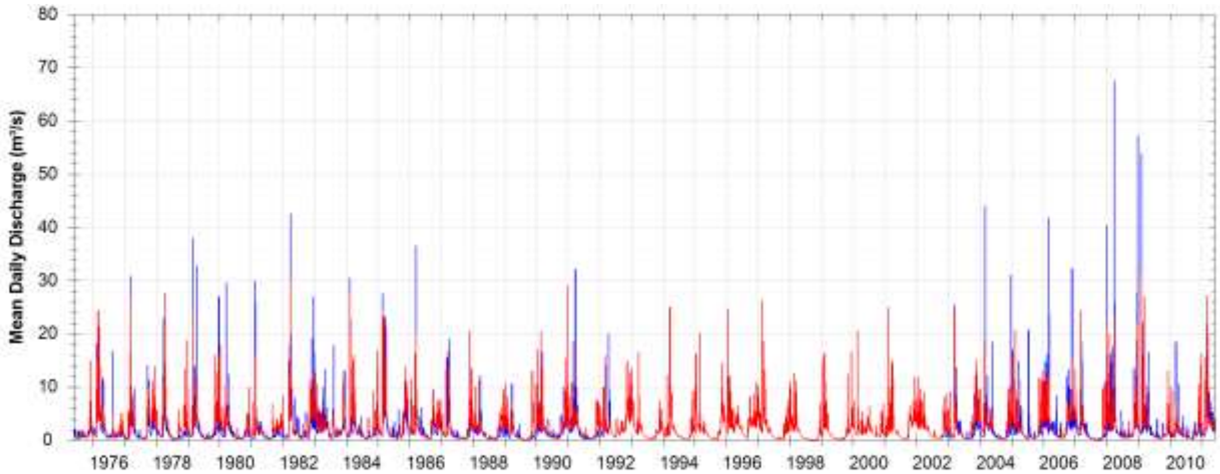


Figure 8.58: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) streamflow at Horner Creek near Princeton (02GB006) 1976-2010.

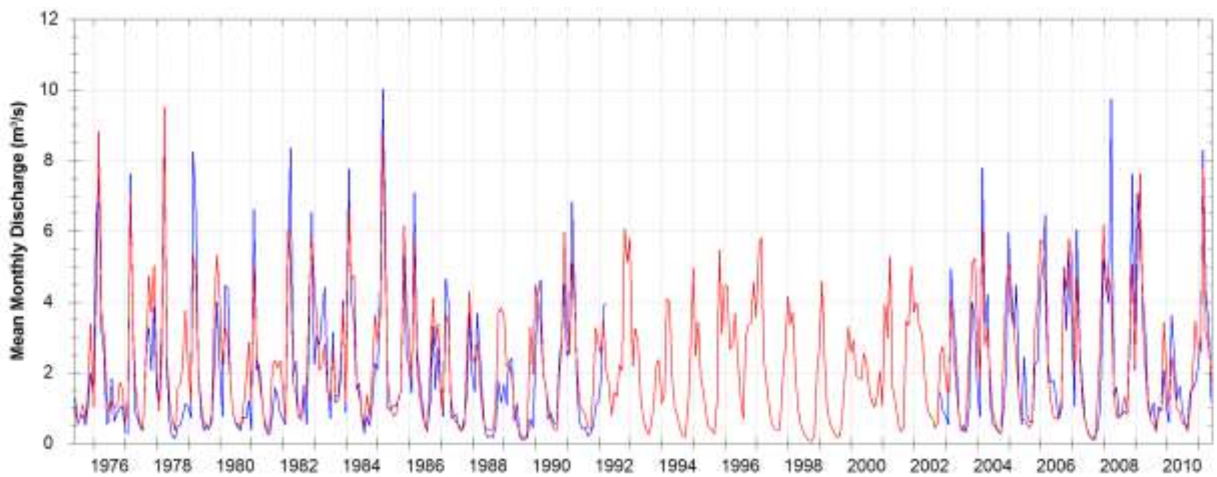


Figure 8.59: Preliminary hydrologic submodel validation; monthly simulated (red) versus observed (blue) log-transformed streamflow at Horner Creek near Princeton (02GB006) 1976-2010.

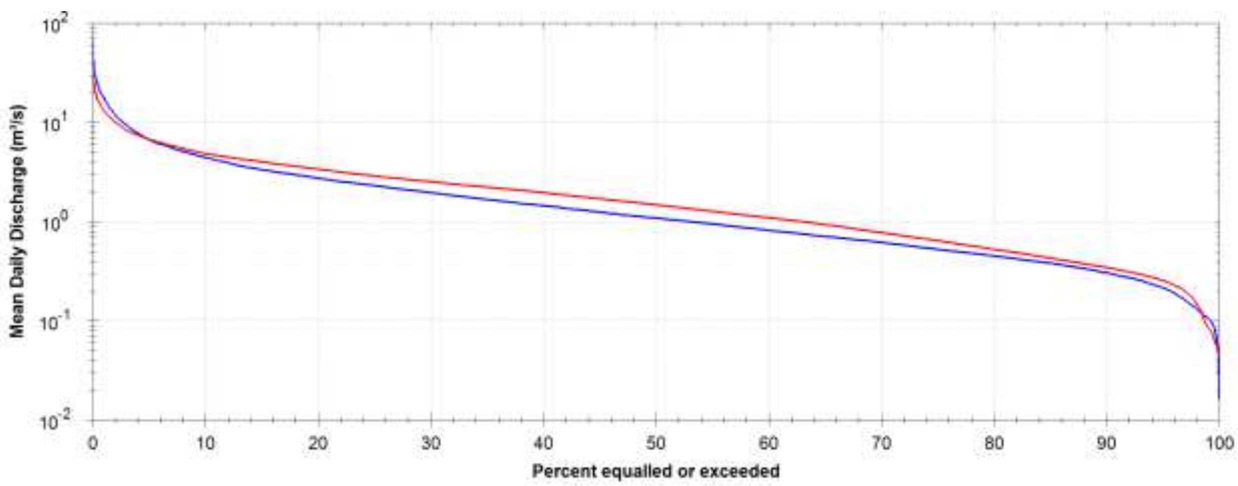


Figure 8.60: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) flow duration curves at Horner Creek near Princeton (02GB006) WY1976-WY2010.

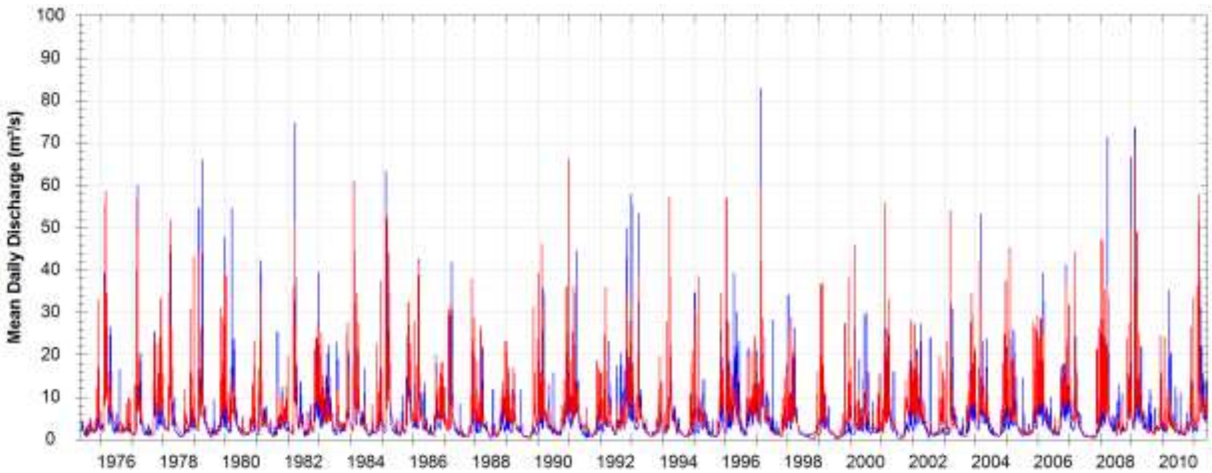


Figure 8.61: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) streamflow at Whitemans Creek near Mount Vernon (02GB008) 1976-2010.

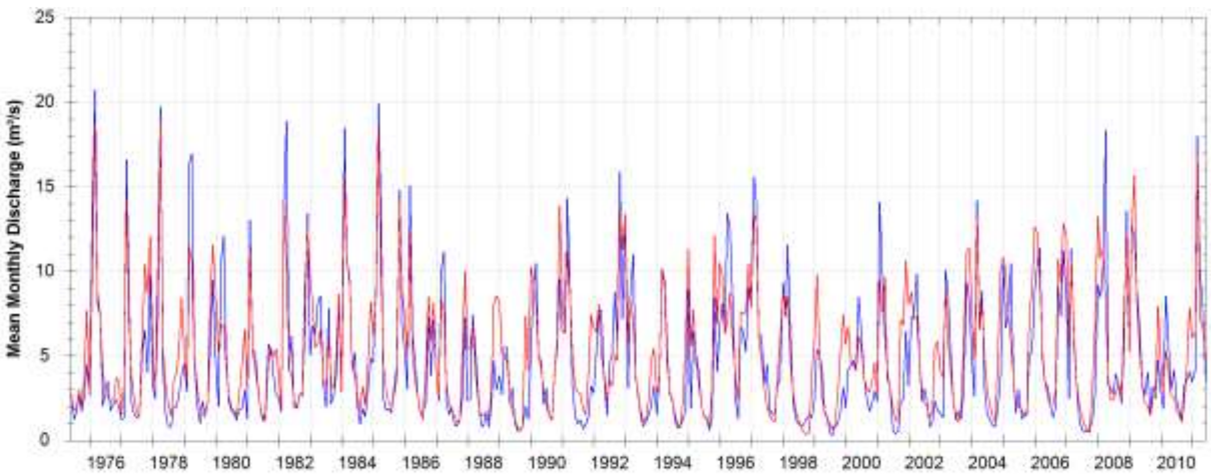


Figure 8.62: Preliminary hydrologic submodel validation; monthly simulated (red) versus observed (blue) log-transformed streamflow at Whitemans Creek near Mount Vernon (02GB008) 1976-2010.

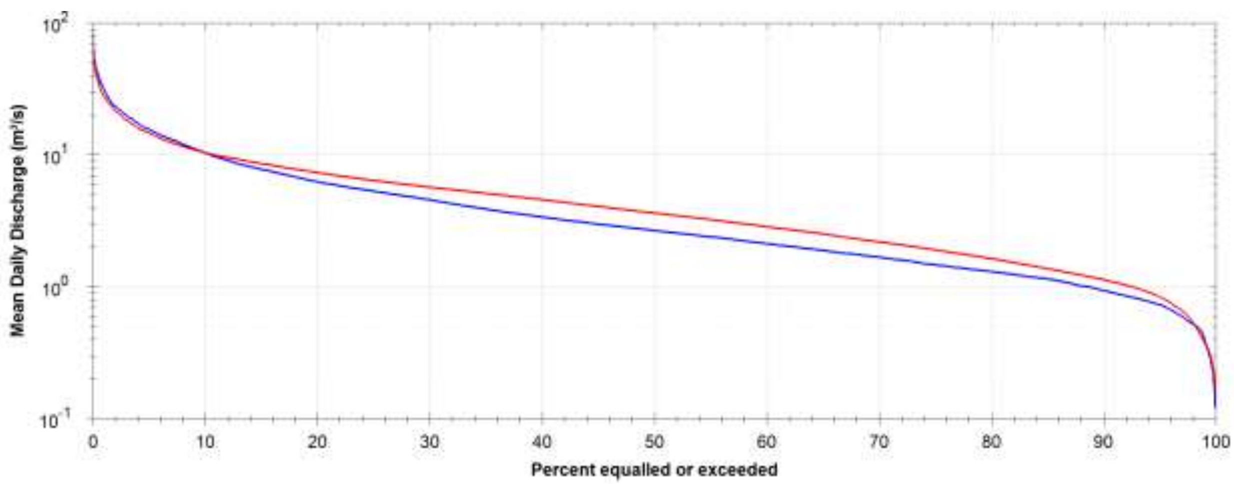


Figure 8.63: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) flow duration curves at Whitemans Creek near Mount Vernon (02GB008) WY1976-WY2010.

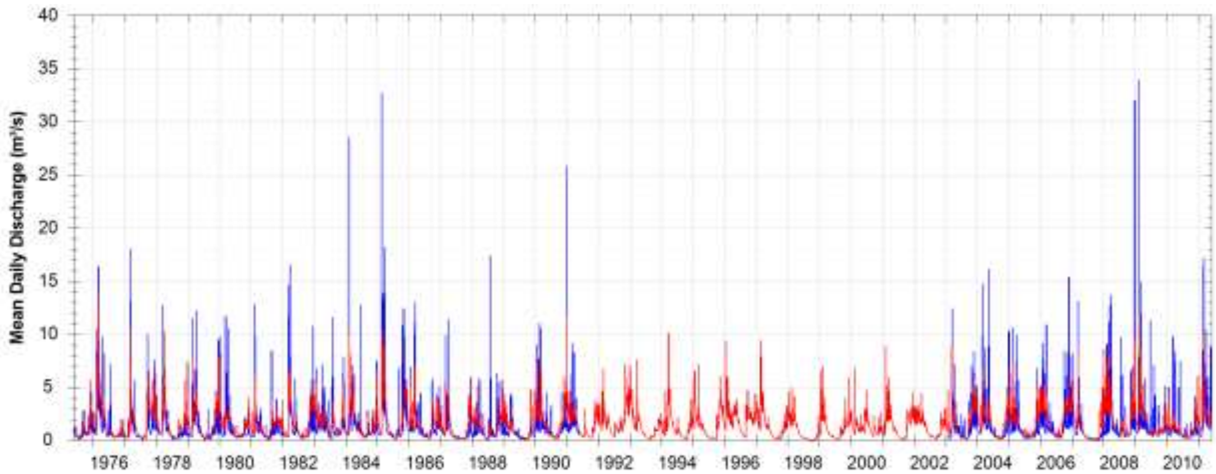


Figure 8.64: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) streamflow at Big Otter Creek above Otterville (02GC017) 1976-2010.

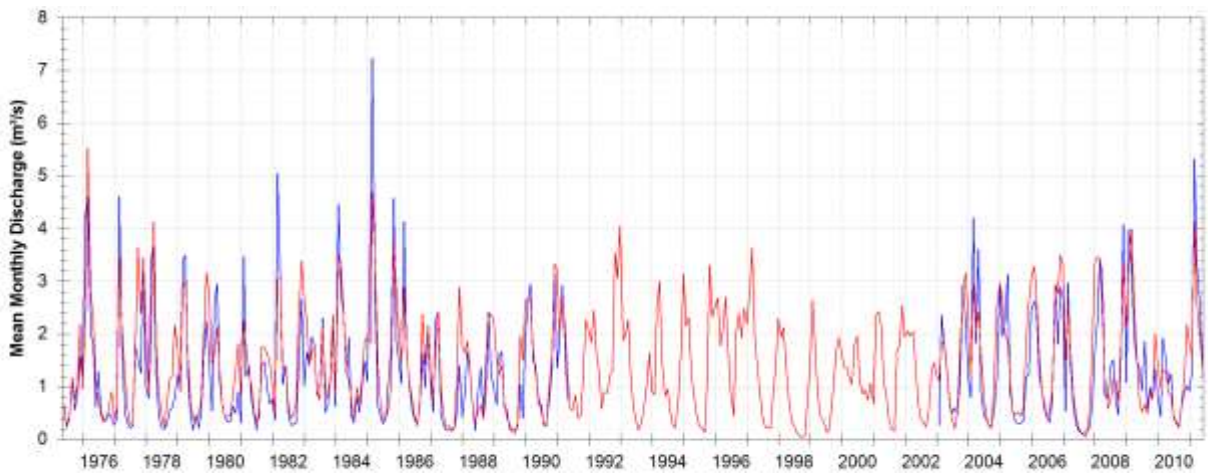


Figure 8.65: Preliminary hydrologic submodel validation; monthly simulated (red) versus observed (blue) log-transformed streamflow at Big Otter Creek above Otterville (02GC017) 1976-2010.

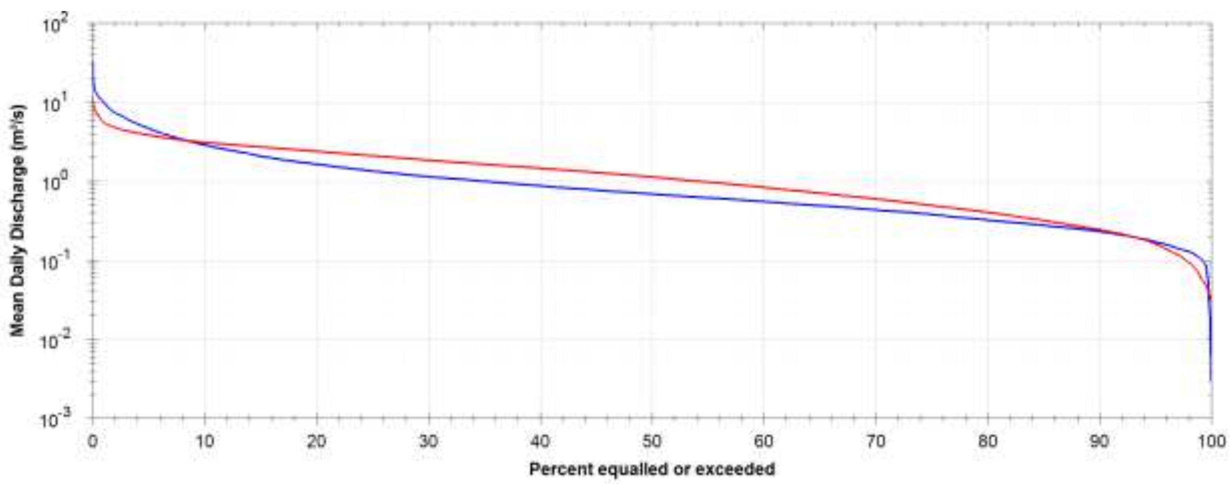


Figure 8.66: Preliminary hydrologic submodel validation; daily simulated (red) versus observed (blue) flow duration curves at Big Otter Creek above Otterville (02GC017) WY1976- WY2010.

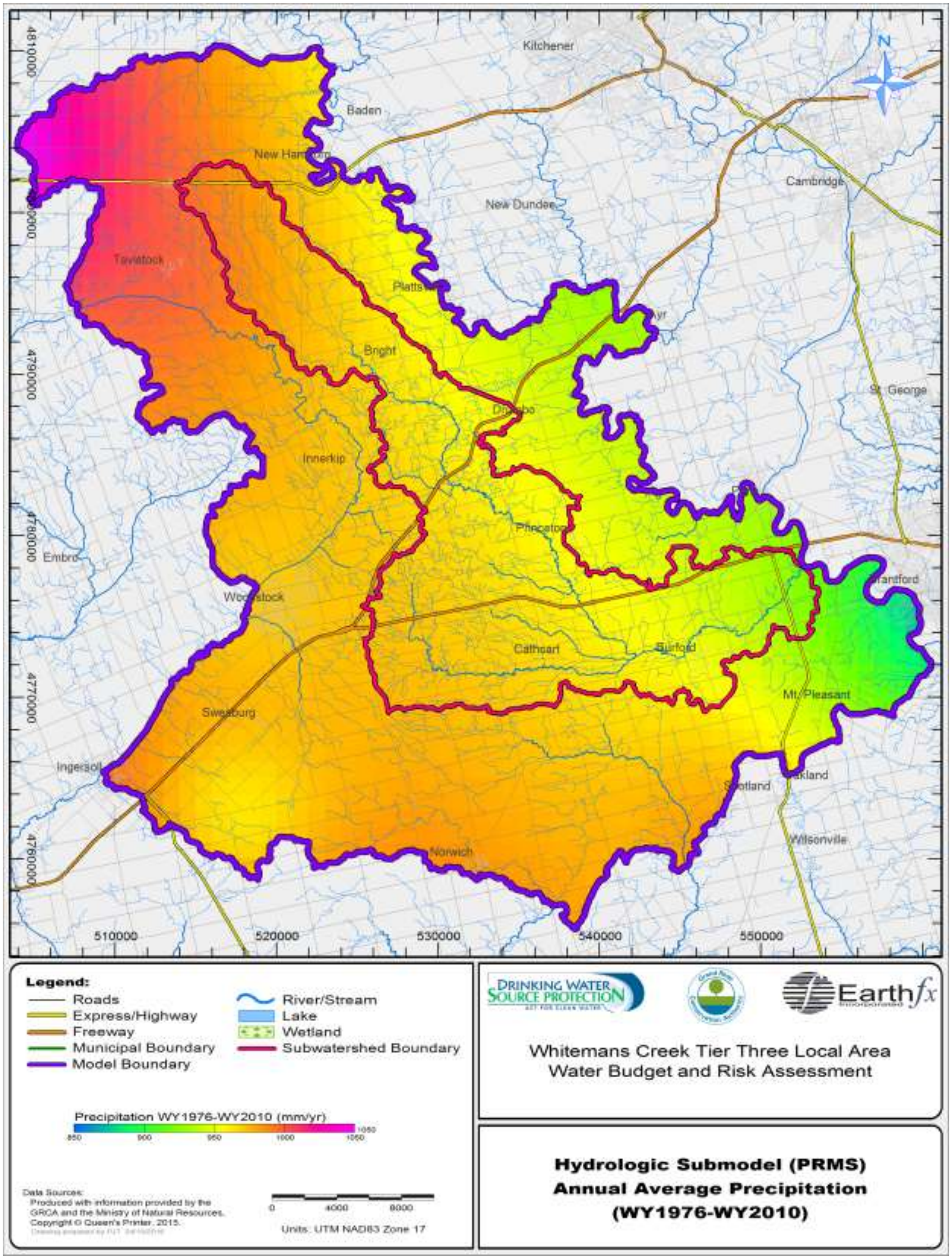


Figure 8.67: Average distribution of annual precipitation from the hydrologic submodel (PRMS).

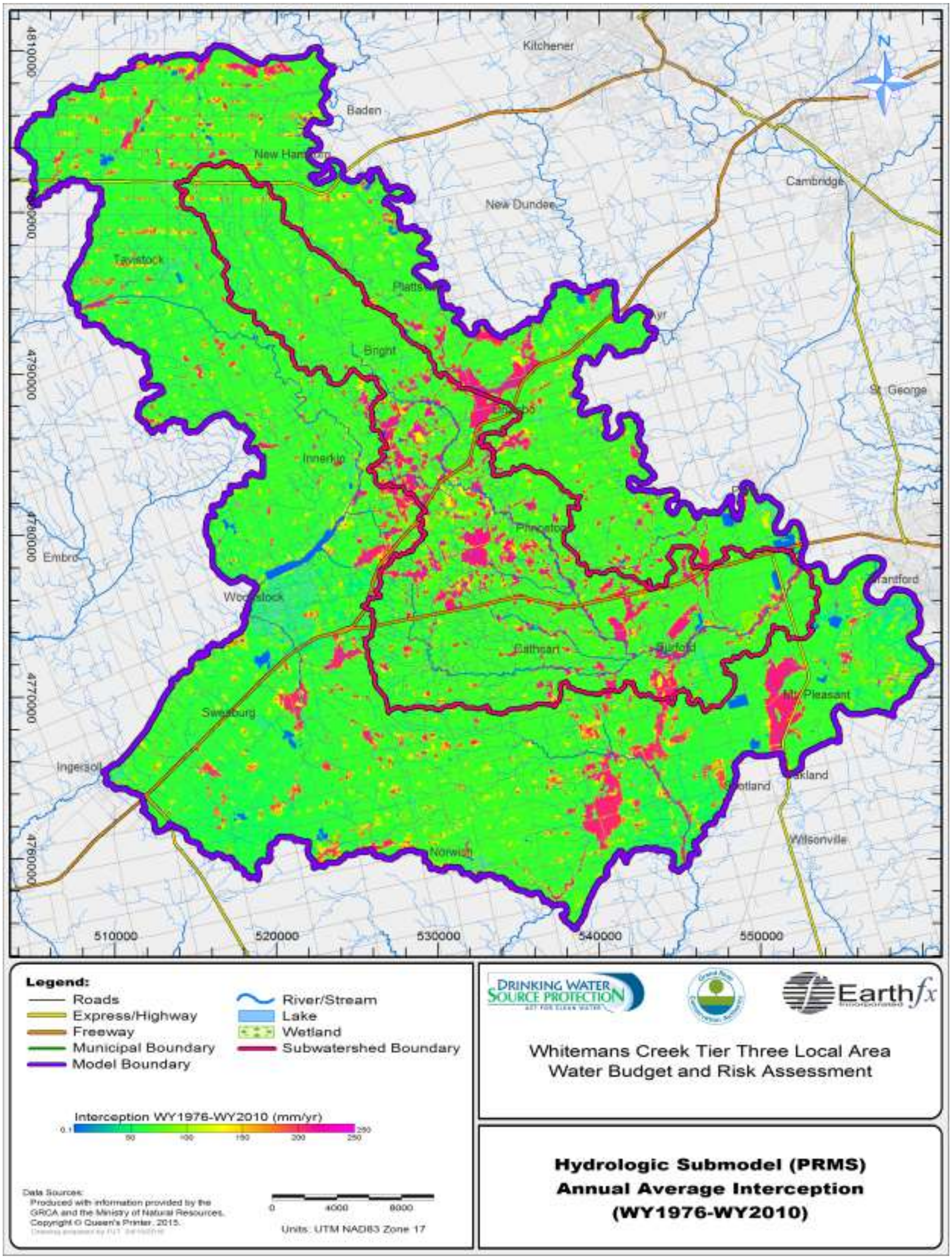


Figure 8.68: Average distribution of annual interception from the hydrologic submodel (PRMS).

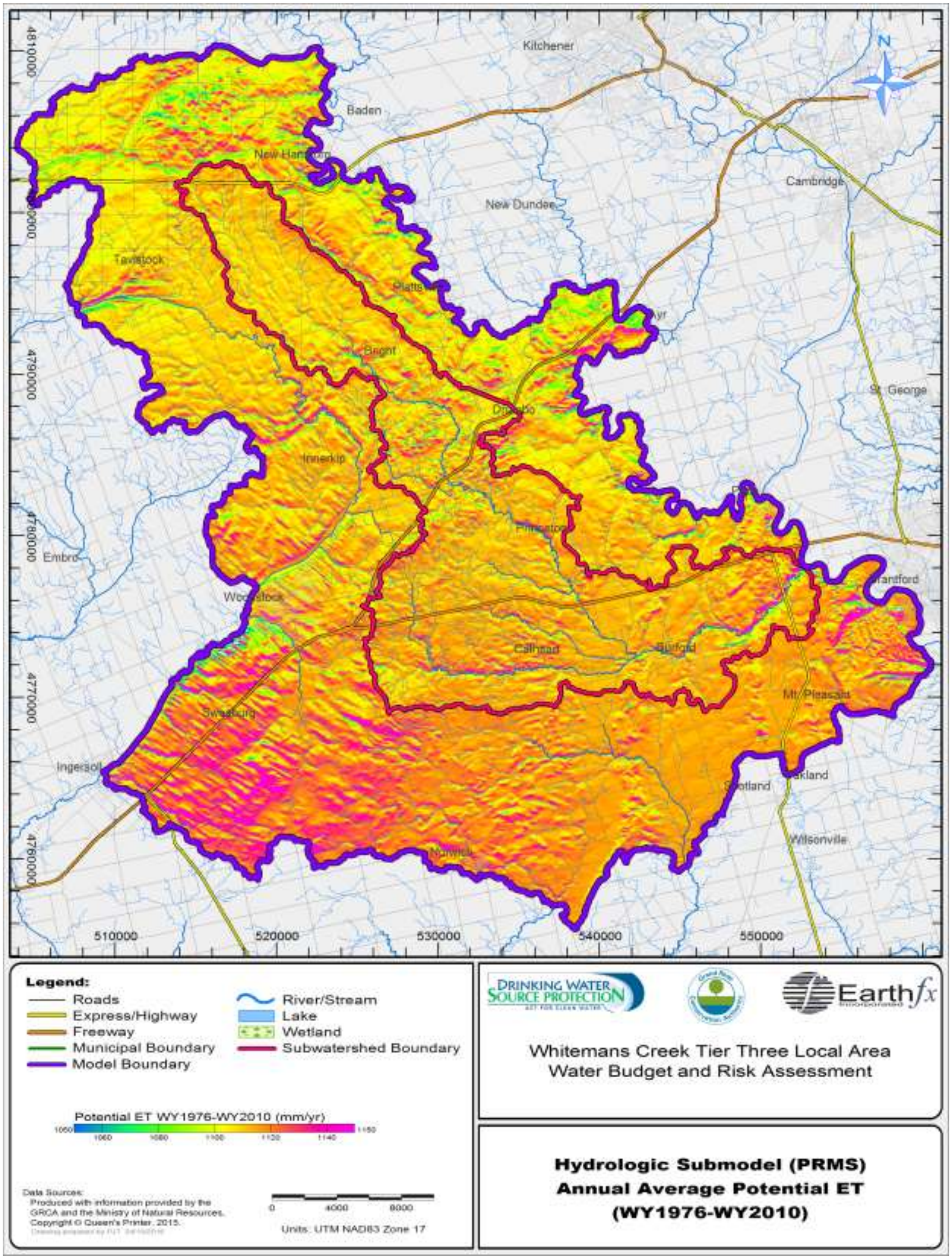


Figure 8.69: Average distribution of annual potential evapotranspiration from the hydrologic submodel (PRMS).

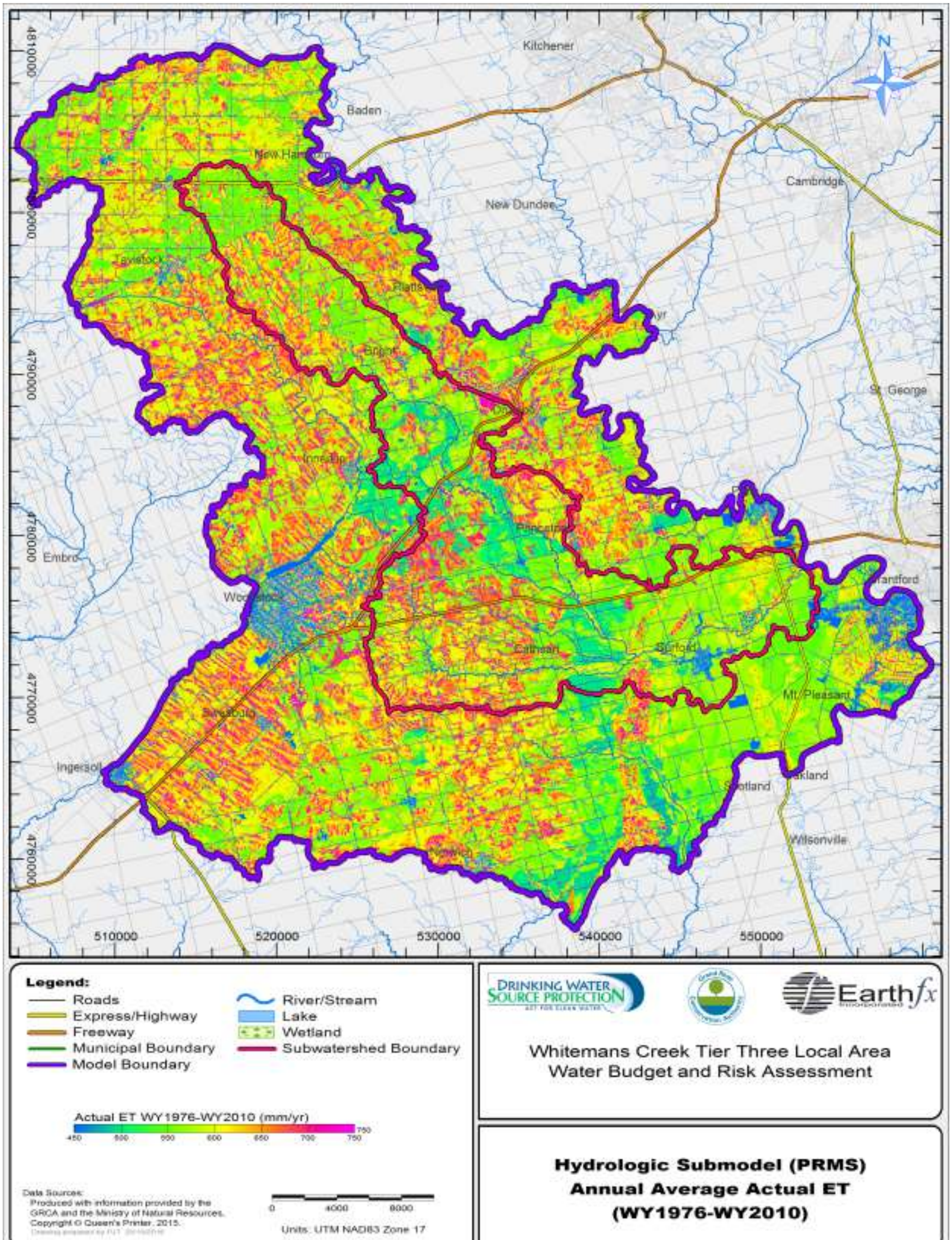


Figure 8.70: Average distribution of annual actual evapotranspiration from the hydrologic submodel (PRMS).

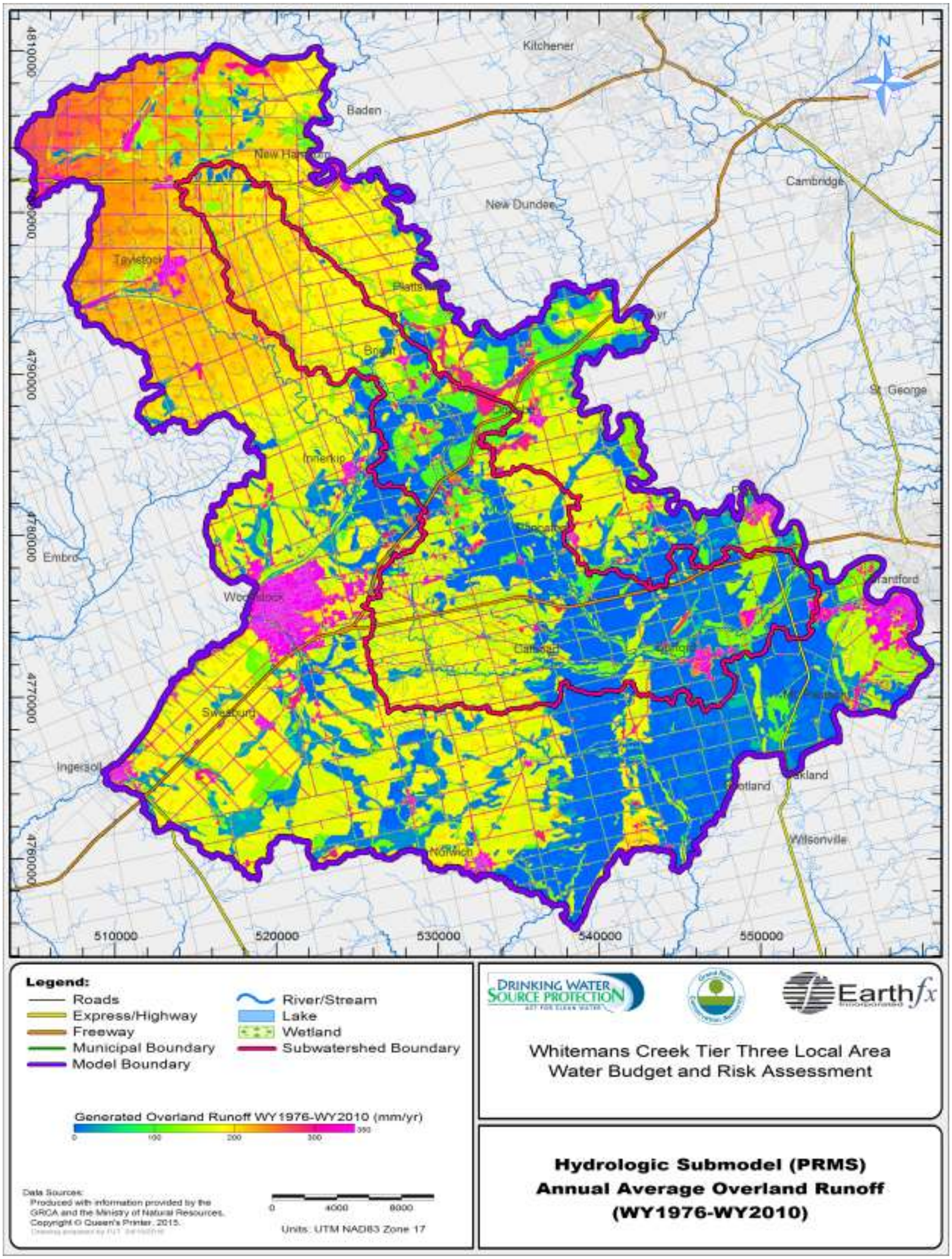


Figure 8.71: Average distribution of annual generated overland runoff from the hydrologic submodel (PRMS).

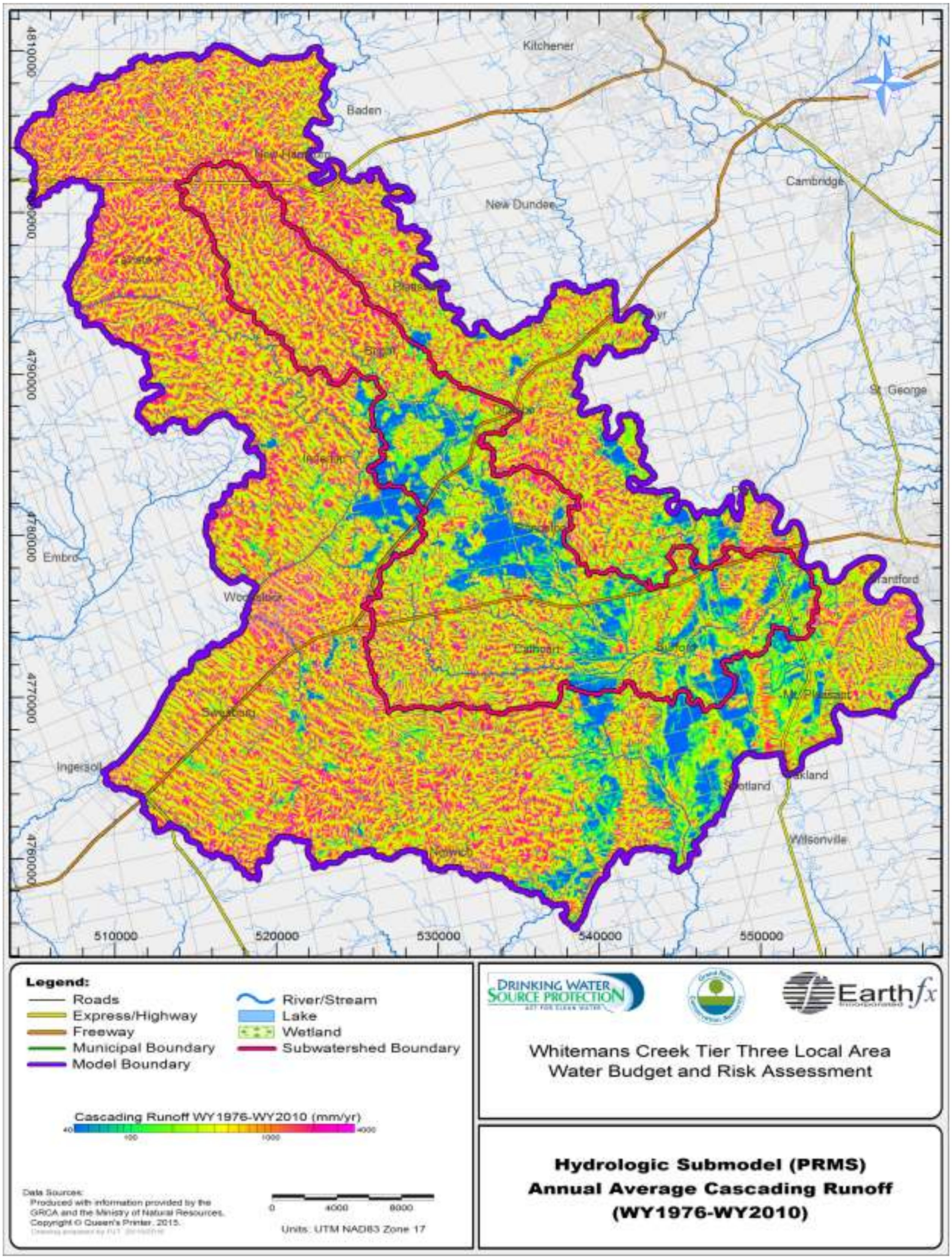


Figure 8.72: Average distribution of annual cascading runoff from the hydrologic submodel (PRMS).

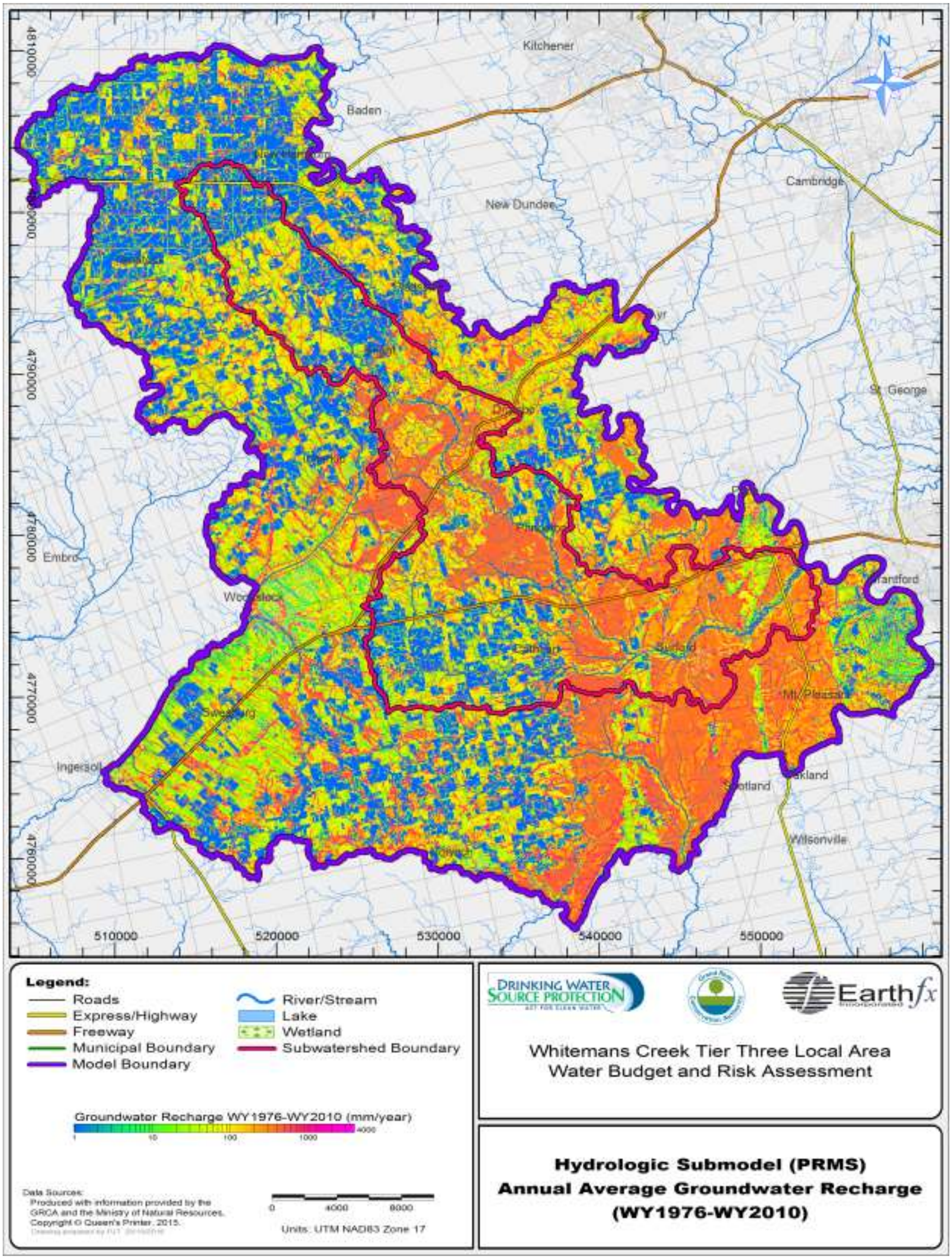


Figure 8.73: Average distribution of annual groundwater recharge from the hydrologic submodel (PRMS).

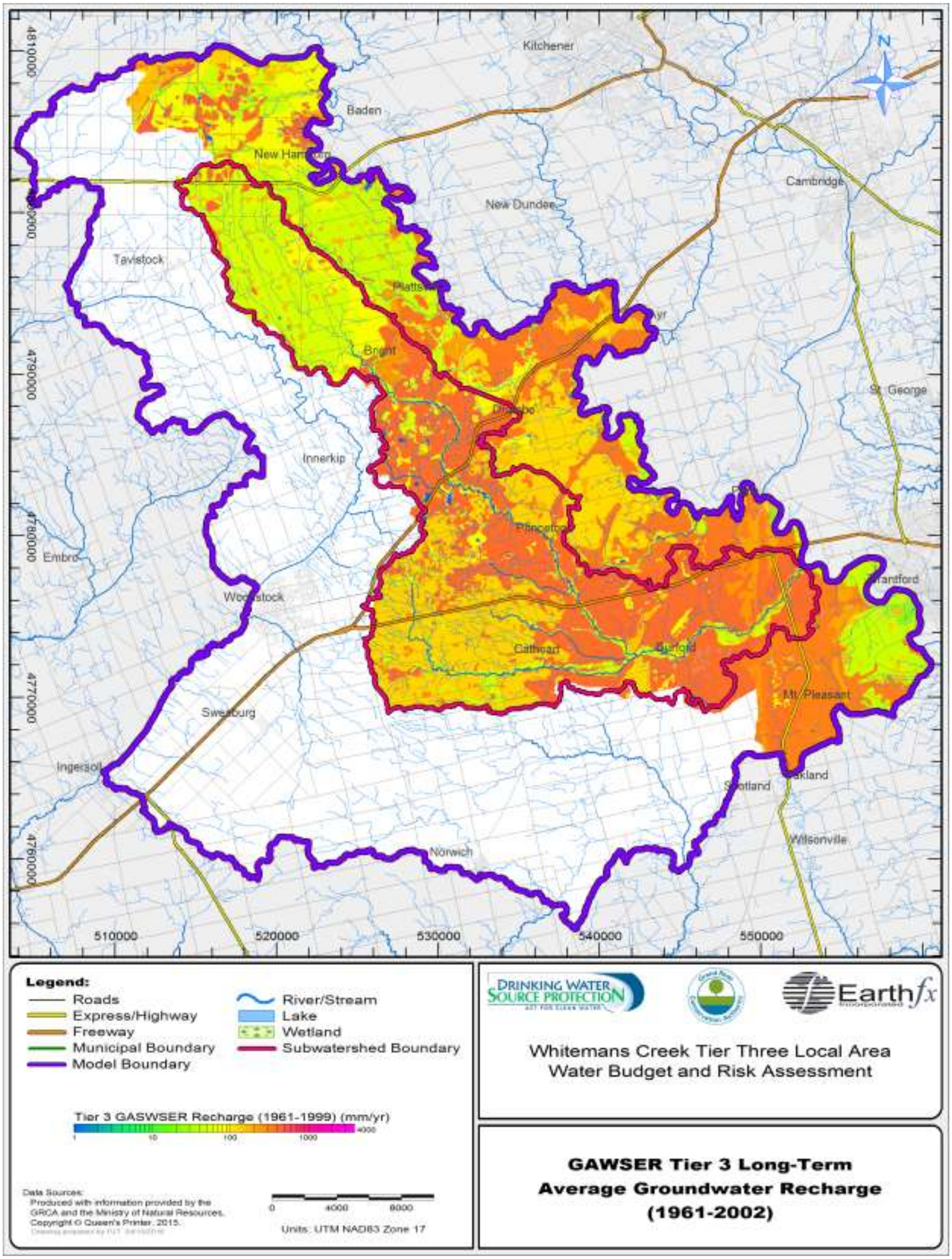


Figure 8.74: Long-term average groundwater recharge as derived by the Grand River Hydrologic Model.

9 Groundwater Flow Submodel Development

A groundwater flow model is a simplified representation of the complex physical, hydrologic and hydrogeological processes that affect the rates and direction of groundwater flow. These processes relate to physical characteristics of the study area and include:

- stratigraphy (the bedrock and overburden stratigraphic layers, their top and bottom surface elevations, lateral extent of the formations, and unit thickness);
- hydrostratigraphy (descriptions of the aquifers and aquitards in the study area, their top and bottom surface elevations, and their lateral extent, thickness, and degree of continuity;
- aquifer and aquitard properties (estimated hydraulic conductivity, anisotropy, saturated thickness, transmissivity, porosity, and storage properties);
- inputs to the hydrologic system (rates of groundwater recharge and discharge and the underlying processes that affect these rates, such as precipitation, ET, overland runoff, infiltration, and baseflow);
- properties of the surface-water system and factors controlling groundwater/surface water interaction;
- anthropogenic inputs and outputs from the groundwater system (pumping rates and return flows); and
- other significant features, including surficial geology and topographic features that may affect recharge and discharge rates.

9.1 *Submodel Description: MODFLOW-NWT*

The groundwater flow submodel used in this study was built with the USGS MODFLOW computer code (Harbaugh, 2005). The basic MODFLOW-2005 code is documented in Harbaugh (2005). The MODFLOW code is extremely suitable for modelling transient groundwater flow in multi-layered aquifer systems and can easily account for irregular boundaries, complex stratigraphy, and variations in hydrogeologic properties. A newer version of the MODFLOW code, MODFLOW-NWT (Niswonger *et al.*, 2011), is especially well suited for representing thin aquifers and sharp changes in model layer stratigraphy, such as those occurring in models with patchy, discontinuous units. MODFLOW-NWT is incorporated in Version 1.1.6 of GSFLOW, which was utilized in this study.

9.2 *Model Boundary Conditions*

While the focus of this Tier 3 study is on the Whitemans Creek subwatershed, with an emphasis on the Bright and Bethel Municipal wellfields, it was recognized that the model boundaries must extend beyond the limits of the subwatershed to properly capture groundwater inflows and outflows across the subwatershed boundaries. These flows likely contribute to the subwatershed water balance and, in turn, influence the sub-regional groundwater and surface water flow systems.

Accordingly, the model area was extended between 1.5 and 18.0 km from the Whitemans Creek subwatershed, except where the main branch of Whitemans Creek meets the Grand River. The model boundary encompasses a total area of about 1,512 km^2 (151,200 ha), as shown in Figure 9.5.

The model extents were also selected to include a total of 15 WSC gauged catchment areas, 9 of which were used in the calibration of the PRMS submodel and GSFLOW integrated model (discussed in Section 8.6.1). Including these catchments extended the surface water calibration dataset and helped reduce uncertainty related to the simulated recharge to the groundwater system.

9.2.1 Constant Head and No Flow Boundary Conditions

Boundary conditions are specified for cells that lie along lines corresponding to the physical boundaries of the groundwater flow system. Three general types of boundary conditions were used in the groundwater flow model: constant head, no-flow, and head-dependent discharge boundaries. Figure 9.5 shows the location of constant head and no-flow boundaries for the model. Constant head cells were applied along model boundaries corresponding to major water courses, including:

- the Grand River between Brantford and Paris, along the eastern model boundary;
- the Nith River between Paris and Philipsburg, along the northeastern model boundary, including a tributary reach for a northern portion of the model boundary;
- the Thames River and nearby tributaries, for a portion of the western model boundary; and
- a portion of Big Creek, along the southern model boundary.

Control elevations for the constant head boundaries were estimated from the 10-m DEM for the study area. No-flow boundaries were imposed everywhere else along the external boundary assuming that cross watershed flow across these boundaries would be relatively small and would not affect flows in the Whitemans Creek subwatershed. A no-flow boundary was imposed along the base of the model flow assuming that inflow from the the Lower Salina Formation would be negligible.

9.2.2 Head-Depended Discharge Boundary Conditions

Head-dependent flux boundaries were used extensively to represent groundwater/surface water interaction between streams and lakes within the model area. Flow between the groundwater system and streams was assumed to be exchanged as "leakage" across streambeds. All mapped streams segments (shown in Figure 9.5) were simulated in the model for a total of 1,919 km of stream channels. Streams were characterized by Strahler classification, which was then used to assign typical stream cross sections and streambed conductance. The rate of leakage is determined based on Darcy's Law where:

$$Q_{Leak} = \frac{K'}{B'} A_L (H_L - h) \qquad \text{Equation 5}$$

where:	Q_{LEAK}	=	volumetric flow rate between aquifer and stream;
	K'	=	vertical hydraulic conductivity of the streambed;
	B'	=	thickness of the streambed;
	A_L	=	wetted area of the streambed;
	H_L	=	stream stage (in masl); and
	H	=	head in the aquifer

Leakage between the stream and the aquifer is calculated on a cell-by-cell basis using the SFR2 module in MODFLOW (Niswonger and Prudic, 2005). In SFR2, a stream "reach" is defined as the portion of a stream within a model cell (*see* Figure 9.1). Head in the aquifer, h, is the head in the cell. H_L, the stage in the centre of the reach, is calculated based on stream channel properties and the sum of upstream inflows, precipitation, evaporation, and overland flow to the reach. Multiple reaches can occur within a single cell and, ideally, cells are small enough so that the head in the cell reasonably represents the head in the aquifer beneath the streambed.

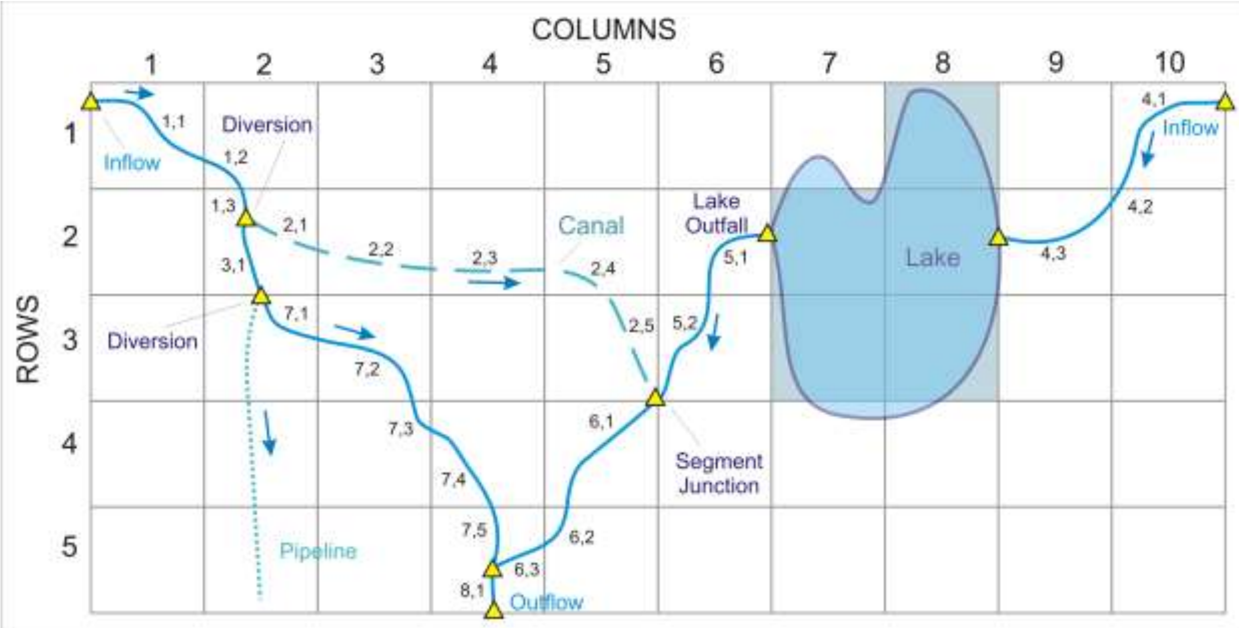


Figure 9.1: Stream network and lake representation in the SFR2 and LAK3 modules (modified from Markstrom, *et al.*, 2008).

Leakage between lakes or other standing bodies of water and the aquifer is also governed by Equation 5 and is calculated on a cell-by-cell basis using the LAK3 module in MODFLOW (Merritt and Konikow, 2000). In LAK3, a cell can represent all or a portion of a lake (Figure 9.1). The area A_L in Equation 5 is equal to the cell area. Head in the aquifer, h, is the head in the cell underlying the lake and H_L is the lake stage. Lake volumes are calculated in a separate water budget analysis based on the sum of upstream inflows (as computed by the SFR2 module), precipitation, evaporation, overland flow to the lake (as calculated by PRMS), and outflow from the lake (also calculated by SFR2 based on lake stage). Lake stage is calculated from stage-volume relationships. Lakes can penetrate multiple model layers and leakage can occur to cells adjacent as well as underlying the lake.

The location and delineation of lakes within the study area was informed by the MNRF Ontario Hydro Network (OHN) water body geospatial dataset (2015b). A total of 17 MODFLOW "lakes" were simulated in the model, shown in Figure 9.5. These correspond to bodies of open water. Some of the smaller (<0.05 km^2) ponds were not explicitly represented in the model at this time. Model lakes were assigned a uniform depth of 3 m where bathymetry data was unavailable, which was then used to incise the lakes into the upper model layers. Wetlands (e.g., fens, marshes, bogs, and swamps) that do not have perennial standing water are represented within the PRMS submodel.

9.2.3 Top of Model Flux Boundary

Head-dependent discharge boundaries were assigned across the top surface of the model so that when the water table rises above ground, groundwater is discharged from the aquifer to land surface when MODFLOW is run in stand-alone mode. Groundwater discharged to land surface is routed as overland flow directly to nearby stream segments. Assignment of stream reaches to model cells was based on an analysis of land surface topography. When run in integrated model mode, groundwater is discharged from the aquifer to the soil zone and PRMS determines whether there is sufficient storage in the soil zone or the water contributes to cascading runoff and interflow. All "surface leakage" boundaries were simulated using the Unsaturated-Zone Flow (UZF1) package for MODFLOW (Niswonger *et al.*, 2006).

Groundwater recharge, groundwater ET (i.e., the loss of water from a shallow water table below the soil zone), and unsaturated flow is also simulated using the UZF module (Niswonger *et al.*, 2006). When run in stand-alone mode, recharge rates are typically estimated and then adjusted as part of the model calibration procedure. Using this approach alone would have led to large changes when the submodels were integrated. Instead, the iterative submodel calibration approach used interim results from long-term PRMS runs to estimate spatially-variable average recharge rates. In this way, reasonable values for the other calibration parameters (hydraulic conductivities and storage coefficients) were obtained and the final calibration focussed on parameters controlling groundwater feedback.

The average annual groundwater recharge estimates from the final PRMS submodel were used in the final calibration of the MODFLOW submodel, presented in Figure 9.6. The southeast portion of the model area is characterized by high recharge areas associated with the Norfolk Sand Plain, while the till plains of the west and northwest parts of the model area have relatively low groundwater recharge estimates. Towards the centre of the Whitemans Creek subwatershed between the Towns of Bright, Innerkip, Drumbo, and Princeton, high recharge areas can be found, associated with the coarser-grained glacial outwash deposits.

9.3 *Model Discretization*

The finite-difference method requires that the study area be subdivided into a grid of small square or rectangular cells. For the Tier 3 Assessment, a grid with variable cell sizes was designed for the MODFLOW submodel. The purpose of the grid refinement was to obtain a detailed representation of the groundwater system in the vicinity of the two municipal wellfields within the Whitemans Creek subwatershed. To this end, a refined grid resolution of 30x30 m was used in the vicinity of the Bright wellfield, while a refined grid resolution of 15x15 m square cells was used in the vicinity of the Bethel Road wellfield. It should be noted that the level of refinement within these two wellfields is sufficient to ensure that no more than one municipal pumping well occupies a single cell. The model grid is shown in Figure 9.7 and consists of 267 rows and 274 columns for a total of 73,158 grid cells for each of the 12 model layers. The maximum cell size in the model was 240 m on a side, located outside of the refinement zones for the two municipal wellfields.

MODFLOW works in a local, grid coordinate system based on row and column numbers. The VIEWLOG-GIS preprocessor (Kassenaar, 2013) was used to help translate geo-referenced map data into MODFLOW coordinates. The local origin for the model grid is at UTM coordinates 503,565 E and 4,755,390 N. All digital data for the study area were referenced using UTM Zone 17 (NAD83) grid coordinates.

A 12-layer numerical groundwater flow model was created, comprising 15 of the 18 hydrostratigraphic layers presented in the hydrogeological site conceptualization (Section 5.2). Table 9.1 presents the stratigraphic model layers, along with the corresponding layers in the numerical model. The upper ten model layers were used to represent the overburden units, while the bottom two layers were used to represent the weathered bedrock contact aquifer, and the Onondaga Escarpment limestone/dolostone aquifer system.

An important consideration when translating the conceptual model layers to numerical model layers is that MODFLOW requires the continuity of simulated numerical layers; whereas hydrostratigraphic models are often created with layers that can pinch out to zero thickness. The hydrostratigraphy of the study area presented a unique challenge because of the discontinuous nature of some of the hydrostratigraphic units. Example of this are the Wentworth Till (ATA2; Figure 5.10) and the extensive Sand Plain and Outwash deposits (AFA2; Figure 5.11), which contribute significantly to the hydrologic function at the lower end of the subwatershed but are not found in any significant thickness west of Princeton. To meet the layer continuity requirements for the numerical model, a minimum layer thickness of 1 m was applied where physical layers pinched out, and hydraulic properties were “inherited” from the next underlying layer. This process is illustrated in Figure 9.8 for a sample section in the Whitemans Creek subwatershed.

Table 9.1: Hydrostratigraphic model layers and corresponding numerical model layers.

Group	Hydrostrat-agraphic Layer	Conceptual Unit	Main OGS Unit	Hydrogeologic Role	Numerical Model Layer
Overburden	1	Whittlesey Sand Aquifer	AFA0	Aquifer/Aquitard	1
	2	Whittlesey Aquitard	ATA1		
	3	Wentworth Aquitard	ATA2	Aquitard	2
	4	Sand Plain and Outwash Aquifer	AFA2	Aquifer	3
	5	Port Stanley/Tavistock Aquitard	ATB1	Aquitard	4
	6	Waterloo Moraine Aquifer	AFB1	Aquifer	5
	7	Maryhill Till Aquitard	ATB3	Aquitard	6
	8	Post Catfish Aquifer	AFB3	Aquifer	7
	9	Catfish Creek Till Aquitard	ATC1	Aquitard	8
	10	Pre-Catfish Aquifer	AFD1	Aquifer	9
	11	Canning Till Aquitard	ATE1	Aquitard	10
Bedrock	12	Weathered Bedrock Contact Aquifer	-	Aquitard	11
	13	Dundee-Lucas-Amherstburg Aquifer	-	Onondaga Limestone Aquifer	12
	14	Bois Blanc Aquifer	-		
	15	Bass Island Aquifer	-		
	16	Upper Salina Poor Aquifer/Aquitard	-	Base of Model	-
	17	Lower Salina Shale Aquitard	-		

9.4 *Simulated Water Takings*

Water use estimates, discussed in Section 6, were simulated in the model as either groundwater takings or surface water diversions. Unlike PTTWs, which have a mixed groundwater/surface water classification, simulated takings must be categorized as either groundwater or surface water. The classification of groundwater sources was therefore expanded to include any wells, sand points, or dug ponds, while surface water sources were limited to diversions from streams, lakes and rivers. The resulting distributions of groundwater and surface water takings are presented in Figure 9.9, and consist of 458 groundwater sources and 99 surface water diversions.

It should be noted that to cover the calibration period, it was necessary to include permitted takings that are considered to be inactive based on their expiration date in the PTTW database (October, 2015). Permits from the PTTW database were included assuming a cut-off date of January 1, 2009, such that any permit with an expiration date after this cut-off and that was not amended by another permit was simulated in the model.

Agricultural water demands are expected to be highly seasonal and are likely underreported and underrepresented in the WTRS database. The Irrigation Demand Submodel developed for this Tier 3 Assessment (presented in Section 10.3) is intended to improve the representation of these water takings; however, the Irrigation Demand Submodel is an extension to the integrated GSFLOW model only. Representing the agricultural takings using the conventional methods (described below) was considered to be a reasonable approach for the calibration of the MODFLOW submodel.

9.4.1 Groundwater Takings

Groundwater takings were represented in the MODFLOW submodel, and in the integrated GSFLOW model, using the WEL7 module in MODFLOW-NWT. Section 6.2 provides an extensive summary of municipal water takings and the available MOECC PTTW and WTRS datasets. As noted therein, major difficulties arose when attempting to implement water takings in the model using the existing MOECC WTRS database. When it comes to representing groundwater takings, this task was made more challenging because the PTTW database does not contain well locations or construction information. Instead, this is contained in the separate MOECC WWIS database. The PTTW database rarely identifies the specific MOECC WWIS database well ID to which the groundwater takings apply, making it difficult to not only reconcile the permits with their actual locations, but also to identify the aquifer from which the pumping takes place. To address this uncertainty, a rule-based framework was developed for assigning groundwater permits to the layers in the model:

- Groundwater permit sources were categorized as either wells (including sand points) or shallow water table interception features (including dug ponds, ditches and sumps).
- Shallow water table interception features were assumed to intercept the shallowest aquifer unit of significant thickness (taken to be 1 m based on the minimum model layer thickness constraint).
- Wherever possible, permits with MOECC WWIS IDs and/or reliable well details were used to make pumped aquifer assignments. This was the case for municipal supply wells.

The remaining unassigned groundwater permits within the well-type category were assigned to model layers based on the method presented in Section 6.2.7. A total of 458 individual groundwater takings from 351 permits were incorporated into the groundwater submodel. These permits include 127 wells and 331 shallow water table interception features. Figure 6.14 shows the location of well-sourced permits interpreted to be from overburden and bedrock units, along with the shallow water table interception features. Across the model, the total simulated groundwater takings was 53,154 m³/d.

9.4.2 Livestock Watering Takings

From the analysis of MPAC datasets and water use statistics from OMAFRA (2007) and AAFC (2009), an updated estimate of livestock water takings within the Whitemans Creek subwatershed was completed for this study (described in Section 6.5). These water takings do not require a permit and are therefore not represented in the MOECC PTTW and WTRS databases. Livestock water takings were estimated and assigned on a parcel-by-parcel basis to land known to contain specific types of livestock. The land parcels with known livestock operations are shown in Figure 6.25, and estimated daily livestock water takings for these farms are shown in Figure 6.26. Total livestock water requirements were estimated to be 4,870 and 1,470 m³/d for the model area and the Whitemans Creek subwatershed, respectively.

To include livestock water takings in the model, a virtual water source was assigned to each of the identified livestock parcels. It was assumed that all livestock watering was supplied by a groundwater source, because best management practices discourage direct access watering approaches (AAFC, 2001). To assign the livestock wells to their appropriate groundwater source aquifer, a similar approach to linking takings to existing well records in the MOECC WWIS database was undertaken (as described in Section 6.2.7). Within the Norfolk Sand Plains area, it was assumed that the livestock watering source would be a shallow water table interception feature such as a dug pond or sand point. A total of 988 livestock watering sources were simulated as groundwater takings in the model. Figure 9.10 presents the locations of the simulated livestock water takings along with their estimated withdrawal rates.

9.4.3 Surface Water Diversions

A total of 99 permitted surface water takings were identified within the study area and simulated as diversions using the SFR2 module in MODFLOW-NWT. The locations of these permits are shown in Figure 9.9. The surface water diversions were incorporated into the model based on spatial proximity of the source in the PTTW database to a simulated stream reach. Water diversion rates where based on the average reported rates from the available WTRS records (2009 to 2014). In total, the average annual reported surface water diversion rate for the model area was 2,951 m³/d.

9.5 Model Parameterization

Reported estimates of the hydraulic properties of the geologic units represented in the model were compiled as part of the initial review process. Sources of hydraulic conductivity values included estimates from aquifer testing as well as calibration values from previous modelling studies in the area, listed below:

Table 9.2: Reports with estimates of hydraulic conductivity values.

	Report Title
1	Water Supply Master Plan Bright (Charlesworth & Associates, 1992)
2	Village of Bright Evaluation of Water Supply Alternatives (R.J. Burnside & Associates, 2001)
3	Report on the Construction and Testing of Test Well TW 1/05 (Lotowater Geoscience Consultants Ltd., 2005)
4	County of Brant Paris – Bethel Road Construction and Testing of Wells PW2/09 and PW5/07 (International Water Consultants Ltd., 2010)
5	County of Brant Paris – Bethel Road Wells Hydrogeologic Study to Examine Groundwater Sources Potentially Under the Direct Influence of Surface Water (International Water Consultants Ltd., 2011)
6	County of Brant Well Construction and Testing North Bethel Wells PW 1/12, PW 2/12 (International Water Consultants Ltd., 2012b)
7	County of Brant Paris – North Bethel Well Field Construction of PW 4/12 and Well Field Testing (International Water Consultants Ltd., 2014)
8	Bethel Road Groundwater Modelling and Wellhead Protection Area Delineation, Brant County (Waterloo Numerical Modelling Corp., 2014)
9	County of Brant Brantford Airport Well Site Well Construction and Testing Well No. 2 (International Water Consultants Ltd., 2015)
10	Vulnerability and Threats Assessment Report Brant County (Golder Associated Ltd., 2010)
11	Category 1 License Application Proposed Olszowka Pit County Brant, Ontario (Golder Associates Ltd., 2012)
12	Brant Business Park, Rest Acres Road County of Brant, Ontario: Scoped Hydrogeology Study Report (LVM, 2011a)
13	Paris Grand Country Club, 150 Paris Links Road Paris, Ontario: Hydrogeology Study (LVM, 2011b)
14	OWRA S34 Permit-To-Take-Water Application and Supporting Hydrologic and Hydrogeologic Study Dufferin Paris Pit County of Brant, Ontario (Conestoga-Rovers & Associates, 2013)
15	Paris Groundwater Modelling and Wellhead Protection Area Delineation, Brant County (Waterloo Numerical Modelling Corp., 2010)
16	Tier Three Water Budget and Local Area Risk Assessment City of Stratford and Village of St. Paul's (Matrix Solutions Inc., 2014a)
17	Tier Three Water Budget and Local Area Risk Assessment Oxford County (Matrix Solutions Inc., 2014b)

Table 9.3 presents a summary of the geometric mean, arithmetic mean, and the minimum and maximum reported hydraulic conductivity values from the sources listed above. The natural range in hydraulic conductivity values for many of the materials vary over several orders of magnitude. The variability may be attributed to natural heterogeneity in addition to the different collection methods (e.g., aquifer testing versus calibrated model parameters). The values presented in Table 9.3 were used to establish initial estimates for hydraulic conductivity values assigned to the groundwater model layers. The final values used in simulations were refined through the process of model calibration. A total of 104 data points were compiled as part of this work.

Table 9.3: Summary of local hydraulic conductivity values from previous studies.

Hydrostratigraphic Unit	Hydraulic Conductivity, K_H (m/s)				Number of Data Points	Source*
	Geometric Mean	Arithmetic Mean	Min.	Max.		
Wentworth Till Aquitard	4.00×10^{-7}	1.04×10^{-6}	8.00×10^{-8}	2.00×10^{-6}	2	12,13
Sand Plain/Outwash Aquifer	1.18×10^{-4}	4.51×10^{-4}	9.00×10^{-7}	3.14×10^{-3}	29	3,8,9,10,11,12,13,14,15
Port Stanley/Tavistock Aquitard	2.04×10^{-6}	1.20×10^{-4}	1.00×10^{-8}	9.20×10^{-4}	8	8,10,13,16,17
Waterloo Moraine Aquifer	1.08×10^{-4}	3.56×10^{-4}	1.20×10^{-9}	1.00×10^{-3}	18	1,2,3,4,6,7,8,13,16,17
Mary Hill Till Aquitard	7.59×10^{-7}	3.00×10^{-4}	5.50×10^{-9}	1.10×10^{-3}	6	8,16,17
Post Catfish Aquifer	1.24×10^{-5}	2.94×10^{-4}	1.70×10^{-8}	1.10×10^{-3}	4	1,8,17
Catfish Creek Till Aquitard	1.10×10^{-7}	1.00×10^{-4}	1.40×10^{-8}	7.00×10^{-4}	7	8,16,17
Pre-Catfish Aquifer	5.18×10^{-6}	1.13×10^{-4}	1.60×10^{-8}	3.00×10^{-4}	4	1,16,17
Canning Till Aquitard	1.39×10^{-7}	1.88×10^{-5}	1.10×10^{-8}	7.50×10^{-5}	4	16,17
Weathered Bedrock	1.69×10^{-4}	2.79×10^{-4}	5.70×10^{-5}	5.00×10^{-4}	2	17
Dundee Formation	5.00×10^{-5}	2.53×10^{-4}	5.00×10^{-6}	5.00×10^{-4}	2	17
Lucas Formation	2.57×10^{-5}	4.33×10^{-4}	5.00×10^{-6}	8.50×10^{-5}	3	16,17
Amherstburg Formation	4.60×10^{-5}	1.48×10^{-4}	5.00×10^{-6}	3.90×10^{-4}	3	16,17
Bois Blanc Formation	1.05×10^{-5}	1.31×10^{-4}	1.00×10^{-6}	3.90×10^{-4}	3	16,17
Bass Island Formation	1.26×10^{-5}	6.67×10^{-4}	1.00×10^{-6}	2.00×10^{-3}	3	16,17
Upper Salina Formation	1.98×10^{-5}	1.34×10^{-4}	2.00×10^{-6}	3.90×10^{-4}	3	8,16,17
Lower Salina Formation	1.00×10^{-7}	5.05×10^{-7}	1.00×10^{-8}	1.00×10^{-6}	2	8,17
Guelph Formation	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1	8

*Number refers to source listed in Table 9.2

The majority of data points documented in Table 9.3 are from overburden aquifer units (e.g., Sand Plain/Outwash Aquifer and the Waterloo Moraine Aquifer). This reflects the large number of aquifer tests pertaining to the Bright and Bethel wellfields along with several shallow hydrogeological investigations associated with land development and aggregate extraction projects. Fewer data points were available for the aquitard units; however, these values generally fall within the expected range, albeit on the high side, for clay- and silt-dominated glacial till, as reported by (from Freeze and Cherry, 1979), reproduced in Table 9.4 for materials similar to those that make up the units within the study area. No data were found to explicitly represent the Whittlesey Sand Aquifer or Whittlesey Aquitard as their extent within the study area is limited; however, initial estimates of hydraulic conductivity were assigned based on observed composition and published values.

Table 9.4: Representative ranges of hydraulic conductivity.

Material	Hydraulic Conductivity (m/s)
Gravel	$1x10^{-3}$ to $1x10^{-0}$
Clean Sand	$1x10^{-6}$ to $1x10^{-2}$
Silty Sand	$1x10^{-7}$ to $1x10^{-3}$
Silt	$1x10^{-9}$ to $1x10^{-5}$
Glacial Till	$1x10^{-12}$ to $1x10^{-6}$
Unweathered Clay	$1x10^{-12}$ to $1x10^{-9}$
Limestone and Dolomite	$1x10^{-9}$ to $1x10^{-6}$
Karst Limestone	$1x10^{-6}$ to $1x10^{-2}$

(Adapted from Freeze and Cherry, 1979)

Bedrock values summarized in Table 9.3 were obtained from previous modelling studies completed in and around the study area. As discussed above, the weathered bedrock/overburden interface represents an important regional aquifer system within the study area, which is supported by the relatively high hydraulic conductivity of this unit. The limestone aquifers of the Dundee, Lucas, Amherstburg, Bois Blanc and Bass Island formations also have similarly high hydraulic conductivity values. The hydrostratigraphic model has been simplified to represent the similarity of these formations by combining them into a single unit, termed the Onondaga Escarpment Aquifer. The measured hydraulic conductivity values from the Upper Salina Aquifer are likely representative of localized extensions of the weathered bedrock surface. The base of the model is bound by the low hydraulic conductivity of the Lower Salina Formation.

The properties of the model layers, such as the top and bottom elevations, hydraulic conductivity, and storage properties, were assigned to each model cell. Layer tops and bottoms were assigned based on the geometry of the hydrostratigraphic model developed for this study. Initial estimates for hydraulic conductivity were made based on previous hydrogeologic investigations (described above). For the bedrock units, an equivalent porous medium (EPM) was assumed for the subwatershed-scale model even though some units may have properties that locally depend on fracture occurrence, aperture, orientation, and connectivity.

By applying the principle of parsimony, spatial variation of hydraulic properties for the remaining layers was represented in a manner that was simple yet did not compromise the reliability of the model. Uniform properties were initially assigned to each of the hydrostratigraphic unit materials identified during the model conceptualization. Maps showing the spatial distribution of the calibrated hydraulic conductivity values for model layers 1 through 12 are presented in Figure 9.11 through Figure 9.22. Table 9.6 lists the calibrated properties for each of the hydrostratigraphic units. The properties listed represent final calibration values for the integrated model.

The “inheritance from below” approach used in this study allowed for multiple hydrostratigraphic unit materials to occupy different areas of the same model layer. For example, the Whittlesey Sand Aquifer and Whittlesey Aquitard are not present across the majority of the northwestern portion of the model area, so hydraulic conductivity values for layer 1 were inherited from the units in the underlying model layers (shown in Figure 9.8).

Storage parameters (specific storage and specific yield) for the hydrostratigraphic units represented in the model are also presented in Table 9.6. Storage values were calibrated through comparison of transient model outputs with continuous groundwater level data. Specific yield values for the bedrock units were found to be quite low (on the order of 10^{-6} m^{-1}), due to the assumption that groundwater flow in these units is dominated by secondary permeability associated with karst and fractures that readily drain. Specific yield values for the bedrock units were found to be quite low (on the order of 10^{-2} m^{-1}), due to the assumption that groundwater flow in these units is dominated by secondary permeability associated with karst and fractures that readily drain. Specific storage values are also low (on the order of 10^{-6} m^{-1}), due to the incompressibility of the rock matrix.

Table 9.5: Calibrated aquifer and aquitard properties for the hydrostratigraphic units.

Hydrostratigraphic Unit	Hydraulic Conductivity (m/s)	Anisotropy (K_H/K_V)	Specific Storage (m^{-1})	Specific Yield (-)
Whittlesey Sand Aquifer	1.9×10^{-4}	7:1	0.00002	0.1
Whittlesey Aquitard	1.6×10^{-9}	9:1	0.0001	0.2
Wentworth Aquitard	8.5×10^{-7}	8:1	0.00004	0.2
Sand Plain and Outwash Aquifer	2.3×10^{-4}	8:1	0.0001	0.2
Tavistock Fine Grained Aquitard	6.3×10^{-9}	5:1	0.00002	0.05
Tavistock Coarse Grained Aquitard	3.6×10^{-8}	4:1	0.00002	0.05
Port Stanley Fine Grained Aquitard	2.7×10^{-7}	7:1	0.00002	0.05
Port Stanley Coarse Grained Aquitard	2.7×10^{-7}	7:1	0.00002	0.05
Waterloo Moraine Aquifer	8.0×10^{-5}	7:1	0.00002	0.1
Maryhill Till Aquitard	1.6×10^{-7}	9:1	0.00002	0.05
Post-Catfish Aquifer	1.8×10^{-5}	7:1	0.00001	0.1
Catfish Creek Till Aquitard	4.4×10^{-8}	10:1	0.000001	0.03
Pre-Catfish Aquifer	1.7×10^{-5}	1:1	0.00001	0.1
Canning Till Aquitard	1.9×10^{-9}	1:1	0.00002	0.05
Weathered Bedrock	2.2×10^{-4}	5:1	0.000001	0.02
Onondaga Escarpment Aquifer	1.2×10^{-5}	5:1	0.000001	0.02
Upper Salina Poor Aquifer/Aquitard	6.7×10^{-7}	10:1	0.000001	0.01

9.6 *MODFLOW Submodel Steady-State Calibration Results*

Steady-state calibration of the groundwater submodel was conducted by adjusting the hydraulic properties assigned to the modelled aquifers and aquitards until a good match was achieved between the simulated and observed water levels. Leading up to the calibration of the MODFLOW submodel, static water level data were filtered to remove wells with obvious errors, such as water levels below the bottom of the monitoring interval, or wells with incorrect spatial coordinates. Wells located outside of the model area were also removed, as were wells with screens below the active model layers. The remaining 6,030 observed static water levels made-up the final calibration dataset, and were assigned to the model aquifers and aquitards based on their screened/open hole intervals.

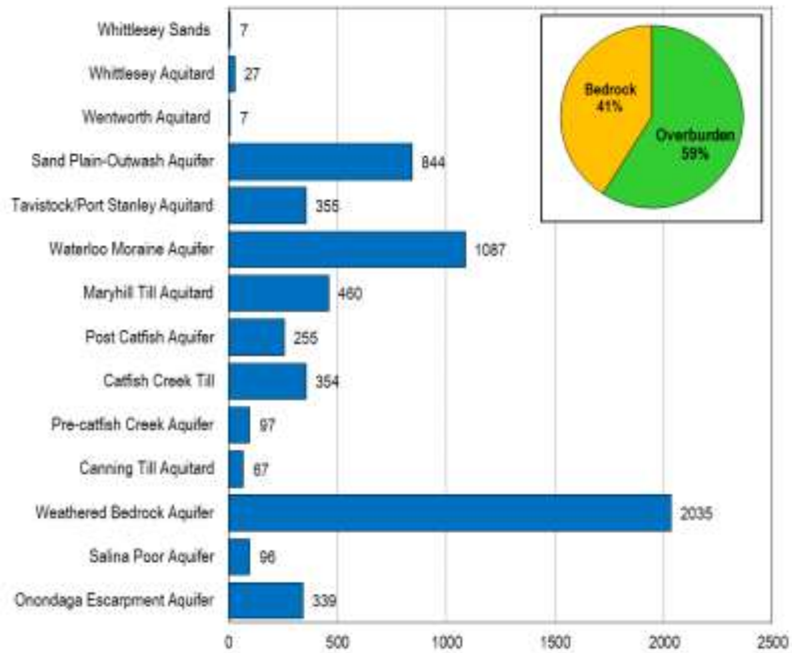


Figure 9.2: Distribution of static groundwater level calibration points by hydrostratigraphic unit.

A scatterplot comparing the static water levels (obtained from the MOECC WWIS database) to the simulated steady-state heads is shown in Figure 9.3a. Ideally, all data points should fall on the 1:1 line shown on the plot or within the ±10 m error interval, defined by the dashed red lines. Figure 9.3b shows that the majority of the residuals vary randomly around the value of zero, though some bias can be seen along the lower and upper extremes. The distribution of the residuals is presented in Figure 9.3c. A normal probability graph of the residuals (Figure 9.3d) suggests that the residuals are indeed normally distributed, because the points generally fall along a straight line. Figure 9.23 shows the location of the steady-state calibration targets for the MODFLOW submodel, along with the calibration residuals (where blue indicates simulated heads are low relative to the observed values).

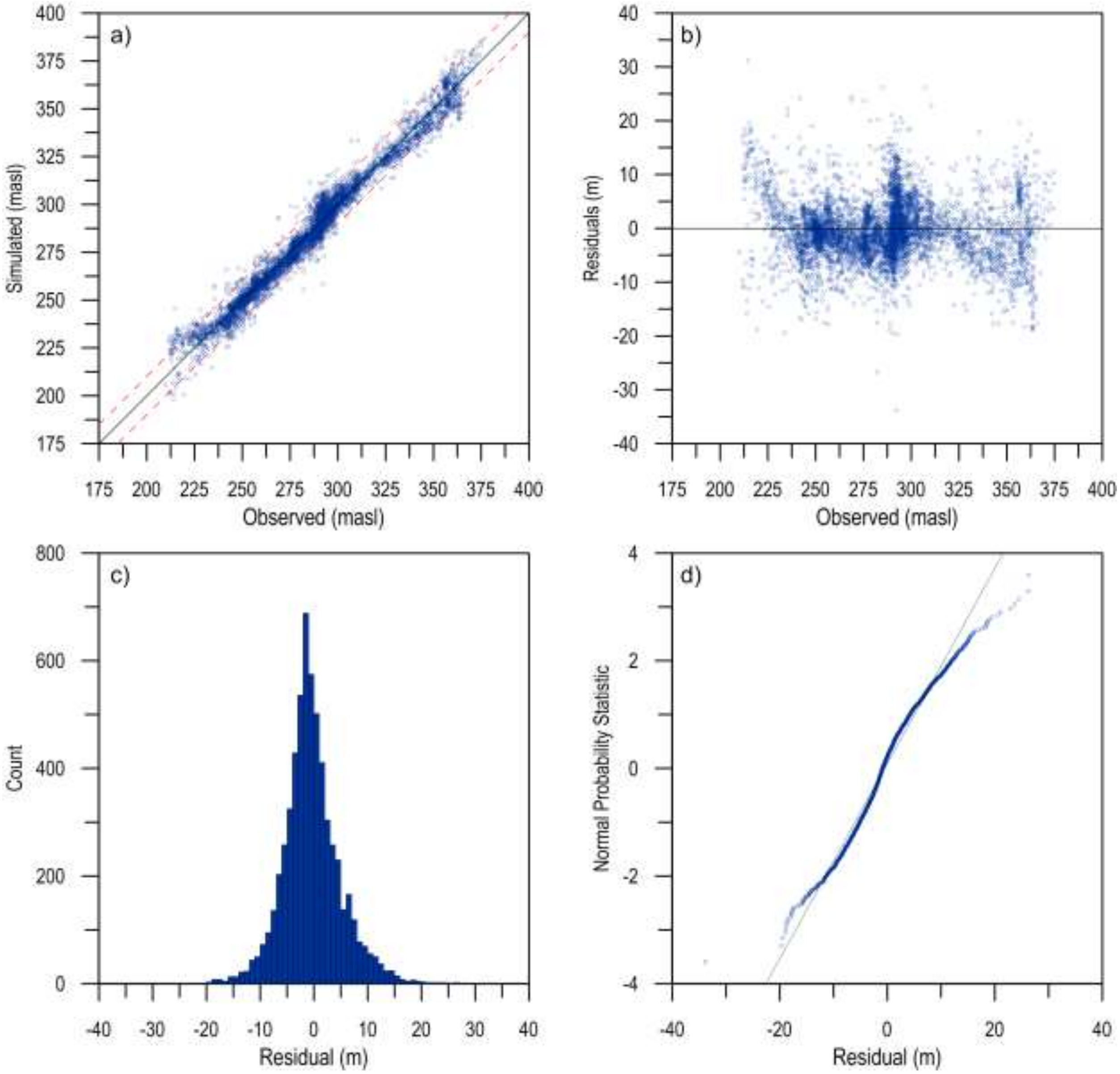


Figure 9.3: Graphical summary of MODFLOW submodel calibration residuals.

Presented as (a) scatterplot of observed versus simulated water levels for groundwater submodel; (b) residuals versus observed data; (c) histogram of calibration residuals; and (d) normal probability graph of calibration residuals.

Three statistics were used to assess the quality of the model calibration: the mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE). These are given by Anderson and Woessner (1992) as:

$$\text{Mean Error} = \frac{1}{n}\sum_{1}^{n}(h_O - h_S)_i \qquad \text{Equation 6}$$

$$\text{Mean Absolute Error} = \frac{1}{n}\sum_{1}^{n}\left|(h_O - h_S)_i\right| \qquad \text{Equation 7}$$

$$\text{Root Mean Squared Error} = \sqrt{\frac{1}{n}\sum_{1}^{n}(h_O - h_S)_i^2} \qquad \text{Equation 8}$$

where:

h_o = observed head;
h_s = simulated head; and
n = number of observations.

Calibration statistics for the 6,030 observed water levels are shown in Table 9.6. Calibration statistics for subsets of the observed water level dataset are also provided in Table 9.6 for each of the major regional aquifers. The negative value for Mean Error (ME) indicates that model predicted values are generally higher than the observed values by 0.41 m. The Mean Absolute Error and the Root Mean Squared Error (RMSE) provide a good estimate of the average magnitude of the difference and variance between observed and simulated values. The groundwater submodel had a MAE of 4.01 m and a RMSE of 5.41 m.

Table 9.6: Calibration statistics for the groundwater submodel.

Unit	Number of Wells (n)	ME (m)	MAE (m)	RMSE (m)	Range in Observations (m)	RMSE as Percent of Range (%)
Whittlesey Sands	7	-1.51	1.51	1.59	1.5	103.1%
Sand Plain-Outwash Aquifer	844	1.38	3.18	4.98	47.7	10.5%
Waterloo Moraine Aquifer	1,087	0.61	3.35	4.41	33.4	13.2%
Post Catfish Aquifer	255	-1.08	3.42	4.78	41.5	11.5%
Pre-catfish Creek Aquifer	97	1.58	4.59	5.62	21.6	26.1%
Weathered Bedrock	2,035	-1.41	4.64	5.87	45.7	12.8%
Onondaga Escarpment Aquifer	339	-2.22	4.22	6.33	54.0	11.7%
Salina Poor Aquifer	96	-2.21	4.78	5.91	26.1	22.6%
Overall	**6,030**	**-0.41**	**4.01**	**5.41**	**186.6**	**2.9%**

Note: Calibration to monitors screened in aquitards (total of 1,270) not shown individually in above calibration table; however, these points have been included in the ***Overall*** calibration statistics.

Generally accepted guidelines indicate that the model is well calibrated when the RMSE is less than 10% of the range of water levels (Spitz and Moreno, 1996). The model RMSE expressed as a percentage of the range in water level observation data was 2.9%, which is less than this calibration guideline. It should also be noted that the MOECC WWIS observations have data quality concerns (discussed in Section 5.3.3) that add a degree of intrinsic error to the data; a perfect calibration to these data is therefore unattainable. The MODFLOW mass balance error for the steady-state model was 0.15%.

The distribution of model residuals shows a tendency for model under-predictions of more than 10 m near the southern portion of the eastern model boundary. In this case, the model error is attributed to the selection of boundary conditions that correspond to the bottom of the incised Grand River and Nith River valleys, which, when combined with the coarser grid resolution in these areas, causes surrounding model heads to be depressed. This could be resolved by incorporating a finer grid resolution in these areas to provide a buffer between the constant head cells in the river valleys and the upland model cells. These boundary artifacts do not extent into the Whitemans Creek subwatershed and are not expected to have any affect upon the results of the Tier 3 WHPA delineation exercise or risk assessment. Therefore increasing the model resolution was not considered necessary for this study.

A second area of high model residuals is noted in the vicinity of Tavistock, near the northwestern boundary of the model, where there is a tendency for the model to overpredict water levels compared to observation data. These residuals are associated with bedrock observation points, and suggest that underdrainage across the model boundary near Tavistock is underestimated by the model in this area. The higher residuals are almost entirely limited to the bedrock aquifers, and generally do not extend into the Whitemans Creek subwatershed.

Another possible source of the error in the model residuals is the intrinsic bias in the well record dataset related to the correlation between well construction and climate. During periods of low precipitation, irrigation is often required to supplement crop water needs, putting additional stress on already drought-stricken groundwater and surface water resources. The increased reliance upon groundwater supplies during periods of drought is evidenced by comparing annual precipitation with the number of wells completed (Figure 9.24a). During years of low precipitation, there was typically an increase in the number of wells installed. The relationship between the two datasets is further presented in Figure 9.24b, which shows an inverse correlation between annual precipitation and well installations. From these results, one can infer that periods of drought encourage people to seek out new sources of groundwater as their existing wells run dry or water needs (such as for irrigation) increase. Because the calibration of the MODFLOW submodel was undertaken assuming average climate conditions, a degree of over prediction is expected when compared to levels from water well records that have a slight bias towards drought periods. As illustrated in Figure 9.25, mean error (indicated as a solid black line) tends to dip below zero during major drought years, such as the late-1980s, late-1990's, and 2007.

9.6.1 Steady-State MODFLOW Submodel Outputs

Model results from the calibrated MODFLOW submodel are provided here to demonstrate the simulated groundwater levels under steady-state conditions. Figure 9.26 presents the simulated groundwater levels in model layer 5, which is equivalent to the Waterloo Moraine Aquifer, where present. Simulated overburden water levels show a pronounced response to sub-regional topographic features, becoming less pronounced in the deeper overburden (layer 5). Figure 9.27 provides a comparison of the interpolated overburden static water level data to the simulated water levels in layer 5. In general, a good match is achieved across the model, with regional trend of highs in the northwest and lows to the southeast being well represented. The influence of the Easthope Moraine at the top of the Whitemans Creek subwatershed is captured by the groundwater model, producing a local high in the simulated overburden water levels.

Figure 9.28 presents the simulated groundwater levels in model layer 11, which is equivalent to the Weathered Bedrock Aquifer across the model area. Simulated water levels in the bedrock are noticeably smooth, with little to no apparent influence of local topographic features, such as the moraines or incised river valleys. Comparison with interpolated static water levels (presented in Figure 9.29) suggests that while the general regional trend is well captured by the model, the influence of sub-regional physiographic features is less pronounced in the calibrated model. This could suggest there may be better communication in some areas through the Maryhill and Catfish Creek tills, which have been interpreted as competent vertical confining layers for the of the bedrock system across much of the north and northwest portion of the model area. This would seem to be the case in the vicinity of the Easthope Moraine (near the town of New Hamburg) and the Woodstock Moraine (located east of Sweaburg at the southwestern end of the model).

The localized areas where simulated bedrock heads achieved a poorer match to interpolated levels are not reflected in the corresponding overburden contours (Figure 9.27), suggesting the model deviations noted in the bedrock system have not significantly affected the overlying overburden aquifers. Because both the Bethel Road and Bright municipal wellfields are screened within overburden aquifers, and a good match to patterns in the bedrock contours was achieved in the vicinity of these wellfields, the deviations between the contours observed near Tavistock and New Hamburg are unlikely to affect the results of the Tier 3 WHPA-Q delineations or risk assessment.

9.6.1 MODFLOW Submodel Water Balance

Water budget components were determined for the Whitemans Creek subwatershed using the calibrated MODFLOW submodel. Specifically, the water budget components related to the modelled groundwater system were evaluated, and only in steady-state, as the integrated model is the preferred tool for capturing a more complete and dynamic system water balance. Major water budget components for the groundwater system include net recharge, surface leakage (i.e., groundwater discharge to land surface), lateral groundwater flows, groundwater discharge to lakes and streams, and pumping (Table 9.7).

Inflows to the subwatershed area are dominated by recharge, which makes up more than 80% of the water entering the area, followed by lateral groundwater inflows at 17%. The remainder of the inflows (approximately 1%) are composed of streambed and lakebed losses to the groundwater system. Lateral groundwater outflows are slightly higher than lateral inflows, representing 23% of the water leaving the subwatershed. As shown in Figure 9.4, the majority of the lateral inflows and outflows take place within the deeper groundwater system where aquifers are largely confined from the surface features where discharge occurs to streams, lakes and wetlands. Instead, regional flow patterns dominate in defiance of topographic catchment areas and shallow boundary conditions (illustrated by relatively uninterrupted bedrock water level contours in Figure 9.28). Constant head boundary conditions exist only along a small portion of the Whitemans Creek subwatershed, where it meets with the Grand River (shown in Figure 9.5). Outflows via constant head cells are therefore minor.

Table 9.7: Water budget for the Whitemans Creek Subwatershed (groundwater system only), as simulated by the MODFLOW submodel.

Water Budget Component	**Inflows (m^3/d)**	**% of Total Inflows**
Groundwater Recharge	216,080	82%
Lateral GW Inflow	44,300	17%
Constant Head Inflow	0	0%
Stream Leakage In	2,790	1%
Lake Leakage In	180	0%
Total Inflows	**263,350**	**100%**
Water Budget Component	**Outflows (m^3/d)**	**% of Total Outflows**
Surface Leakage	47,850	18%
Lateral GW Outflow	60,090	23%
Constant Head Outflow	1,220	0%
Stream Leakage Out	142,880	54%
Lake Leakage Out	1,480	1%
Well Pumping	9,890	4%
Total Outflows	**263,410**	**100%**

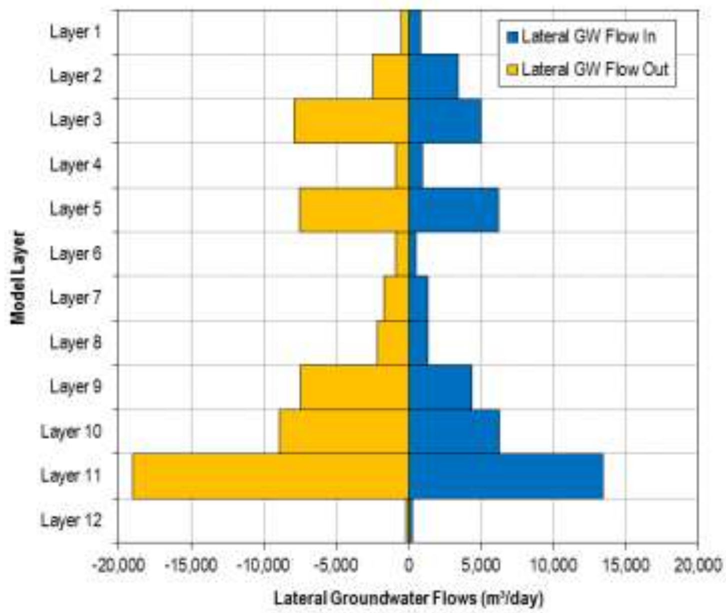


Figure 9.4: Simulated lateral groundwater flows across Whitemans Creek subwatershed according to model layer.

The simulated water budget for the Whitemans Creek study subwatershed shows the system to be generally well-drained by the network of streams and rivers, which account for more than half (54%) of the outflows from the subwatershed. Adding to this is the discharge to lakes and surface leakage component, both of which are routed to the receiving stream network in the model, accounting for a further 1% and 18% of the water budget, respectively. An additional water budget component that must be considered is that of rejected recharge; because the recharge distribution applied to the MODFLOW submodel is based on the calibrated PRMS submodel, it is reasonable to assume that any excess volume of applied recharge represents a valid component of the water balance. The volume of rejected recharge can be calculated as the difference between applied recharge (274,770 m³/d) and the effective groundwater recharge (210,420 m³/d), equivalent to 64,350 m³/d. Based on these results, total flows out of the subwatershed conveyed via the Whitemans Creek stream network are estimated at approximately 248,630 m³/d under average long-term average conditions. This value compares well against median flows (210,816 m³/d) observed at WSC gauge 02GB008 (near Burford). Stream diversions, both known (estimated at 2,870 m³/d) and unknown, would further reduce the model estimate, bringing the simulated and observed streamflows even closer in line with one another.

9.7 *Comparison with the Grand River Tier 2 Model*

A comparison between the three-dimensional model used in the Tier 2 study of the Grand River Basin (AquaResource, 2009a) and the Whitemans Creek Tier 3 Assessment groundwater submodel was conducted as part of the scope of this study. This section focuses on the differences and similarities between the hydrostratigraphic models and the function of the two models with respect to estimating the steady-state water balance for the Whitemans Creek subwatershed.

Figure 9.30 compares the FEFLOW model to the Tier 3 Assessment groundwater submodel in the southwest corner of the Whitemans subwatershed along southwest-northeast Section F. Note that the Tier 2 model does not extend beyond the watershed boundary. The comparison shows that there is a thick Layer 2 (defined as an aquifer/aquitard) covering the entire section in the Tier 2 model. Beneath FEFLOW Layer 2 is an aquifer that is generally thinner but more uniform than the Whitemans Waterloo Moraine aquifer. The Tier 2 Layer 5 aquifer is considerably thicker than the post-Catfish aquifer. Finally, the Bois Blanc unit in the Tier 2 model rises quickly and does not extend as far into the watershed.

Figure 9.31 compares the Tier 2 FEFLOW model to the Tier 3 Assessment groundwater submodel in the vicinity of the Sand Plain and Outwash aquifer along north-south Section G. Note again that the Tier 2 model does not extend beyond the watershed boundary. Comparison of the figures shows that the Tier 2 model contains significant till aquitard materials in the sand plain area, while the Whitemans model shows a significant sand plan aquifer. Figure 9.32 compares the Tier 2 FEFLOW model to the Whitemans Model in a cross section down Kenny Creek to the Grand River outfall (Section K). As above, there is a thick Layer 2 (“aquifer/aquitard”) in the upper reach of the Tier 2 model. The Whitemans model appears to better represent the Bois Blanc and Lower Salina units.

Using the Tier 2 model, a water budget analysis was conducted on the Whitemans Creek subwatershed, which was then compared against the results of the steady-state water budget for this study in Table 9.8. Applied recharge estimates compare well between the two models; the Tier 2 estimate of 277,920 m^3/d is closely matched by the calibrated PRMS recharge estimate of 280,580 m^3/d. Stream leakage in represents a small component of the inflows in both of the models, and the Tier 2 stream leakage out estimate of 233,671 m^3/d is very similar to the net catchment outflow estimates of 250,880 m^3/d, presented in the previous section. No lakes were simulated within the Whitemans Creek subwatershed in the Tier 2 model.

Of particular note is that the Tier 2 model employs constant head type boundary conditions along more than half of the southwestern side of the subwatershed, as Whitemans Creek lies at the very edge of the Grand River catchment model extents. As a result, flows through the constant head cells make up 27% and 34% of the Tier 2 inflow and outflow water balance components, respectively. By comparison, fluxes through the constant head boundaries in the Tier 3 Assessment groundwater submodel are less than 1% of the inflow and outflow budgets. An overall comparison of the net groundwater flow in and out of the models (including flows through constant head boundaries) yield very similar estimates from the Tier 2 model (-15,460 m^3/d) and the Tier 3 Assessment groundwater submodel (-14,570 m^3/d). These results show that at the subwatershed-scale, the water budget results provided by the two models are comparable, though the significant contribution of inflows and outflows from constant head boundary conditions could suggest an over-constrained numerical representation in the Tier 2 model within the Whitemans Creek subwatershed.

Table 9.8: Comparison of simulated water budgets for Whitemans Creek subwatershed using the Tier 3 Assessment groundwater submodel (this study) and the Grand River Tier 2 model.

	Whitemans Tier 3 Model		Grand River Tier 2 Model	
Water Budget Component	**Inflows (m³/d)**	**% of Total Inflows**	**Inflows (m³/d)**	**% of Total Inflows**
Recharge	216,080 (280,580)[3]	82%	277,921	71%
Lateral GW Flow[2]	44,300	17%	7,851	2%
Constant Heads	0	0%	105,600	27%
Stream Leakage	2,790	1%	1,642	0%
Lake Leakage[1]	180	0%	-	-
Total Inflows	**263,350**	**100%**	**393,014**	**100%**
Water Budget Component	**Outflows (m³/d)**	**% of Total Outflows**	**Outflows (m³/d)**	**% of Total Outflows**
Surface Leakage[1]	47,850	18%	-	-
Lateral GW Flow[2]	60,090	23%	-	-
Constant Heads	1,220	0%	128,909	34%
Stream Leakage	142,880 (250,880)[4]	54%	233,671	62%
Lake Leakage[1]	1,480	1%	-	-
Well Diversions	9,890	4%	14,732	4%
Total Outflows	**263,410**	**100%**	**377,312**	**100%**

Notes:

1) Lakes and surface leakage are not represented in the Tier 2 model.
2) Tier 2 value for lateral groundwater flow represents the net lateral flow (i.e., inflow minus outflow). It should be noted that total inflows and outflows have not been adjusted to account for this.
3) The total applied recharge in the Tier 3 Assessment groundwater submodel was 280,580 m³/d, based on the calibrated PRMS submodel; value specified above represents the amount accepted by the modelled groundwater system.
4) Tier 3 estimates of total surface outflow is 250,880 m³/d when rejected recharge is included.

As noted in Section 9.2.3, the Tier 3 Assessment groundwater submodel had head-dependent discharge boundaries assigned across the top surface of the model, allowing for groundwater to discharge from the top of the model as “surface leakage” when the water table rises above ground surface. The surface leakage component represented 18% of the simulated water budget. The Tier 3 representation of surface leakage has two primary advantages over the Tier 2 model: (1) it accounts for losses from the groundwater system to the surface system outside of the explicitly represented streams and lakes; and (2) groundwater discharged as surface leakage is routed (via topographic cascade network) to nearby streams and lakes (Dunnian runoff) where it has the potential to return to the groundwater system. This process is not represented in the Tier 2 model. In the Tier 2 model, groundwater can only discharge to specified river nodes, after which it is removed from the model.”

Overall, the comparison between the Grand River Tier 2 model and the Tier 3 Assessment groundwater submodel with respect to Whitemans Creek subwatershed illustrated the similarities and differences between the two modelling studies. In the case of both the hydrostratigraphic model and the groundwater model construction, the Tier 3 model follows the Source Water Protection framework whereby each successive tier becomes more complex, and represents an increased certainty of the water budget. The Tier 3 hydrostratigraphic model takes advantage of the most recent studies conducted by the OGS and the Counties of Brant and Oxford in the Whitemans Creek study area, reflecting an incremental improvement on the representation used in the Tier 2 model. To better quantify the water budget within the subwatershed, a modelling approach was undertaken that de-emphasised the reliance on constant head boundary conditions close to the area of interest, and better represents the complete hydrologic system through the use of an integrated surface water/groundwater flow model.

9.8 *Figures*

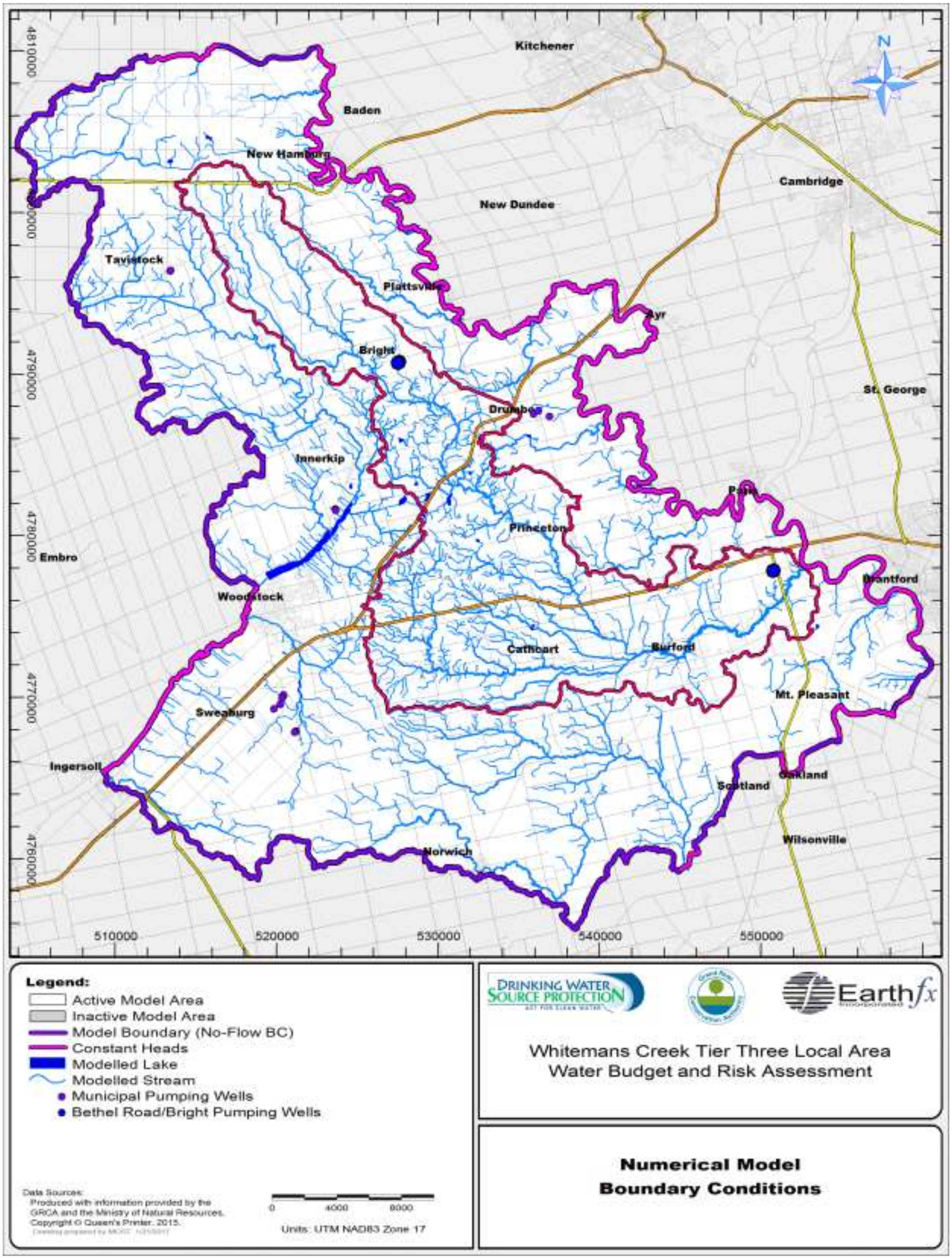


Figure 9.5: Boundary conditions for the numerical groundwater flow submodel.

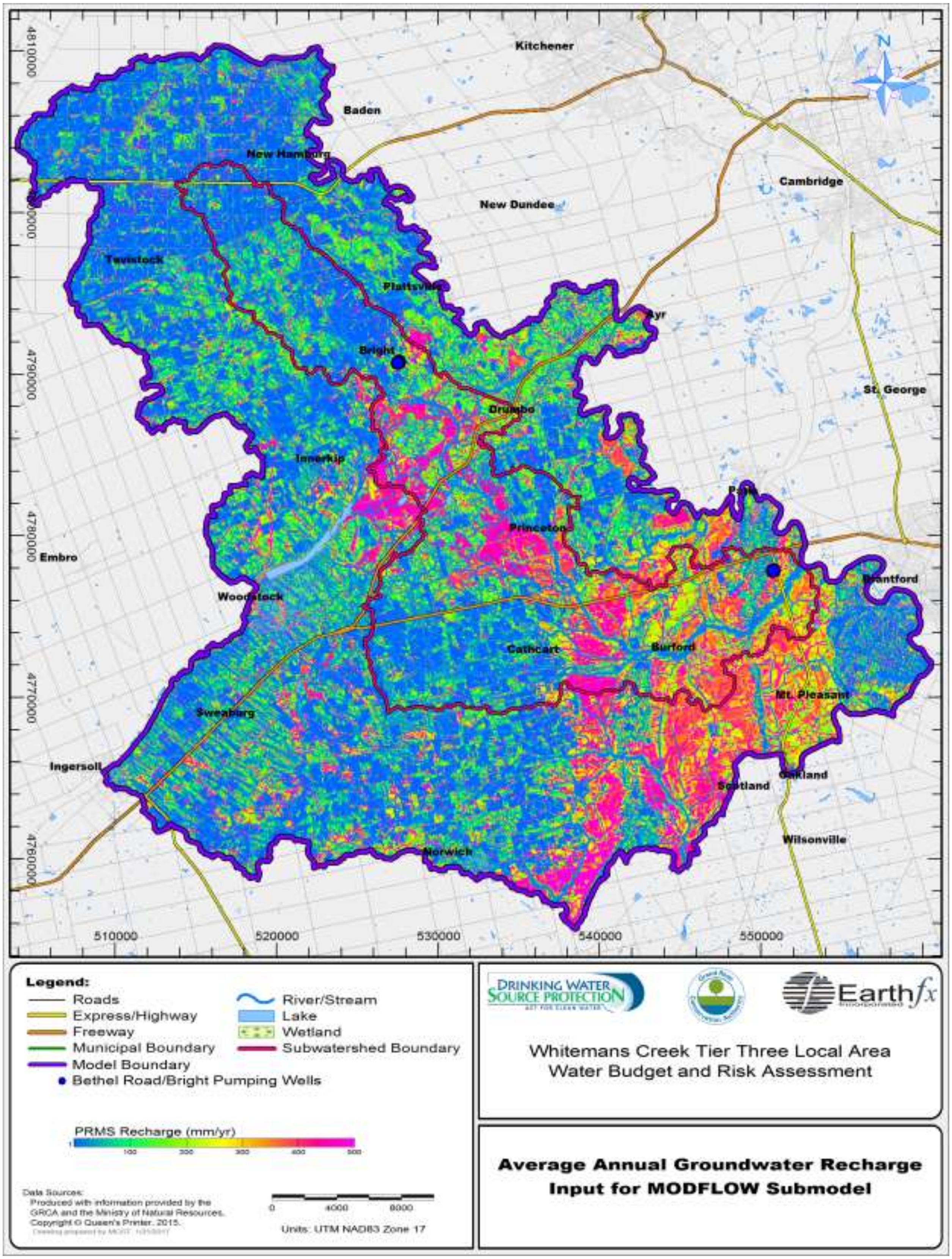


Figure 9.6: Average annual groundwater recharge (mm/yr) applied to the MODFLOW submodel.

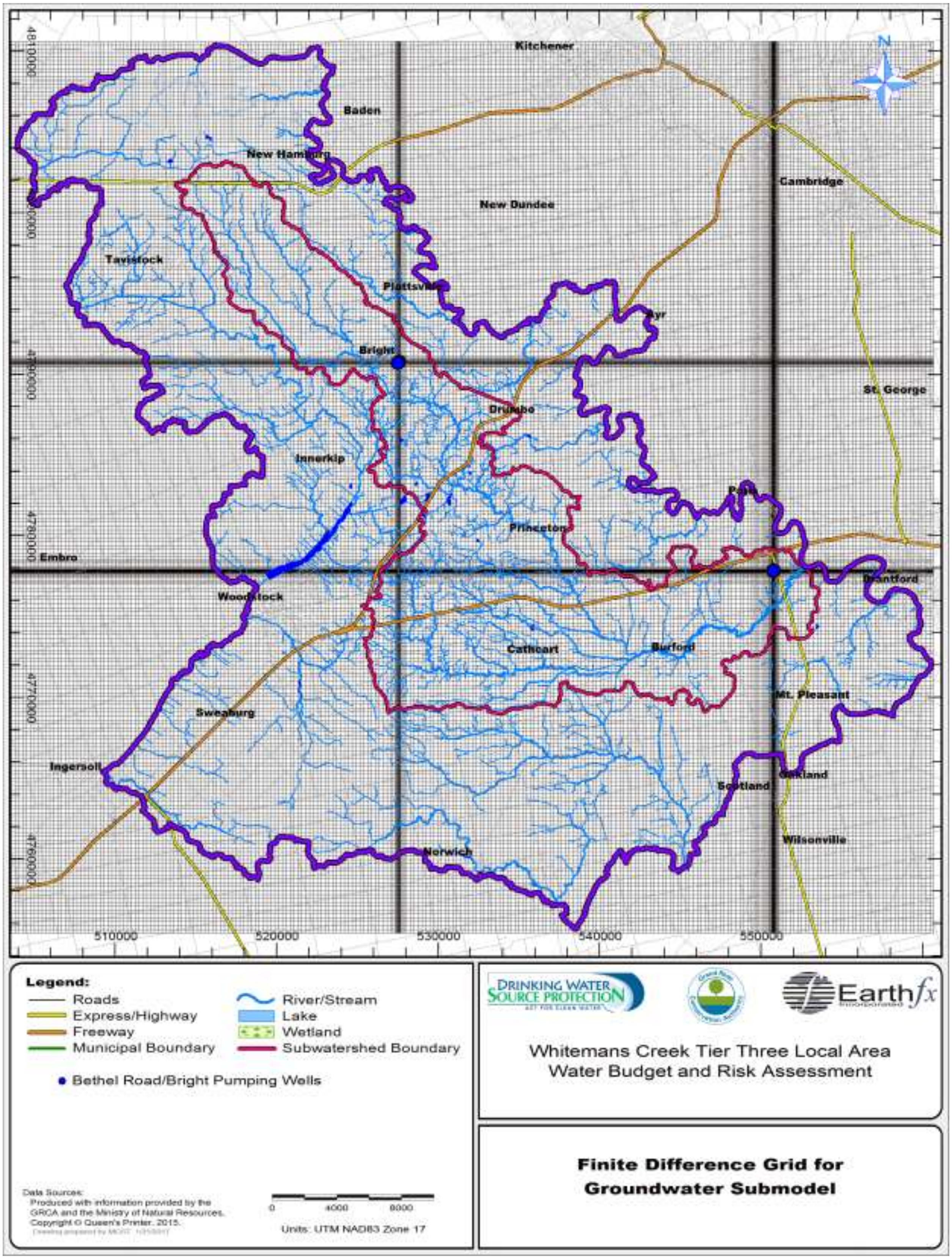


Figure 9.7: Model grid with 240 m cells and refinement in the wellfield areas.

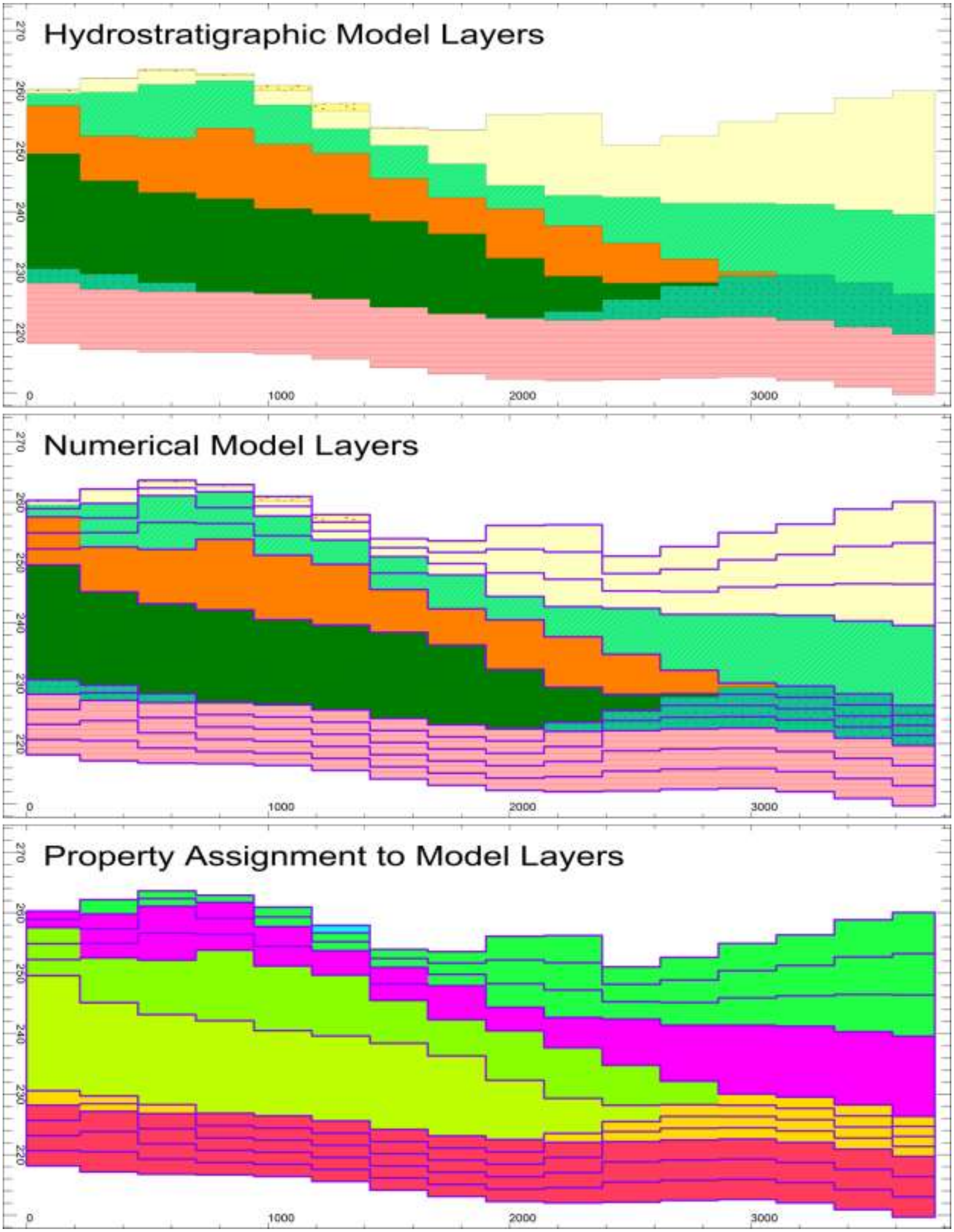


Figure 9.8: Illustration of pushdown approach for MODFLOW model layers.

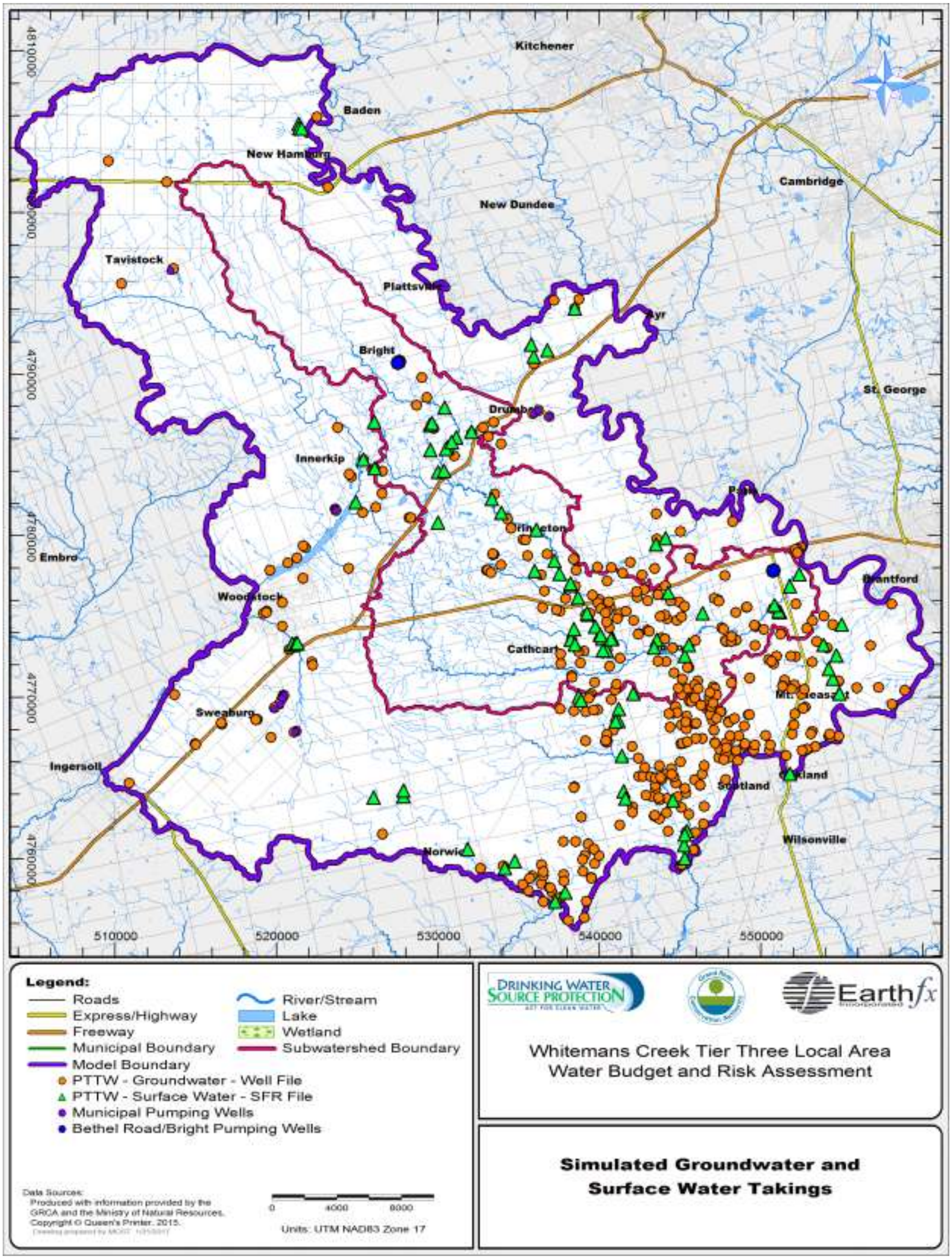


Figure 9.9: Locations of surface water and groundwater PTTWs simulated in the groundwater submodel.

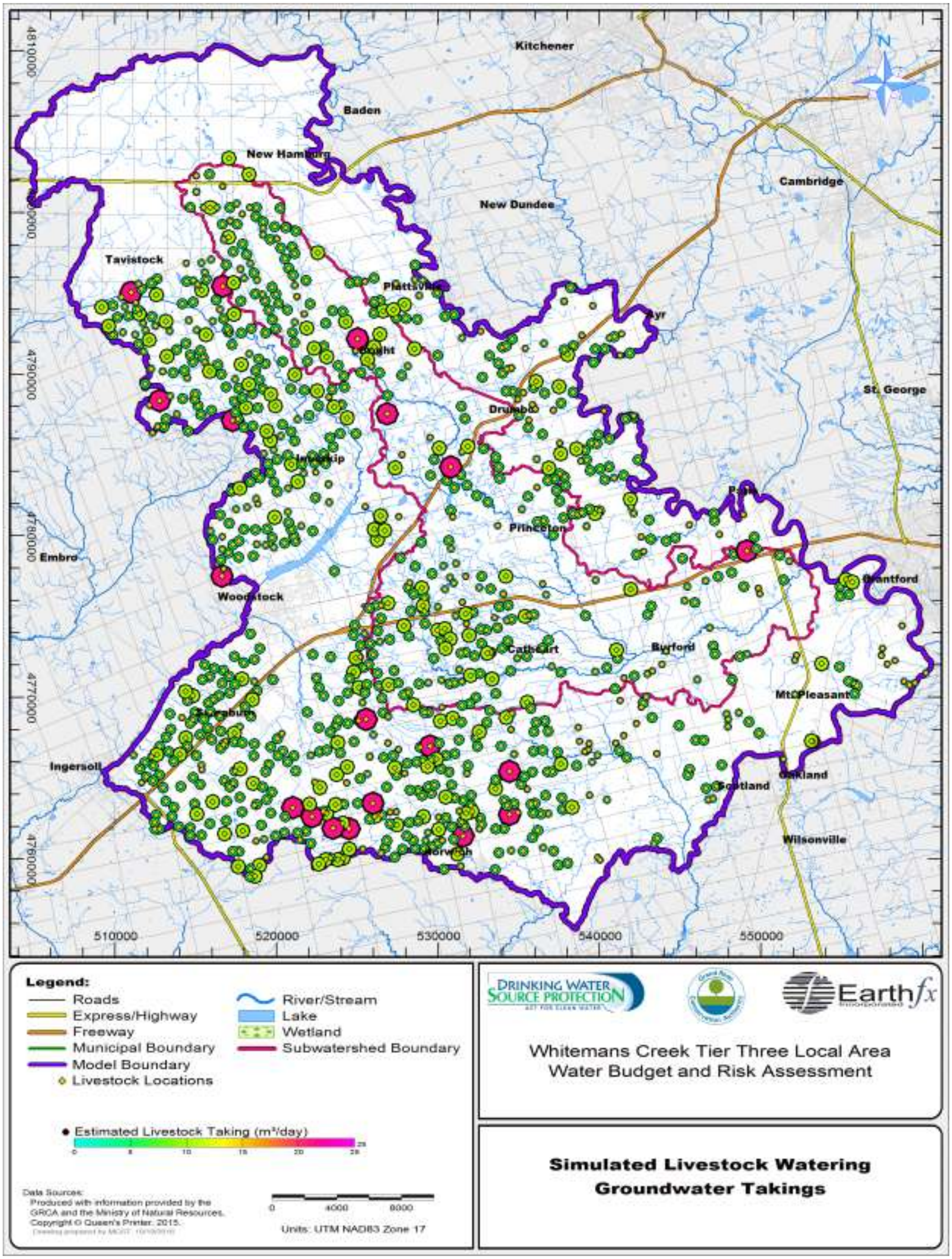


Figure 9.10: Locations of groundwater takings for livestock watering simulated in the groundwater submodel.

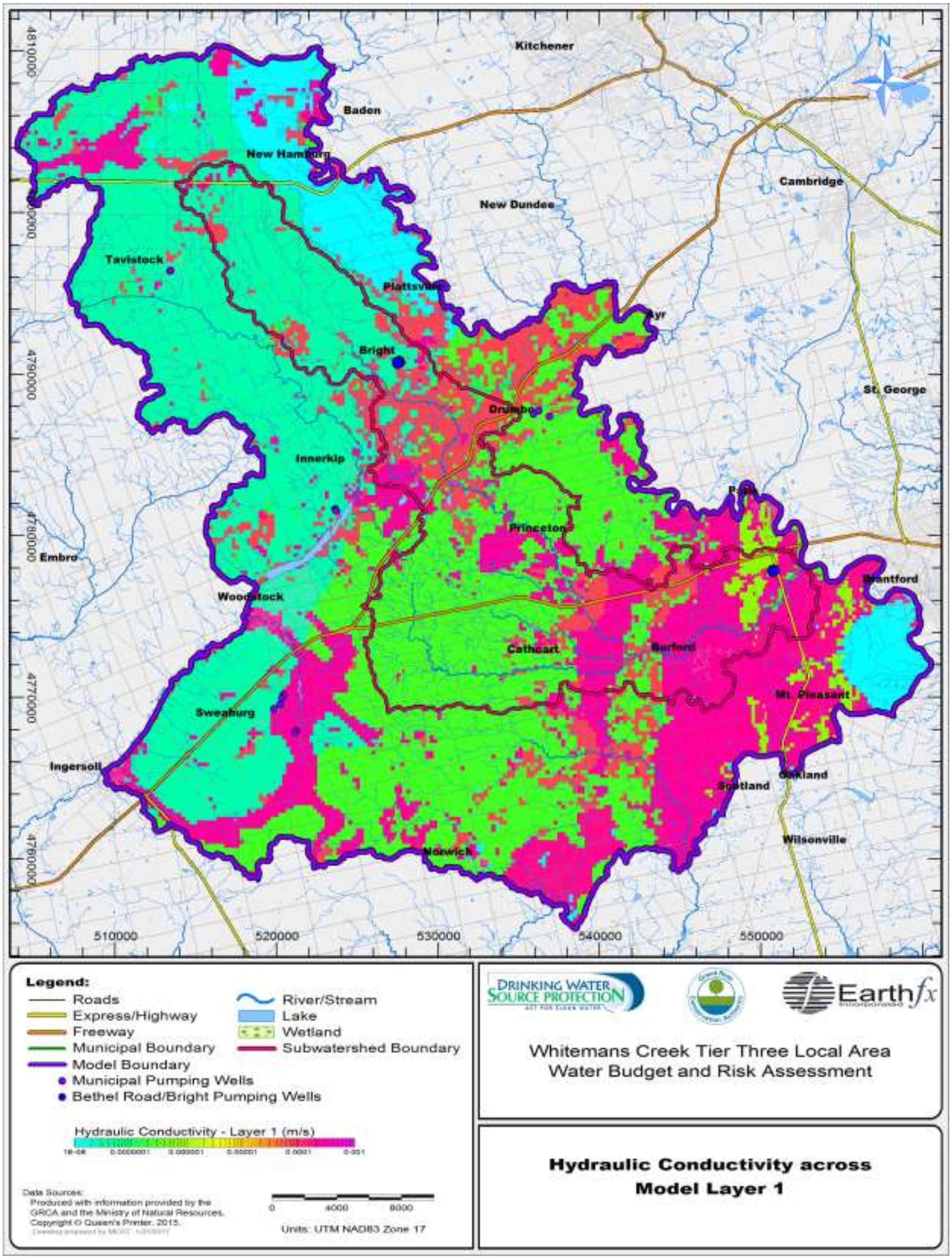


Figure 9.11: Hydraulic conductivity distribution in model layer 1.

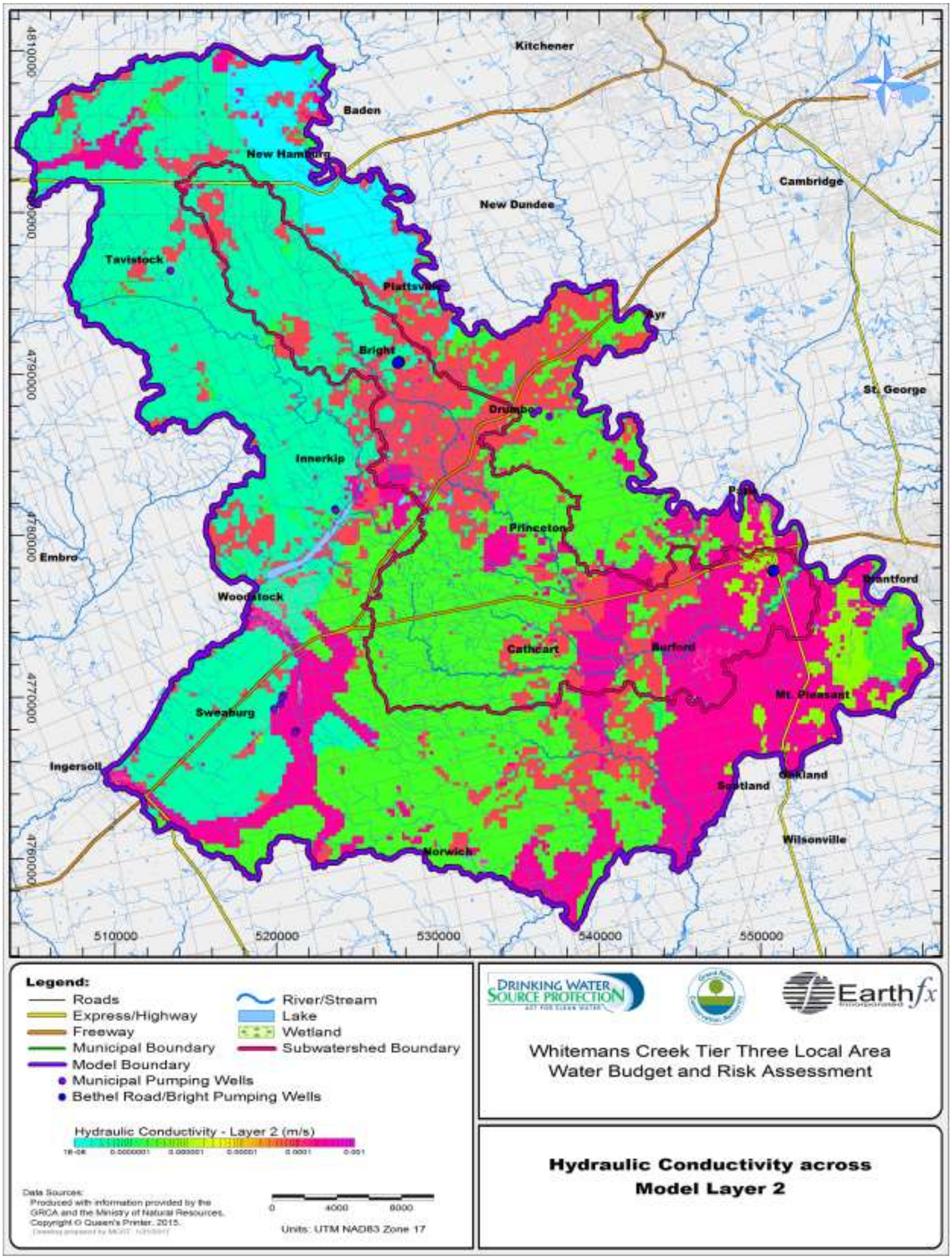


Figure 9.12: Hydraulic conductivity distribution in model layer 2.

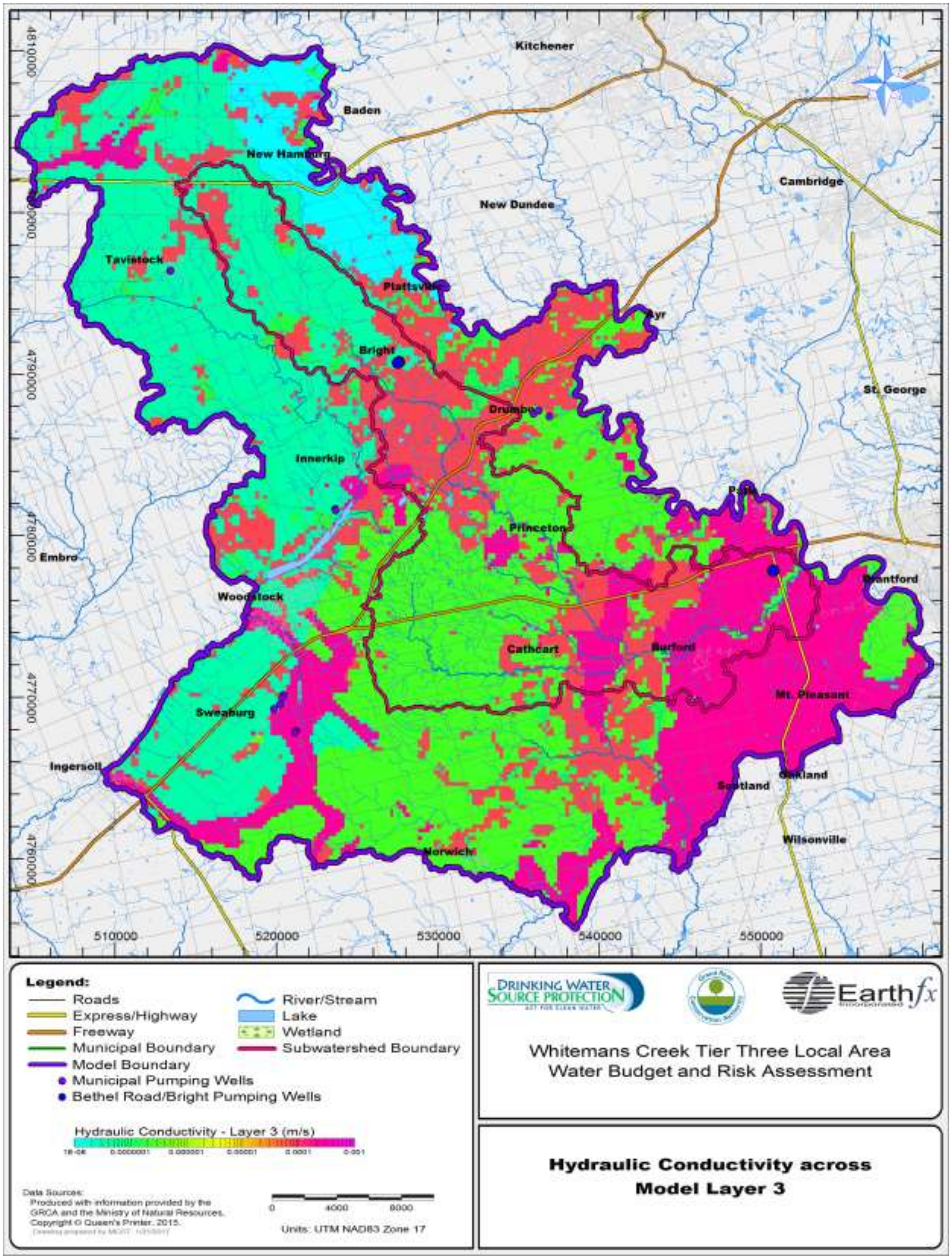


Figure 9.13: Hydraulic conductivity distribution in model layer 3.

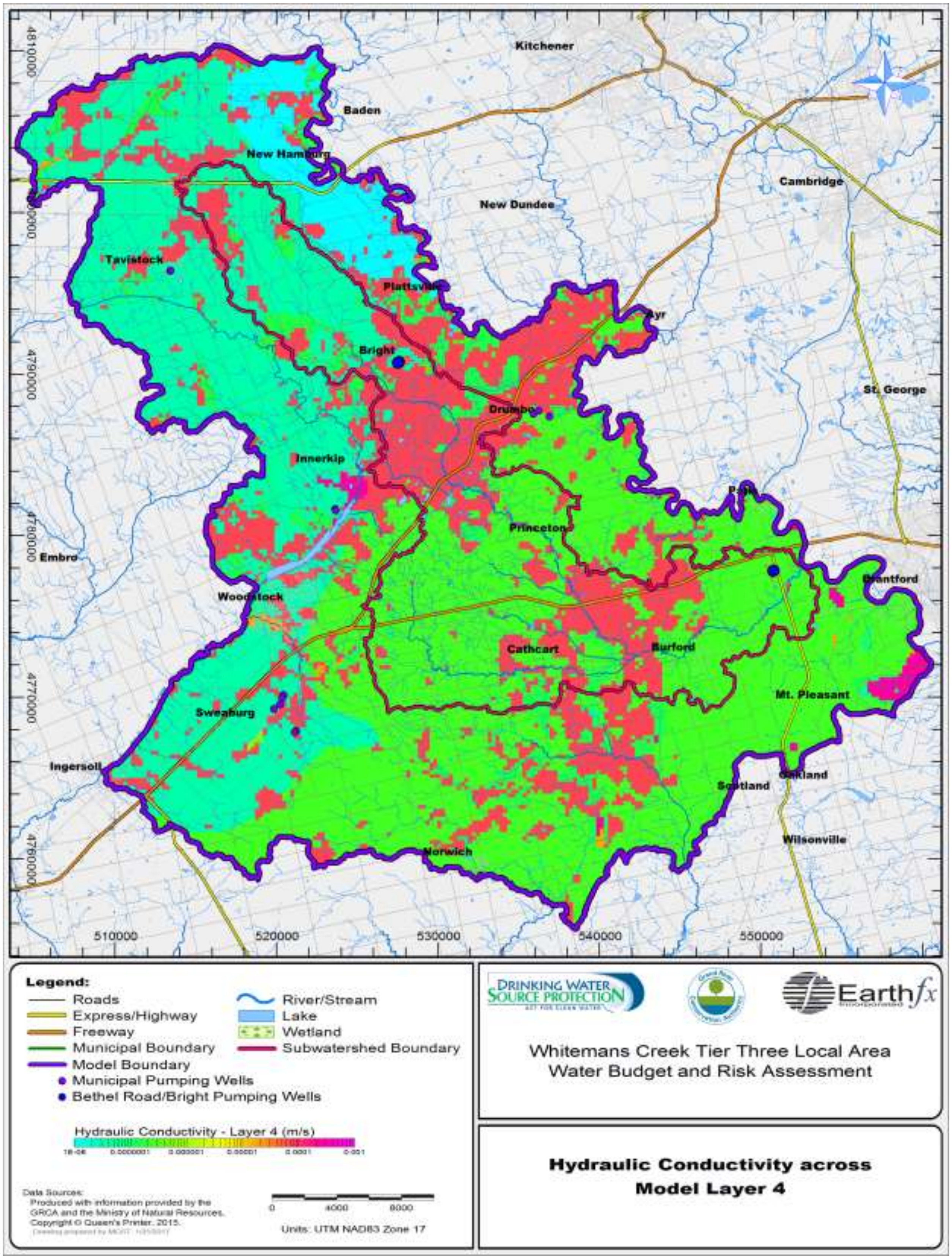


Figure 9.14: Hydraulic conductivity distribution in model layer 4.

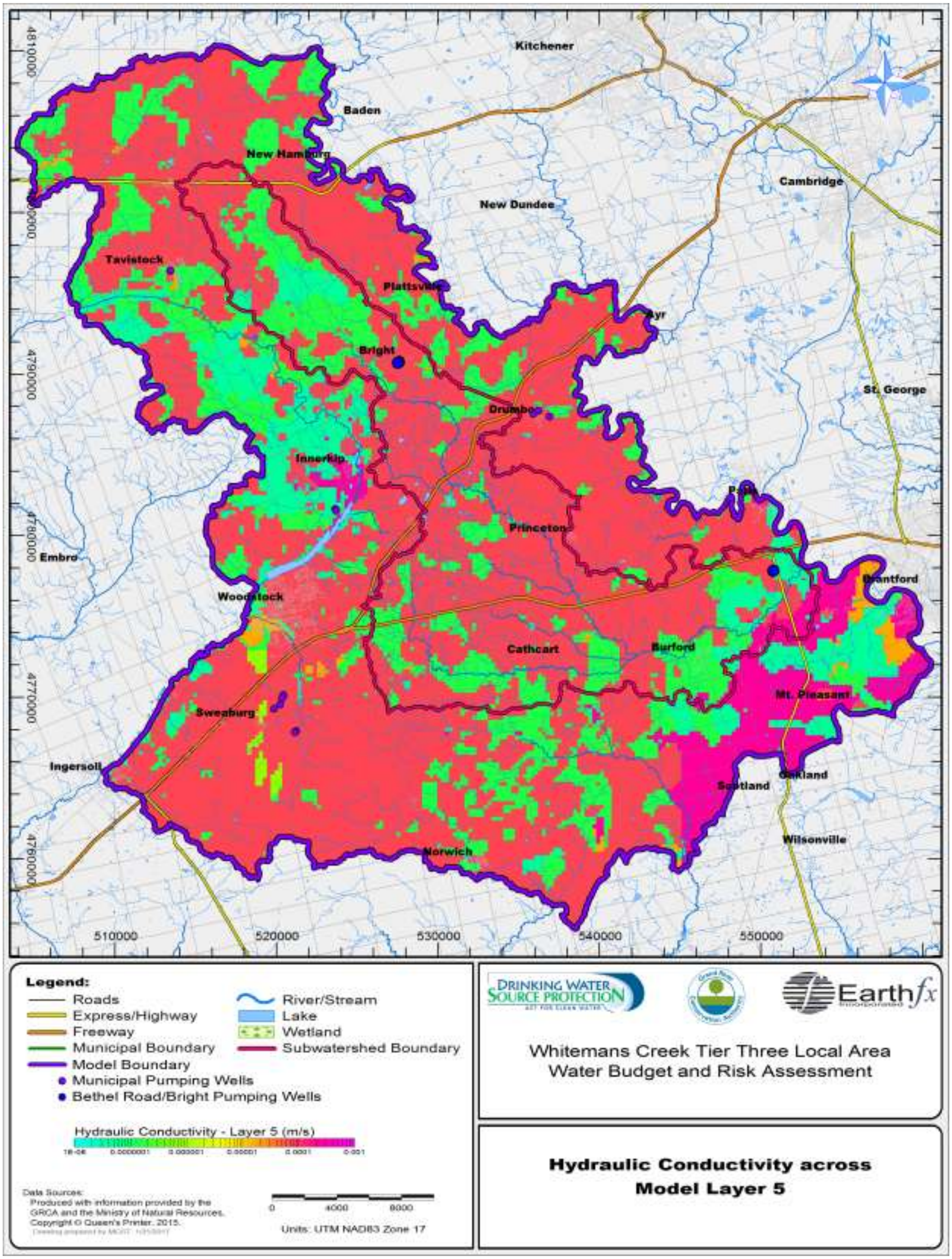


Figure 9.15: Hydraulic conductivity distribution in model layer 5.

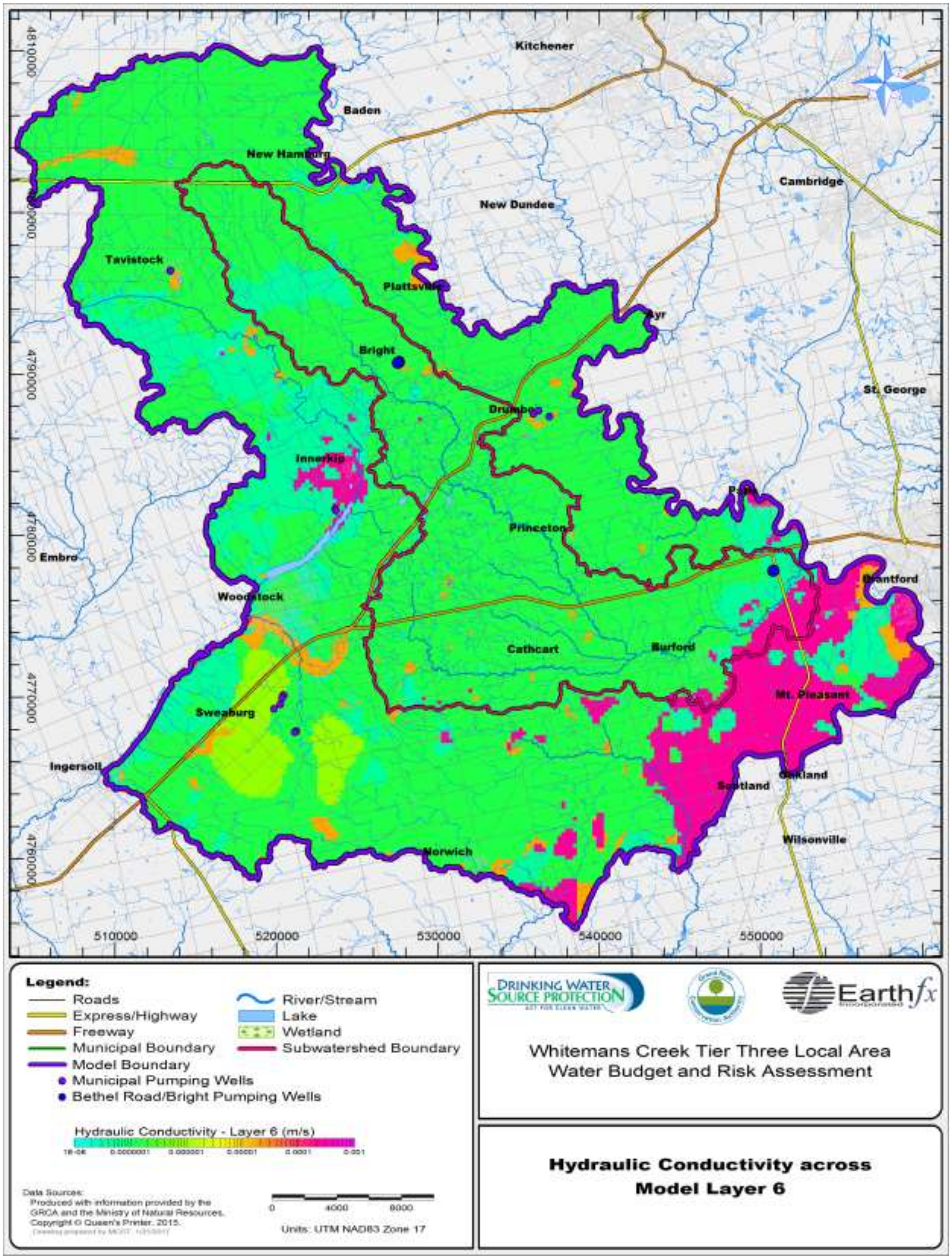


Figure 9.16: Hydraulic conductivity distribution in model layer 6.

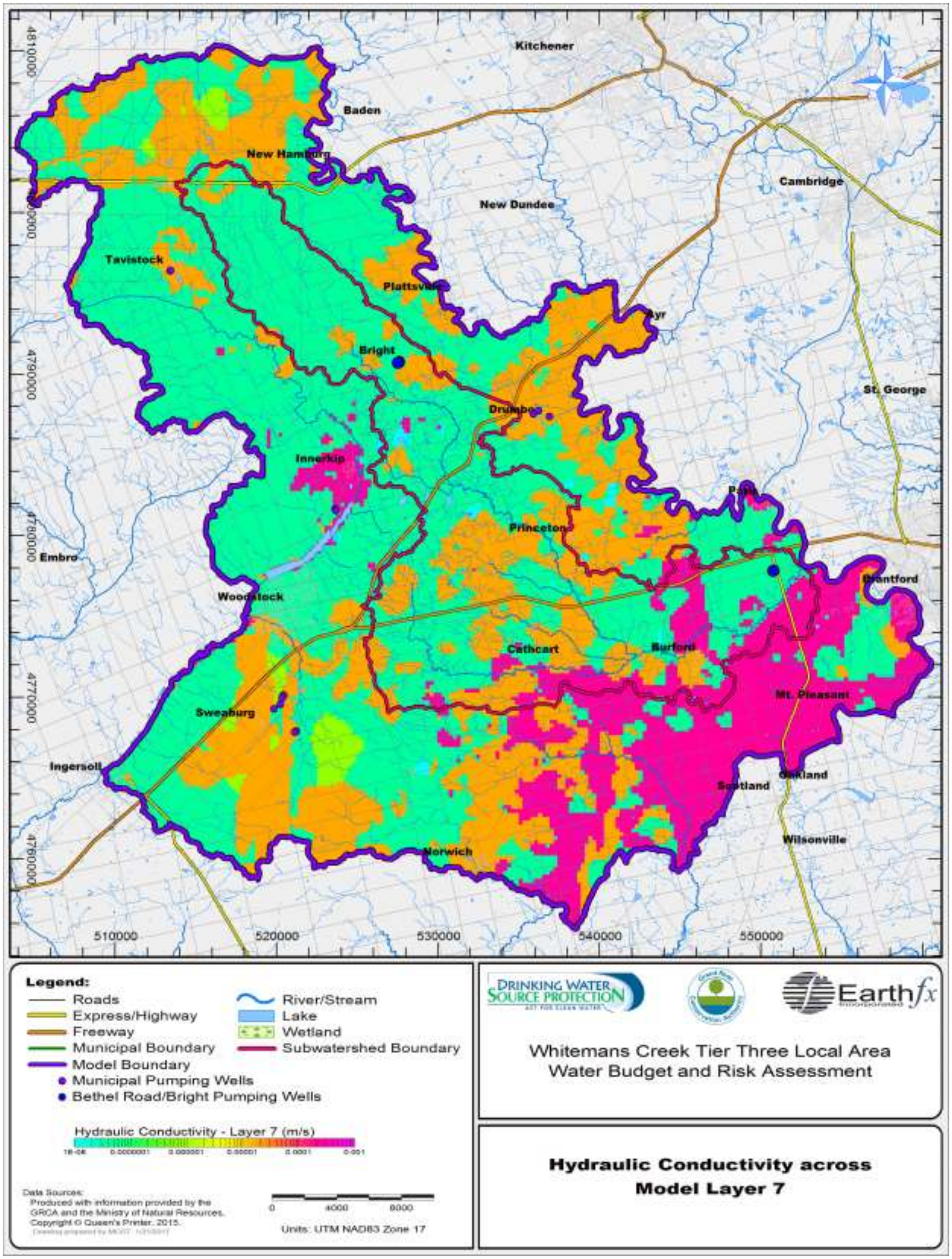


Figure 9.17: Hydraulic conductivity distribution in model layer 7.

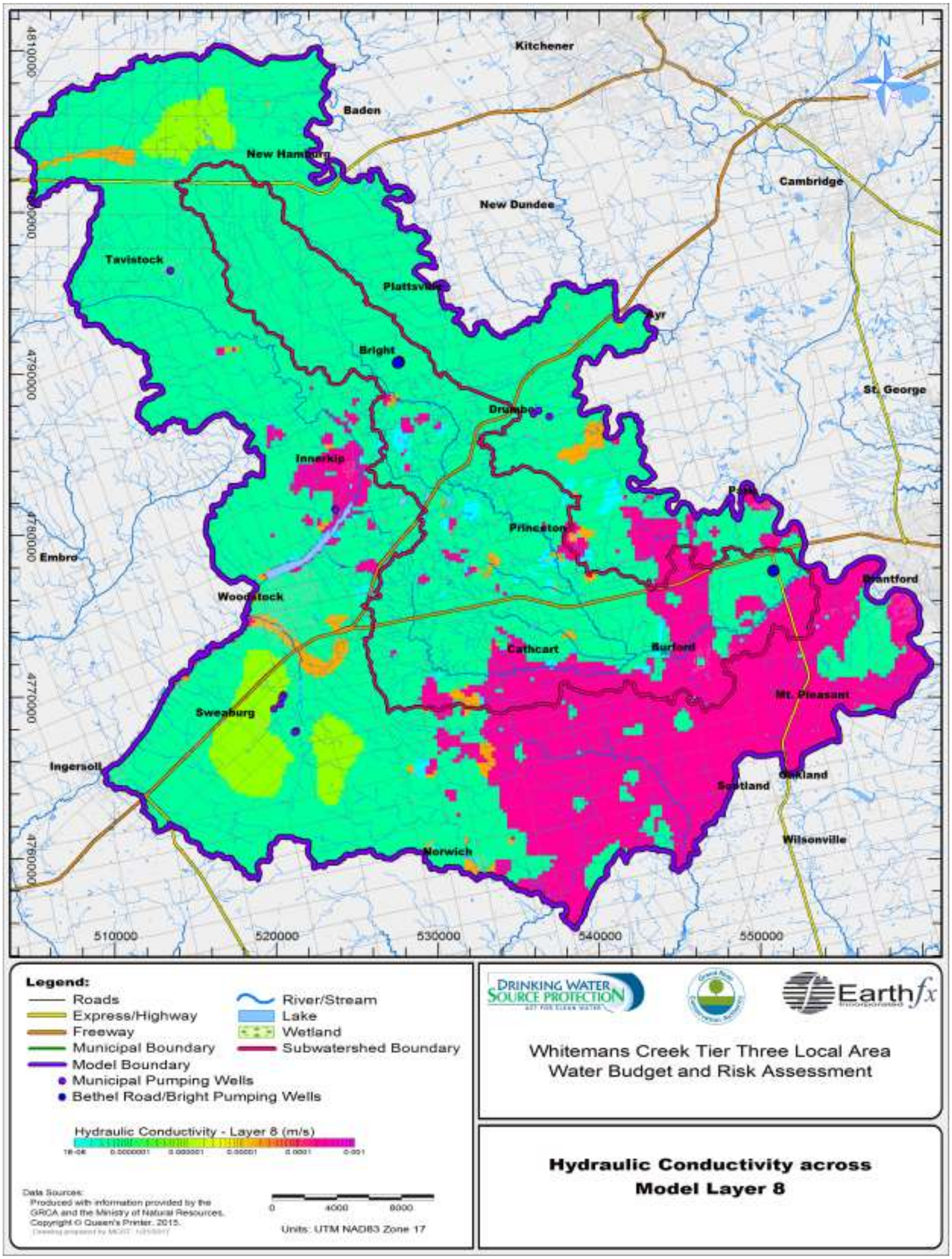


Figure 9.18: Hydraulic conductivity distribution in model layer 8.

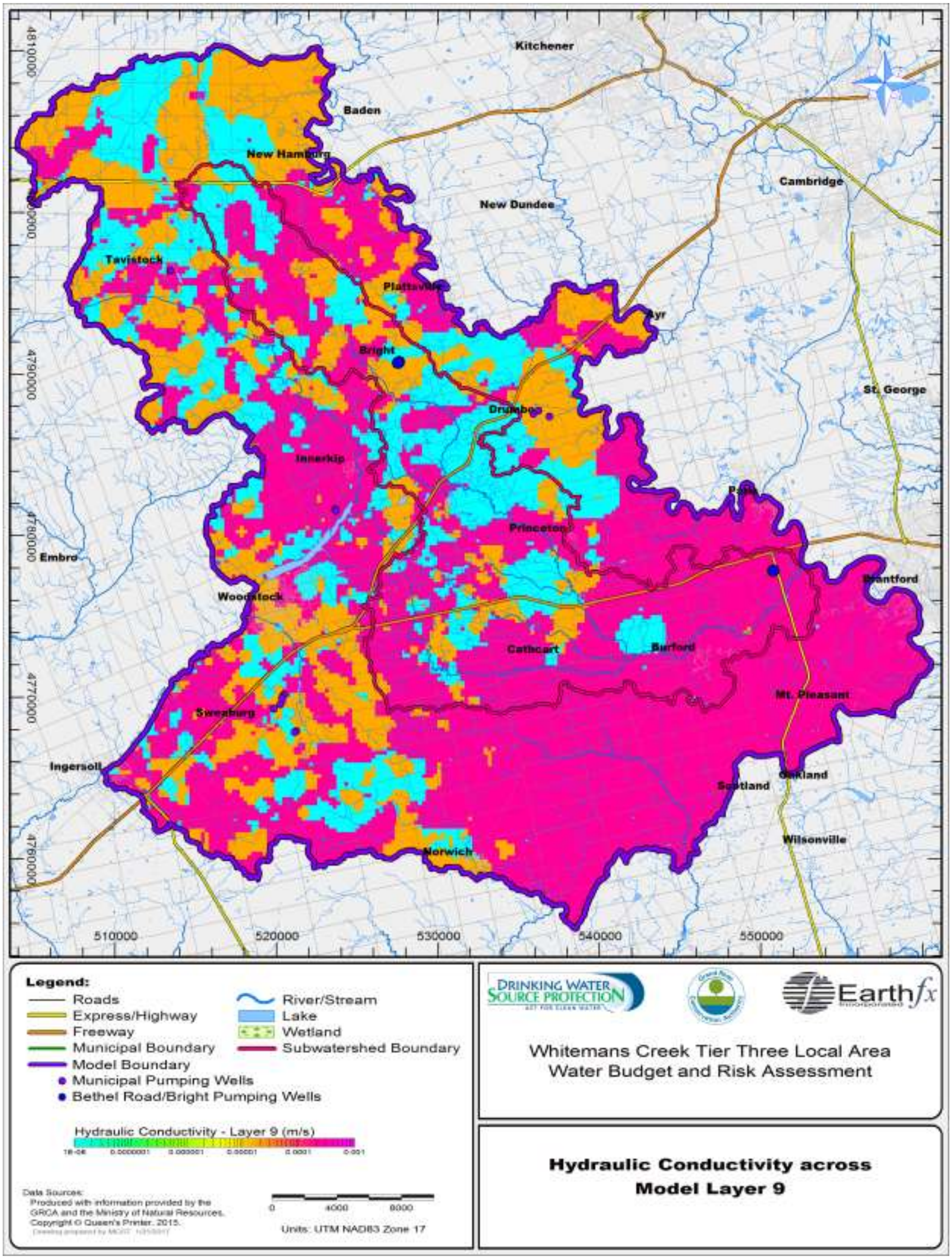


Figure 9.19: Hydraulic conductivity distribution in model layer 9.

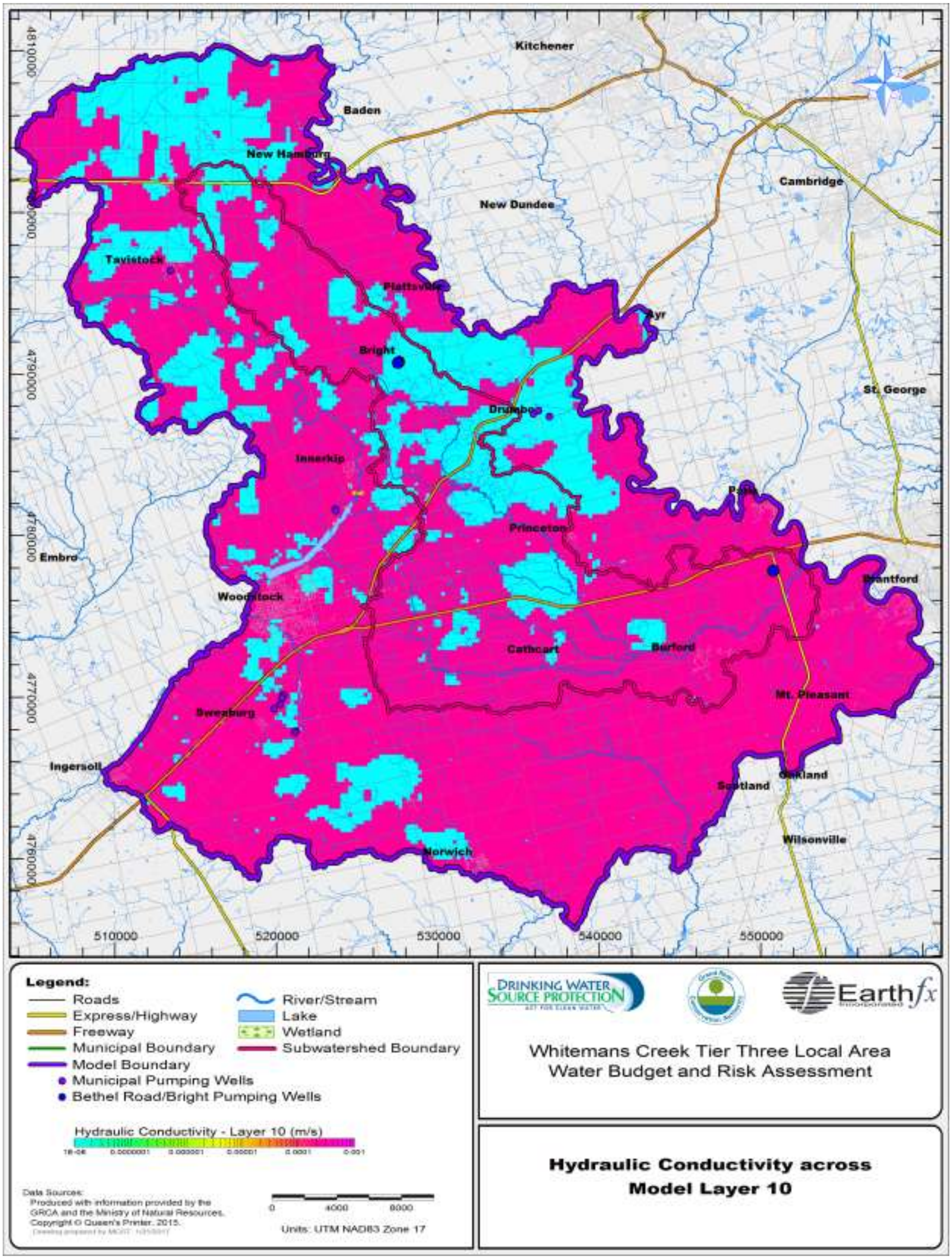


Figure 9.20: Hydraulic conductivity distribution in model layer 10.

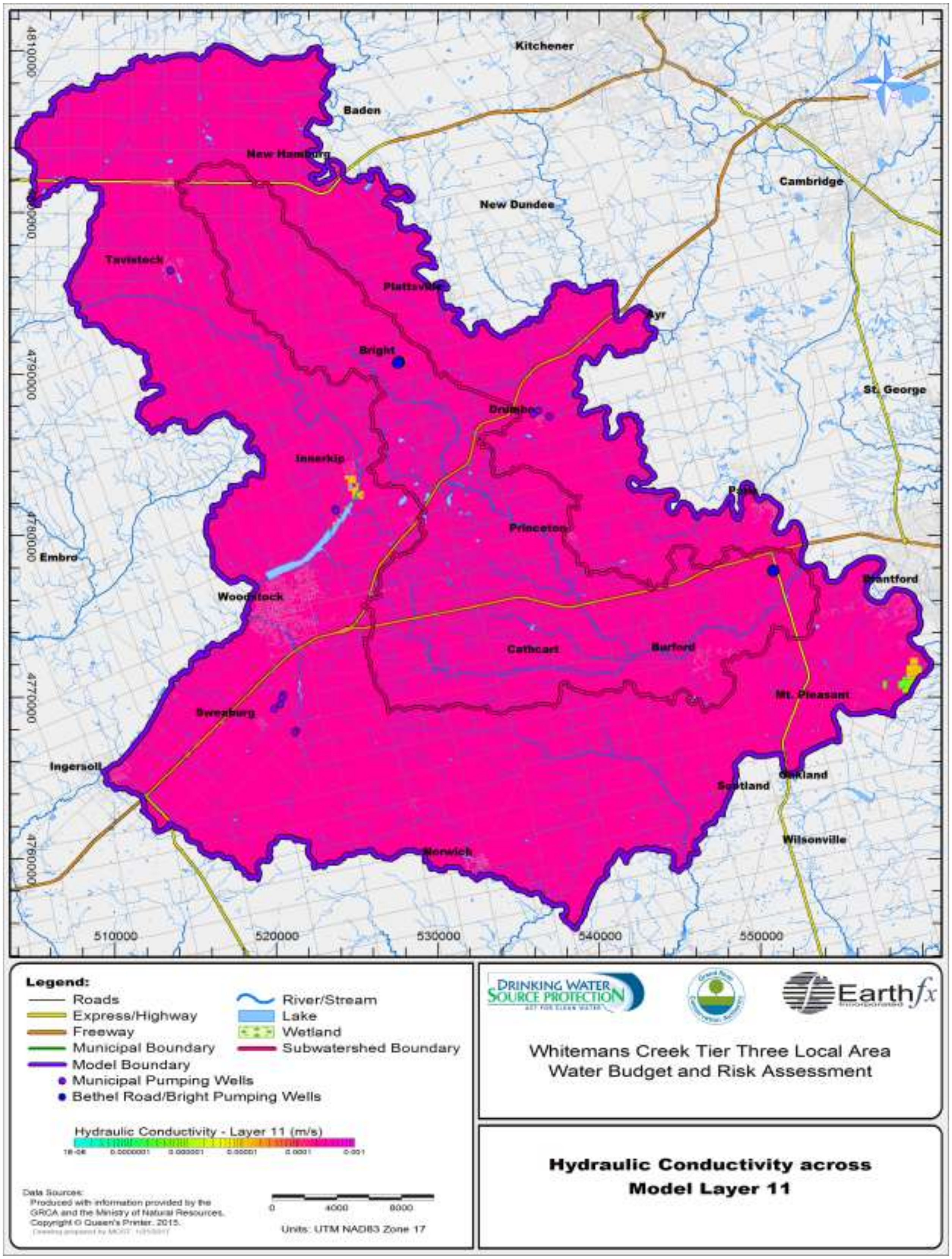


Figure 9.21: Hydraulic conductivity distribution in model layer 11.

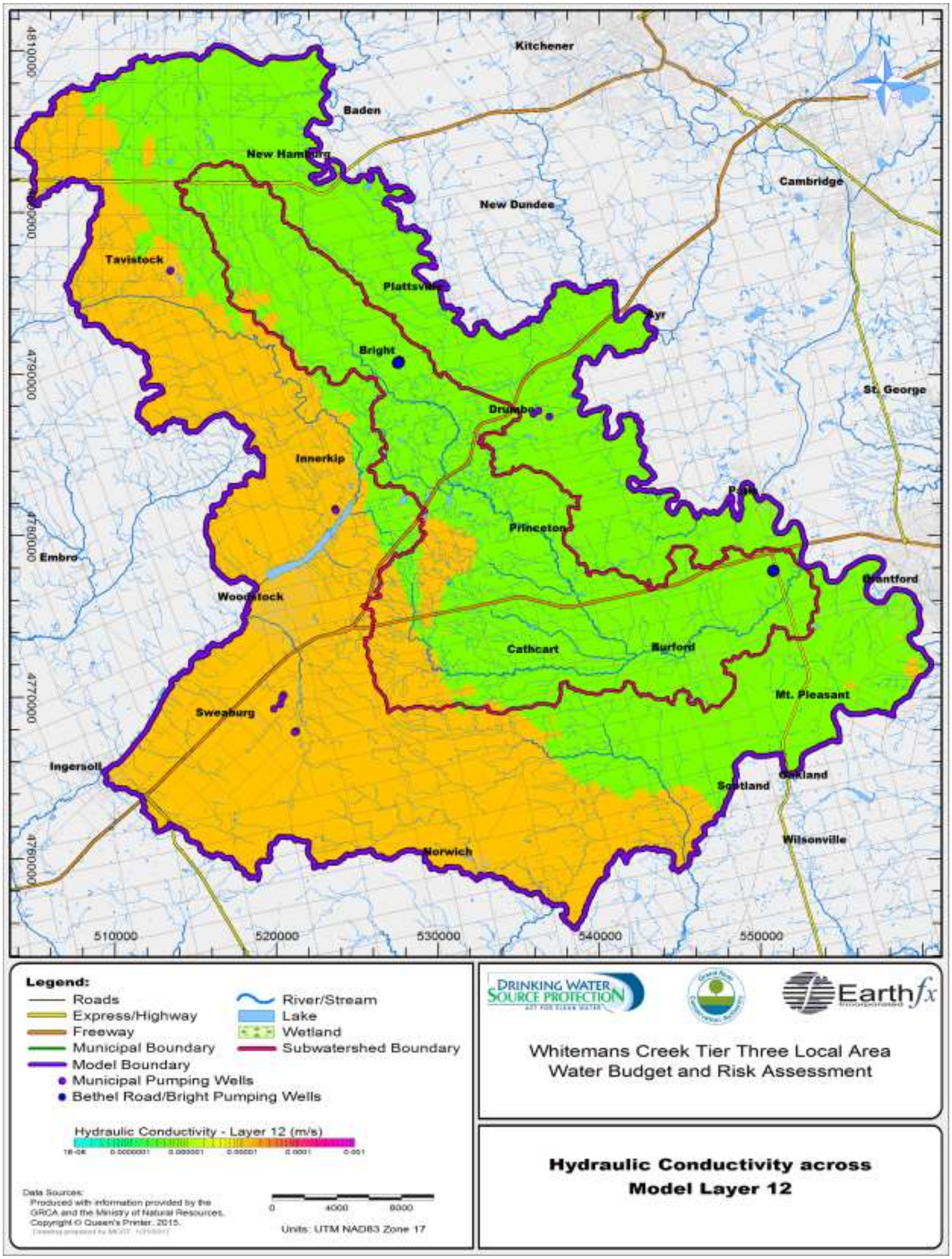


Figure 9.22: Hydraulic conductivity distribution in model layer 12.

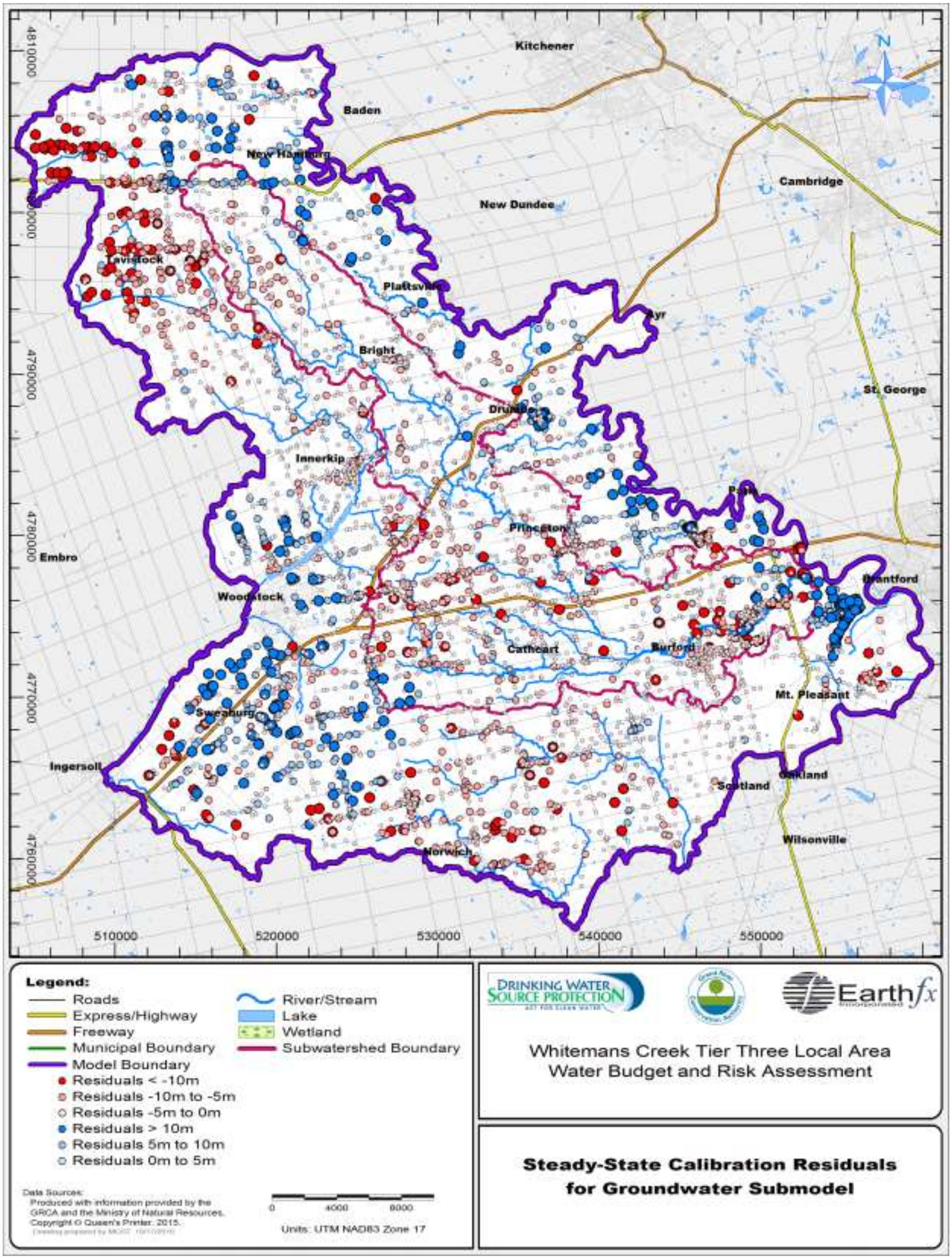


Figure 9.23: Distribution of calibration residuals for the groundwater submodel.

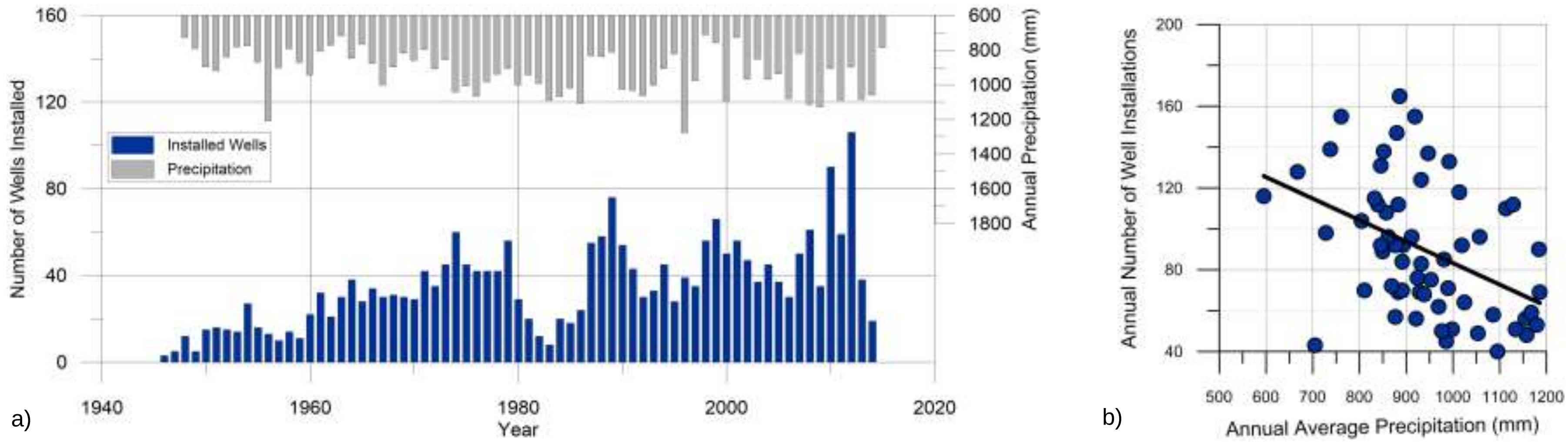


Figure 9.24: Comparison of precipitation and number of well installations (from MOE WWIS database), presented (a) on an annual basis, and (b) as a scatter plot.

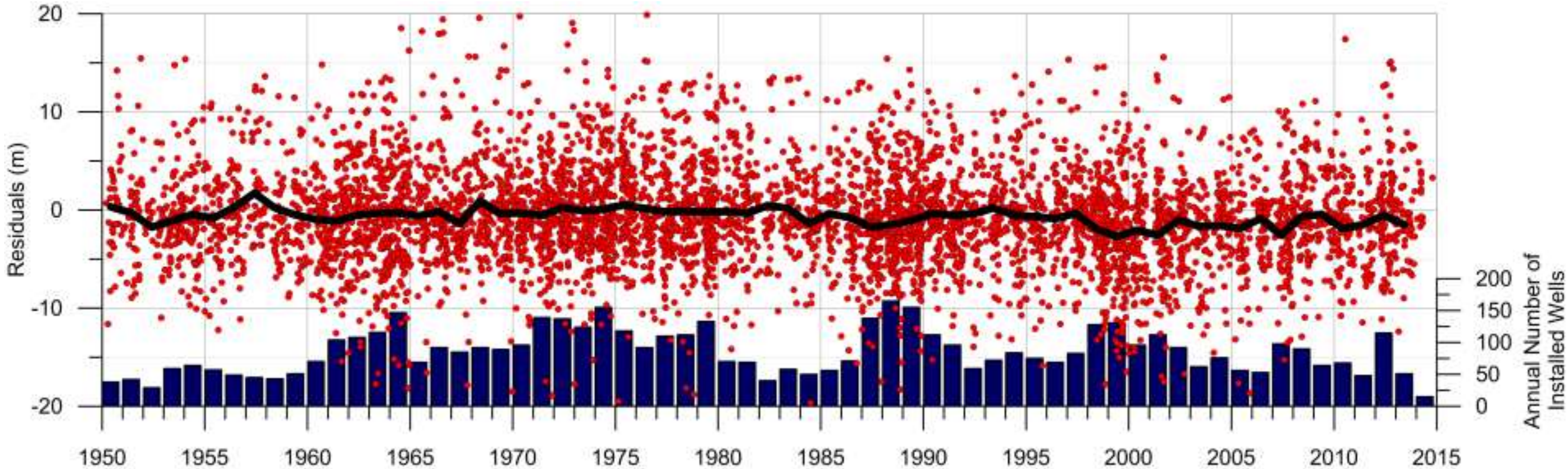


Figure 9.25: Simulated steady-state residuals plotted against measurement date with annualized well construction totals.

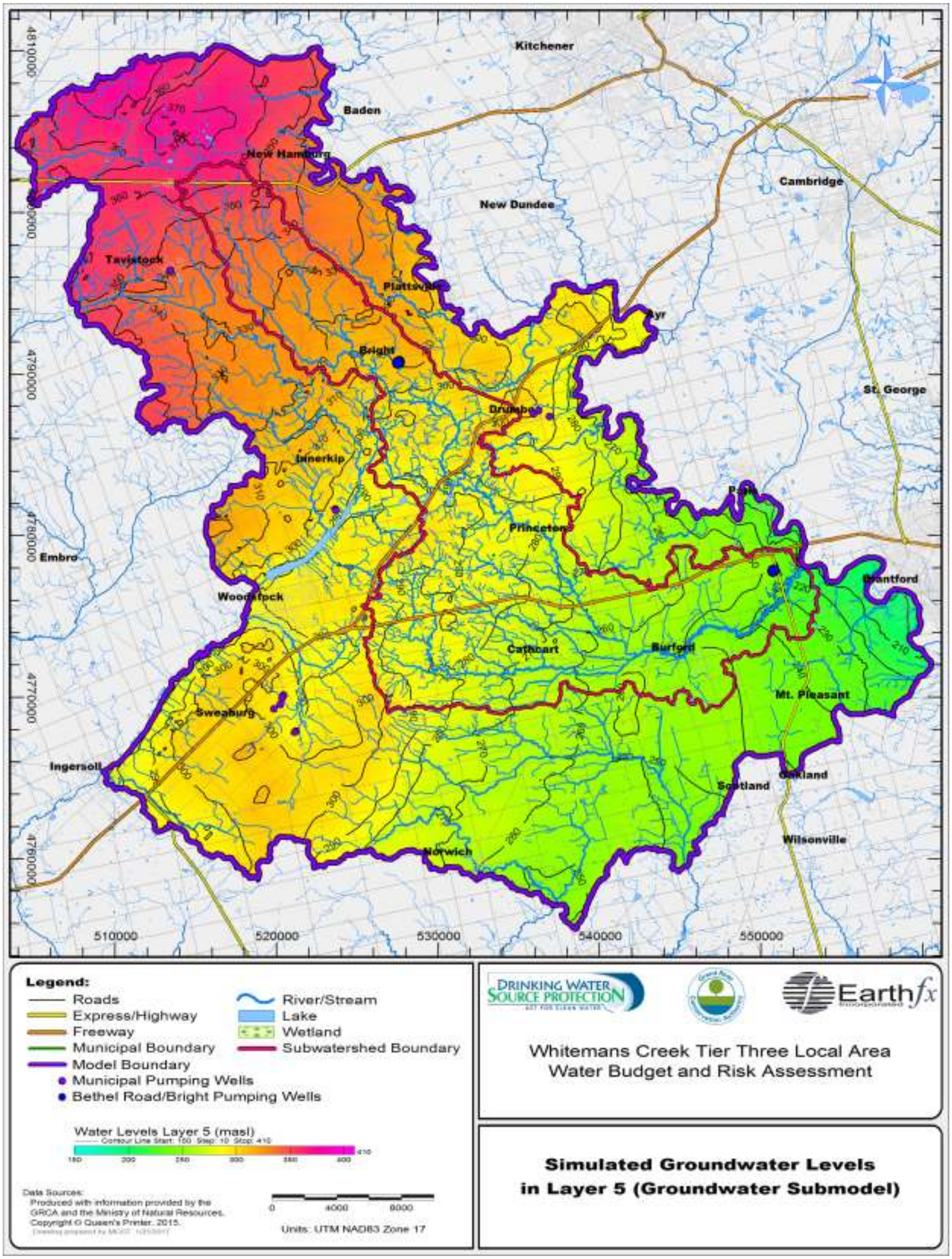


Figure 9.26: Simulated groundwater levels in model layer 5 (equivalent to Waterloo Moraine Aquifer).

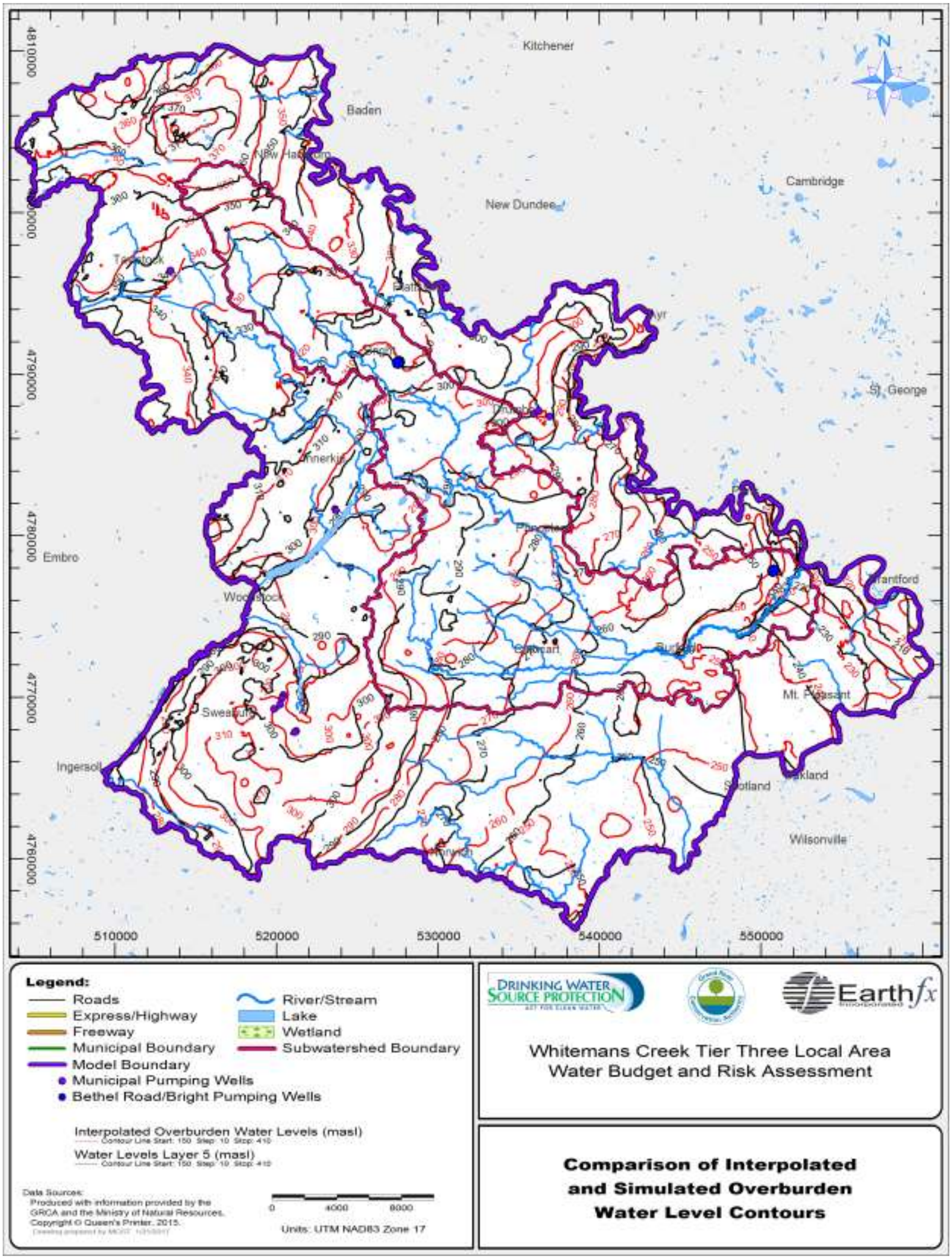


Figure 9.27: Comparison of interpolated overburden water levels and simulated water levels in layer 5.

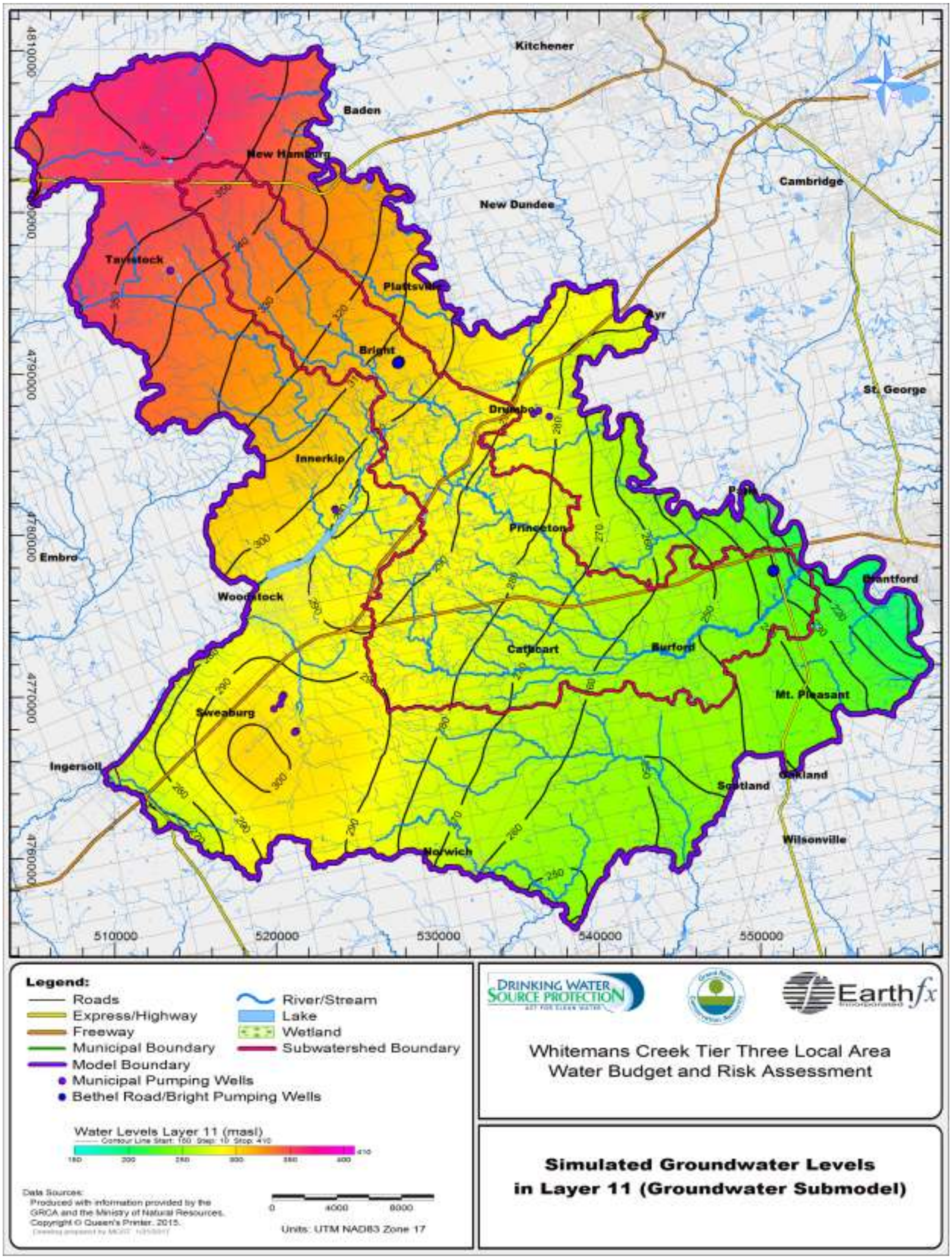


Figure 9.28: Simulated groundwater levels in model layer 11 (equivalent to Weathered Bedrock Aquifer).

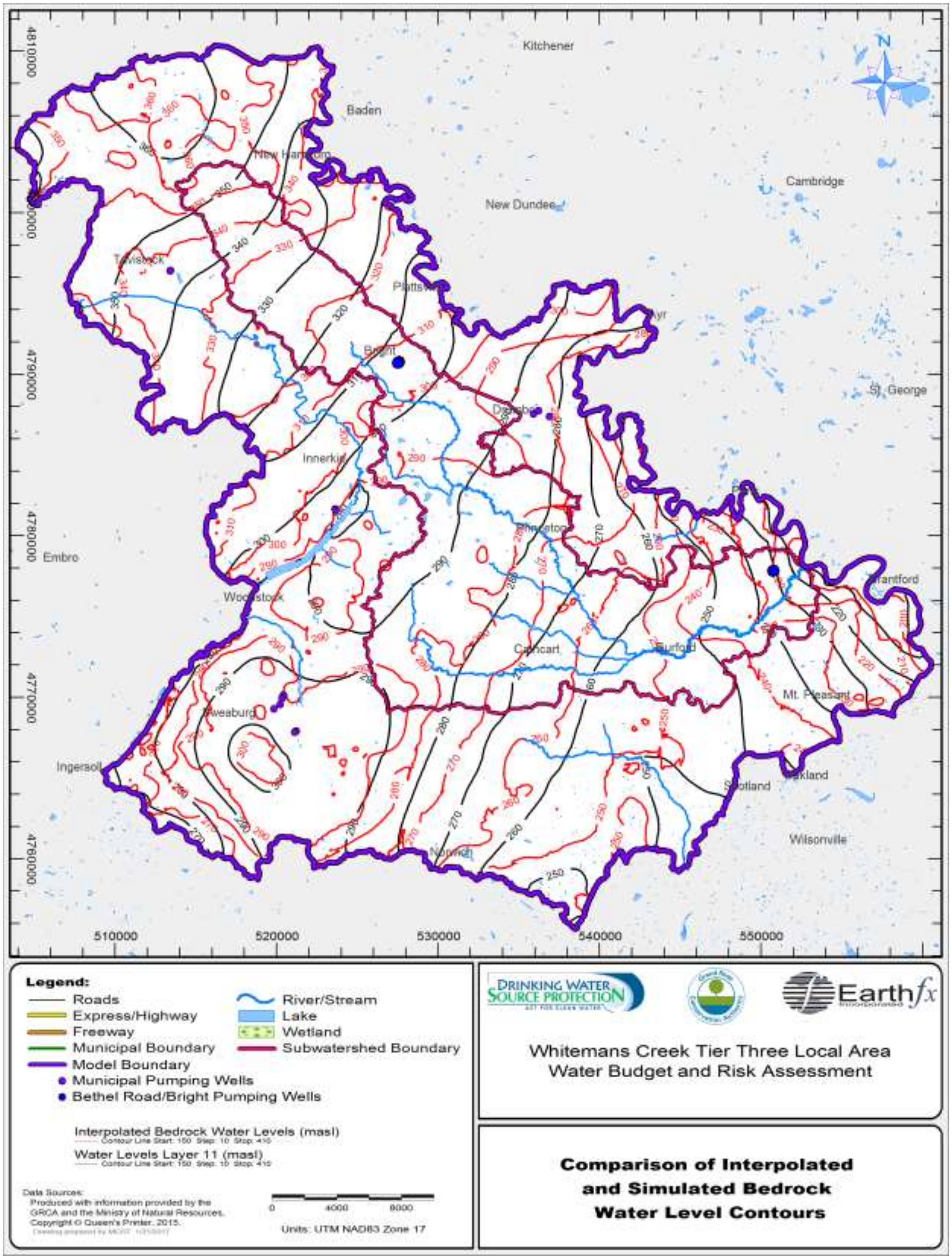
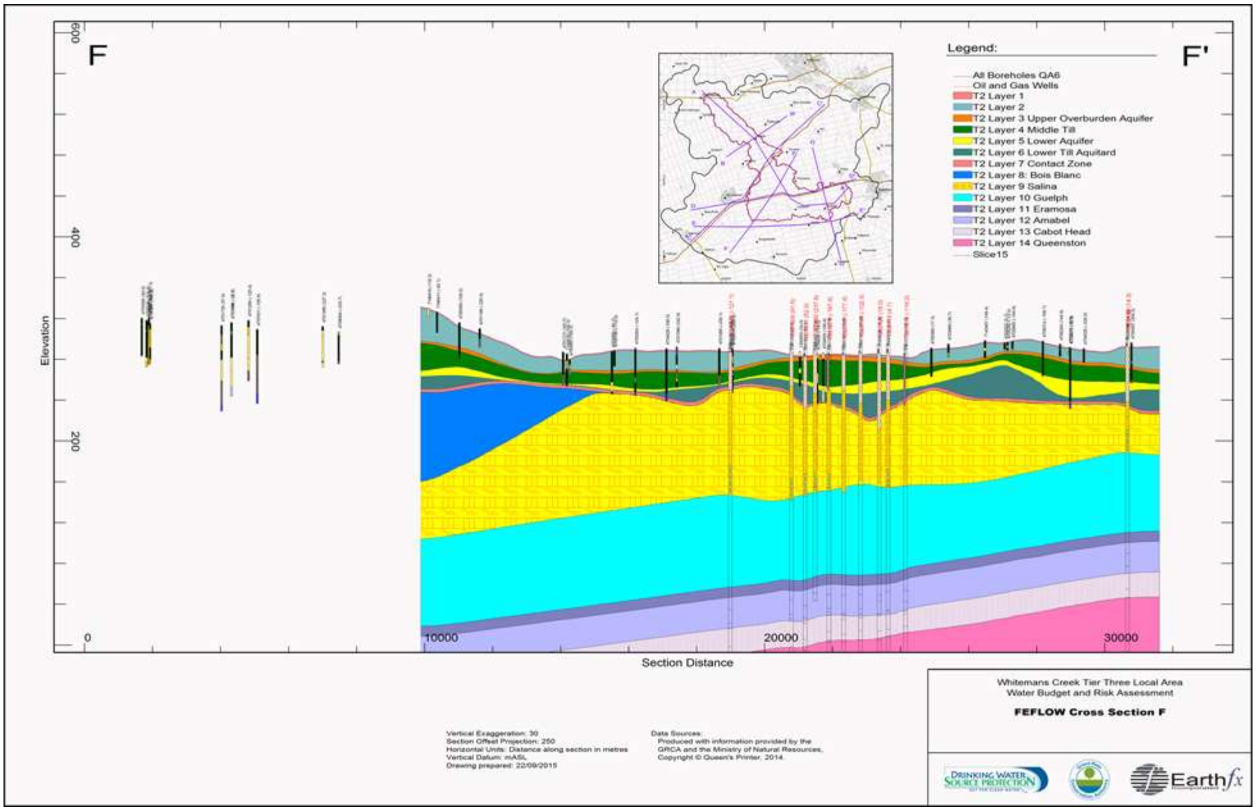


Figure 9.29: Comparison of interpolated bedrock water levels and simulated water levels in layer 11.



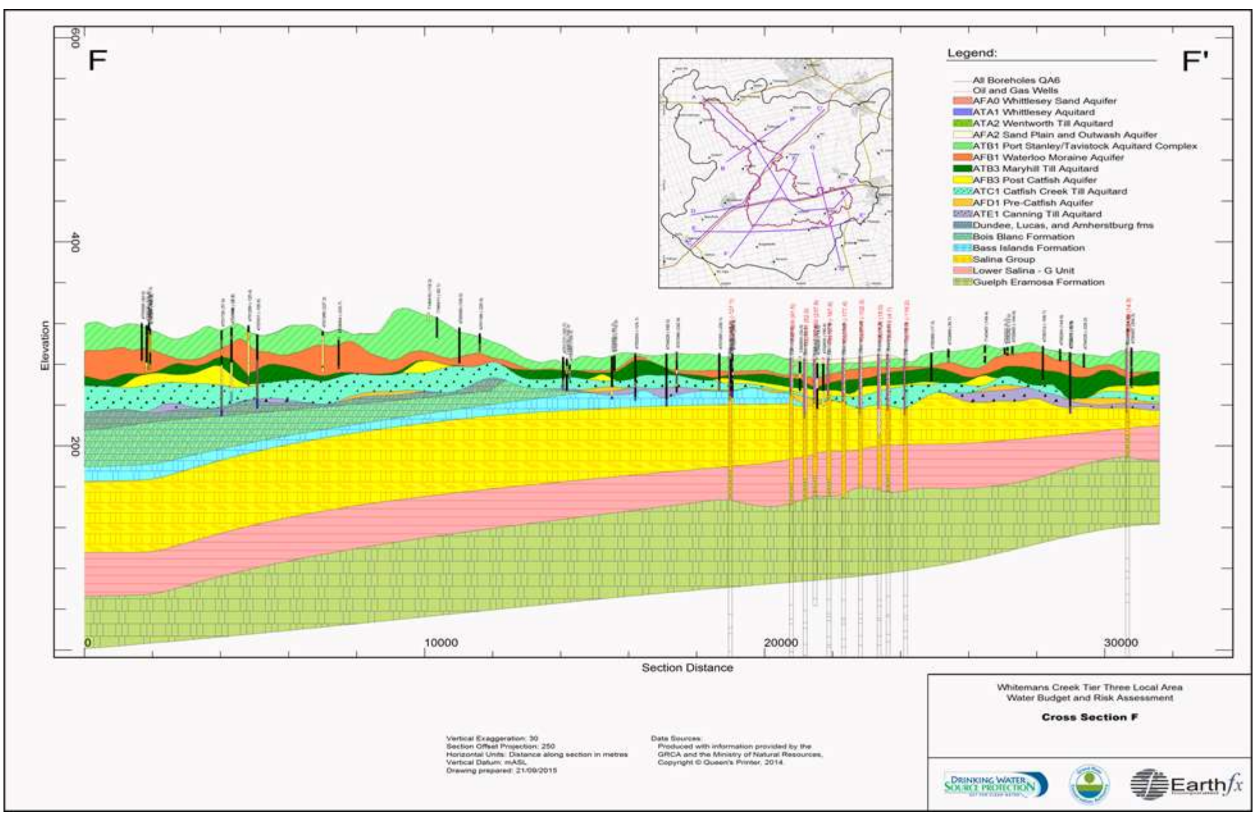
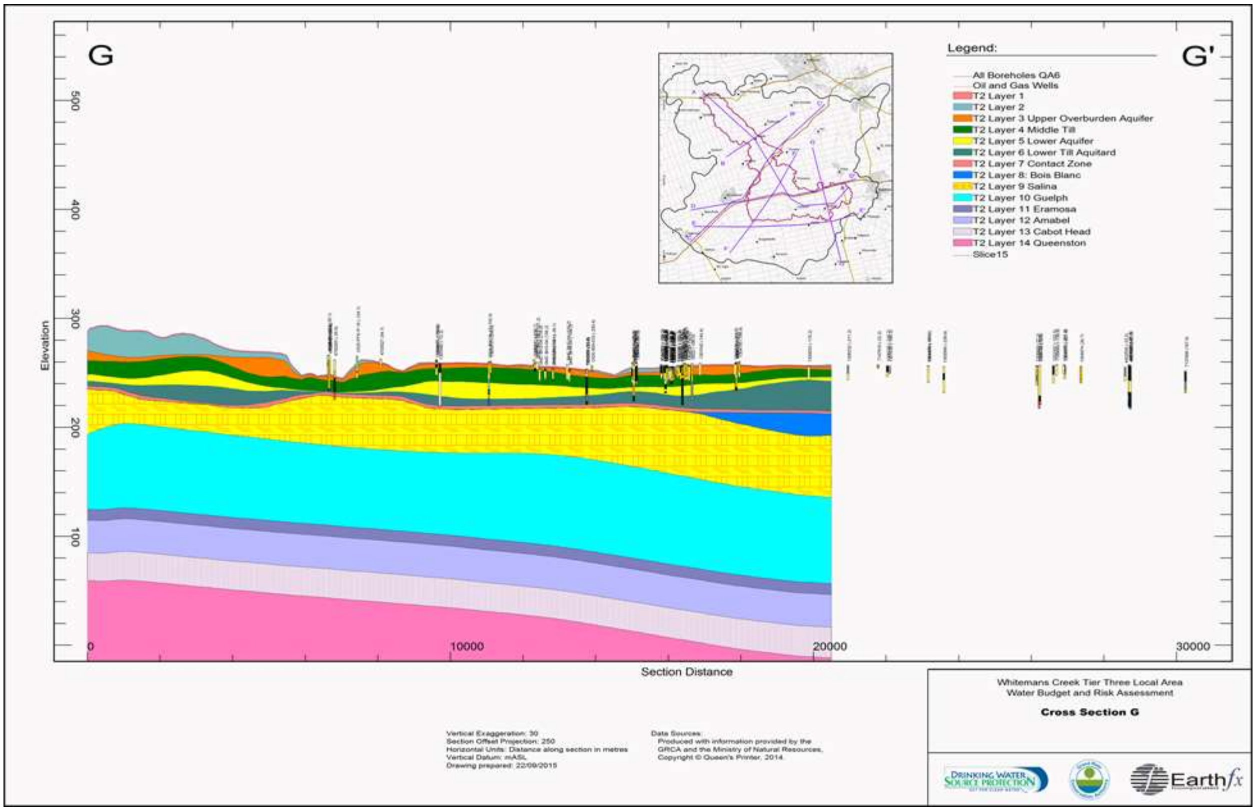


Figure 9.30: Comparison of GRCA Tier 2 Model (upper image) to Whitemans Tier 3 Hydrostratigraphic Model (Lower) along Section F-F'.



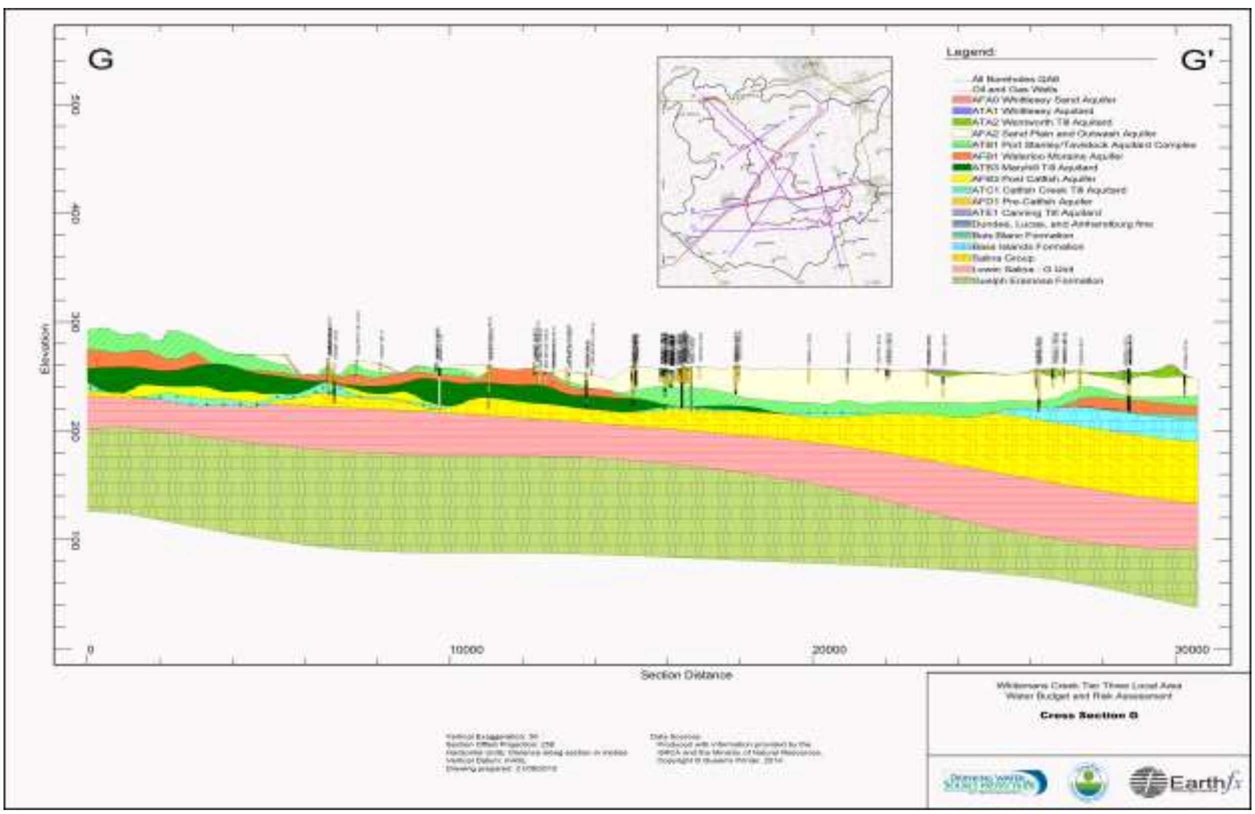


Figure 9.31: Comparison of GRCA Tier 2 Model (upper image) to Whitemans Tier 3 Hydrostratigraphic Model (Lower) along Section G-G'.

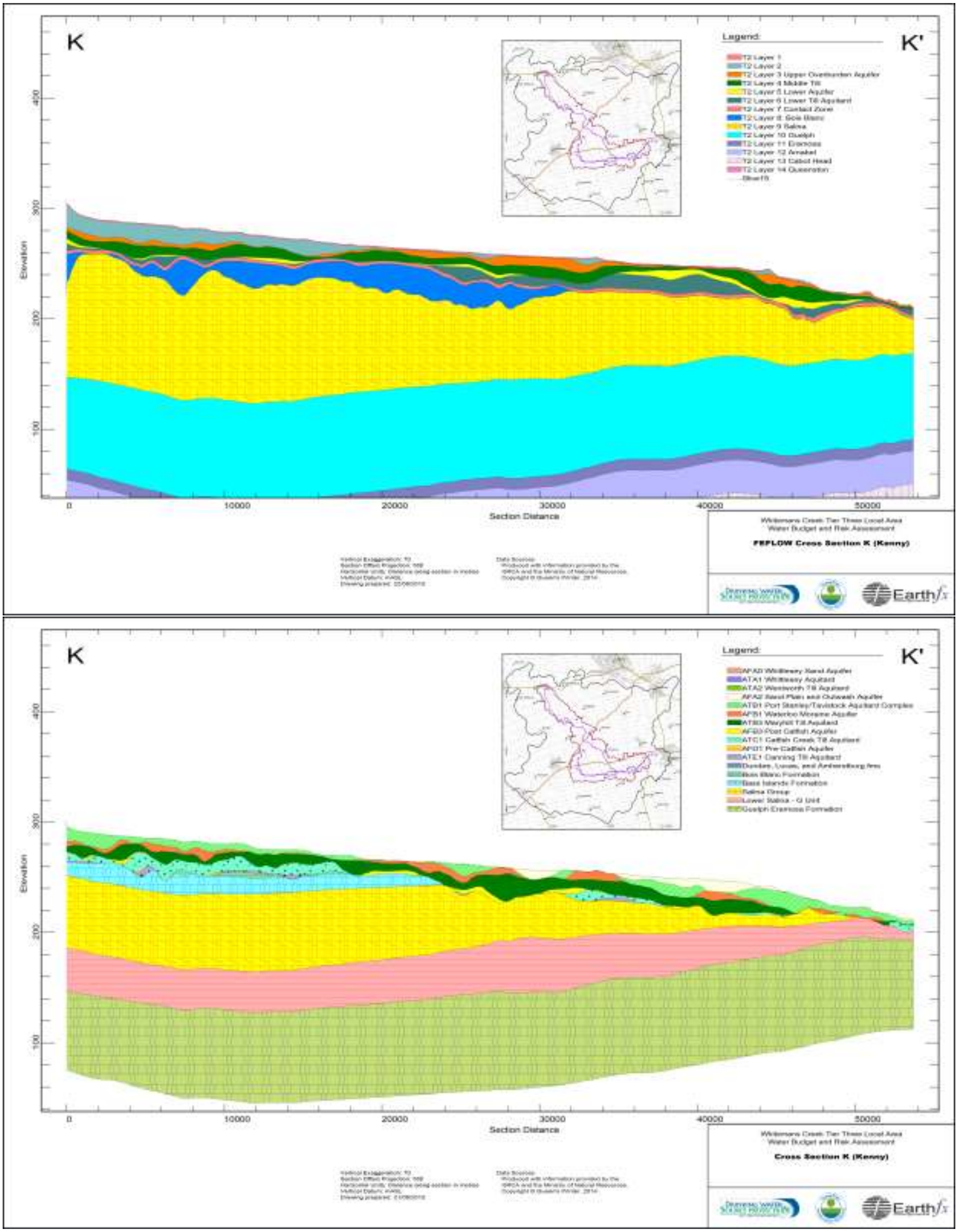


Figure 9.32: Comparison of GRCA Tier 2 Model (upper image) to Whitemans Tier 3 Hydrostratigraphic Model (Lower) along Section K-K'.

10 Irrigation Demand Submodel Development

As discussed in Section 6.2, the reported agricultural takings within the subwatershed do not capture the total water use associated with crop irrigation. To improve the representation of actual agricultural water demand and the overall accuracy of the model, a number of steps were undertaken including further analysis of available agricultural data, modifications to the GSFLOW model code, and model recalibration. The following sections briefly introduce the Irrigation Demand Submodel developed for the GSFLOW code; as well as the rationale, design considerations, processes, and required inputs for the Irrigation Demand module. Validation of the Irrigation Demand model code is also presented. Final model results and model validation are discussed in Section 11.

10.1 *Rationale*

Understanding the cumulative effects of irrigation water use on the groundwater and surface water system is central to water management in the Whitemans Creek subwatershed. Assessing these effects requires the ability to predict irrigation events, which, in turn, requires an understanding of the dynamic interaction between climate, soil moisture, crop needs, farm practices, and equipment limitations. Assessing the cumulative effects of groundwater takings and streamflow diversions also requires a modelling tool that can simulate these processes as well as the induced changes to groundwater/surface water interaction in the shallow subsurface.

The integrated surface water/groundwater model developed for the Whitemans Creek subwatershed can simulate many of the critical processes that are needed for predicting irrigation events and cumulative impacts. Specifically, the GSFLOW code simulates soil moisture conditions on a daily basis using the PRMS submodel. The PRMS submodel takes climate inputs (i.e., daily rainfall, solar radiation, and temperature) and calculates components of the water budget (i.e., interception, potential and actual evapotranspiration, runoff, interflow and recharge to groundwater). As well, the integrated model can simulate the effects of groundwater takings, surface water diversions, and interaction between the streams and shallow aquifer.

To calculate irrigation requirements on a daily basis, Earthfx modified the GSFLOW code and added an Irrigation Demand module. The module first processes input data describing farms properties and crop types and then uses the simulated daily soil moisture conditions and crop tolerances to trigger irrigation events on a farm-by-farm basis. The volumes taken in an irrigation event, as pumped groundwater or diverted streamflow, are determined based on a series of rules related to crop needs, pump capacity, and permit restrictions, as discussed further on. Irrigation water is applied to portions of each farm by adding the pumped volume above or below the plant canopy based on the irrigation method. The added water is subject to interception, runoff of excess, and “losses” to groundwater recharge as calculated by the PRMS submodel. Volumes of water taken and the applied water are tracked on a daily basis. The additional runoff and groundwater recharge (irrigation return flow), and other changes to the water balance, such as higher groundwater recharge rates or runoff over irrigated areas during subsequent rainfall events, can be calculated by comparing model runs with and without the Irrigation Demand module turned on.

The soil-moisture based simulation of agricultural takings can be applied to:

- estimate actual historic consumptive water use;
- evaluate projected water use under future drought;
- simulate the effect of changing crop types, irrigation sources, and irrigation equipment; and,
- simulate response to a range of future climate change conditions.

The effects of the steeper groundwater recession and reduced streamflow during extended drought and likely future climate on agricultural water use can now be represented within the GSFLOW framework.

10.2 *Design Approach*

Several design considerations influenced the development of the Irrigation Demand module for the GSFLOW code. These dealt with how the data related to farms, crops, and irrigation water sources were processed; how the simulated daily soil moisture conditions and crop tolerances were assessed across each farm, how to trigger irrigation events; and how to distribute the irrigation water over the farms. These design considerations are discussed below.

10.2.1 Model Code Selection and Design Considerations:

Many available groundwater models have modules that simulate irrigation demand and application. These include the USGS Farm Process (Schmid and Hanson, 2009) and the USGS MODFLOW-OWHM model (Hanson *et al.*, 2014) which includes the Farm Process as one of many interrelated processes. There are also surface water models, such as HSPF (Bicknell *et al.*, 2005), that can trigger irrigation events and apply the water to the model catchments.

There are several compelling reasons to work with the GSFLOW code. As introduced in Section 7, the GSFLOW code is an integrated model that simulated both surface water and groundwater flow on a continuous basis. All the relevant hydrologic processes including rainfall, interception, evapotranspiration, Hortonian and Dunnian runoff, interflow, groundwater recharge, and groundwater discharge to the soil zone are built into the PRMS submodel and function in a unified manner. Water applied as irrigation is subject to many of the same processes as precipitation, and the Irrigation Demand module was developed to capitalize on existing functionality.

Secondly, the GSFLOW code is a fully-distributed model. The water balance is done on a cell-by-cell basis so that spatial variability in soil properties, topography, and vegetative cover, and depth to water table is well represented at a scale smaller than typical catchment models. As well, runoff generated in one cell can be routed downslope to re-infiltrate and affect soil moisture properties and runoff in adjacent cells. Finally, the soil water balance in GSFLOW is done for the entire model area and not just for the farms (as done in some farm process modules). In this way, the effect of the irrigated areas on the catchment water balance can be simulated and calibration of parameter values can be done to match observed streamflow and water level change in groundwater monitors across the study area.

In addition to taking advantage of existing PRMS submodel capabilities, the Irrigation Demand module was designed to link with existing features of the MODFLOW submodel with as few code changes and input data changes as possible. The model uses the standard MODFLOW well package (Harbaugh, 2005) to simulate takings by irrigation wells and the SFR2 streamflow-routing module (Niswonger and Prudic, 2005) to simulate surface water takings as streamflow diversions.

10.2.2 Data Structure Design – Farms, Parcels, Crops, and Sources

The Irrigation Demand module was developed with the intent to simplify the input data requirements and capitalize on the type of agricultural and water use data available for the study area. Data are organized around the properties of farms, parcels, crops, and sources, each linked through unique identifiers, as described below:

Farms: The basic data unit for the Irrigation Demand module is the farm. The schematic in Figure 10.1 shows three different farms. Each farm in a simulation has associated properties, listed in Table 10.1, including a unique numerical identifier (1, 2, and 3 in this example). Each farm can have one or more irrigation sources, for example, Farm 1 has a surface water source and a groundwater source while Farm 2 has a single surface water diversion and Farm 3 has a single groundwater source. Farms are also assumed to have a practical limit on the area that can be irrigated in a single day, based on equipment, labour requirements, and/or farm layout.

Parcels: Each farm is subdivided into smaller units referred to as “parcels” as shown in Figure 10.1. A farm can have a single parcel (Farms 1 in this example) or multiple parcels (Farms 2 and 3). Parcels are assumed to have a single crop type. The crop type can be determined from agricultural survey data or from satellite imagery. For modeling purposes, it was assumed that the only one parcel per farm is irrigated per day. For farms with multiple parcels, the parcel to be irrigated is selected based on the highest average moisture deficit for the parcels (discussed further below). Each parcel has operational rules, such as the number of days between irrigation events on a part of the parcel, to ensure that irrigation is cycled around the entire parcel and between parcels.

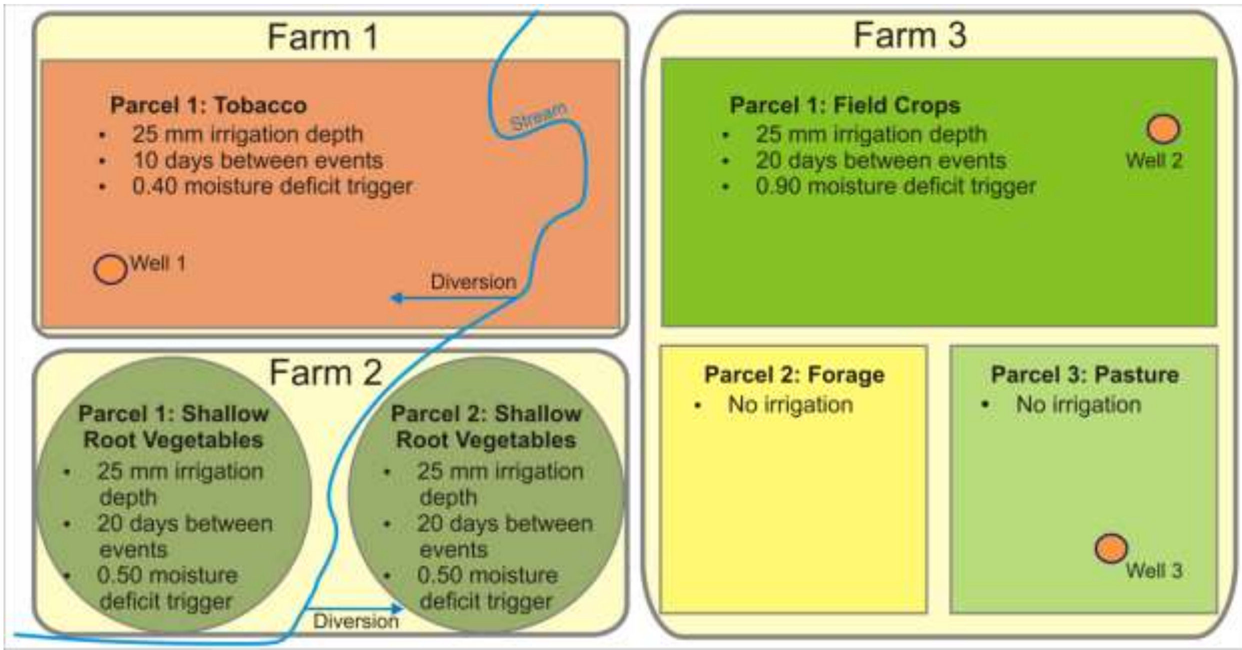


Figure 10.1: Schematic showing the linkages between farms, parcels, crops, and sources.

Table 10.1: Properties related to model farms, parcels, sources, and crops.

Farm
Unique Farm ID
Maximum Irrigated Area per Day
Number of Parcels
Number of Sources
Moisture Deficit Selection Option (1 or 2)
Farm Name (*optional*)

Parcel
Unique Parcel ID
Farm ID
Crop ID
Maximum number of consecutive days on (HRU)
Minimum days betweenirrigation events (HRU)
Model Cells (HRUs) assigned to parcel

Crop
Unique Crop ID
Irrigation Type (above/below canopy)
Irrigation Start and End Months
Deficit Trigger (0.0 to 1.0)
Delivery efficiency (0-1.0)
12 Monthly Values for Daily Irrigation depth (m)
Crop Name (*optional*)

Source
Unique Source ID
Farm ID
Source Type (well or surface water diversion)
Maximum taking per day (by permit or pump size)
Source Name

Crops: Each crop type has unique irrigation needs. The average depth of an irrigation event (in mm/d) is specified for each crop and can vary from month to month. Multiple crop types can be used to specify different irrigation needs for different irrigation methods. For example, shallow-rooted vegetables with drip irrigation may need 12.5 mm of water and would be treated as a different crop type than shallow-rooted vegetables with spray irrigation which requires higher amounts. The moisture deficit trigger is another property associated with the crop type. Some crops, such as sod, have a low tolerance for dry soil conditions while others, such as field crops, have a higher tolerance.

Other crop information related to the irrigation technique includes (1) an irrigation method flag indicating whether the water is applied above or below the crop canopy and subject to interception losses, and (2) a delivery efficiency; for example, a high-pressure spray gun may lose a considerable amount of water when the spray evaporates or blows away before it hits the ground while a low pressure system will have a higher efficiency (http://water.usgs.gov/edu/irmethods.html). Multiple crop types may be used to represent the different methods; for example, soybeans with high-pressure spay gun irrigation and soybeans with low-pressure spray would be treated as two different crop types.

Sources: For groundwater sources, a unique identification number is assigned to each well represented by the standard MODFLOW well package. A maximum water taking, based on a permit to take water (PTTW) or based on pump capacity is assigned to the well. The actual daily taking is determined by the Irrigation Demand module based on the irrigation needs and physical limitations. Representation of groundwater takings with the MODFLOW WEL module is discussed in more detail further on.

Surface water sources are represented as in-stream diversions using the SFR2 streamflow routing module. The number assigned to the stream segment representing the diversion also serves as the unique source identifier. The SFR2 module represents several types of diversions that differ based on the rules used to calculate the water available for diversion. Representation of diversions with the MODFLOW SFR2 module is discussed in more detail further on.

Linkages: The Irrigation Demand module reads in data on crops, farms, parcels, and sources at the start of a model run. Farms, parcels, sources, and crops are linked through their unique identifiers. For example, the input data set for an irrigation source contains the identifier for the associated farm. Similarly, the input data set for parcels contains the identifiers for the associated crop types and farms (Table 10.1). Specific input data instructions are discussed in more detail in Appendix C. The data sets can be updated periodically during a model simulation (e.g., at the start of a water year) to account for crop rotations or changes in farm capacity. Parcels and farm layouts are assumed to remain constant over the model simulation period, however.

10.2.3 Parcel representation in the PRMS submodel

Each parcel is represented by one or more PRMS submodel cells (HRUs) as shown schematically in Figure 10.2. Water balances are computed for each cell underlying a parcel on a daily basis. A PRMS data set containing the Parcel ID associated with each HRU is read in at the beginning of the model run.

Critical HRU properties relating to the Irrigation Demand module include the HRU area, the maximum soil moisture capacity, and the actual soil moisture at the beginning of the day. The maximum soil moisture capacity is given by:

$$maximum\ moisture\ capacity\ = \left(\theta_{field\ capacity} - \theta_{wilting\ point}\right) \quad Eq. 10.1$$

and the actual moisture capacity is given by:

$$actual\ moisture\ capacity = \ \left(\theta_{actual} - \theta_{wilting\ point}\right) \quad Eq. 10.2$$

where θ_{actual} is the current moisture content of the soil, $\theta_{wilting\ point}$ and $\theta_{field\ capacity}$ are the moisture contents at field capacity and wilting point, respectively. The quantities in parenthesis are represented in the PRMS submodel using the variables *soil_moist_max* and *soil_moist*, respectively.

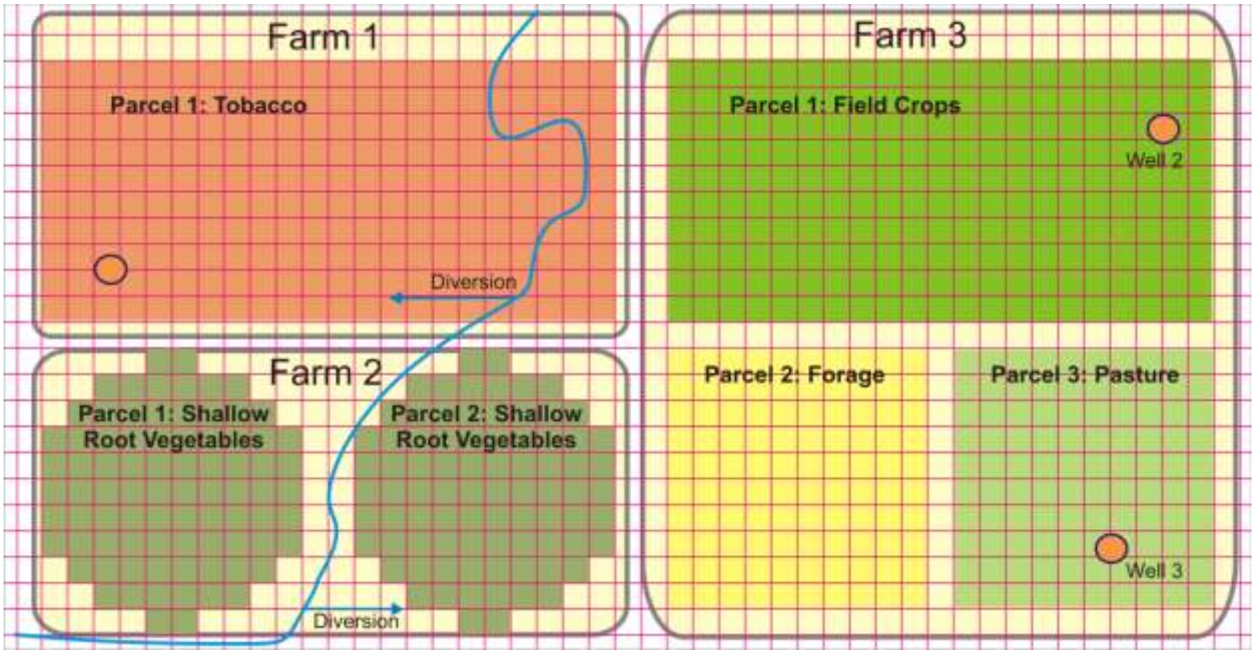


Figure 10.2: Schematic showing parcels represented by PRMS cells (HRUs).

10.2.4 Moisture Triggers

The main part of the Irrigation Demand Module is called on a daily basis demand just prior to the calculation of daily rainfall and interception. The soil moisture deficit factor is calculated in PRMS for each HRU as:

$$soil\ moisture\ defict\ factor = \frac{(soil\_moist\_max\ - soil\_moist)}{(soil\_moist\_max)} \quad Eq.\ 10.3$$

The soil moisture deficit factor is averaged over the parcel to determine an average moisture deficit factor. This value can also be compared against the irrigation trigger level for the particular crop type to give a relative moisture deficit:

$$relative\ soil\ moisture\ defict\ factor = \frac{soil\ moisture\ defict\ factor}{trigger} \quad Eq.\ 10.4$$

Figure 10.3 shows an example, with two adjacent parcels. Parcel 1 on Farm 1 has an average maximum soil moisture capacity of 0.025 m and a current soil moisture of 0.015 m. This yields a soil moisture deficit factor of 0.40. Parcel 1 on Farm 3 has a lower current soil moisture of 0.010 m yielding a higher soil moisture deficit factor equal to 0.60. However, because of the different moisture deficit trigger values, Parcel 1 on Farm 1 has a higher relative moisture deficit factor of 0.8 while Parcel 1 on Farm 3 has a relative moisture deficit factor of 0.67.

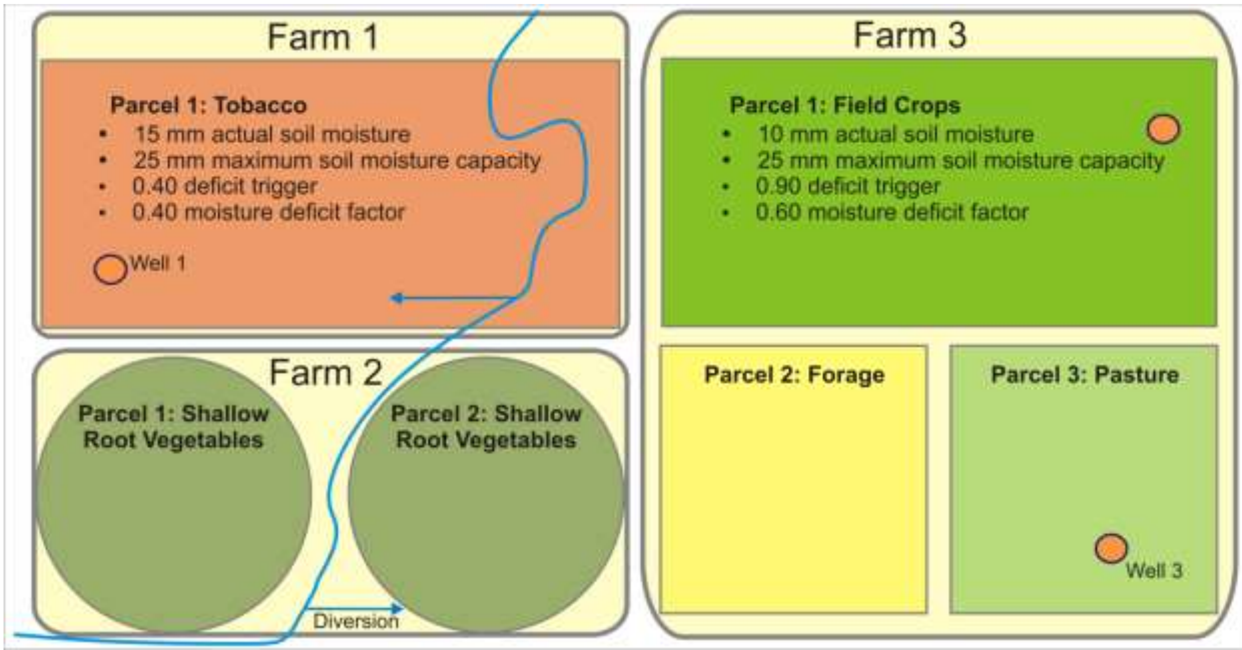


Figure 10.3: Schematic showing the moisture deficit factor versus the relative moisture deficit factor for two parcels.

On farms having multiple parcels, selecting the "driest" parcel to irrigate can be done based on either (1) the parcel with the highest moisture deficit factor using Eq. 10.3 or (2) the highest relative moisture deficit using Eq. 10.4. The selection method is defined for each farm.

If the driest parcel has a moisture deficit factor above the moisture deficit trigger, an irrigation event can occur. A preliminary check is made to see if there was a significant precipitation event (currently set at 2.5 mm) that day. If no significant precipitation event occurred, the irrigation demand for the parcel is calculated.

10.2.5 Demand Calculations

Once an irrigation event is triggered, a series of calculations are made and a set of rules are applied to compute the actual water demand per farm. First, the required water is calculated based on the depth of irrigation for the crop type and the maximum area that can be irrigated in a day on the farm. This value is compared against the maximum volume that the associated source can provide (for modeling purposes, it is assumed that farms with multiple sources can take the combined maximum takings). The smaller of the two values is used to compute "available supply".

Next, the HRUs making up the driest parcel are inspected. To ensure that all HRUs are covered eventually, two criteria are assigned to the parcel: (1) the minimum days that must pass between irrigating a particular HRU, and (2) the maximum number of consecutive days that any particular HRU can be irrigated. HRUs that have been irrigated for more than the maximum allowable consecutive days and HRUs that have been irrigated within the minimum separation time between events are rejected. The demand for the remaining HRUs is added, one at a time, based on the HRU area and irrigation depth, as long as the net demand remains less than the "available supply". The accumulated demand is the value passed to either the WEL or SFR2 package, based on the source type. If the farm has multiple sources, the accumulated demand is distributed among the sources equally. Alternate distributions options, such as a priority basis, could be added in the future if required.

As an example, the parcel on Farm 1 (Figure 10.4) has an area of 55 ha. It is represented by 220 HRUs, each 50 m on a side. The maximum area that can be irrigated, based on existing equipment, is 20 ha/d.

There are two sources with a combined capacity of 4500 m^3/d. To irrigate the maximum area to a depth of 25.4 mm would require 5,080 m^3. This is more than the combined maximum capacity, so the “available supply is limited to 4500 m^3/d. Each HRU requires 63.5 m^3 of water, so 70 HRUs can be irrigated on the first day. On the next two days, a different 70 HRUs would be irrigated because of the requirement that 10 days pass before any HRU can be irrigated again. On the fourth day, the remaining 10 HRUs would be irrigated and the required water demand passed to the WEL and SFR2 modules would be 635 m^3.

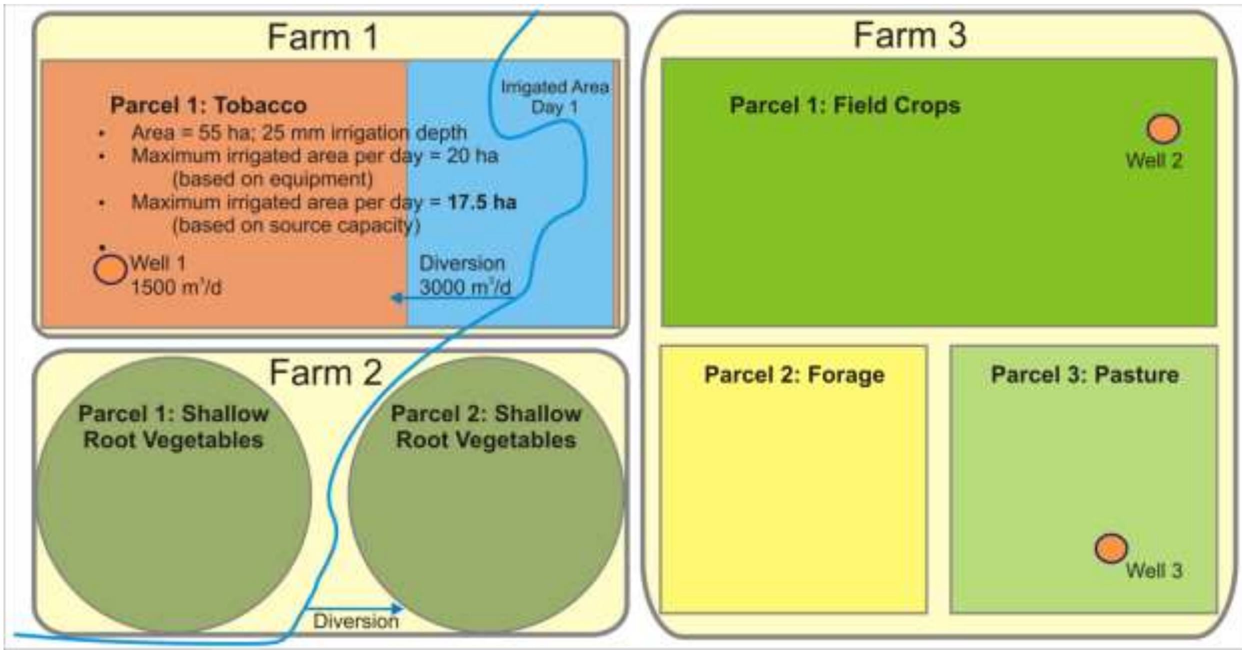


Figure 10.4: Schematic showing sample demand calculation.

10.2.6 Fate of the Applied Water

The demand calculated for each HRU is multiplied by the crop irrigation water delivery efficiency factor to account for losses such as evaporation and wind drift. The final applied water per HRU is stored in a PRMS array and transferred to the PRMS Interception module. If the irrigation method is subject to canopy interception, the Interception module adds the applied water to the “observed” daily precipitation, as shown schematically in Figure 10.5. Interception is calculated using the standard PRMS methods based on the vegetative cover density, seasonal adjustment factors, and the maximum and current interception storage (described in Section 8.3.3).

If the irrigation method is not subject to canopy interception, the module adds the applied water to the “net” daily precipitation (after interception). Hortonian runoff and infiltration are calculated using the pre-selected PRMS calculation method based on soil properties and antecedent conditions.

Irrigation return flows, that is, the excess runoff and groundwater recharge caused by over-irrigation, are computed by the model but are not tracked separately as water budget items. These values can be best determined by first simulating a baseline, “no-irrigation” scenario, and then comparing the simulated runoff, ET, groundwater recharge, and streamflow on a daily basis. Earthfx has written post-processing codes to facilitate the comparisons.

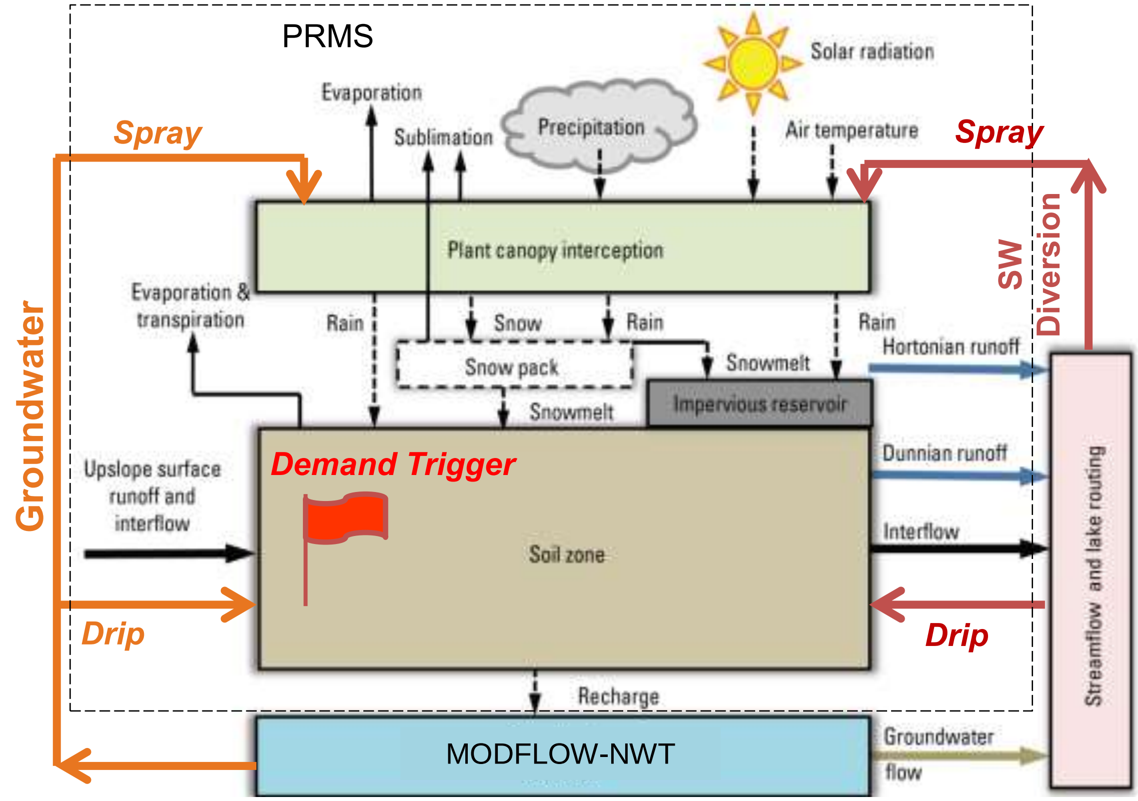


Figure 10.5: Modified GSFLOW flow chart showing the incorporated Irrigation Demand module processes.

10.2.7 Source Representation in the MODFLOW Submodel

As noted earlier, groundwater sources are represented by the standard MODFLOW WEL package. The only modification is that each irrigation source must be identified by a unique ID number. Well locations are assigned by specifying the appropriate MODFLOW model grid row, column, and layer. The maximum water taking, based on a permit to take water (PTTW) or based on pump capacity, is assigned in the input data set for the Irrigation Demand module. The actual daily taking is determined by the Irrigation Demand module based on the irrigation needs and physical limitations. Any water taking value assigned in the WEL module input data is ignored.

The well package has an automated procedure for limiting the water taking when the well is close to running dry, (i.e., when the simulated head in the MODFLOW cell approaches the base of the model layer). The corrected water taking is provided as feedback to the Irrigation Demand module to adjust “available supply”.

Surface water sources are represented as in-stream diversions using the SFR2 streamflow routing module. The only requirement is that a new stream segment be added to represent the diversion. The new stream segment number serves as the unique source identifier.

Streamflow diversions can be represented in multiple ways. For example, a Type 0 diversion takes the required flow and can take all available flow when the streamflow falls below the required amount. A Type 1 diversion takes the required flow but takes no water when streamflow falls below the required amount. Type 2 diversions take a specified percentage of streamflow – this diversion type is not currently supported by the Irrigation Demand Module and should not be used for surface water sources. Type 3 diversions take available flow in excess of a threshold amount up to the required quantity. Type 4 diversions were added by Earthfx and take available flow up to a fixed percentage of the total flow. The SFR2 package determines the water available for the diversion based on the required amount (provided by the Irrigation Demand module), diversion type, and available streamflow. The corrected water taking is provided as feedback to the Irrigation Demand module to adjust "available supply".

10.3 *Whitemans Creek Tier 3 Irrigation Demand Module Inputs*

Multiple data sources were drawn upon to develop the inputs required to drive the Irrigation Demand module within the Whitemans Tier 3 model. The following section outlines the major datasets and inherent assumptions applied within the model.

10.3.1 Unique Farm Identification Numbers

The foundational unit within the Irrigation Demand module is the farm (Section 10.2.2). Each farm within the model requires a unique farm identifier which is used to link crop parcels and irrigation sources to equipment types and operating procedures. The Municipal Property Assessment Corporation (MPAC) assessment maps were obtained for the portion of model intersected by the Lake Erie Source Protection Region and the Counties of Brant and Oxford. MPAC property and farm assessment codes were provided by Brant and Oxford counties for assessment parcels within their jurisdiction. MPAC assessment parcel data were unavailable for parts of Perth County which lie outside of the Lake Erie Source Protection Region. For this small portion of the model area, concession lots were taken to represent the basic farm unit. There is only one PTTW in this area, and irrigation demand is low.

Where available, the MPAC farm codes were used to identify assessment parcels associated with agricultural activities. For areas where farm codes were unavailable, agricultural properties were selected by interpretation of aerial photography. To eliminate insignificant or erroneously-coded assessment parcels, farms with an area less than 1.62 ha (4 acres) were removed from the dataset. The identified farms are shown on Figure 10.10 with the data source used to identify the spatial extent of the farm. Within the model area, 4,270 unique farm properties were identified; of these, 1,238 farms are found within the Whitemans Creek subwatershed.

The MPAC parcel layer is highly detailed, with properties boundaries having nearing sub-metre accuracy. However, the MPAC database does not contain any ownership information; thus, it is not possible to identity adjacent farm properties that are owned and worked by a single operator. Each assessment parcel is assumed to represent an individual farm. Further grouping could be undertaken to combine properties that are operated as a single unit. However, as the Irrigation Demand submodule treats irrigated crops at the sub-farm (crop parcel) scale (Section 10.2.2); further grouping of the identified farm properties will not significantly affect the simulated demand.

Each of the 4,270 identified farms was assigned a unique integer identifier. These were colour –coded and shown on Figure 10.11. All crop parcels and irrigation sources are linked to this farm ID number. While the majority of these properties likely do not irrigate, each farm in the Tier 3 model area was assigned an ID to allow flexibility in the development and testing of future water management scenarios.

10.3.2 Linking Farms to Groundwater and Surface Water Sources

Farm operations simulated by the Irrigation Demand module must be provided with one or more sources for irrigation water. The irrigation water sources take the form of either: (1) a well simulated by the MODFLOW WEL package (Harbaugh, 2005); or (2) a stream diversion simulated as an extension of the MODFLOW SFR2 package (Niswonger and Prudic, 2005). The applied rate for each source is determined by the Irrigation Demand Module.

A methodology was developed to assign at least one well source and/or stream diversion source for each farm properties. These sources are toggled on or off to accommodate various simulation scenarios. Within the Irrigation Demand module, each source (whether well-type or stream diversion-type) is required to have its own unique Source ID number and must also be assigned to one specific Farm ID.

The generation of irrigation source inputs for the Irrigation Demand module utilized several different datasets, which needed to be interpreted using existing hydrostratigraphic and numerical model inputs. A summary of these datasets and model files is provided in Table 10.2.

Table 10.2: Summary of Required Input Datasets for Irrigation Source Inputs.

Require Dataset	Well-Type Source	Surface Diversion-Type Source
MOECC Permit to Take Water Database	✓	✓
MOECC Water Well Information System Database	✓	
Study Area Farm Property Mapping (i.e. Farm IDs)	✓	✓
Numerical Model Layers (Geometry and Hydrostratigraphic Unit Type)	✓	
Base MODFLOW SFR2 Input File (Model streams and watercourses))		✓

As an initial step, irrigation source inputs were generated for each of the mapped farms without considering the available PTTW dataset. Each farm was assigned a “virtual” groundwater source and, where applicable, a “virtual” surface water source to represent a best guess of where the farm might obtain irrigation water. With over 4,200 farms in the model area, it was necessary to rely on automated methods to assign locations for the virtual sources. Accordingly, “virtual” sources locations may not correspond to the actual source locations, however, the spatial error of the source assignment should not significantly affect the results at the subwatershed scale. Once the virtual irrigation sources were generated for each of the farm properties, the existing agricultural sources in the PTTW database were linked, through a proximity analysis, to the Farm ID, as discussed below.

10.3.2.1 Well Source Inputs

The input requirements for the MODFLOW WEL module were modified slightly to require specification of a unique Source ID number along with the standard source location information (in terms of model layer, row, and column). Data from the MOECC WWIS database were utilized to assign reasonable values for assigning source location, as follows:

- Where a single WWIS well record was identified on the property, the irrigation source location (row and column) was assigned according to the well coordinates and the well screen information was used to assign the model layer.
- Where multiple well records were identified on the property, the irrigation source location was assigned to the centroid of the farm property. The well screen information from all of the wells was reviewed, and the source layer was assigned based on the most commonly screened unit.
- Where no WWIS well records were identified on the property, the irrigation source location was assigned to the centroid of the farm property. The well screen information from the closest well within 400 m of the property was used to assign the source layer. If no well was found within 400 m, the search radius was extended out to 1500 m and all intersected well records were reviewed. The most commonly occurring screened unit was assigned as the source layer.

Using this approach, a total of 4,270 virtual groundwater (well) sources were generated for each of the 4,270 mapped farm properties. Figure 10.12 presents the assigned virtual groundwater sources for delineated farms in an area adjacent to Whitemans Creek.

10.3.2.2 Surface Diversion Inputs

Surface water sources were represented as streamflow diversions and were assigned as an additional source to each farm property considered to have reasonable access to a stream. For this study, it was assumed that a farm property had to be within 800 m of a Strahler Class 2 or higher (based on the distance from centroid of the property). A farm could also access a lower Strahler Class 1 stream, provided it was within 400 m of the stream. This automated approach ensured that larger streams with greater flows were favoured.

To create a stream diversion using the MODFLOW SFR2 streamflow routing module, a new stream segment had to be created by providing a stream location (row and column) and stream segment number. The diversion type and upstream segment number must also be identified. For this study, all virtual stream diversions for irrigation were added as Type 4 diversions which were allowed to divert up to 20% of the available streamflow. A total of 2,855 stream diversions were added for 2,855 of the 4,270 mapped farm properties. Figure 10.12 shows the virtual stream diversions assigned to farms in a small area adjacent to Whitemans Creek.

10.3.2.3 Linking Existing PTTW to Farms/Validation Dataset

Permit sources from the MOECC PTTW database with a primary purpose listed as "agricultural" were linked to the farm properties using a spatial join. A total of 933 individual agricultural permit sources within the model area were successfully linked to the farm properties. Figure 10.12 and Figure 10.13 provide examples of farms with identified virtual sources linked to permits. Properties with identified permits are presented on Figure 10.14 showing the entire subwatershed. Farms with identified permits and WTRS data were used as calibration/validation targets for the Irrigation Demand module.

Figure 10.15 illustrates the permits within the study area that were not matched to any specific farm. A total of 80 agricultural permits (8%) could not be joined to a specific property. Of the 80, only 8 had WTRS data associated with the permit. These permits were assigned to a unique farm by hand based on air photo interpretation of the source. Every permitted source with non-zero WTRS data has been assigned to a farm property within the model area.

10.3.3 **Maximum Allowed Daily Takings per Farm**

At the farm scale, an estimate of the maximum irrigated area per day and/or maximum allowed daily taking is required as an input into the Irrigation Demand module. This latter limitation is needed to prevent the irrigation demand for a large farm from exceeding the available supply from a stream or aquifer unit. For example, a 40 ha farm may need to irrigate the majority of the crop lands, however, these takings are usually split over a 5, 7, or 14-day period. As such, this farm may generate 10,000 m³ of demand, but the water takings to satisfy this demand would be 720 m³/d if split over two weeks. While the maximum daily takings vary between individual operators, reasonable estimates can be inferred from the PTTW database.

Agricultural PTTW applications usually require the operator to submit a calculation worksheet which provides information for the farm. While this information is not included in the PTTW database, paper records are maintained at MOECC offices. In 2006-2007, the GRCA compiled the MOECC records for permitted agricultural users within the GRCA. Data relating to installed irrigation equipment and crop types were added to a separate GRCA database. Within this database, 69 entries were found that corresponded to current or lapsed permits within the model area. A brief assessment of these data was undertaken to determine typical daily irrigation rates at farms within the study area.

Irrigation pump capacity was included in the database for 62 of the 69 linked permits. The daily irrigation capacity was calculated by multiplying the system capacity by the maximum allowable pumping time associated with each PTTW. Figure 10.16 illustrates the installed capacity of permitted irrigators within the GRCA database. The average daily capacity of the 62 operators is 1,785 m³/d. Assuming a 12-hour work day, this corresponds to an average pump capacity of 41 L/s or 550 IGPM. This value closely agrees with Latornell (1962) who surveyed 184 irrigators and found an average installed capacity for farms in the Whitemans Creek subwatershed of 580 IGPM. This installed capacity estimate also compares favourably to the maximum permitted taking volume (Figure 10.6). This is not surprising, as the MOECC uses the equipment and scheduling information submitted with the PTTW application to set the maximum daily permitted rate.

With respect to the input data for the Irrigation Demand module, farms that were linked to current PTTWs were assigned the maximum daily permitted rate specified in the PTTW database. If this value exceeded 5,000 m³/d, the value was capped at 5,000 m³/d to ensure that it matched the reasonable application rates based on the analysis of the GRCA permit database. Where no PTTW source was found, farms were assigned a default maximum value of 1,785 m³/d. This value is equivalent to a maximum daily irrigated area of 4.5 ha/d, assuming a typical irrigation depth of 25 mm.

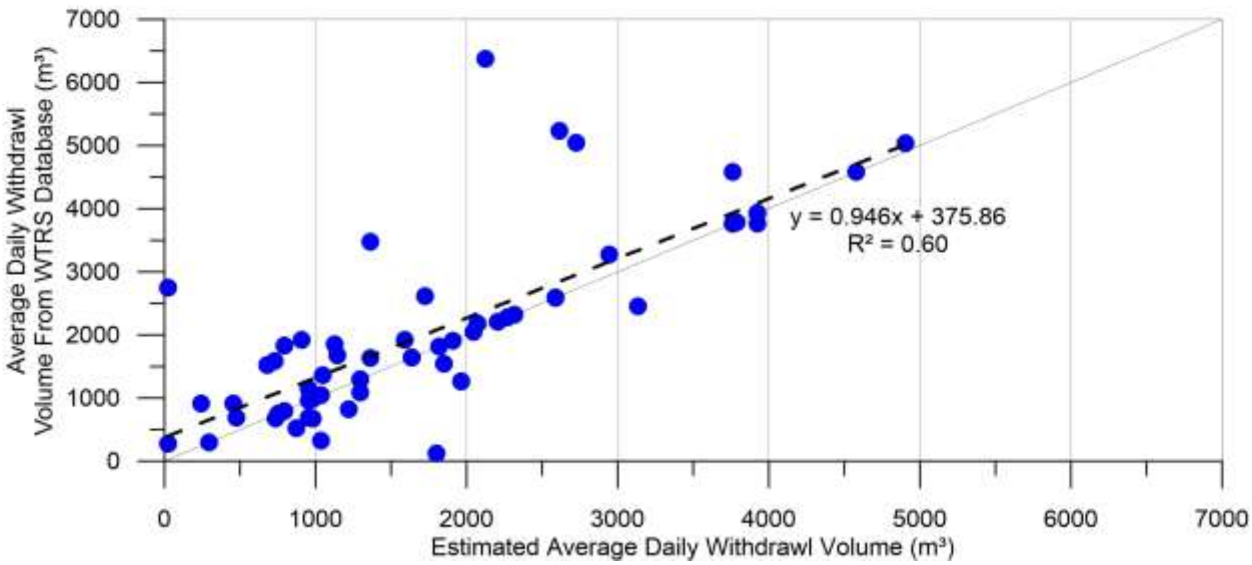


Figure 10.6: Installed irrigation capacity versus maximum permitted rates for selected agricultural permits within the model area.

10.3.4 Parcel and Crop Identification Numbers

As discussed in Section 2.3, there are several mapping products available which describe the crop coverage within the study area. The various vintages and types of mapping have differing crop schemas, descriptions, and levels of detail. To simplify the model inputs, crops were categorized with a simplified schema which grouped crop types by irrigation requirements. For example, beans, beets, carrots, celery, cucumber, garlic, lettuce, onion, pepper, eggplant, and potato have all been classified as shallow-root vegetables because the irrigation rules that govern these crops are similar. The various agricultural cover types within the study area have been grouped into 11 classes, 8 of which include crop types which typically require irrigation.

The 2013 and 2016 OMAFRA Agricultural Resource Inventory mapping is presented in Figure 10.17 and Figure 10.18, respectively, with the generalized classification scheme. The AAFC annual crop inventories for the years 2011 through 2015 are presented on Figure 10.19 to Figure 10.23, respectively. Because the AgRI crop coverage's are primarily derived from field observations, this dataset represents the preferred source for model inputs; however, this coverage does not extend to the model boundaries. Both OMAFRA and AAFC products exist for 2013, and an analysis of the remotely sensed AAFC mapping suggests its predictive capability is high (Section 2.3).

The final crop inputs for the Whitemans Tier 3 model were created by merging the 2013 and 2016 OMAFRA AgRI mapping products, with preference given to the 2013 coverage. Gaps and areas with unknown crop types were infilled with the 2013 AAFC annual crop inventory. The merged coverage is presented on Figure 10.24. The breakdown of crop types, as incorporated into the Whitemans Tier 3 Assessment model, is provided in Table 10.3. The historical 1983 AgRI coverage was also converted to the simplified scheme (Figure 10.26). One obvious change that can be seen in this representation is the marked decrease in the extent of tobacco growing in the southeastern part of the study area. The data set could be used in future studies to represent historical irrigation demand within the study area.

Table 10.3: Simplified crop schema breakdown.

Description	Whitemans Creek Subwatershed		Model Area	
	Area (km²)	Proportion	Area (km²)	Proportion
Non-Agricultural	112	27.8%	390	25.6%
Unknown	0	--	0	--
Roughland	9.80	2.4%	13.3	0.87%
Pasture	7.54	1.9%	9.31	0.61%
Forage	25.6	6.4%	177	11.6%
Field Crops	227	56.5%	882	58.0%
Berries	0.01	0.003%	0.814	0.053%
Fruit Orchards	0.25	0.062%	2.65	0.17%
Shallow-rooted Vegetables	6.65	1.66%	14.7	0.97%
Deep-rooted Vegetables	0.292	0.073%	0.338	0.022%
Tobacco	7.77	1.94%	18.0	1.19%
Ginseng	1.44	0.36%	4.37	0.29%
Sod	0.65	0.16%	0.774	0.05%
Potato	2.76	0.69%	7.93	0.52%
Total Irrigable Crop Area	***19.8***	***4.94%***	***49.6***	***3.26%***

(Grey shading indicates crops requiring irrigation.)

Further post-processing was required to generate the required inputs for the Irrigation Demand module. Within each identified farm, subareas (referred to as parcels) were delineated for each crop grown. Each parcel was assigned a unique identification number. As was discussed earlier, the model assumes that only one parcel or part of a parcel can be irrigated on a given day. Each parcel, in turn, is represented by one or more HRUs (PRMS model cells).

Parameters related to irrigation demand calculation and operational rules for each crop type are provided as input to the Irrigation Demand module. These parameters are critical to estimating the daily volumes of water extracted from the irrigation sources and the volumes applied and area covered on each parcel. Background information and the methodology for selecting parameter values are discussed below.

10.3.5 Irrigation Rates and Rules

Irrigation rules for each crop type identified in the study area were estimated through a review of previous studies in Ontario as well as some additional data from other provinces. Efficiency factors were derived from book values for equipment typical employed in Ontario. The following section provides a summary of the literature review conducted to develop input parameters for the Irrigation Demand Submodel. Values applied in the Whitemans Tier 3 Assessment model are described in Section 10.3.5.4.

10.3.5.1 Literature Review

The Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) recommends several best management practices for irrigation, the most accessible and most widely adopted is irrigation scheduling. A crucial component of irrigation scheduling is knowing when irrigation is required in order to maximize yield and minimize costs associated with water use. Bernier *et al.* (2010) analysed irrigation practices in southern Ontario and noted:

> *"…most growers schedule irrigation by drawing on past experience: observing the condition of the plants, examining and feeling the soil to determine the soil moisture content, and adhering to weather forecasts. Even if this subjective method of determining soil moisture can become fairly accurate with practice and diligence, UMA Engineering Ltd. (2007) showed that with few exceptions, this technique largely overestimates the crop water needs."*

Other, more standardized, methods have been developed (see ARD, 2013; Brouwer *et al.*, 1989; and OMAFRA, 2004, 2011). The first step in any irrigation scheduling plan is to determine, whether or not irrigation is necessary on that day. To make an informed decision, the antecedent moisture conditions must be known. This is done either by manually measuring soil moisture or by estimating soil moisture using a running water balance. The water balance approach requires tracking precipitation and irrigation volumes and the rate of crop water use. Crop water use is calculated by multiplying the evapotranspiration (ET) rate by a crop factor (typically between 0.2 and 1). Examples of the water demand of different crop types derived from ET values over the Ontario irrigation season are provided in Figure 10.7. The irrigator must then decide what the critical moisture conditions are to trigger irrigation. This threshold is called the maximum allowable depletion (MAD), also referred to as the management allowable depletion. The concept of a soil moisture-based irrigation demand trigger is fundamental to the Irrigation Demand module.

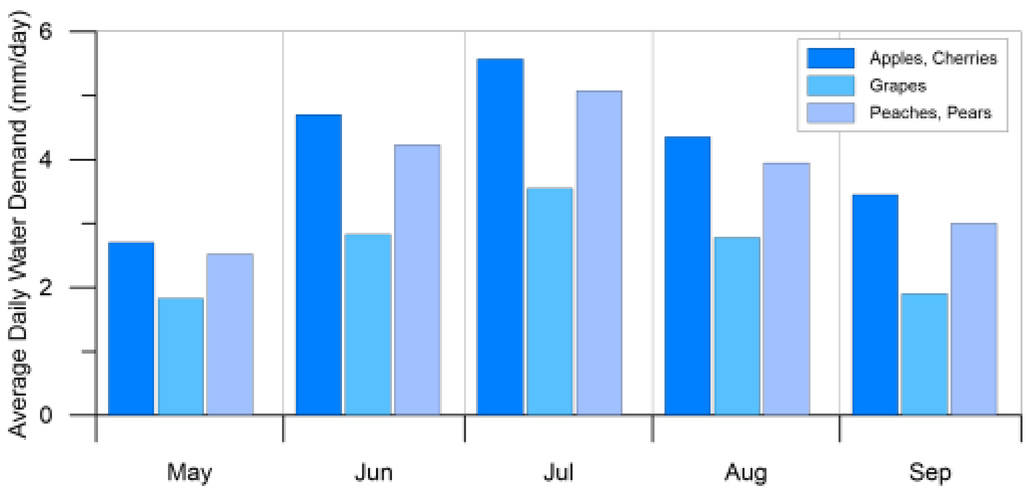


Figure 10.7: Average daily water demand of various fruit types over the irrigation season (Monthly averages taken from OMAFRA (1990a)).

MAD is a parameter that irrigators use to determine, for a given crop type, when it is appropriate and how much to irrigate. MAD is a measure of the percentage of the available soil water (ASW) within the root zone that may be used by a crop before yield-reducing water stress occurs. The ASW corresponds to soil water between field capacity and the wilting point of the crop (Bernier *et al.*, 2010). Studies by Kashyap and Panda (2003) and Panda *et al.* (2003, 2004) investigated the optimal MAD for potato, wheat and maize crop, respectively. All three studies reached similar conclusions; finding that a critical MAD of 45% produced maximum yields while avoiding water-stressed conditions. While these studies were conducted in a sub-tropical region, they produce reasonable estimates for southwestern Ontario. For instance, OMAFRA recommends, as a rule-of-thumb, target depletions of 50% and 20% for sprinkler and drip irrigation systems, respectively (OMAFRA, 2011).

10.3.5.2 Irrigation Efficiency Factors

Irrigation methods within the study area include sprinkler systems, and micro-irrigation (drip irrigation). Sprinkler irrigation systems spray water above the crop canopy while micro-irrigation delivers water either directly onto or slightly beneath the soil surface near individual plants. Statistics Canada (2010) showed that sprinkler irrigation is the most widely-used application method for all crop types by a large margin, apart from irrigation of fruit crops where sprinkler and micro-irrigation methods were equally popular.

It is important to consider the efficiency of each irrigation method (Bos and Nugteren, 1990). The efficiency factor includes losses from the irrigation system such as wind drift of water droplets outside target area and evaporation of water droplets before entering the soil zone. Values of estimates of the application efficiency factors of different irrigation methods are summarized in Table 10.4. Efficiency factors are specified as part of the crop data input for the Irrigation Demand module.

Table 10.4: Application efficiencies for different Irrigation Systems. .

Irrigation Method	Irrigation System	Application Efficiency (%)
Surface Irrigation	Furrow (conventional)	45-65
	Furrow (Surge)	55-75
	Furrow (with tail water reuse)	60-80
Sprinkler	Solid Set and Hand Move	65-85
	Lateral Moving	75-85
	Center Pivot	75-85
	Volume Gun / Traveler	65-75
Micro-irrigation	Spray	85-90
	Surface Drip	85-95
	Subsurface Drip	>95

Source: Irmak et al. (2011)

10.3.5.3 Irrigation Rates per Crop Types

Determining irrigation rates requires consideration of the crop type, soil type and the slope of the land surface. General water requirements of different crop types are presented in Table 10.5. The values were obtained from OMAFRA sources, where available; and supplemented by more comprehensive estimates by Ecologistics Limited (1993) (see Appendix D). For comparison, reported irrigation rates for different crops within the GRCA are also presented in Table 10.6. Some minor crop types have been combined into larger categories due to their similar irrigation demands.

Table 10.5: Literature values of water requirements and typical irrigation methods organized by crop type.

Crop Category	Crop Type	Water Requirement	Irrigation Method	Comments
Field and Pasture	Berries (Blueberries, Raspberries, Strawberries, Other)	25 - 50 mm per week[1]	Trickle, Sprinkler	Strawberries need to maintain ASW above 50%. Irrigation not to exceed field capacity.
	Shallow-rooted Vegetables (Beans, Beets, Cole Crop, Carrot, Celery, Cucumber, Garlic, Lettuce, Onion, Pepper, Eggplant, Potato)	25 mm every 7 days, 40-50 mm every 7 days during critical growth stages[1]	Sprinkler, Trickle, Subsurface drip	Low pressure nozzles commonly used
	Medium-rooted Vegetables (Tomatoes)	25 mm every 10 days, 40-50 mm every 10 days during critical growth stages[1]	Trickle, Sprinkler	
	Deep-rooted Vegetables (Asparagus, Sweet Corn, Sweet Potato, Watermelon)	50 mm every 14 days[1]	Sprinkler	
	Field Crop (Wheat, Oats, Barley, Corn, Rye, Hay, Forage, Canola, Soybeans, Dry Field Beans)	Not Irrigated[3]		
Fruit Orchards	Tree Nuts (Filbert/Hazelnut, Heartnut, Chestnut, Walnuts, Pecans)	Not Found	Trickle, Sprinkler	May or may not require irrigation on an annual basis
	Apples	25 mm every 14 days (7 days in July and Aug)[1]	Trickle, Sprinkler	Irrigation rate to maintain 50 - 100% ASW
Mkt. Garden / Flowers		Not Found		
Nursery	Seedbeds	12.5-25 mm per week[1]	Sprinkler	Irrigation rate to maintain soil near field capacity
	Liner Beds		Sprinkler	
	Caliper trees		Drip, Sprinkler	
Tender Fruit	Peaches & Nectarines	25 mm every 14 days (7 days in July and Aug)[1]	Trickle, Sprinkler	Irrigation rate to maintain 50 - 100% ASW. Best management practice is to maintain 50% ASW
	Pears	25 mm every 14 days (7 days in July and Aug)[1]		Irrigation rate to maintain 50 - 100% ASW
	Plums	Not Found		
	Cherries	35 mm per application[3]		
	Apricots	Not Found		
	Grapes	1.2 - 4 mm per day[2]		
Tobacco	Tobacco	20-40 mm per application[1]	Sprinkler	Irrigate at 60% ASW[1]
Sod Farm	Sod	25 mm per application[3]	Sprinkler	
Other	Ginseng	25 mm per application[3]		

[1] Estimated irrigation water requirement of crop from OMAFRA (2004)

[2] Average daily water requirement derived from ET calculations from OMAFRA (1990a)

[3] Ecologistics Limited (1993)

Table 10.6: Reported irrigation rates within the GRCA, organized by crop type.

Crop Type	Number of Records in GRCA	Number of Records in Whitemans Creek	Average Irrigation Application (mm)	Average Irrigation Frequency (days)
Tobacco	714	59	22.32	7.62
Shallow rooted vegetables	237	21	21.29	7.61
Ginseng	184	17	16.97	11.56
Vegetables - undefined	143	2	19.88	7.56
Potato	94	27	24.18	7.95
Sweet Corn	67	-	22.27	7.15
Berries	53	4	18.24	6.9
Corn	51	7	21.27	8.82
Deep rooted vegetables	45	-	22.01	9.21
Golf/Recreational Grass	32	-	11.15	3.92
Medium rooted vegetables	29	1	26.49	6.96
Nursery	19	-	22.06	13.72
Sod/Turf	18	6	20.46	7.9
Tender Fruit	14	-	28.58	8.77
Field and Pasture	12	4	28.58	11.44
Apples	8	-	19.05	11.5
Mkt. Garden / Flowers	8	-	16.67	6.86
Tree Nuts	5	4	20.32	9.25
Other	5	-	20.32	10.88

The average irrigation depth shown in Table 10.6 is based on estimates from irrigators in the GRCA. These values were used to develop irrigation rules for different crop types to drive the Irrigation Demand module. For instance, land parcels that are known to grow vegetables may be irrigated approximately 20 mm every 7 days provided there is a crop water deficit.

To assess the suitability of these estimates, WTRS data were compared with irrigation equipment data and irrigation rate data provided by the GRCA. The datasets were linked by their PTTW identifier. 92 of the reported irrigation rate records had reported water takings between 2009 and 2014 and were able to be matched with their irrigation equipment specifications. A comparison between the estimated and the reported average withdrawal volume is shown in Figure 10.8 and the data were found to be reasonably well correlated.

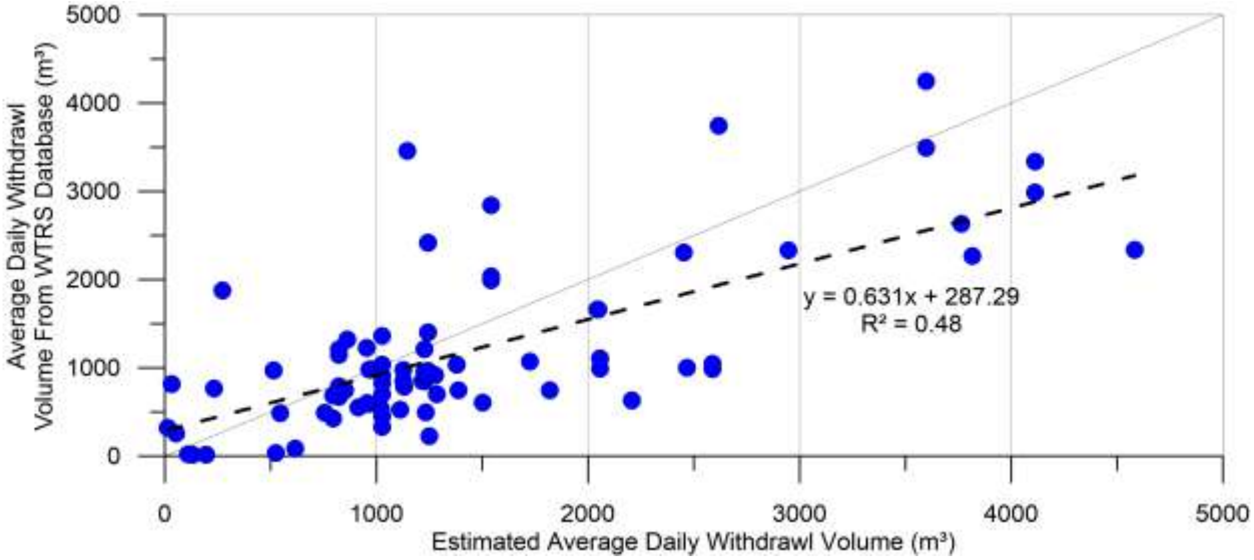


Figure 10.8: Estimated withdrawal volume vs. average reported taking volume (m³).

10.3.5.4 Crop Parameter Inputs

Based on the review of typical irrigation patterns by crop type in Ontario and an assessment of irrigation patterns within the Grand River watershed, irrigation rules were developed for each crop type within the model area. Table 10.7 presents the moisture deficit triggers for each crop type as well as information on equipment efficiencies. The minimum required period between irrigation events for crop type is based on the value provided in Table 10.5 and Table 10.6. All crop types, other than field crops, were assumed to follow the irrigation schedule regardless of whether the operator held a permit or not. Field crops have been included in the irrigation schedule, because there is evidence that operators irrigate field crops during drought conditions. However, only farms with field crops and with valid permits were simulated using the Irrigation Demand module. Table 10.8 presents the irrigation application rates per watering event for each simplified crop type identified within the Whitemans Creek subwatershed.

The Irrigation Demand module can vary the application rate on a monthly basis. This allows crops types which do not require continuous irrigation to simulated. For example, ginseng typically only requires one or two annual watering in late-June to late-July during berry development (OMAFRA, 2004). Tobacco has differing irrigation demands over the growing season. The period immediately after transplanting the seedling into the field requires excess moisture to establish the rooting systems; therefore, application rates are higher during this window.

Table 10.7: Moisture triggers, equipment types, and irrigation frequencies by crop type.

Description	Whitemans Creek Subwatershed		Moisture Deficit Trigger (% ASW)	Irrigation Equipment		Minimum Days Between Irrigation (*Irrigation Frequency*)
	Area (km²)	Proportion		Type	Application Efficiency (%)	
Field Crops (permitted farms growing corn only)	227	56.5%	20	Sprinkler	75	14
Berries	0.01	0.003%	50	Subsurface Drip	95	7
Fruit Orchards	0.25	0.062%	75	Surface Drip	90	7
Shallow-rooted Vegetables	6.65	1.66%	50	Sprinkler	75	7
Deep-rooted Vegetables	0.292	0.073%	50	Sprinkler	75	10
Tobacco	7.77	1.94%	60	Sprinkler	75	7
Ginseng	1.44	0.36%	50	Sprinkler	75	14
Sod	0.65	0.16%	85	Sprinkler	75	5
Potato	2.76	0.69%	60	Sprinkler	75	7

Table 10.8: Irrigation application rates by crop type.

Description	Whitemans Creek Subwatershed		Application Rate (mm per watering event)				
	Area (km²)	Proportion	May	June	July	August	September
Field Crops (permitted Farms only)	227	56.5%	25	25	25	25	0
Berries	0.01	0.003%	25	25	25	25	25
Fruit Orchards	0.25	0.062%	025	30	30	30	30
Shallow-rooted Vegetables	6.65	1.66%	25	25	25	25	0
Shallow-rooted Vegetables (drip)	--	--	7	7	7	7	0
Deep-rooted Vegetables	0.292	0.073%	25	25	25	25	0
Tobacco	7.77	1.94%	25	25	25	25	25
Ginseng	1.44	0.36%	25	25	25	25	0
Sod	0.65	0.16%	25	25	25	25	25
Potato	2.76	0.69%	25	25	25	25	0

10.4 *Submodel Validation*

As might be expected, the performance of the Irrigation Demand module is most sensitive to the calculation of the average soil moisture on a HRU and parcel basis. Most of the other input parameters are based on crop information that has been determined from data within or near the study area. Accordingly, correct functioning of the Irrigation Demand module relies upon a good calibration of the integrated GSFLOW model. An initial calibration was done prior to the implementation of the Irrigation Demand module and produced reasonable results. The following presents a validation of the Irrigation Demand module and inputs. Upon completion of the Irrigation Demand module inputs, a final round of calibration was undertaken, discussed in Section 11.

10.4.1 Test Scenario Inputs

To validate the irrigation package, a test scenario based on the inferred crop mapping for the model (Figure 10.24) was developed. During periods of drought, some field crops are also irrigated. Specifically, it was assumed that corn fields cultivated by PTTW holders would be irrigated but only during periods of stress; this is reflected by the low moisture trigger for field crops (Table 10.7). Figure 10.27 presents the areal distribution of simulated crop types for the simulation, Table 10.3 summaries the irrigated area by crop type. Virtual wells, shallow ponds, and stream sources were assigned to each farm found with a valid crop type. Crop and parcel information, presented in Section 10.3.4, was input into the model; these values were not altered during the course of the multi-year simulations.

Table 10.9: Applied crop breakdown.

Description	Whitemans Creek Subwatershed		Model Area	
	Area (km²)	Proportion	Area (km²)	Proportion
Corn	10.7	2.76%	30.3	1.99%
Berries	0.01	0.003%	0.814	0.053%
Fruit Orchards	0.25	0.062%	2.65	0.17%
Shallow-rooted Vegetables	6.65	1.66%	14.7	0.97%
Deep-rooted Vegetables	0.292	0.073%	0.338	0.022%
Tobacco	7.77	1.94%	18.0	1.19%
Ginseng	1.44	0.36%	4.37	0.29%
Sod	0.65	0.16%	0.774	0.05%
Potato	2.76	0.69%	7.93	0.52%
Total Irrigable Crop Area	***30.5***	***7.71%***	***79.9***	***5.26%***

Simulations were undertaken between WY2011 and WY2015, which includes the three-year period with reliable WTRS data (2012-2015). Figure 10.29 presents the applied irrigation water distributed to the various farms over the model area for 2012. Applied volumes ranged from 50 to 300 mm/yr depending primarily on crop type, but also on soil type and antecedent moisture conditions. Figure 10.30 illustrates the distribution of simulated AET; as can be seen, areas with irrigation had elevated annual ET values. Figure 10.31 and Figure 10.32 present simulated irrigation water and actual ET for a portion of the Lower Whitemans Creek watershed. At this scale, it is possible to discern the variation in applied irrigation water and AET for the different crop types.

Annual soil moisture volumes across the model are presented on Figure 10.33. The increase in average soil moisture can be seen at some farms. The other areas of higher moisture in the figure are associated with the groundwater-fed wetland features in the centre of the figure. Simulated soil moisture patterns for August 2012 are shown on Figure 10.34. The relative increase in soil moisture over irrigated crops in the summer months is clearly discernable.

The GSFLOW model runs on a daily basis and the soil moisture deficit over each farm parcel is calculated. Low moisture levels can trigger irrigation events based on the operating rules for each farm and crop type. Figure 10.9 shows the calculated soil moisture deficit at a tobacco farm southeast of Burford. Irrigation water is applied when the available soil moisture, averaged over the farm parcel, drops below the trigger. The series of three panels on Figure 10.35 illustrates the change in irrigation over a three-day period in the Lower Whitemans Creek. The figure shows the farms are applying irrigation water over a period of several days at a rate limited by the crop type and the available water supply. Note the elevated residual soil moisture on previously irrigated parcels.

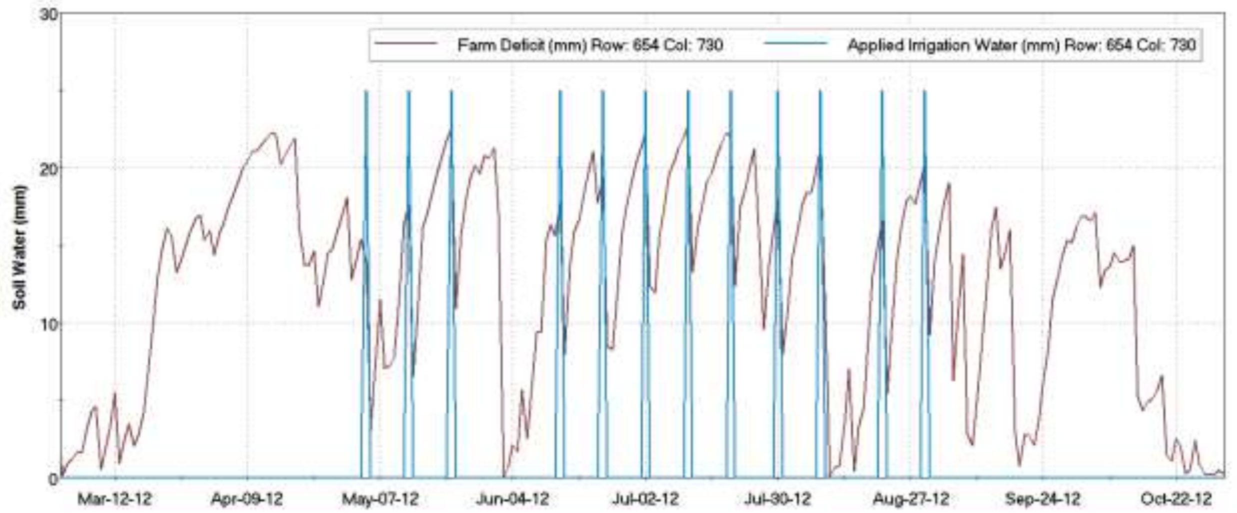


Figure 10.9: Simulated moisture deficit and applied irrigation water at a tobacco farm on the Norfolk Sand Plain near Burford during the 2007 growing season (with recommended deficit triggers).

10.4.2 Validation against Water Taking Reporting System data

As a test of the Irrigation Demand module's ability to reasonably predict agricultural takings, estimated water takings from the Irrigation Demand module were compared against WTRS data. The simulated applied irrigation water volumes were compared with WTRS values for each farm that could be linked back to a current PTTW with some certainty. Large operations and water users with multiple years of reported takings were favoured for this validation exercise

Figure 10.36 through Figure 10.45 present hydrographs of daily and monthly reported WTRS data (in blue) versus the predicted applied irrigation water (in red) at ten farms within the Whitemans Creek subwatershed. The hydrographs cover different periods corresponding to the availability of WTRS for a particular permit. The scales also differ between plots based on the magnitude of the takings. There are year-long gaps in some of the WTRS data. This could be due to incomplete reporting or, possibly, the parcels have been rotated to non-irrigated crops or the fields have been left fallow.

To further evaluate the Irrigation Demand module, takings were evaluated on a subwatershed basis. Table 10.10 presents the total annual reported volumes of irrigation water reported through WTRS. Simulated irrigation volumes triggered by the irrigation module generally compare well, but overpredict during the wet year (2014.)

Table 10.10: Simulated agricultural water use versus reported WTRS values for the model area.

Year	Observed WTRS Takings at Matched Farms (m^3/d)	Simulated Irrigation Volume (m^3/d)
2012	8,810	10,100
2013	7,380	8,540
2014	4,520	8,290

In general, the match between the reported and predicted monthly volumes is reasonable and was felt to be adequate for model calibration, although discrepancies in timing do exist. For example, Figure 10.36 shows the reported and simulated takings for Farm 438 which was classified as a shallow-rooted vegetable farm. The model tends to under-predict the length of the irrigation period with reported irrigation starting earlier in spring and ending later in the fall. The volumes are close for 2013 and 2014, but are low for the 2012 drought. The opposite is true in most of the other hydrographs with the model over-predicting the length of the irrigation period in some years and generally over-predicting monthly volumes.

While every effort was made to collate a comprehensive crop map for the study area, there are undoubtedly some areas where the mapped crop types do not match the parcel dimensions exactly, where crop types may have changed over the years, and where reported takings are incomplete. In addition, the triggers are based on recommended practices which may or may not be followed at individual farms. As well, the simulated average soil moisture for the parcel may not always correspond to the moisture content determined by a farmer examining and feeling the soil or calculating a water balance. Farmers also tend to be conservative and may delay irrigation and the associated expenses in the hope that rain will come within a reasonable time. These factors may result in an overestimation or underestimation of true application rates for individual farms. However, the timing of the application should still be similar and through adjustments of the model assumptions and model inputs, we were able to improve initial results over the course of this work.

One concern is that the predicted rates do not appear to vary significantly from year to year (see the monthly averages presented in Figure 10.36 and Figure 10.37, for example) despite the differences in annual precipitation (Figure 4.17). The reported data generally shows more year-to-year variation. The simulated soil moisture deficit varies considerably from day-to-day (see Figure 10.9 for example) and it was suspected that the triggers assigned are generally too low. The original deficit triggers were assigned based on best management practices; based on preliminary results, the deficit triggers were relaxed to improve the overall match to observed takings. It was determined that many operators irrigate at moisture triggers 10-20% lower than recommended by best management practices.

10.5 *Application to the Tier 3 Model*

There are few large, permitted agricultural operations or inferred irrigable croplands located near the Bethel or Bright wellfields. Accordingly, the irrigation demand module inputs were found to have negligible impact on the calibration at either location. The application of the irrigation demand module was, however, found to offer an improvement in the calibration to streamflow compared to when using just the WTRS data. Figure 10.46 presents four hydrographs comparing the flow observed in Whitemans Creek to scenarios with no water takings, applying reported WTRS takings only, takings simulated with the Irrigation Module (irrigable crops and permitted corn), and takings simulated with the Irrigation Module and with irrigation at all permitted farms (irrigable crops, permitted corn, and permitted field crops).

Because the irrigation demand obtained from the scenario described in Section 10.4.1 (with modified crop irrigation rules) appeared reasonable, this inputs for this scenario were used during the final calibration of the GSFLOW model. More aggressive scenarios (e.g., irrigation at all permitted farms) appear to better simulate streamflow during the summer months; however, takings from these simulations are high (>30,000 m^3). Likely, the distribution of water taken from the virtual sources could be improved. For example, a better representation of summer low flows could be obtained if more takers were assumed to be drawing directly from the stream system rather than from wells. Additionally, if a farm has multiple sources available, irrigation takings are balanced between stream diversions and groundwater wells. Further analyses could be undertaken to vary this percentage; for example, farms with easy access to a surface water source could be assumed to prefer that source.

Evaluation of the effects of irrigation on the watershed or specific natural features are planned to be undertaken in future studies.

10.6 *Figures*

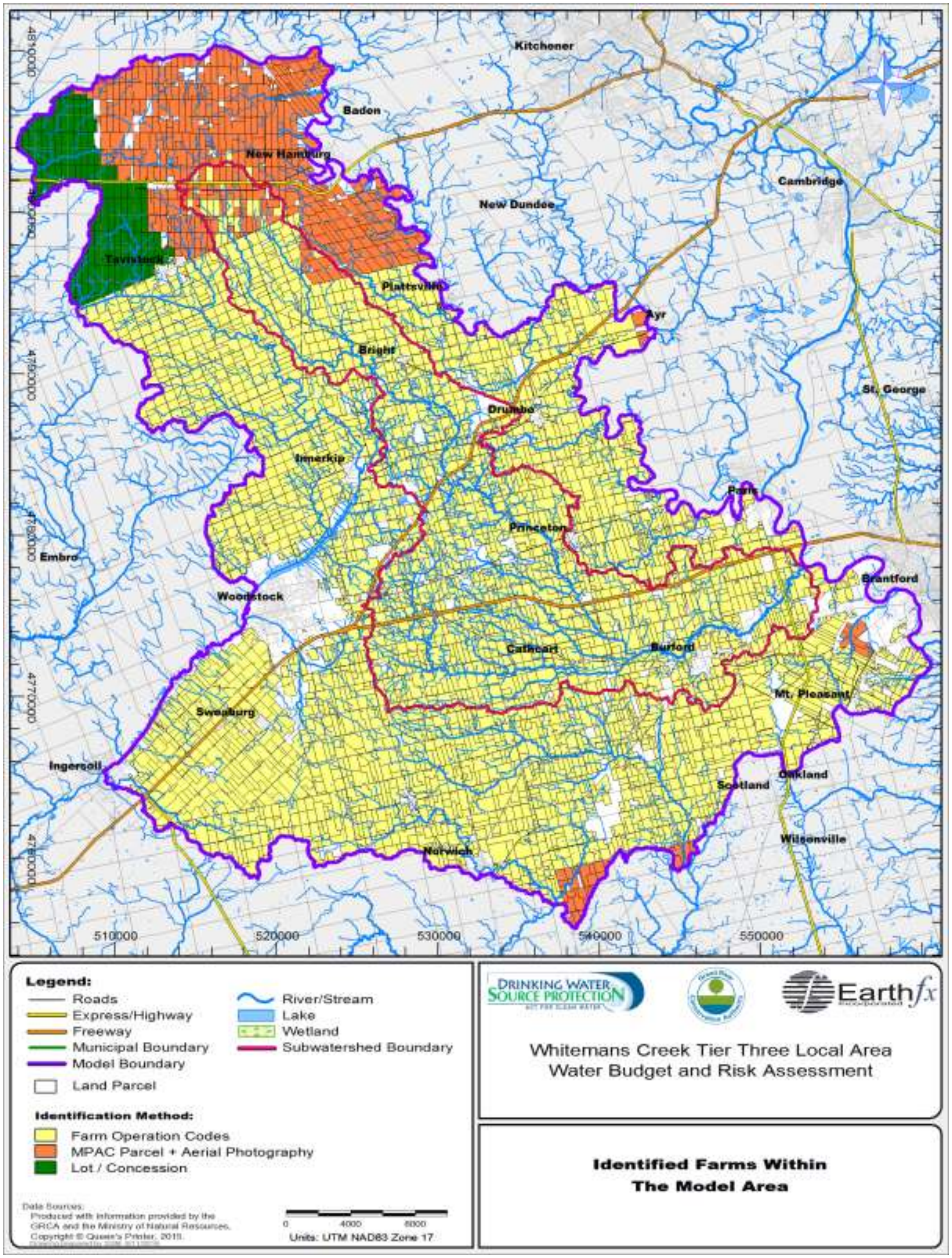


Figure 10.10: Unique farm parcels identified by source.

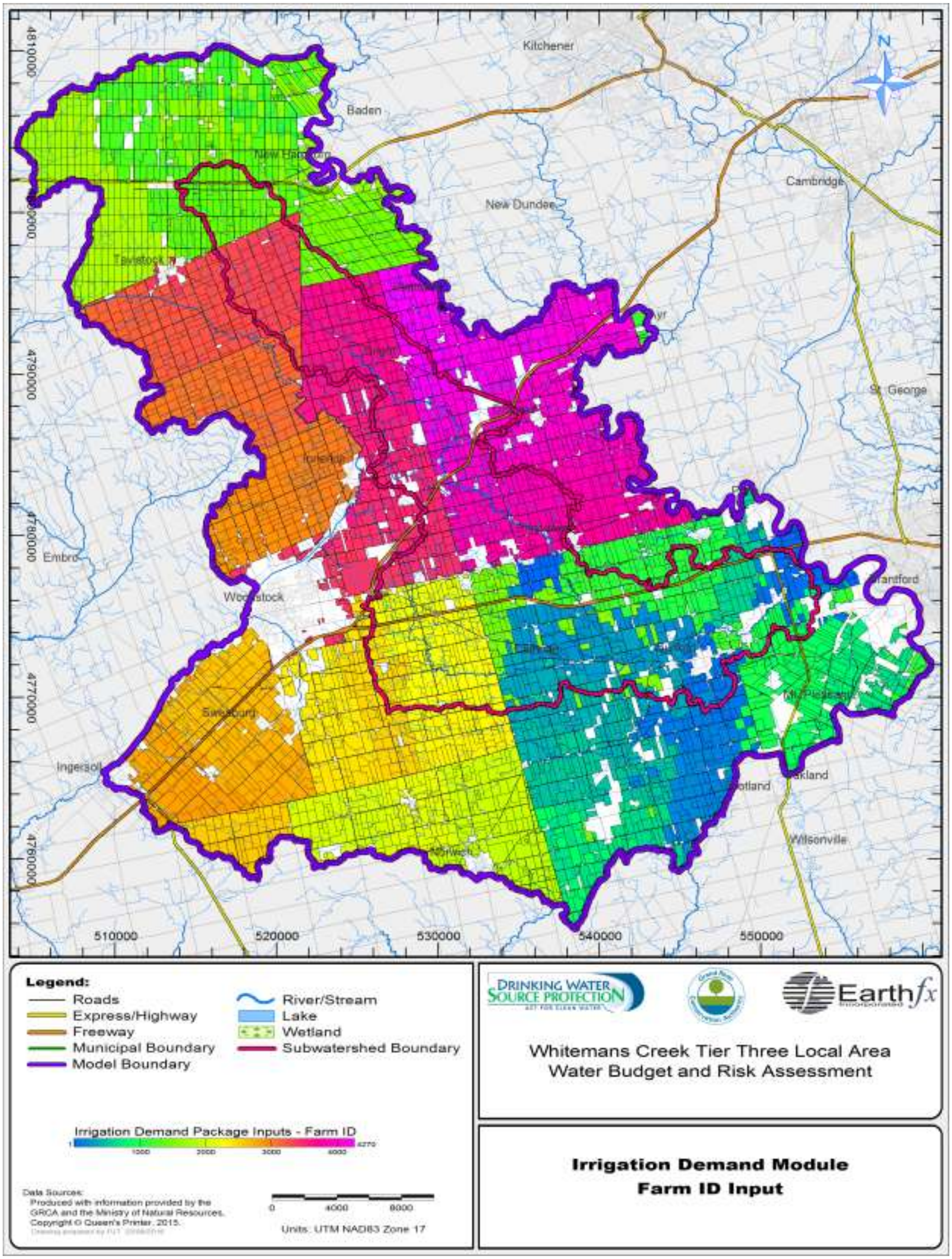


Figure 10.11: Unique farm parcels identified by integer ID.

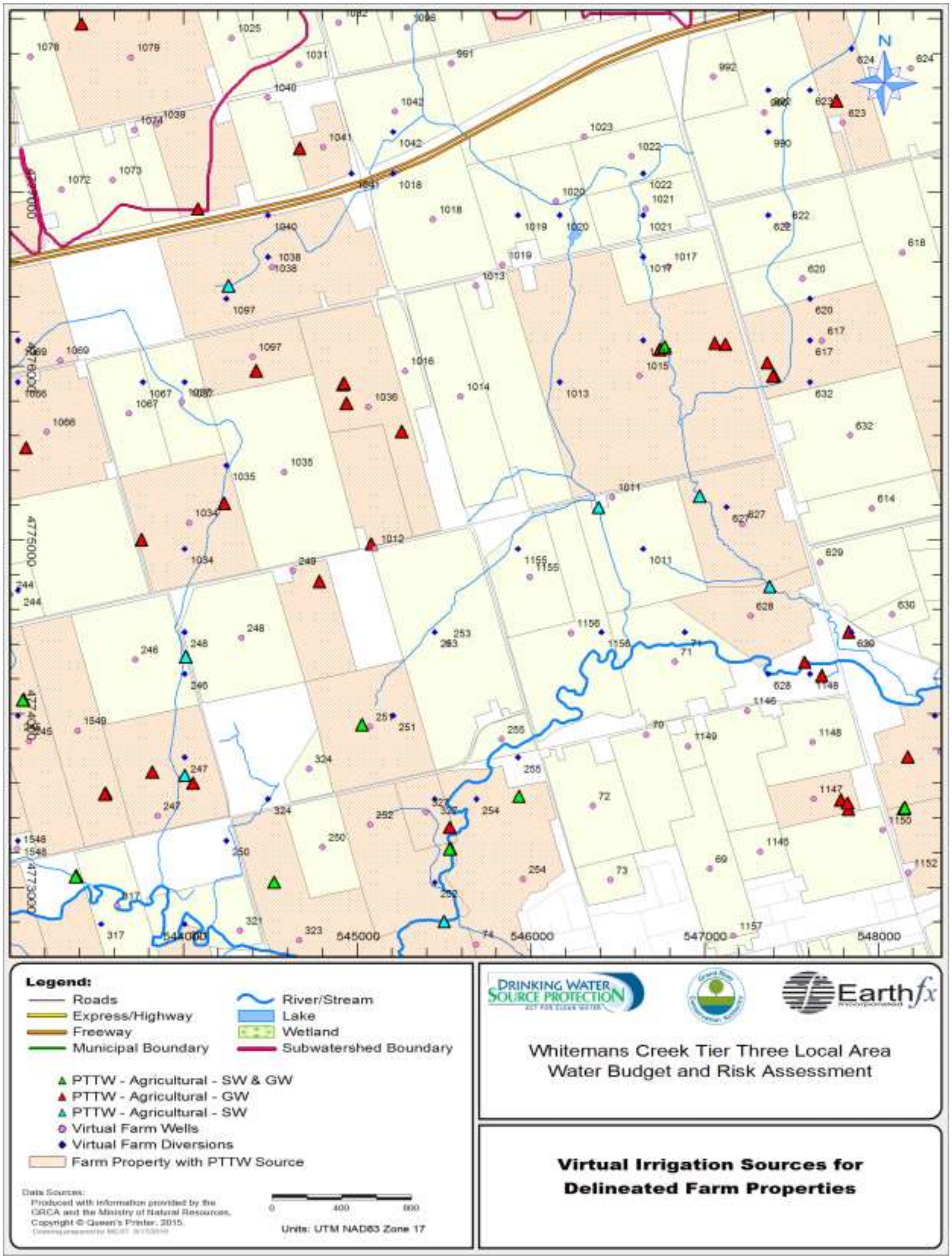


Figure 10.12: Example of assigned virtual irrigation sources for delineated farm properties.

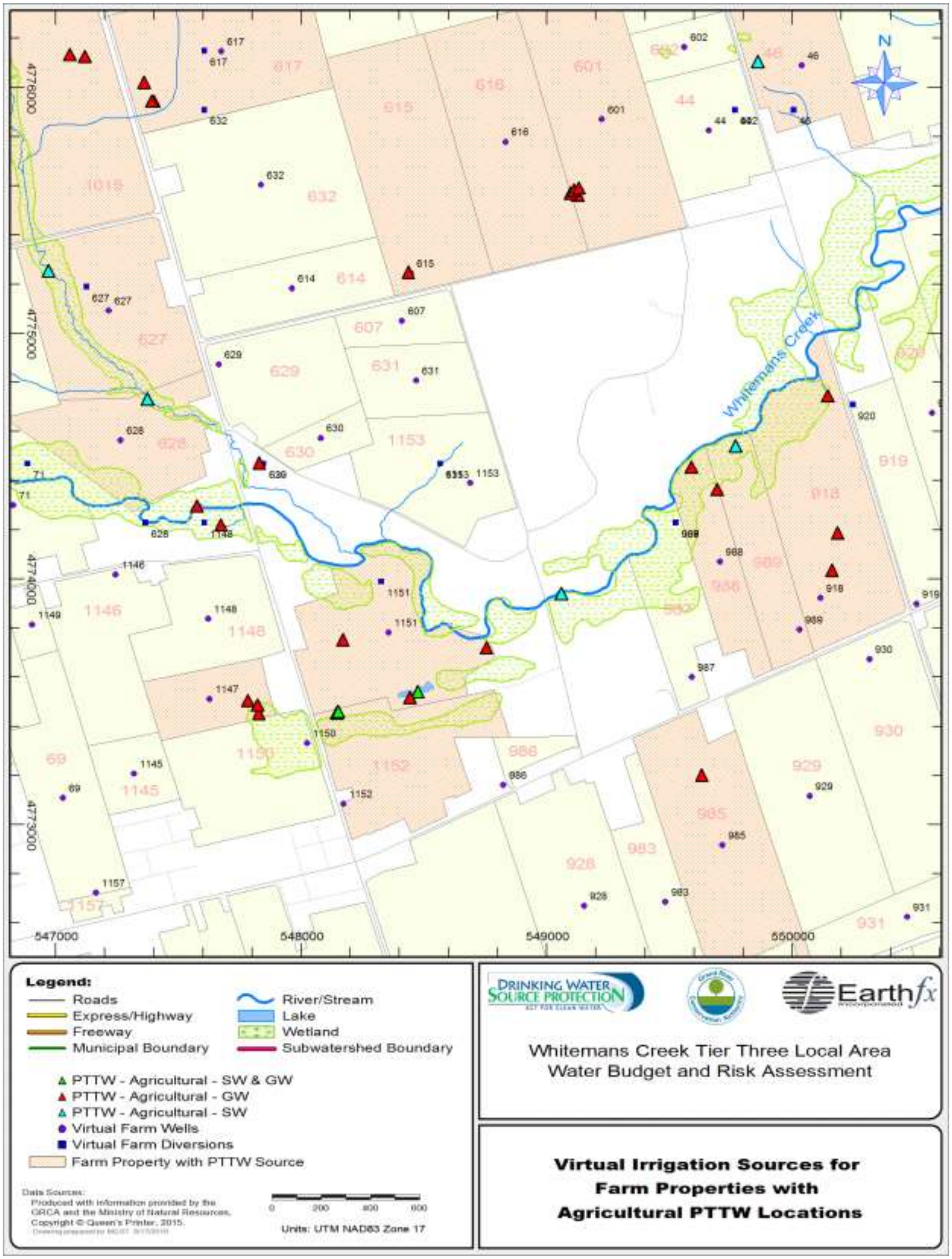


Figure 10.13: Example illustrating correlation between farm properties and PTTW locations.

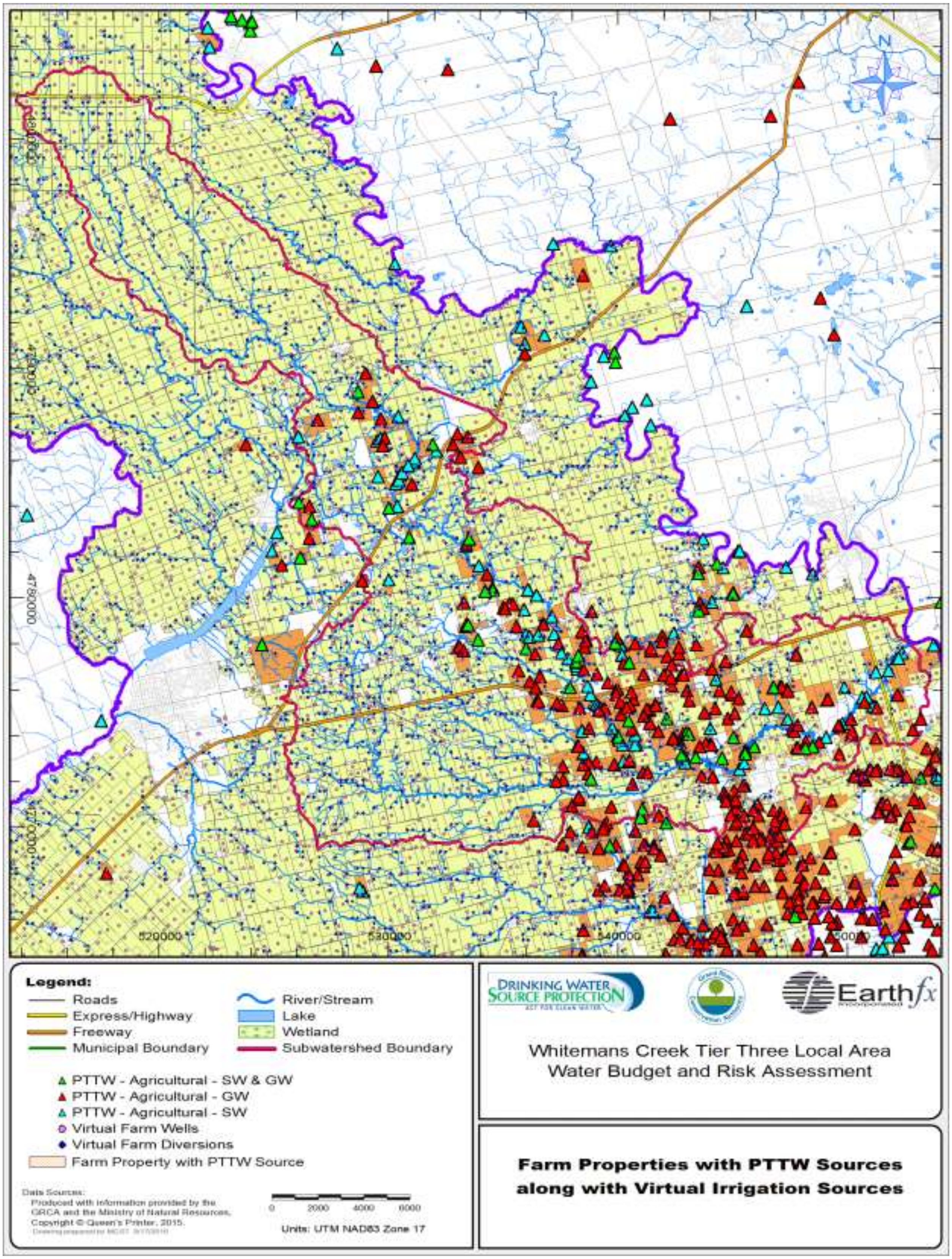


Figure 10.14: Subwatershed farm properties with PTTW sources and virtual irrigation sources.

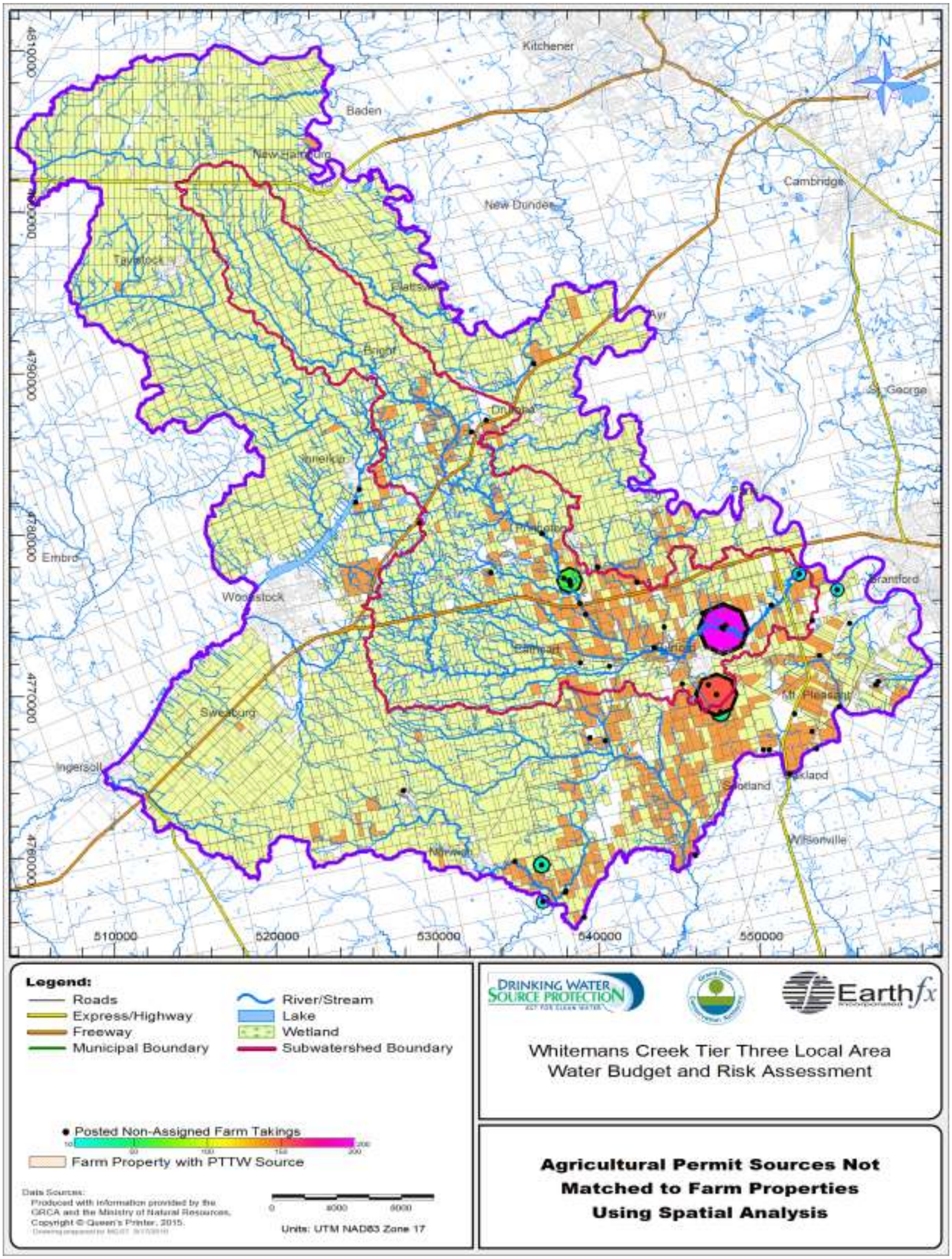


Figure 10.15: Agricultural PTTW sources not linked to a specific farm property with average annual WTRS takings.

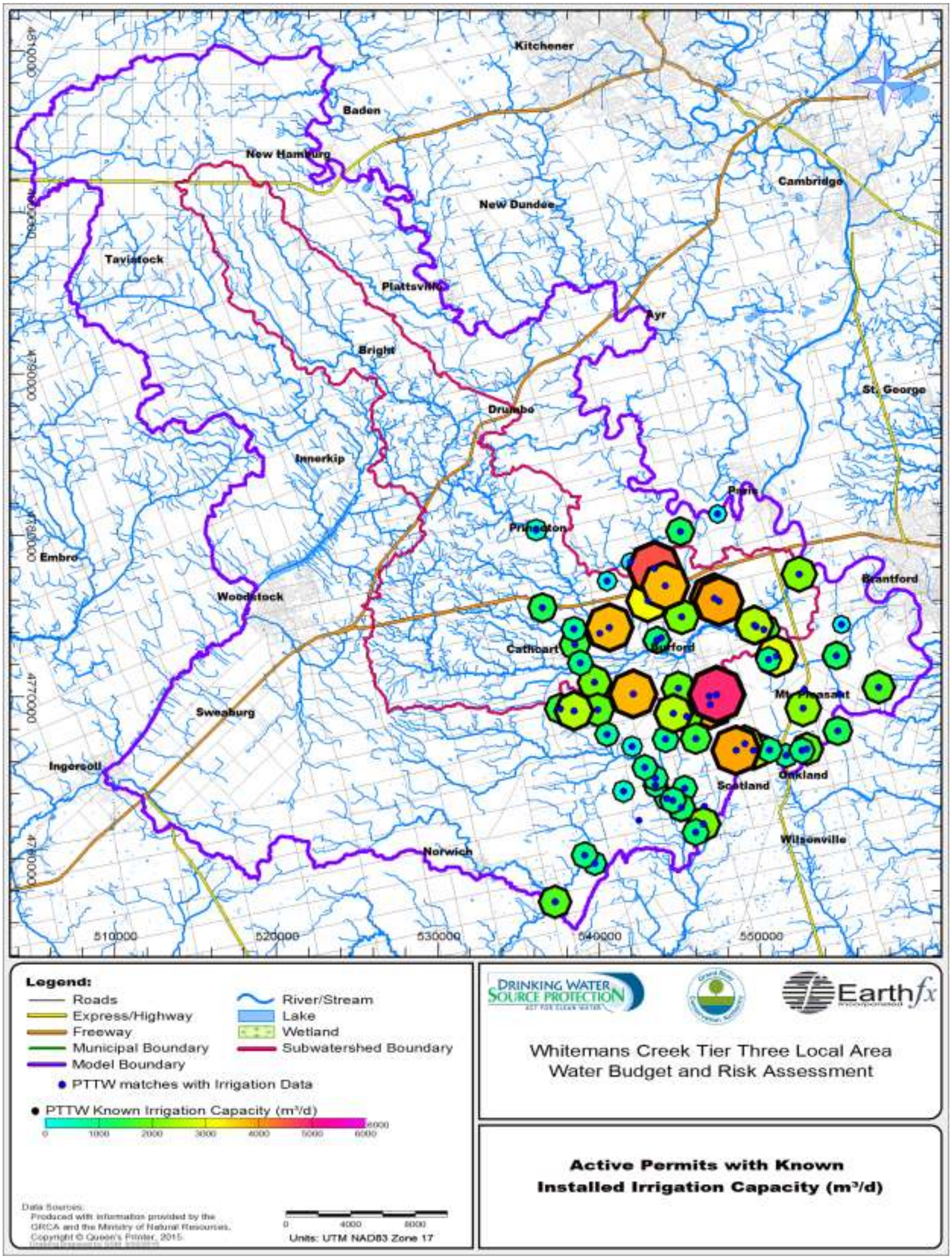


Figure 10.16: Active permits with known installed irrigation capacity.

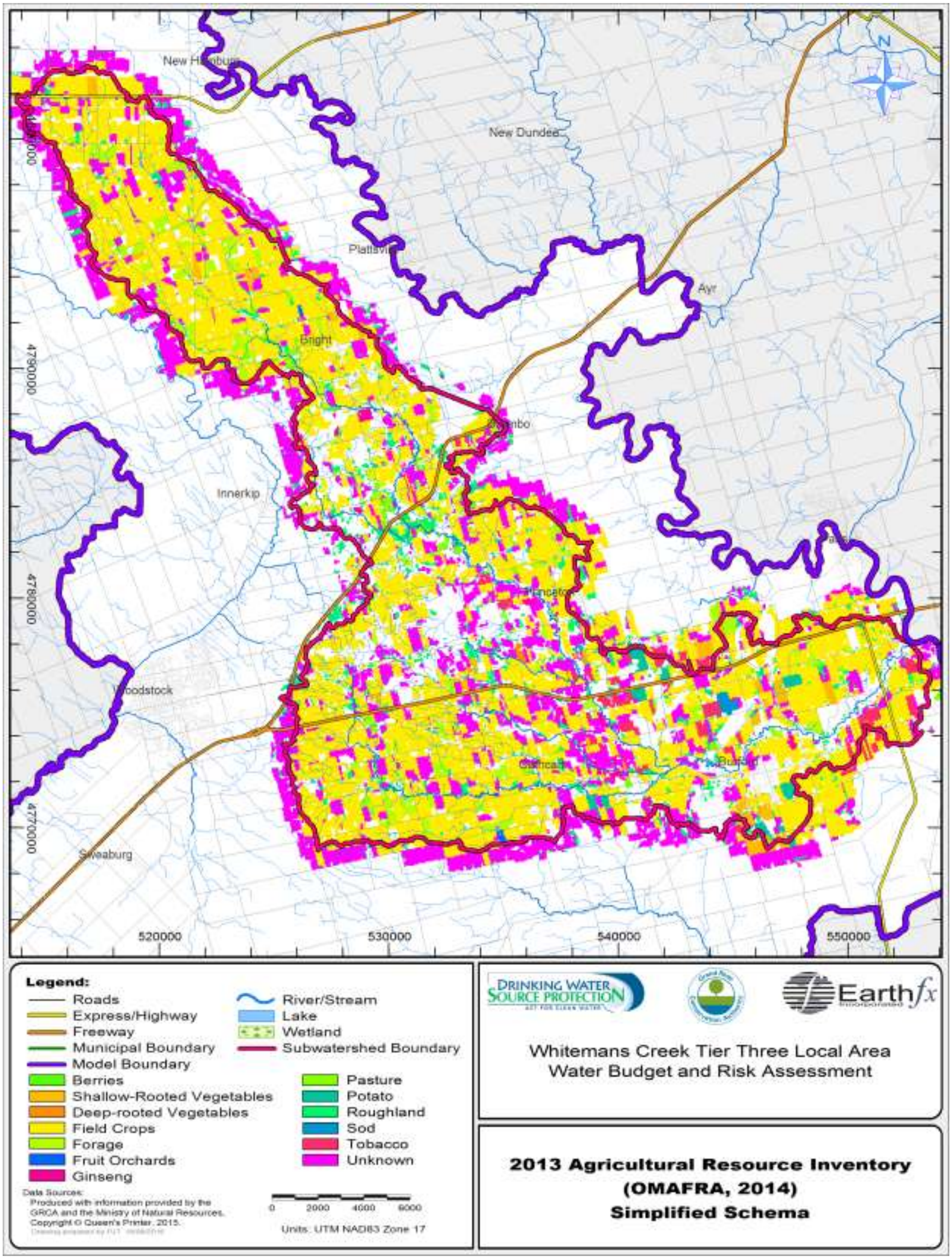


Figure 10.17: Simplified crop schema - 2013 Agricultural Resource Inventory (OMAFRA).

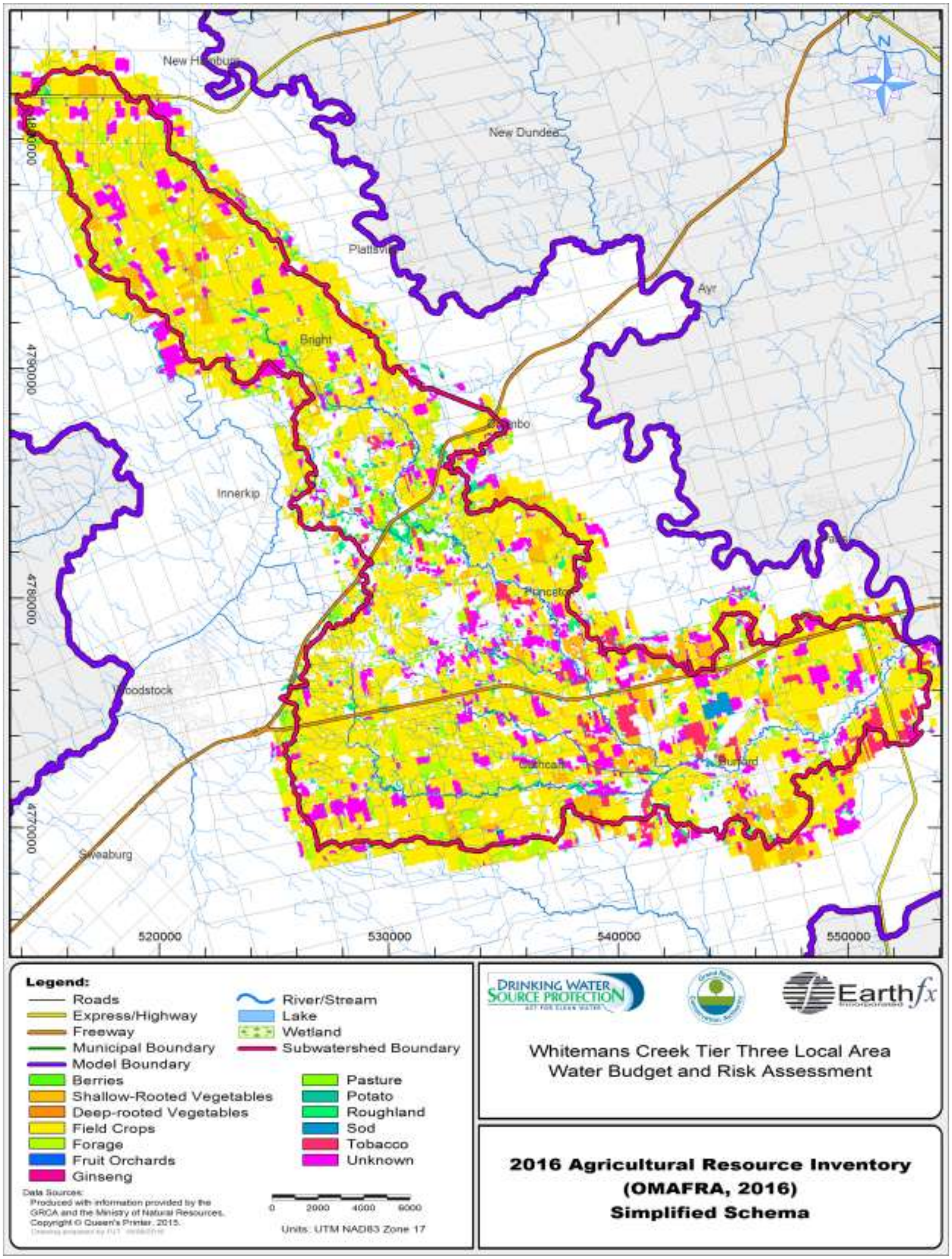


Figure 10.18: Simplified crop schema - 2016 Agricultural Resource Inventory (OMAFRA).

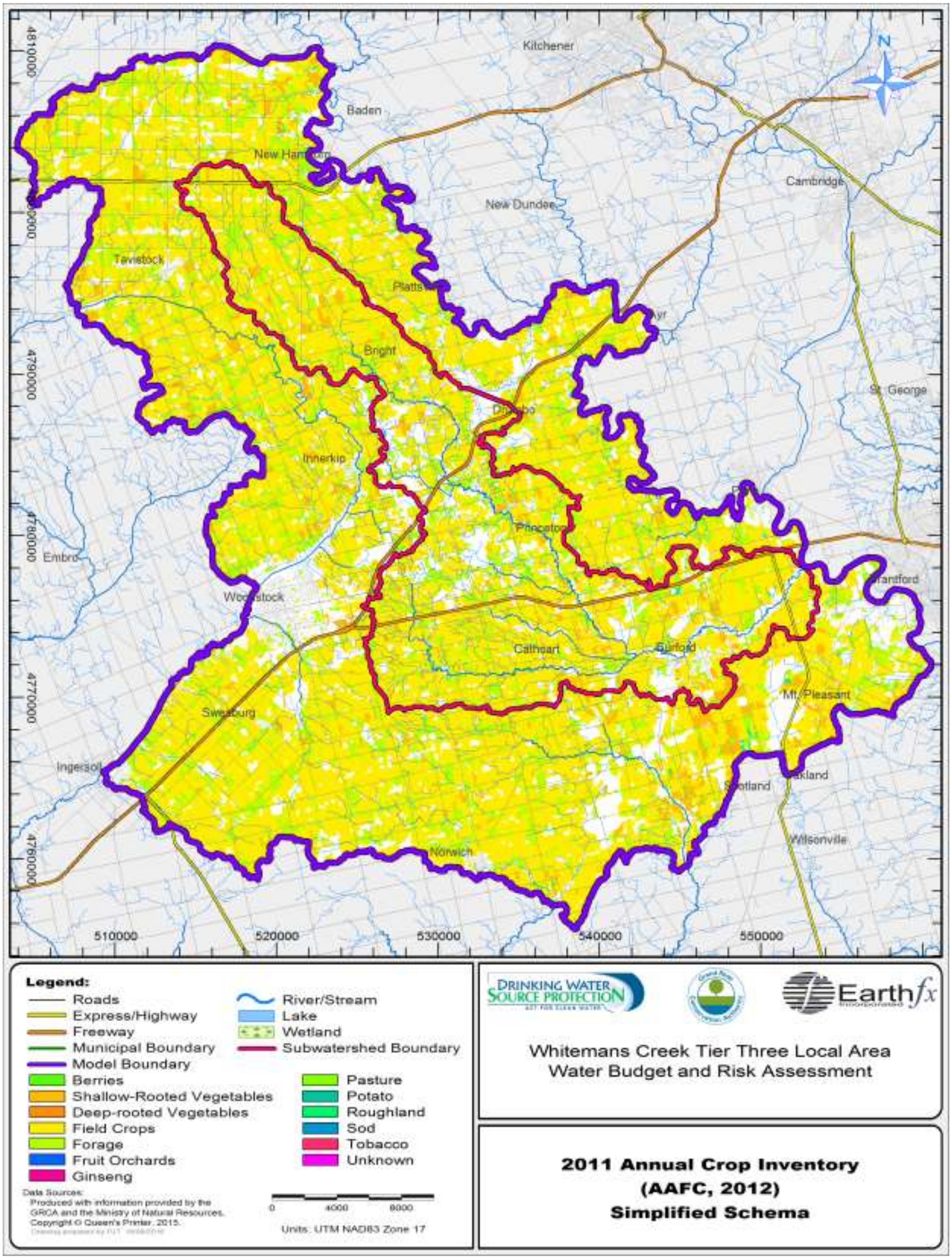


Figure 10.19: Simplified crop schema - 2011 Annual Crop Inventory (AAFC).

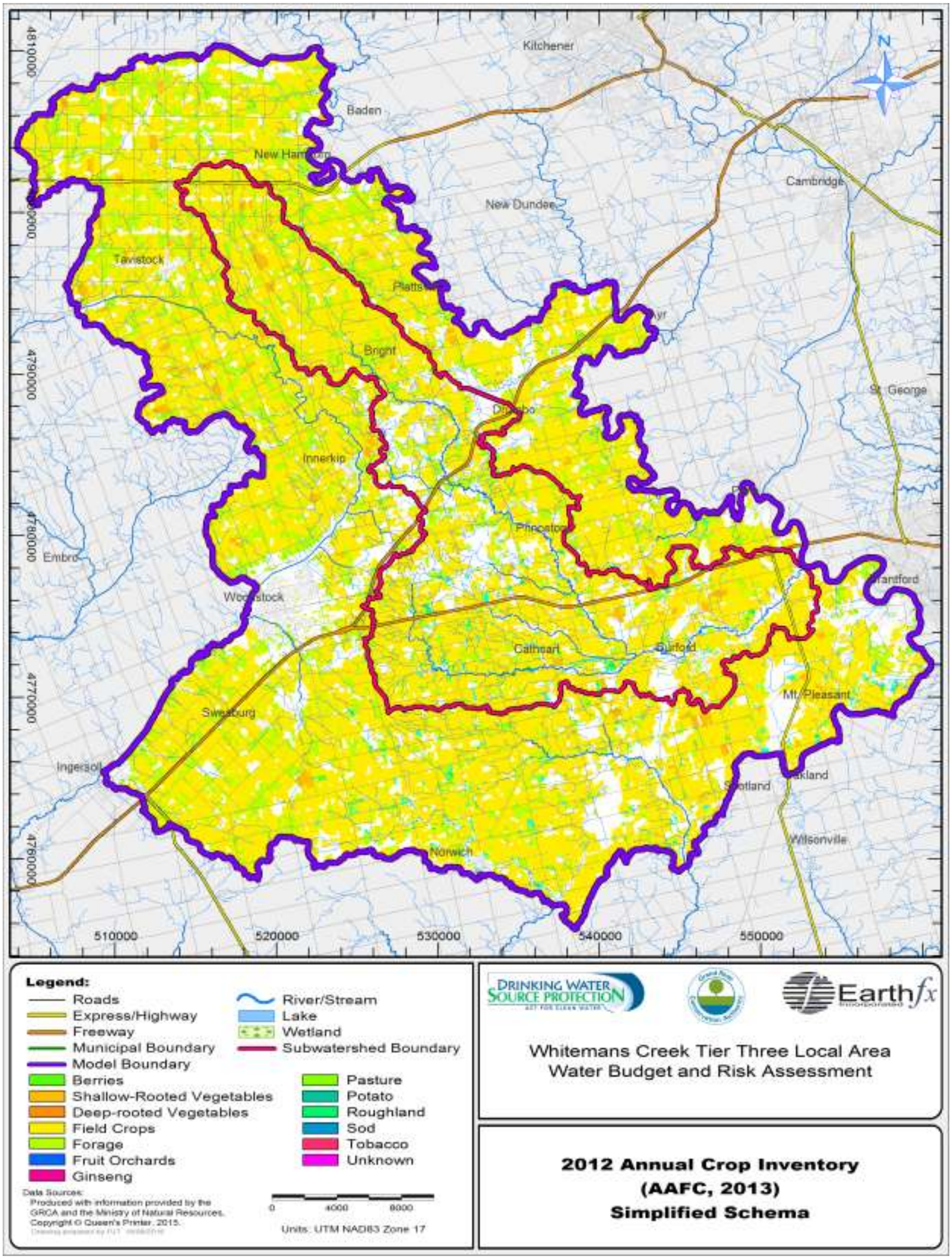


Figure 10.20: Simplified crop schema - 2012 Annual Crop Inventory (AAFC).

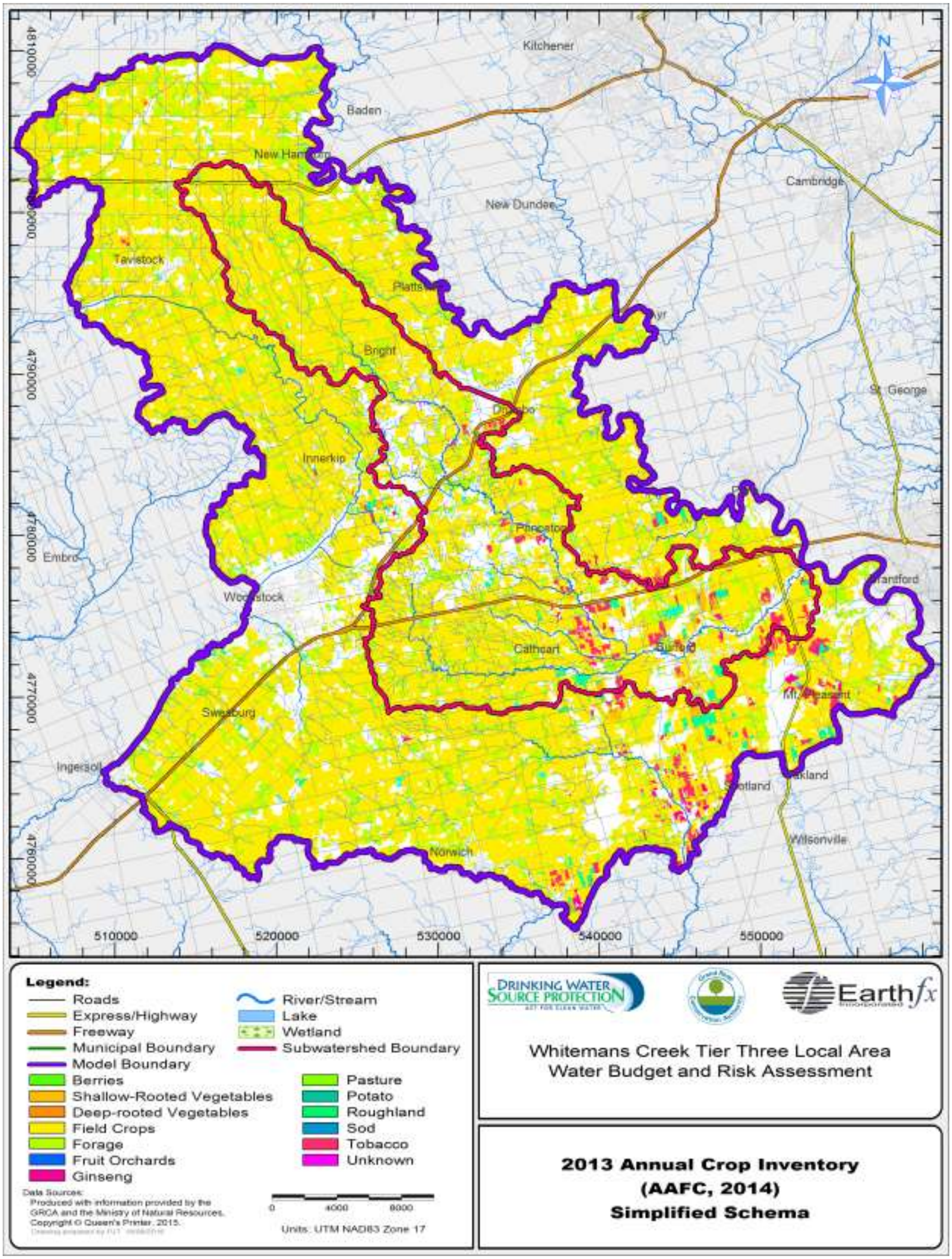


Figure 10.21: Simplified crop schema - 2013 Annual Crop Inventory (AAFC).

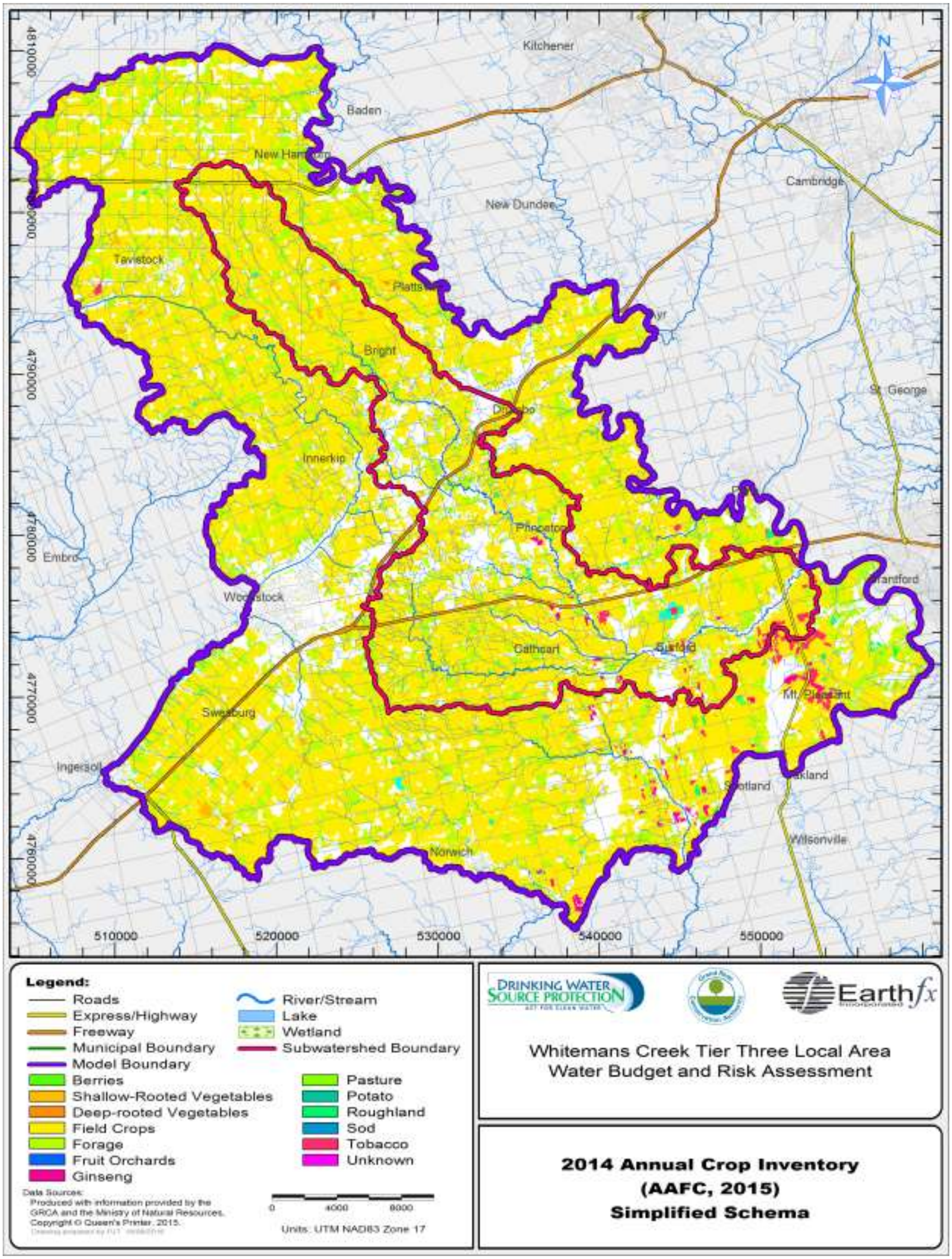


Figure 10.22: Simplified crop schema - 2014 Annual Crop Inventory (AAFC).

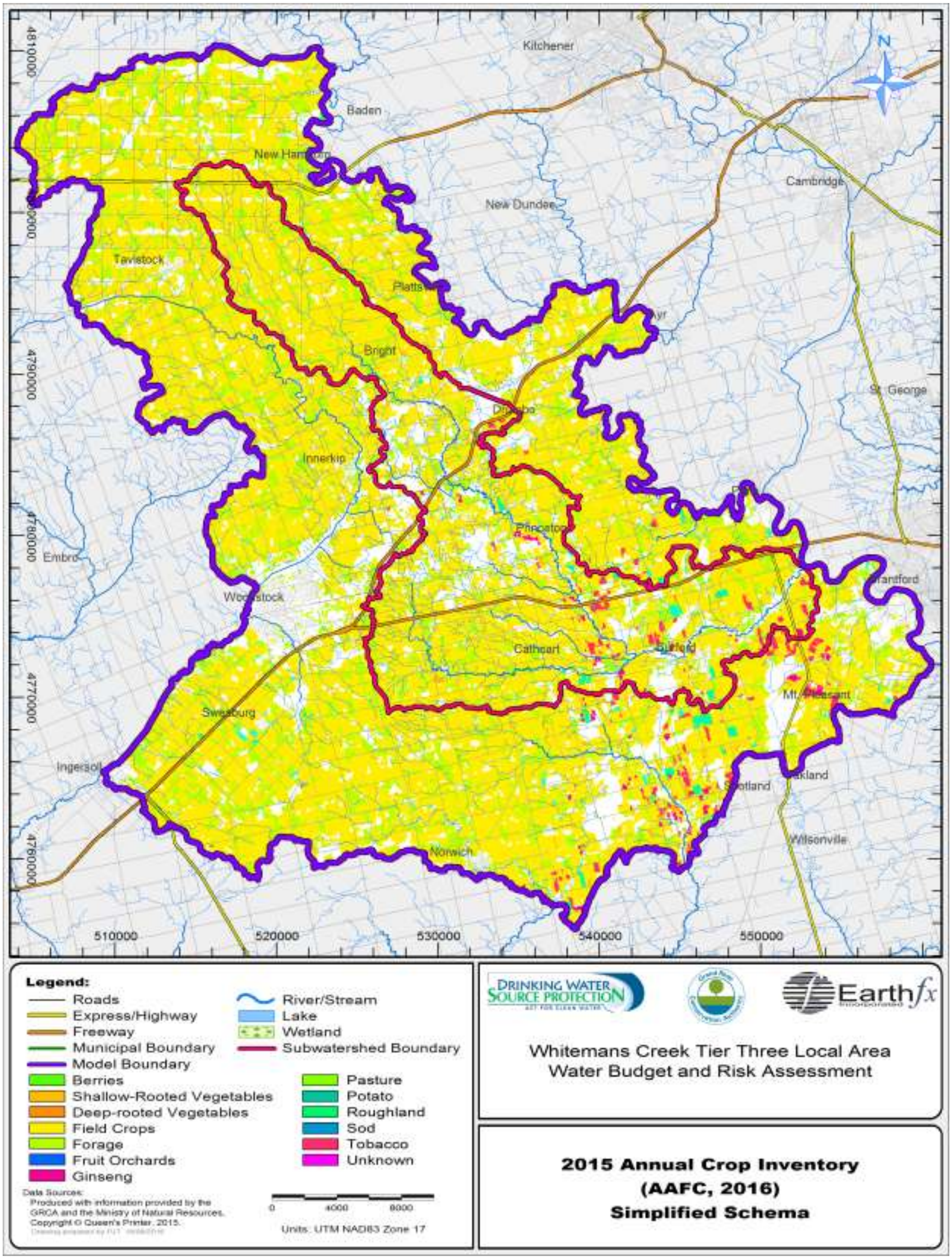


Figure 10.23: Simplified crop schema - 2015 Annual Crop Inventory (AAFC).

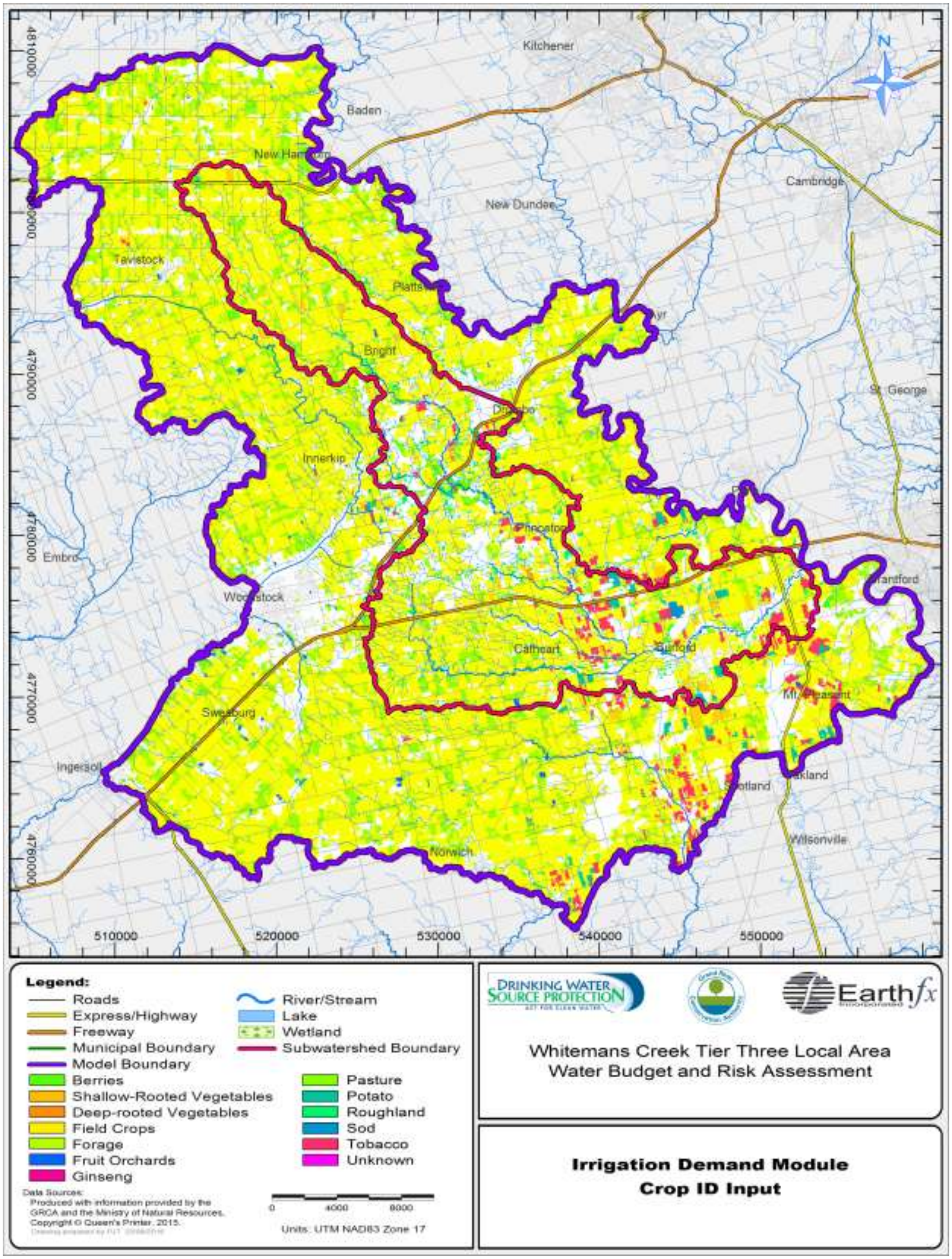


Figure 10.24: Final simplified crop schema – Whitemans Tier 3 Assessment model crop inputs.

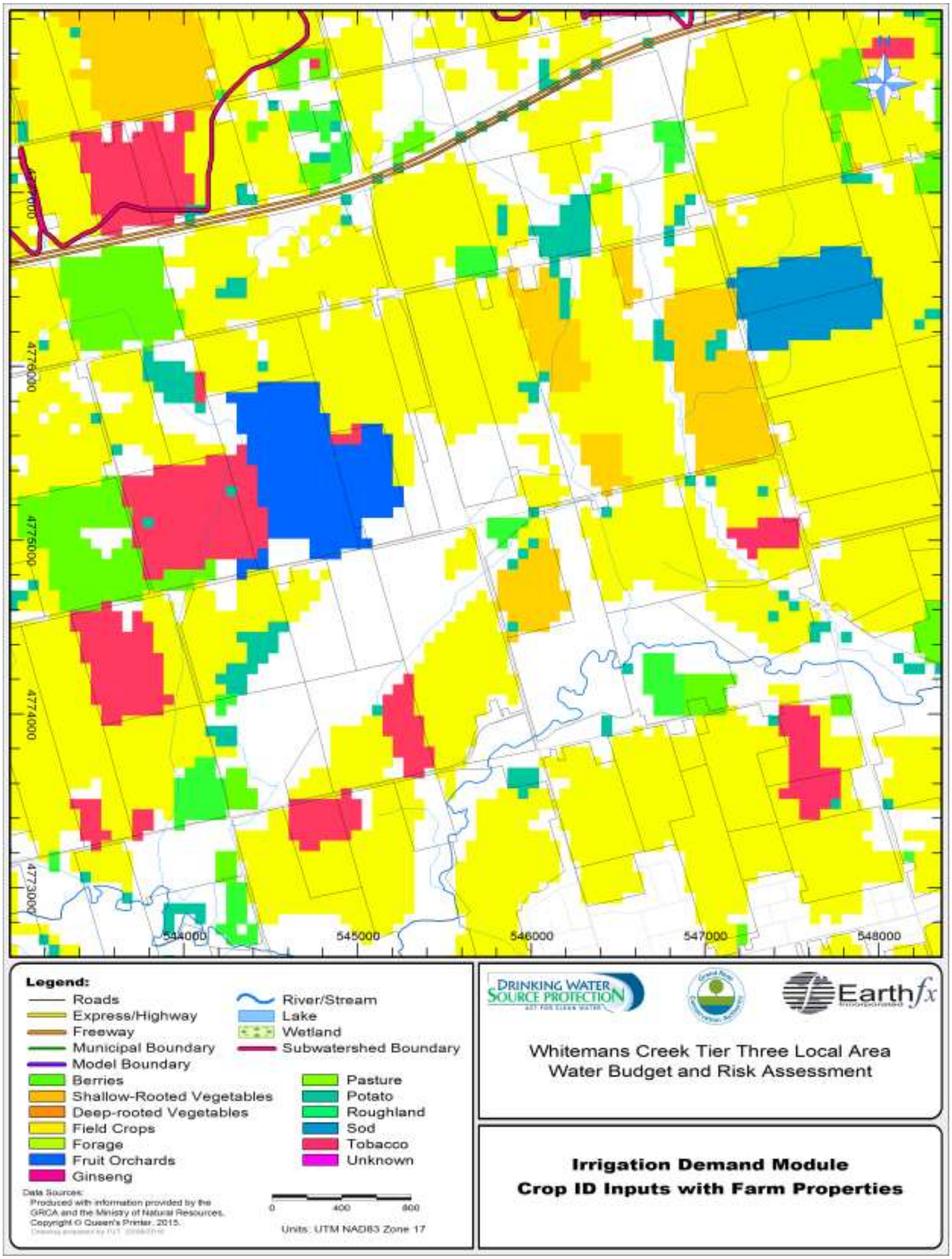


Figure 10.25: Example of crop inputs with identified farm properties.

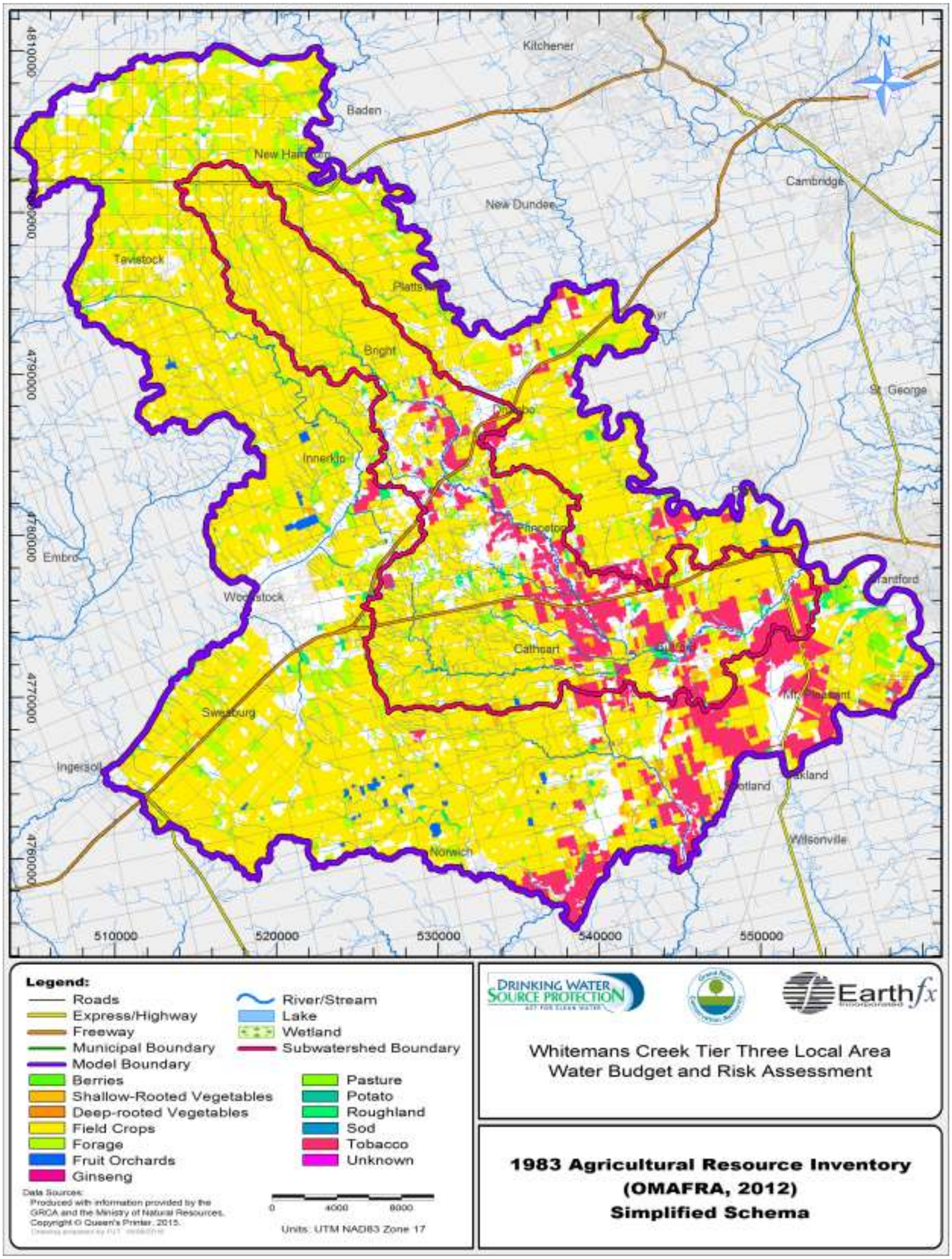


Figure 10.26: Final simplified crop schema for historical simulations in the Whitemans Creek subwatershed based on the 1983 Agricultural Resource Inventory (OMAFRA).

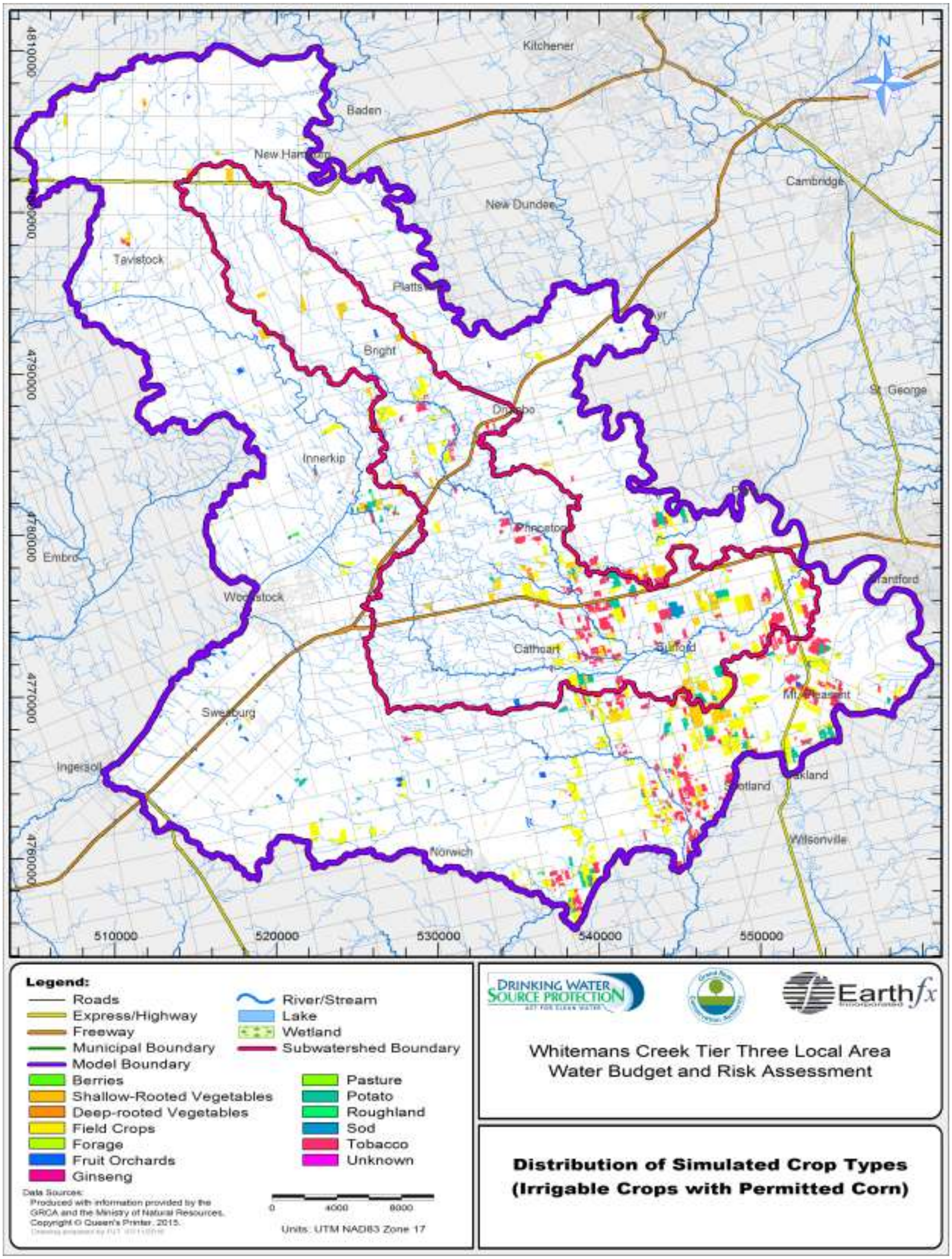


Figure 10.27: Distribution of simulated crop types within the model area.

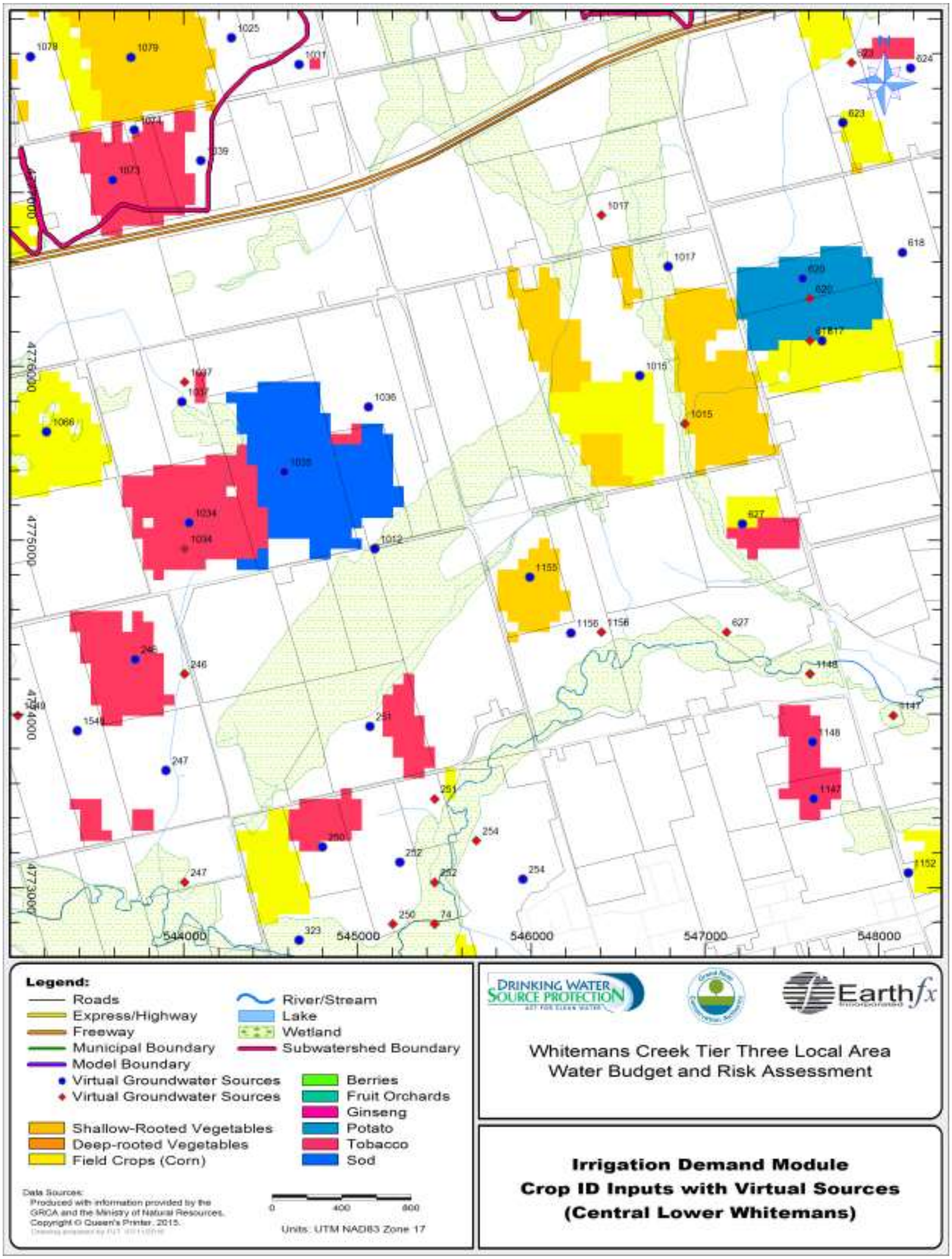


Figure 10.28: Crop inputs with linked virtual water sources (Central Lower Whitemans Creek).

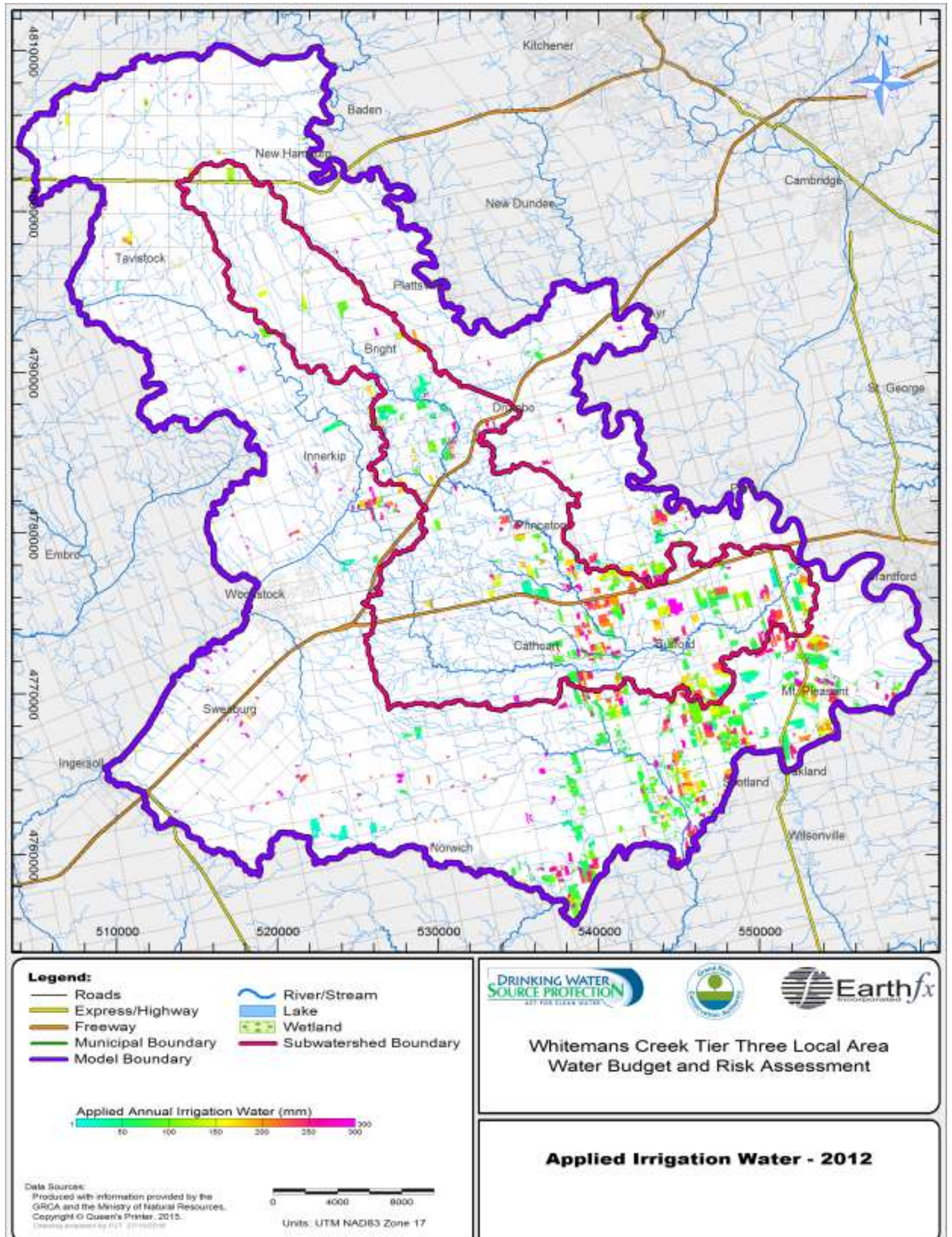


Figure 10.29: Simulated applied irrigation water - 2012.

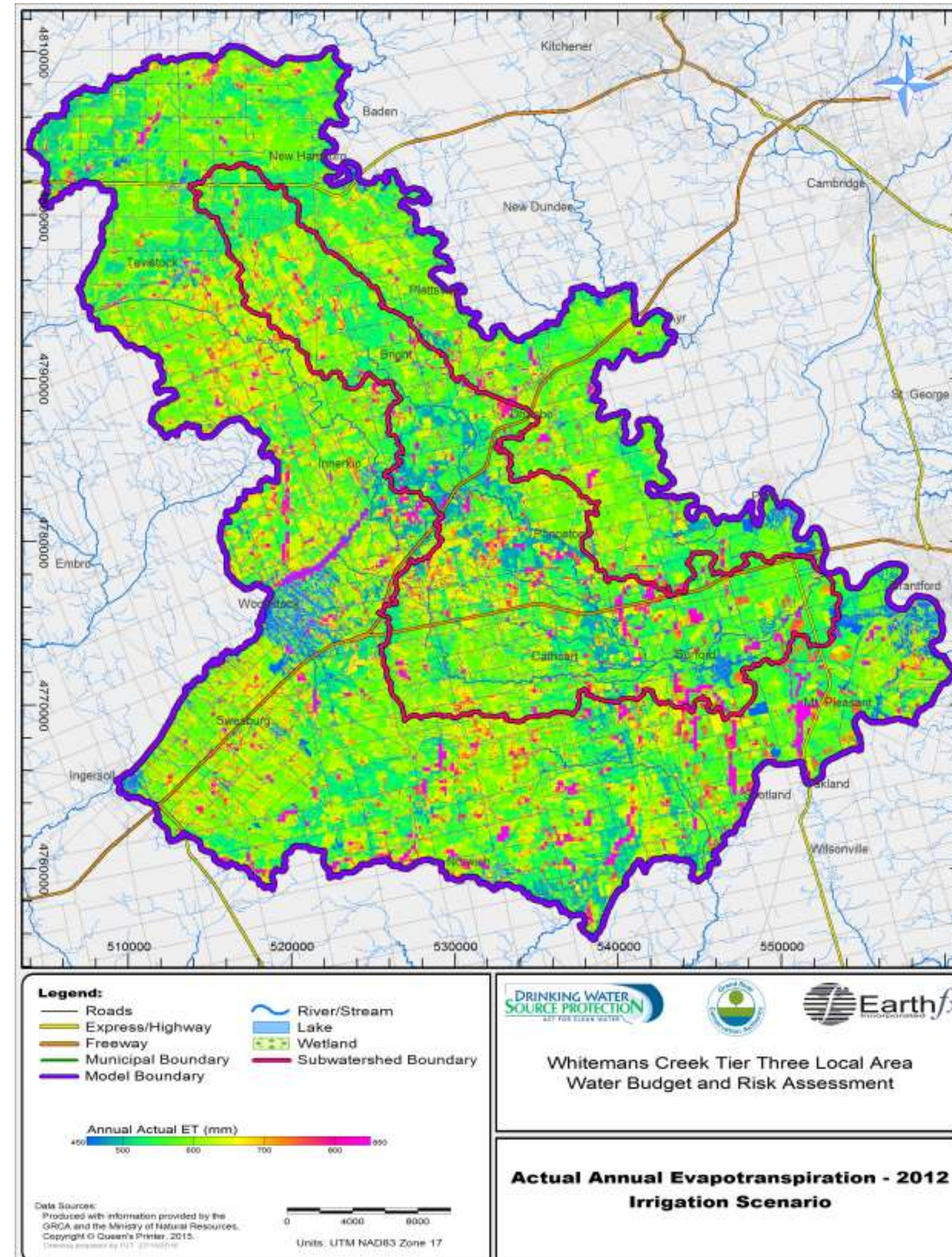


Figure 10.30: Simulated actual evapotranspiration – WY2012.

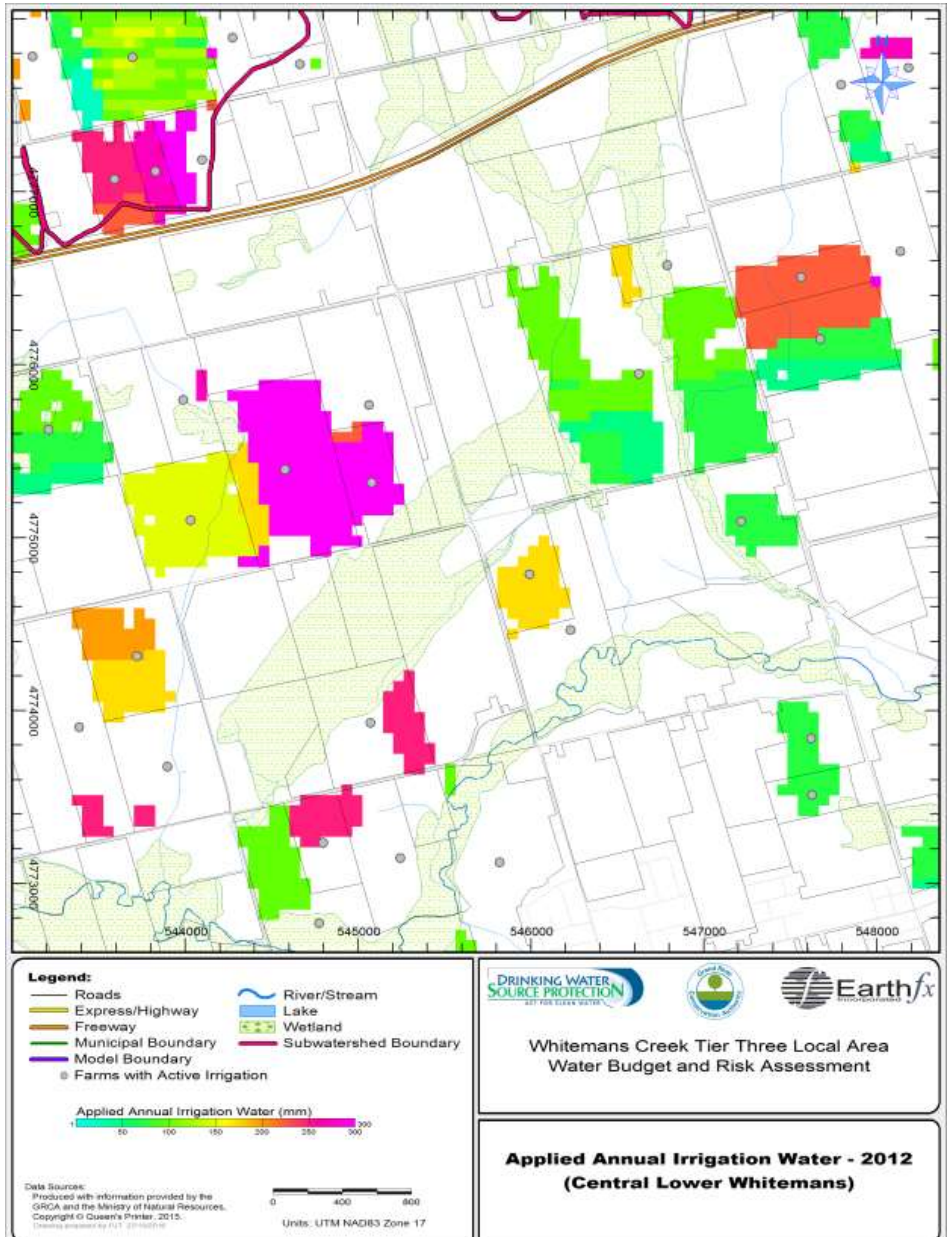


Figure 10.31: Applied annual irrigation water (2012) in Lower Central Whitemans Creek.

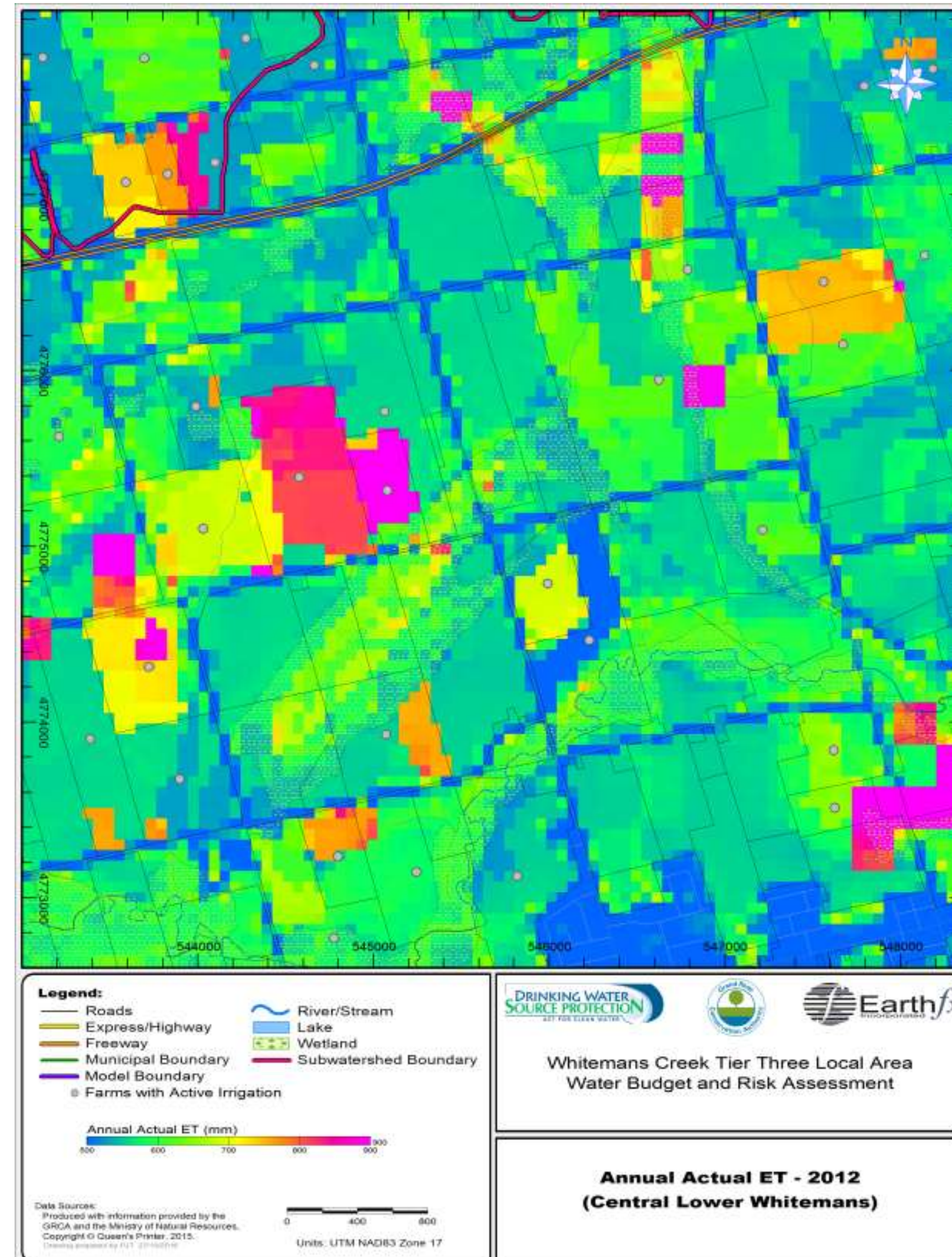


Figure 10.32: Simulated actual evapotranspiration (WY2012) in Lower Central Whitemans Creek.

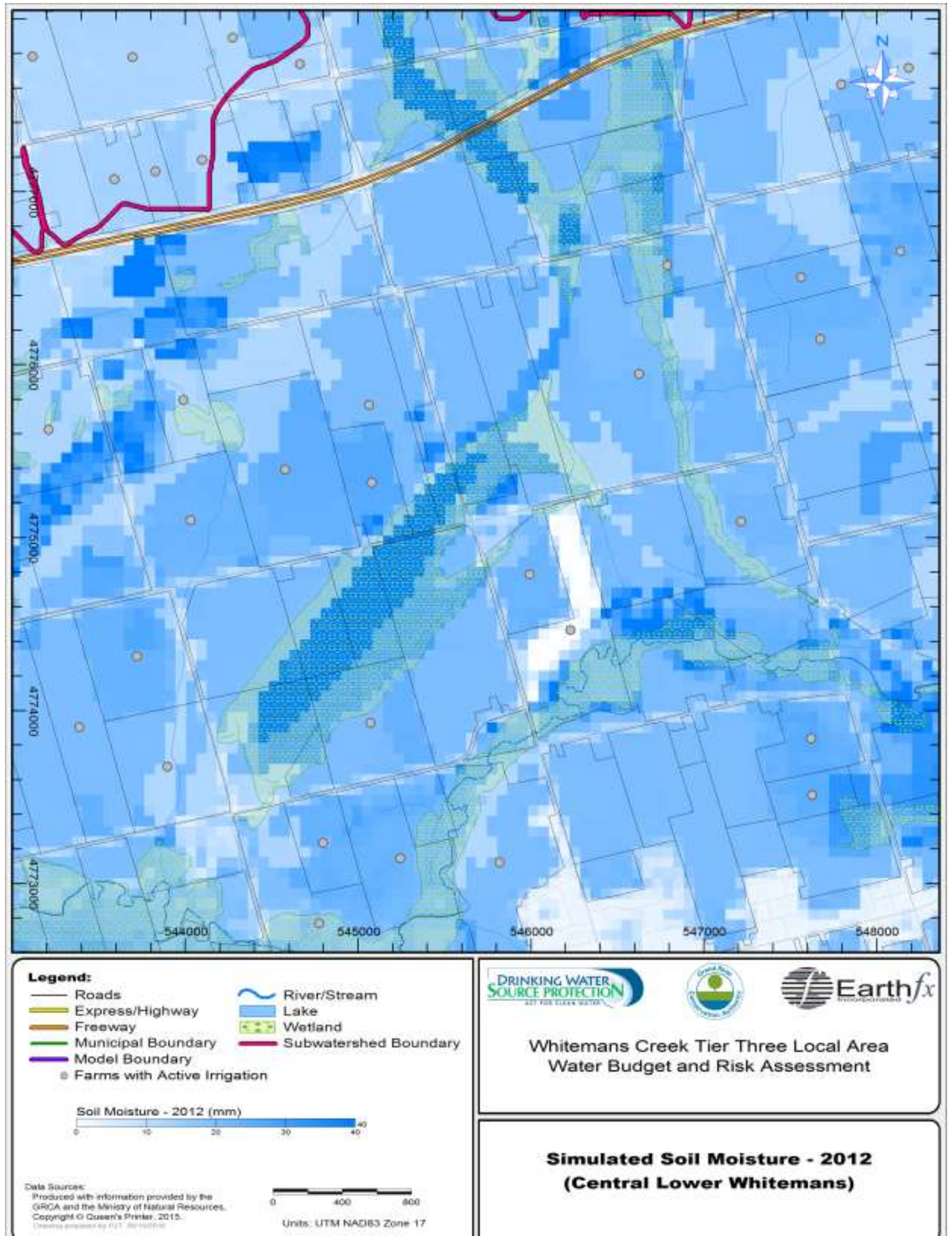


Figure 10.33: Simulated soil moisture - WY2012.

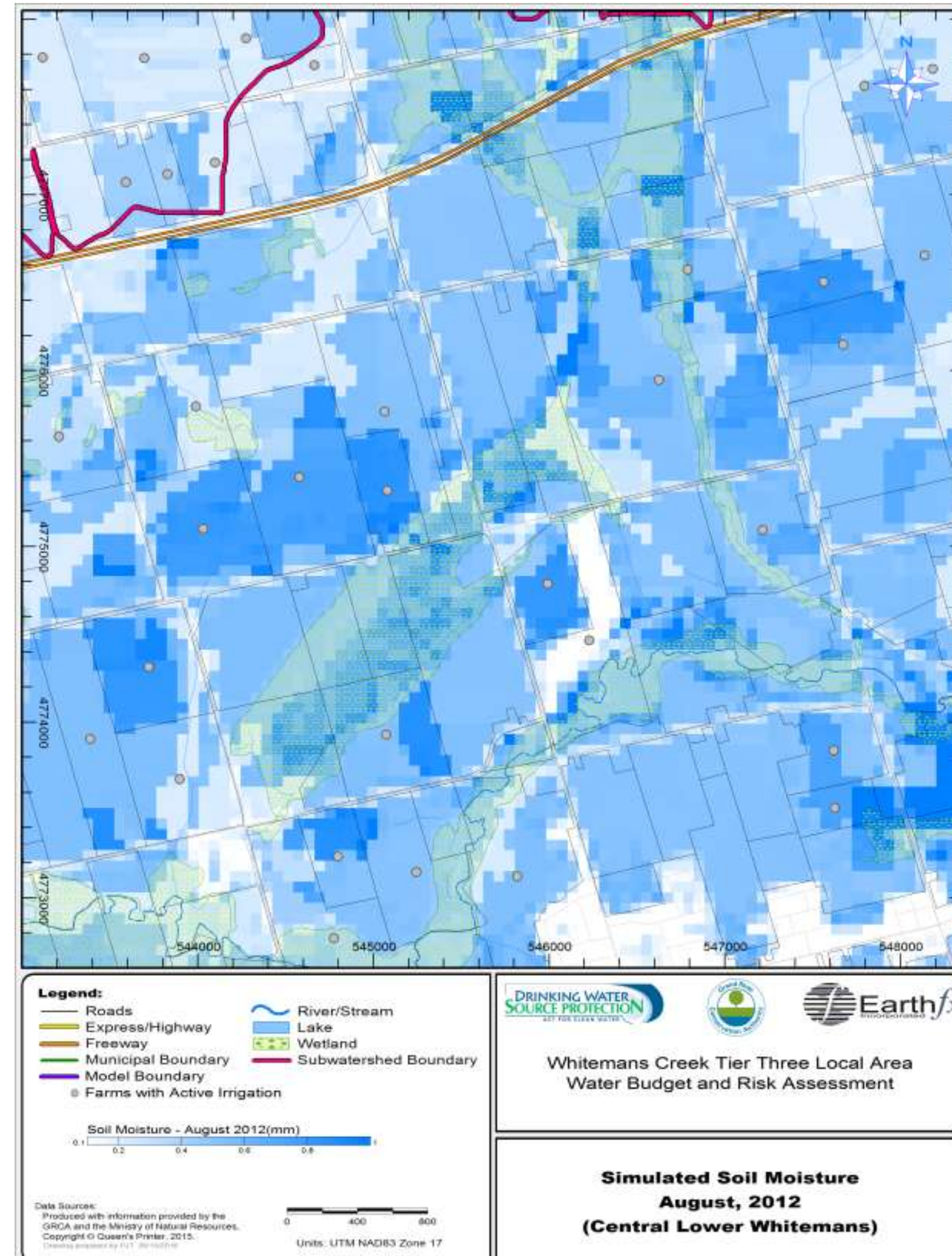


Figure 10.34: Simulated soil moisture – August 2012.

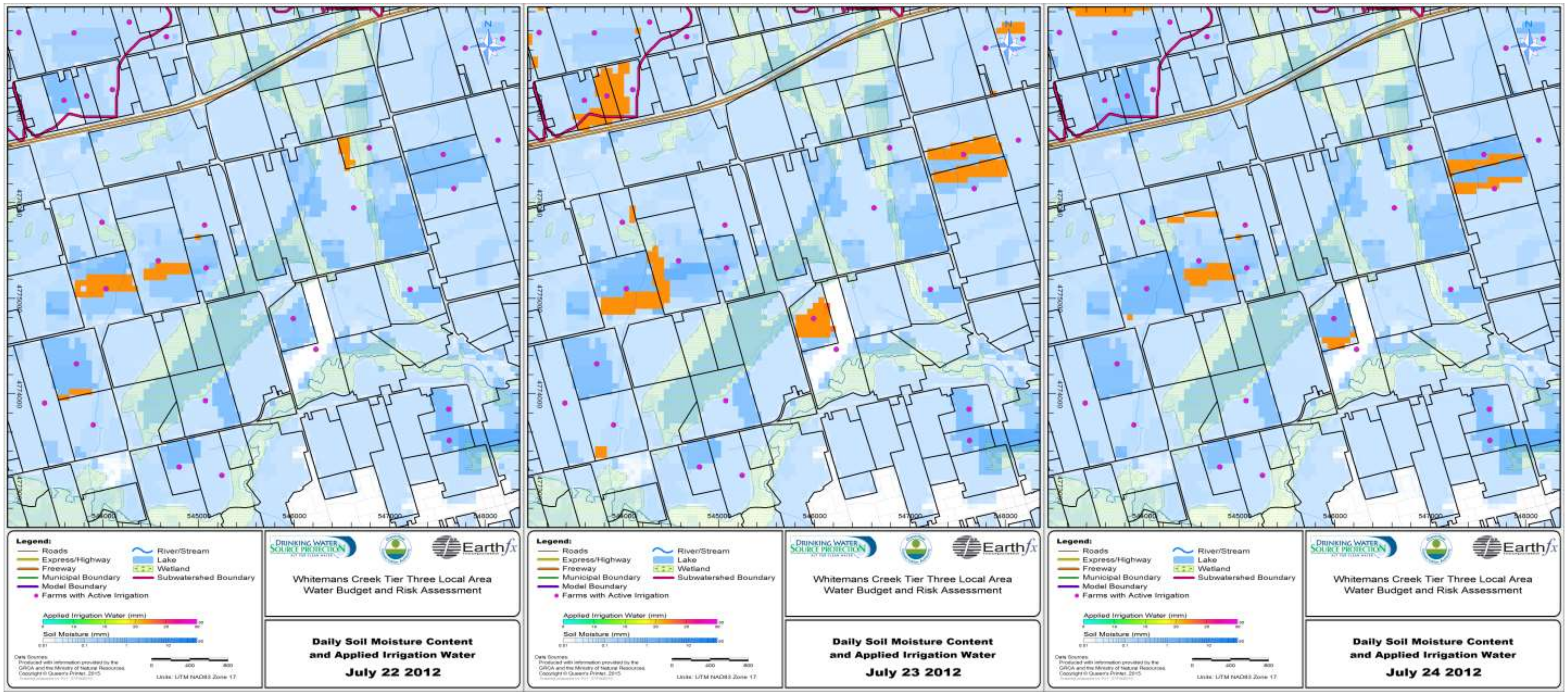


Figure 10.35: Simulated applied irrigation water and available soil moisture for a three day period in July 2012.

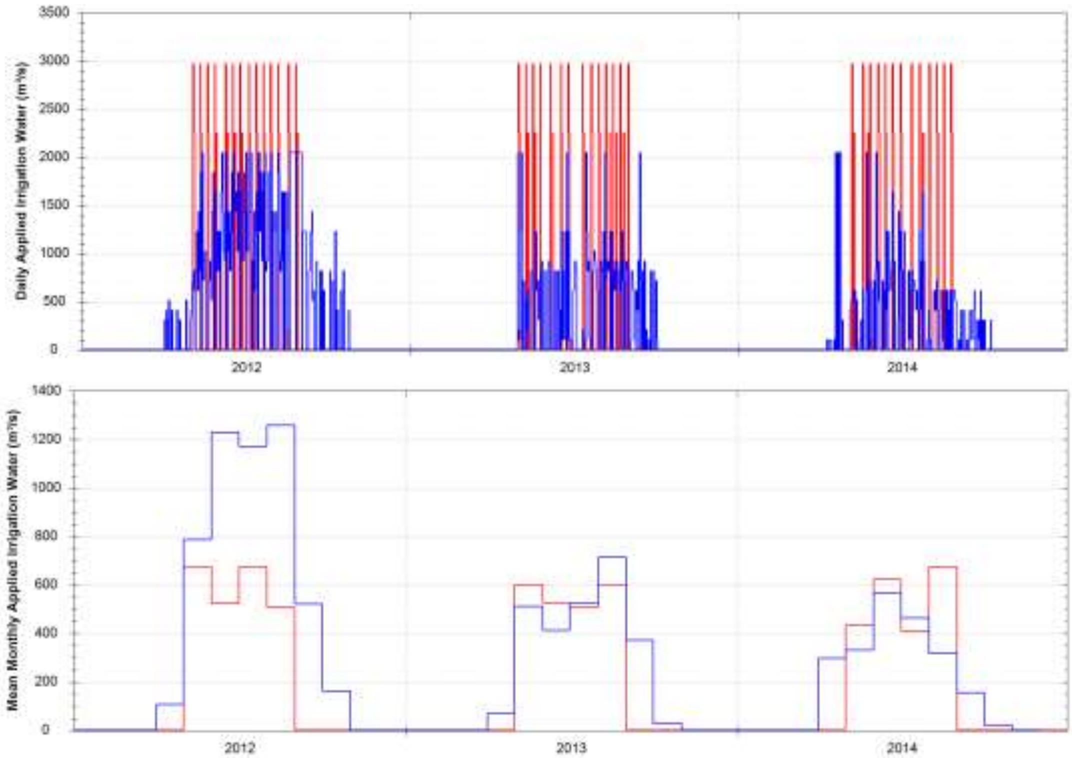


Figure 10.36: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at a sod farm within Whitemans Creek (ID: 438).

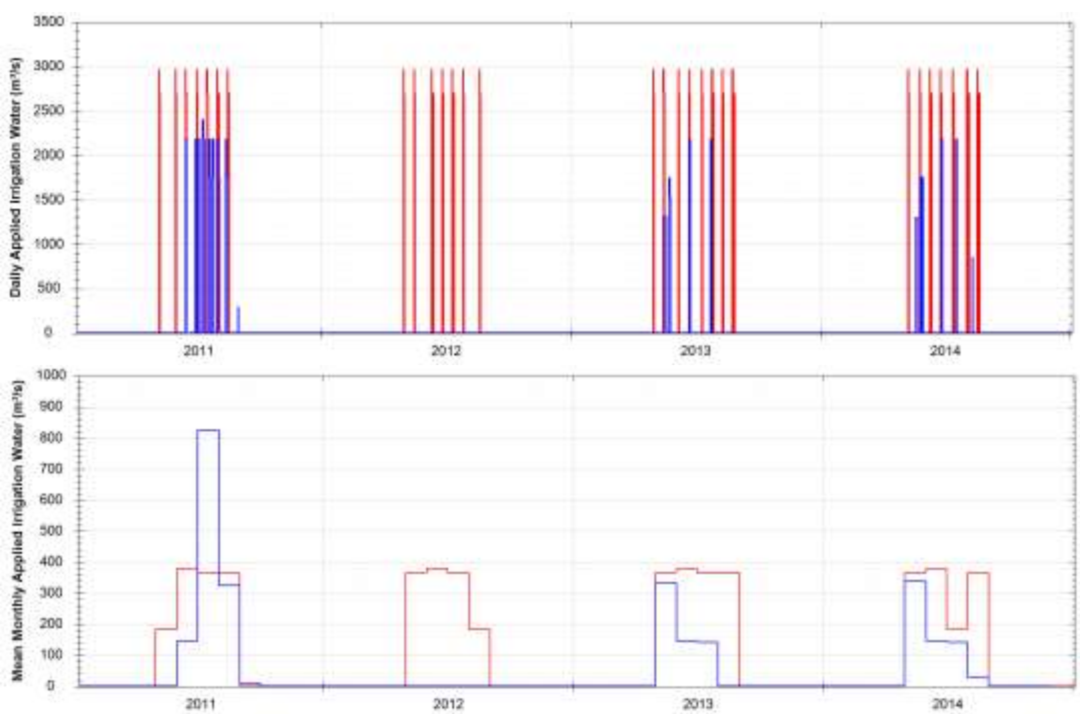


Figure 10.37: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 904.

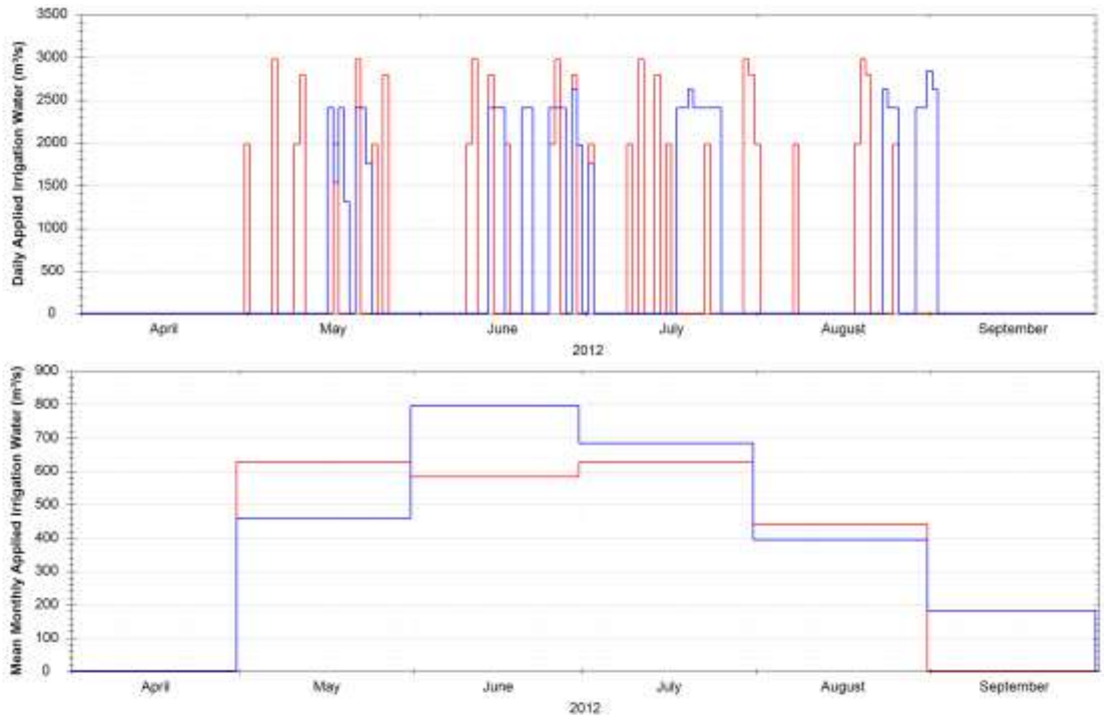


Figure 10.38: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 154.

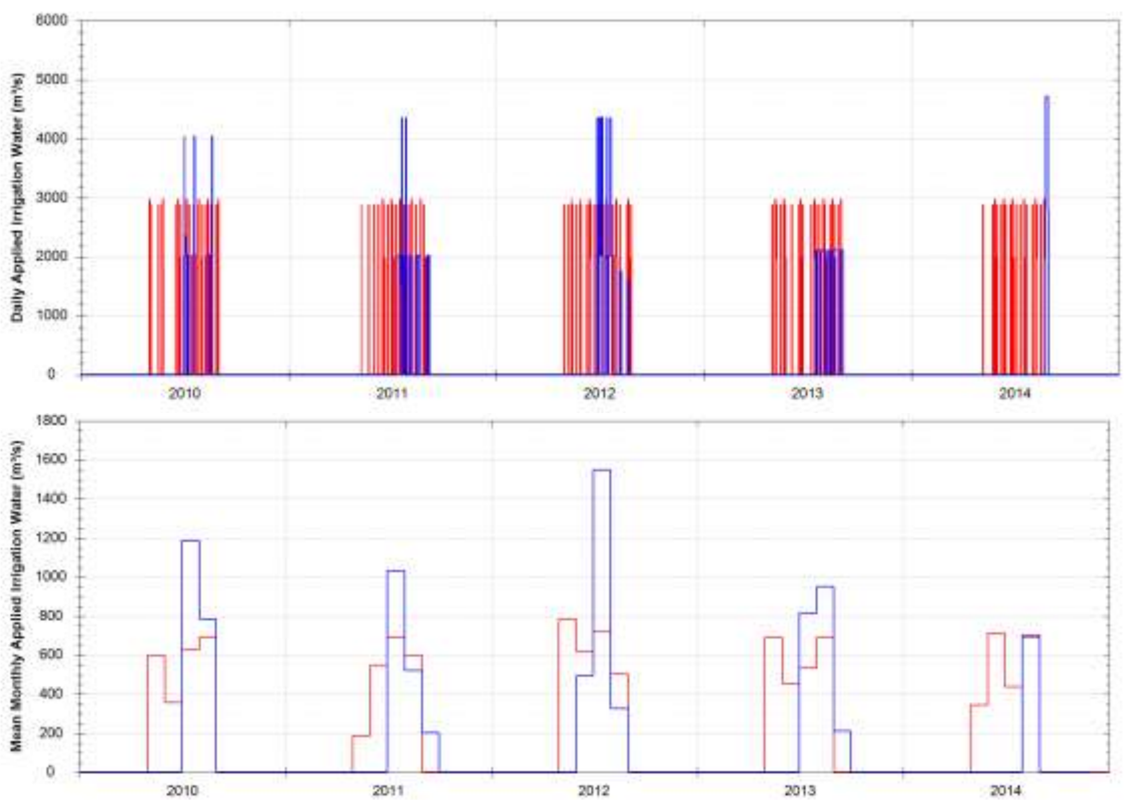


Figure 10.39: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 149.

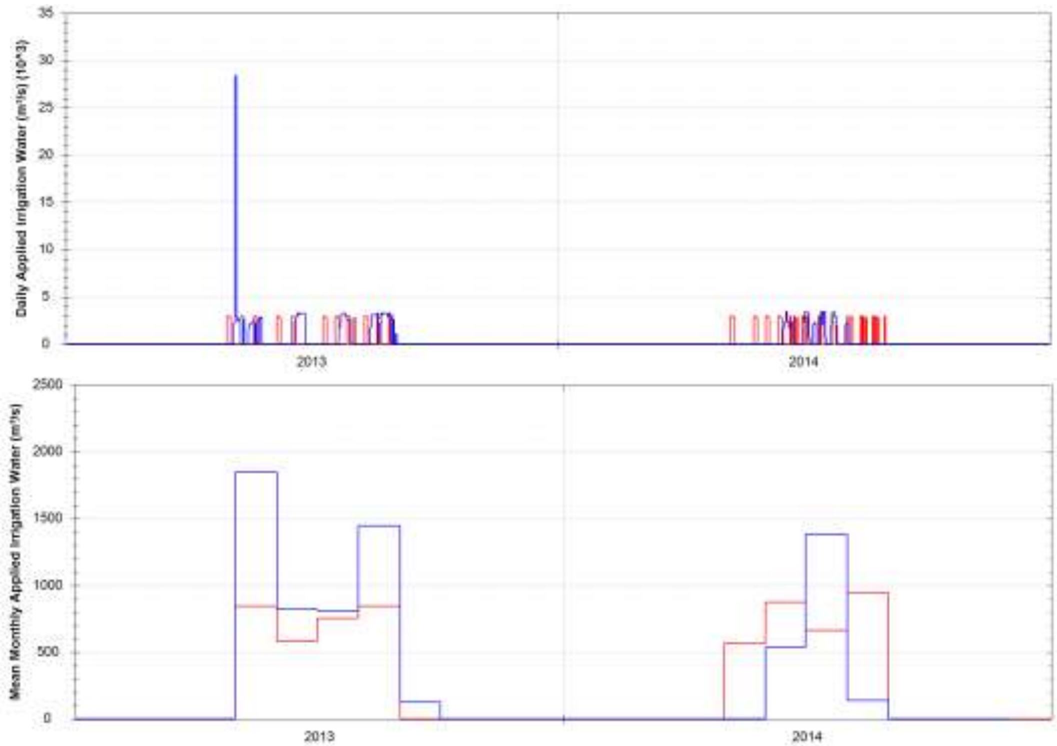


Figure 10.40: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 145.

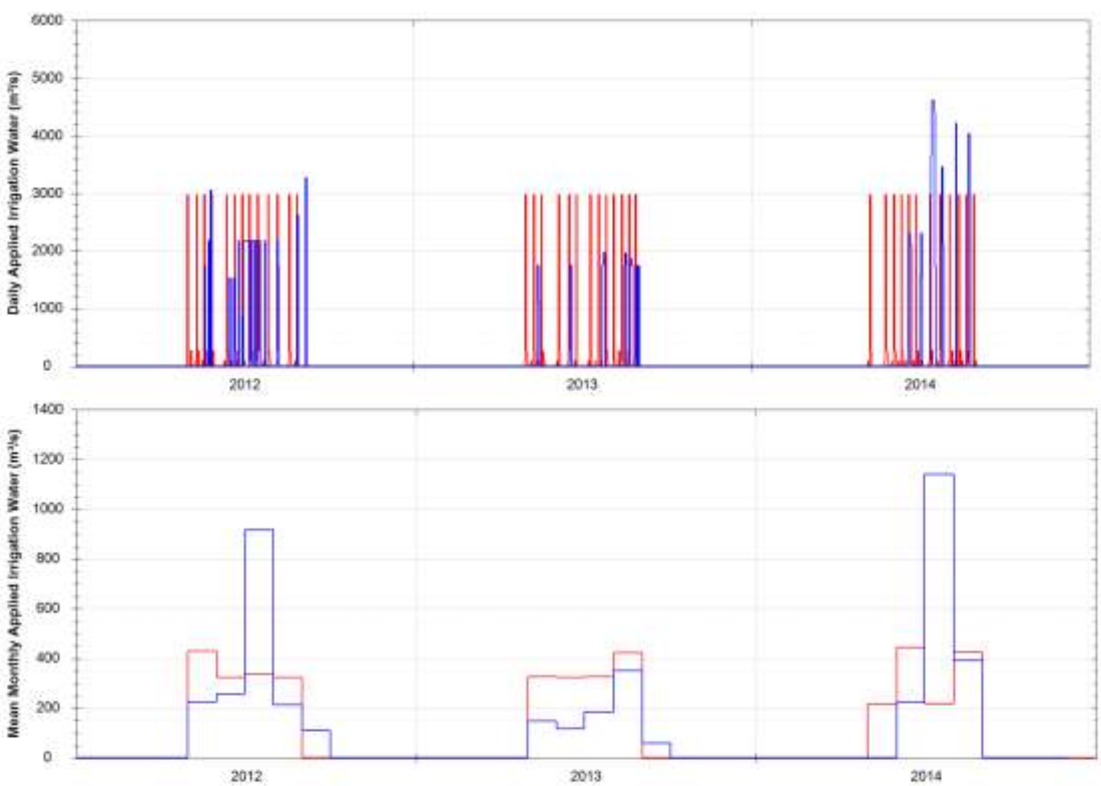


Figure 10.41: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 146.

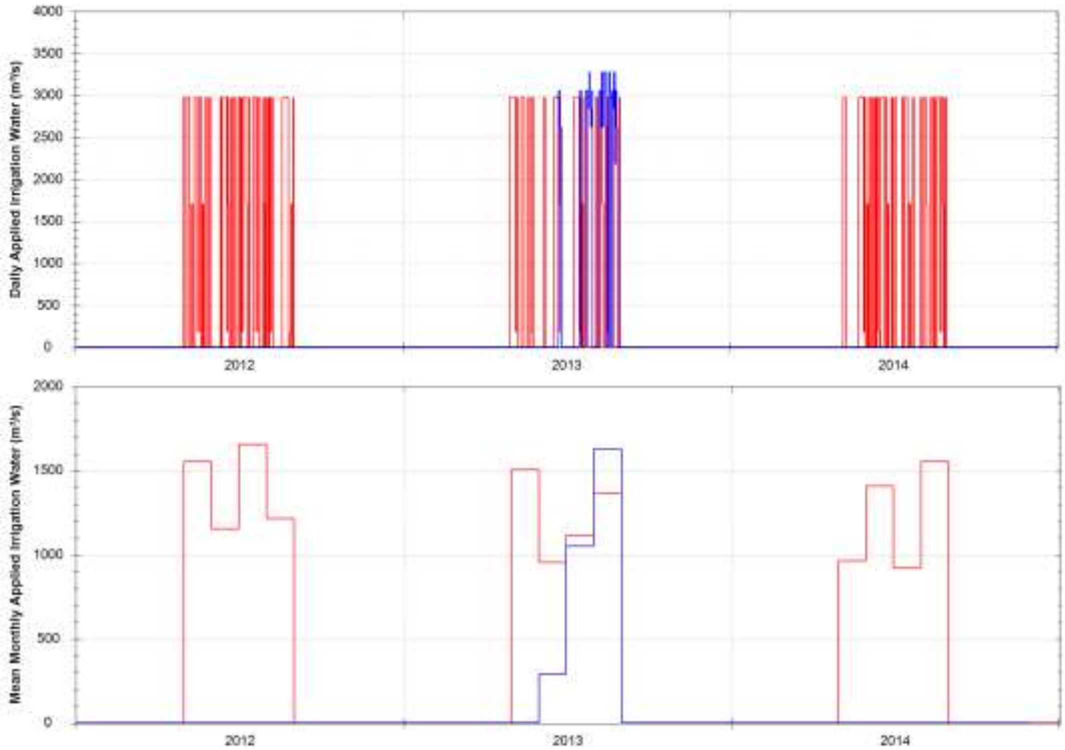


Figure 10.42: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 1015.

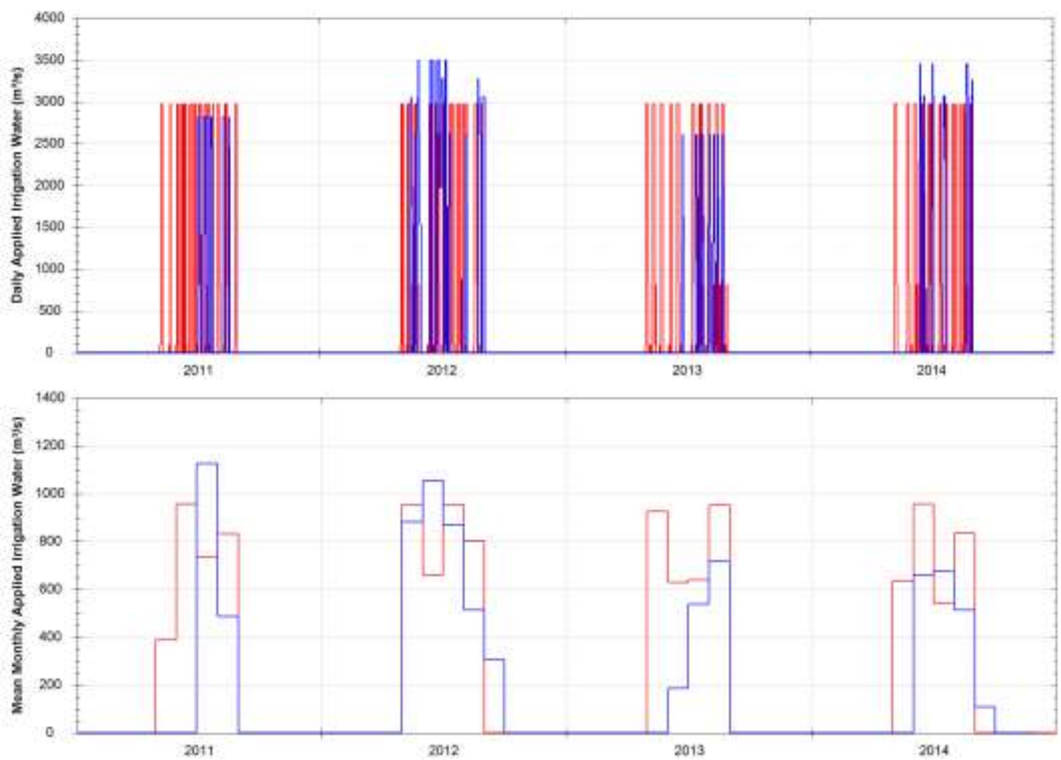


Figure 10.43: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 142.

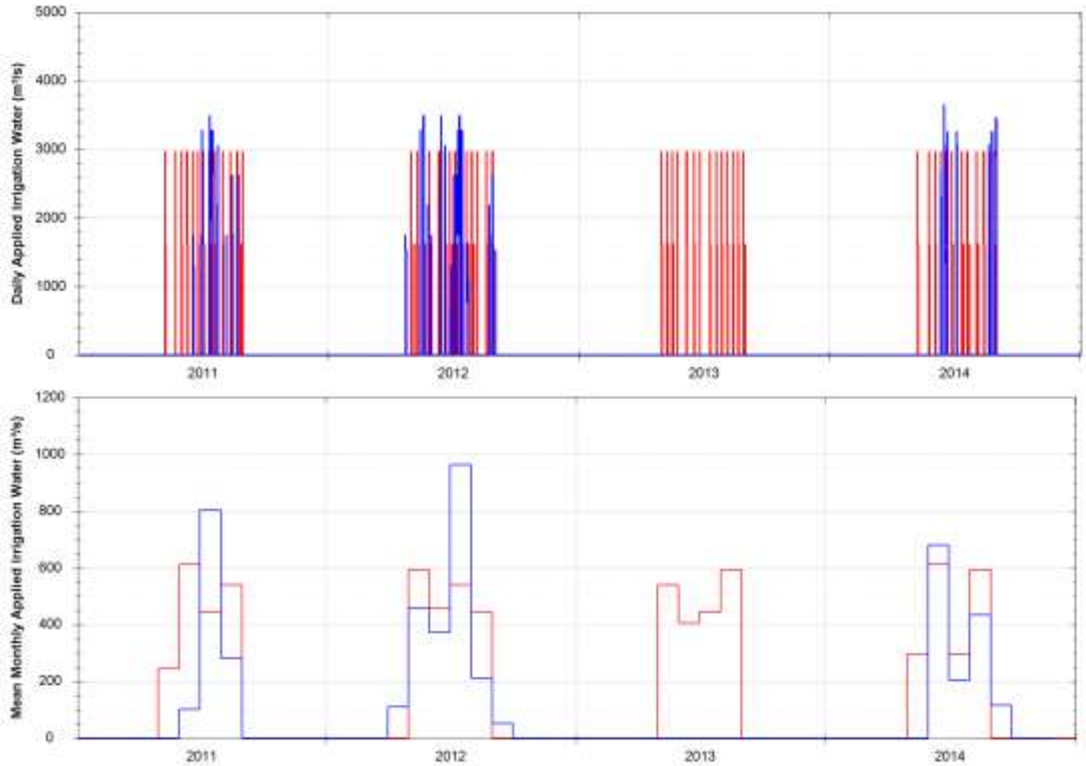


Figure 10.44: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 371.

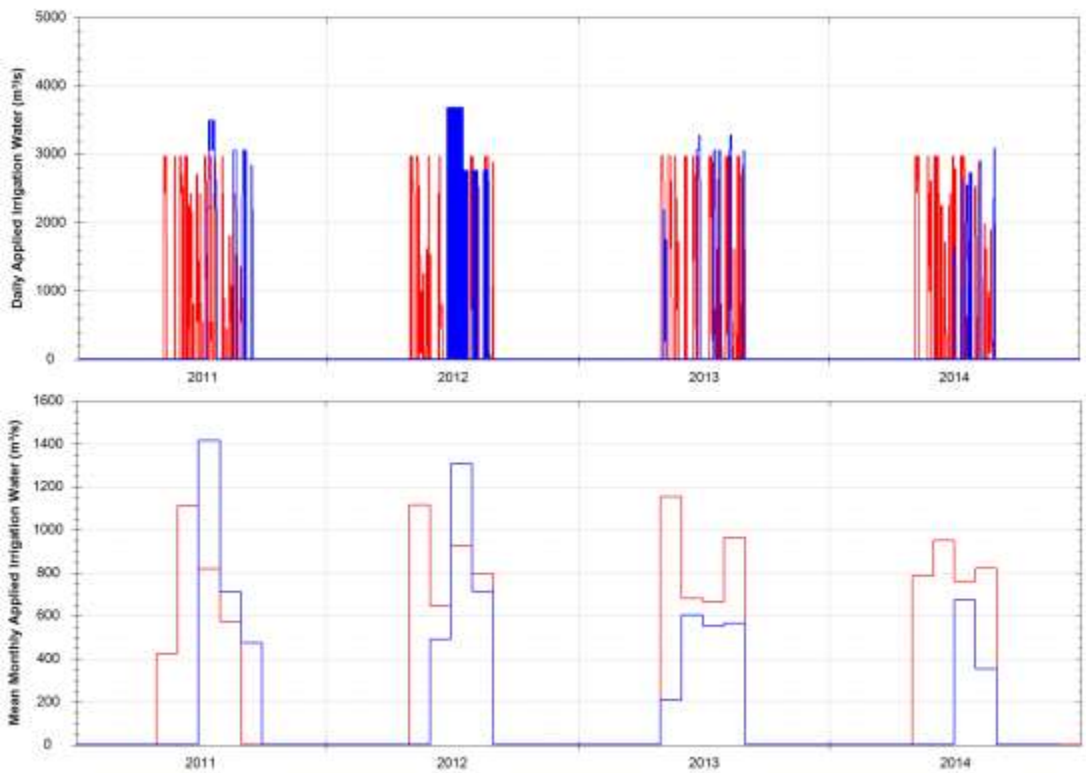


Figure 10.45: Daily (top) and monthly (bottom) reported WTRS data (red) versus simulated applied irrigation water (blue) at farm ID 1079.

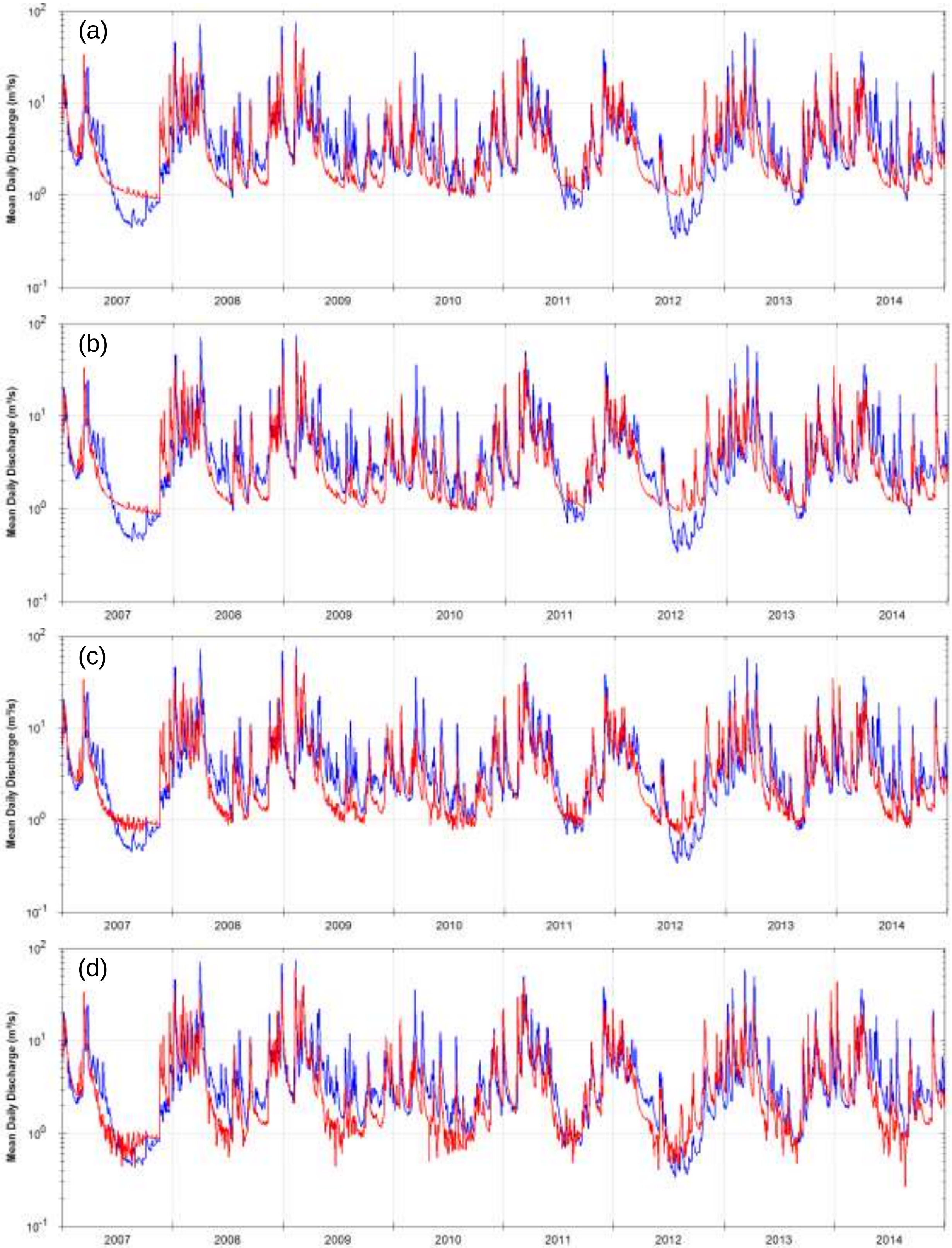


Figure 10.46: Observed (blue) versus simulated (red) log-transformed daily streamflow at WSC gauge Whitemans Creek near Mount Vernon (02GB008) with (a) no water takings, (b) reported WTRS data (c) Irrigation Module (irrigable crops), and (d) Irrigation Module (all permitted farms).

11 Integrated GSFLOW Model Calibration

11.1 *Inputs and Calibration Targets*

Once the PRMS and MODFLOW submodels were reasonably well pre-calibrated, the focus shifted to the integrated GSFLOW final calibration. Climate data, a key input to the GSFLOW model, had been assembled for the PRMS-only analyses (Section 8.4). Continuous groundwater level data, discussed in Section 5.3 and streamflow data, discussed in Section 4.3 and 8.6, were used as the primary calibration targets. An extensive assessment of water use within the model area, presented in Section 6, was used to represent surface water diversions and groundwater takings on a daily basis in the integrated model.

As discussed in Section 7, cascading runoff and interflow from the PRMS hydrologic submodel contributes to the simulated streamflow within GSFLOW. An important task is mapping these cascading flow paths to the appropriate SFR stream segment defined in the MODFLOW submodel. Figure 11.1 presents the contributing area of each SFR stream segment (for clarity, the individual cascade flow paths are not shown, but a sample of the cascade network is shown in Figure 8.15).

The GSFLOW model was calibrated to available streamflow monitoring and groundwater level monitoring for the 10-year period from October 2006 to September 2015 (WY2007 to WY2015). The calibration period covers the 2007 and 2012 drought years, as well as several average and wet climate periods to test the model response across a range of climate conditions. While temporal coverage of the regional streamflow and groundwater calibration datasets is good throughout this period, transient calibration data available for the Bethel Road wellfield is limited to the latter third of the simulation period. In addition, data collected from instrumented piezometers and private wells as part of the Tier 3 field program (described in Section 5.3.4) are mostly limited to WY2015.

The model was found to be stable, and preliminary simulations indicated that a long model “start-up”, prior to the calibration period, was not needed. The integrated model require long run times – between 40 and 62 hours - for the 10-year simulation; the exact length depended on the configuration of water takings and the Irrigation Demand module.

11.2 *GSFLOW Model Calibration Results*

After incorporating the results of the submodel pre-calibration, the integrated model calibration proceeded in an iterative manner in which results of successive model runs were reviewed and used to improve the estimates of model parameters. Storage properties for the groundwater system and hydrologic parameters affecting groundwater recharge and groundwater feedback process were a particular area of review and refinement.

11.2.1.1 Streamflow

Section 8.6.1 described the three streamflow gauges within the study subwatershed that formed the primary calibration targets; Whitemans Creek near Mount Vernon (02GB008), Horner Creek near Princeton (02GB006), and Kenny Creek near Burford (02GB009). The remaining six gauges outside of the Whitemans Creek subwatershed were used as validation gauges following calibration. Calibration statistics for the three primary gauges are provided in Table 11.1. Two periods are shown, a 3-year period which overlaps with the hydrologic submodel calibration period and the primary GSFLOW calibration period which spans WY2006 through WY2015.

Table 11.1: Calibration statistics for the integrated GSFLOW model.

Gauged Basin	Daily		Monthly		Volumetric Difference
	NSE	***Log NSE***	***NSE***	***Log NSE***	
Calibration Period 1 ***Short***	**(October 2008 – September 2011)**				
Horner Creek near Princeton	0.58	0.64	0.77	0.62	-8.8%
Whitemans Creek near Mount Vernon	0.66	0.55	0.74	0.50	-5.4%
Big Creek Near Kelvin	0.61	0.61	0.73	0.59	-8.4%
Big Otter Creek above Otterville	0.44	0.58	0.71	0.59	-5.7%
Cedar Creek at Woodstock	0.55	0.44	0.71	0.38	-9.8%
Thames River at Innerkip	0.61	0.34	0.75	0.35	-11.9%
Avon River above Stratford	0.52	0.17	0.79	0.49	-5.9%
Calibration Period 1 ***Long***	**(October 2006 – September 2015)**				
Horner Creek near Princeton	0.52	0.66	0.70	0.70	-5.5%
Whitemans Creek near Mount Vernon	0.57	0.64	0.67	0.63	1.0%
Big Creek Near Kelvin	0.50	0.57	0.61	0.59	-2.9%
Big Otter Creek above Otterville	0.44	0.63	0.67	0.70	0.2%
Cedar Creek at Woodstock	0.52	0.55	0.66	0.59	-6.1
Thames River at Innerkip	0.55	0.47	0.69	0.48	-13.1%
Avon River above Stratford	0.49	0.19	0.72	0.36	-17.2%

The model achieved Nash-Sutcliffe Efficiencies (NSEs) between 0.52 and 0.66 for the daily values during the calibration period. Log NSEs compare favourably, with values in excess of 0.64, suggesting a good match to low flow conditions. Daily results were aggregated over each month, and monthly NSEs from 0.67 to 0.77 were calculated, but monthly Log NSEs generally showing slightly poorer results compared to the non-transformed monthly flows. The model provides a good match to net streamflow volume (model bias), with a tendency to underpredict.

Daily streamflow calibration hydrographs are presented in Figure 11.2 and Figure 11.4 for the Horner Creek and Whitemans Creek gauges. Monthly and daily scatter plots are provide in Figure 11.3 and Figure 11.5, respectively. Model performance appears to drop off significantly in 2014 and 2015. An inspection of Environment Canada daily precipitation data for this period shows frequent gaps at nearby stations. Additionally, recent data have been flagged as having yet to undergo the standard level of QA/QC usually performed by Environment Canada. In general, the hydrographs indicate a good match to events, with the exception of several large freshet events which are underpredicted.

It is believed the low water extremes observed during drought years are related to under-reported water takings for irrigation. While the Irrigation Demand Module estimates the diversion volumes within the model, only permitted users are represented in the Tier 3 Assessment simulation runs. Because non-permitted users are not simulated, there will likely be some underpredictions of actual diversions and subsequent overprediction of summer streamflow in drought years. This behaviour is more pronounced in the smaller catchments; there is no tail-end bias observed for flows in the main branch of Whitemans Creek as measured at the Whitemans Creek near Mount Vernon (02GB008) gauge.

Similar model performance was observed at the validation stream gauges outside of the Whitemans Creek subwatershed. Figure 11.6 though Figure 11.15 presents daily streamflow hydrographs and scatter plots at the validation gauges. A good match to observed levels is obtained in Big Creek (02GC011) which has a similar hydrologic setting as lower Whitemans Creek. Good performance was also obtained at Thames River at Innerkip (02GD021) which shares a similar hydrologic setting as the upper portion of Horner Creek. Watersheds distal to Whitemans Creek offer inferior performance, which is not unexpected as the primary focus of this study has been within the Whitemans Creek subwatershed.

11.2.1.2 Groundwater Levels

The groundwater component of the integrated GSFLOW model was calibrated to time series data from observation wells assembled across the model area. Specifically, the calibration targets for the groundwater model comprised three observation datasets:

(1) PGMN monitoring well data from the three monitors located inside of the Whitemans Creek subwatershed, along with three others from outside the subwatershed.

(2) Monitoring wells and supply wells from the Bright and Bethel Road wellfields were used to calibrate the model to local groundwater patterns at the two municipal water supply systems. This included two monitoring wells and the two supply wells for the Bright system, and eight monitoring wells and one supply well for the Bethel Road wellfield.

(3) Monitoring data from the Tier 3 Field Program; drive point monitors were used as calibration targets for the upper model layers. A subset of five drive point piezometers was selected to represent the middle and lower portions of the Whitemans Creek subwatershed.

The quality of the calibration was assessed based on the match between simulated heads and the corresponding observation data. In particular, the focus was on replicating the timing and the magnitude of the water level fluctuations. The groundwater results are therefore presented as comparisons between relative heads, which highlight the match to observed fluctuations, because local differences in the absolute elevation were found, despite the close overall match obtained with the steady-state model. This has been the convention is previous Tier 3 studies (Earthfx, 2014a; Earthfx, 2013; Matrix, 2014a; Matrix, 2014b). Figure 11.16 to Figure 11.36 compare observed (blue) and simulated (red) heads at observation wells across the model area.

To capture the regional behaviour of the groundwater system, water levels from PGMN wells were compared to the simulated water levels from the corresponding model layer. Figure 11.16 to Figure 11.20 compare the observed and simulated groundwater levels at five PGMN wells across the study area. Simulated water levels show a good match to the timing and magnitudes of the fluctuations at the PGMN observation points, both in the central portion of the subwatershed (W0000478-1; Figure 11.16), as well as at the bottom of the subwatershed in the Norfolk Sand Plains (W0000477-1, W0000065-4 and W0000015-1; Figure 11.18, Figure 11.19 and Figure 11.20, respectively). Simulated water levels at PGMN well W0000180-1 show a close match to the observed dataset, which is interpreted to be influenced in-part by the operations of the nearby Pittock Reservoir and the Innerkip municipal wellfield (located approximately 500 m and 250 m away, respectively).

Field data from shallow piezometers installed as part of the Tier 3 Assessment were compared against simulated water table elevations. Figure 11.21 to Figure 11.22 present the observed versus simulated water levels at five locations. Though the monitoring period for these locations was limited to WY2015, the recorded water levels illustrate consistent responses to the spring freshet, the late spring recharge period, and the steady water level decline over the summer months (in most locations). These patterns are well-represented in the simulated water levels, particularly the timing and magnitudes of the spring freshet and late-spring recharge events.

The calibration period covers the available municipal datasets at the Bethel Road and Bethel wellfields. The model calibration in the Bright wellfield is demonstrated in Figure 11.26 and Figure 11.27 for pumping well 4A and 5, respectively. For the pumped wells, the model was calibrated to the maximum of the observed daily water levels. In both cases, simulated levels show a close match, tracing the top of the range in observed water levels. The use of the maximum water level was based on two reasons: First, maximum water levels are more likely to represent conditions within the aquifer surrounding the supply wells. Secondly, the observed levels in Well 4A and Well 5 (prior to August 2010) fluctuate on a sub-daily basis by approximately 6 m, which has been interpreted as being related to well losses. Previous well rehabilitation work conducted on the original Well 4 (Well Initiatives, 2008a) identified extensive mechanical plugging due to iron precipitate and the accumulation of sand in the well screen as being an ongoing problem with the well. Because replacement Well 4A was drilled 5 m away, it is reasonable to assume that similar well efficiency problems exist. Well efficiency problems have been documented at Well 5 since its construction in 2003, leading to the installation of a telescopic well screen in 2008 (Well Initiatives, 2008b) and the accompanying reductions in well capacity (ARL, 2010).

Observed water levels at monitor MW1 Deep, located approximately 17 m south of Well 4A, show none of the large fluctuations present in the pumped wells, suggesting the dramatic pumping-imposed water level variations are restricted to the pumped wells. The model calibration to the MW1 Deep monitoring interval is presented in Figure 11.28. The simulated water levels at this location appear to match well with respect to the timing of seasonal fluctuation, although the magnitudes of the fluctuations are muted compared to the observed levels. This could be due to the relatively shallow completion depth of this well relative to the two Bright supply wells, and the influence of shallow, local recharge pathways not presently captured in the model.

At the Bethel Road municipal well, transient water level data are limited to WY2012 to WY2015, and are even sparser for the four pumping wells. The calibration for this wellfield therefore focused on matching the surrounding municipal monitoring wells, presented in Figure 11.29 to Figure 11.36. Monitoring wells MW2/04 (Figure 11.29, Figure 11.30), TW2/11 (Figure 11.31), and MW1/14 (Figure 11.32) are located the closest to the four Bethel Road pumping wells. The sub-daily fluctuations in observed water levels at all of these monitors are not consistently captured in the simulated water levels, in-part due to the daily time-step employed in the model. Nevertheless, the simulated and observed seasonal water level patterns generally compare well. Simulated levels overpredict the local water level rise in the spring, however. This may be the result of the Brant Business Park being developed directly to the north of the wellfield (under construction and not currently represented in the model). The related increase in impermeable area could reduce the volume of freshet-generated recharge in the vicinity of the municipal monitors.

Monitoring wells TW3/12 (Figure 11.33) is located approximately 65 m west of the wellfield, and generally shows a good match between observed and simulated water levels. The calibration hydrographs for Bethel Road monitoring wells MW3/04-1, MW3/04-2 and MW3/04-3 are presented in Figure 11.34, Figure 11.35, and Figure 11.36, respectively. These wells are interpreted to be beyond the influence of the municipal pumping wells (IWC, 2012). Across all three of the monitoring intervals, simulated water levels compare well with the magnitudes in the observed data. Key exceptions are the notable “recharge spikes” observed in the shallow monitor MW3/04-3, which were not observed in any of the other municipal wells and are attributed to a highly localized anomaly in the direct vicinity of MW3/04. Further investigation revealed that the well is across the street from a road-side ditch network that does not appear to have an outlet culvert. Ponding in this swale during spring runoff may be the cause of the “spikes” observed in the shallow monitor interval MW2/04.

In addition, the match in the three MW3/04 monitoring intervals and TW3/12 seems to degrade in mid-WY2014, with simulated levels undergoing a steady decline into WY2015 while observed level remain stable or undergo minor increases. This period has been problematic across other transient groundwater calibration points, as well as streamflow calibration targets. The poor match has been attributed to limitations in recent meteorological observation datasets, a significant amount of which have yet to undergo the standard level of QA/QC by Environment Canada. Additionally, the number of available climate stations is significantly reduced compared to earlier periods, as discussed in Section 4.2.

In general, the hydrographs show that the calibrated model provided a good match to both the magnitude and timing of the observed seasonal patterns in the regional (PGMN) and shallow system monitors (Tier 3 piezometers). At the wellfield scale, the modelled water levels capture the natural seasonal fluctuations in the water levels, as well as local response to pumping, particularly in the Bethel Road wellfield. The transient calibration results show that the model generally captures the aquifer response to pumping outside of the pumped wells on a daily-basis; while peaks and troughs observed at sub-daily time scales are beyond the capabilities of the model at this time. This is not considered to be a significant limitation to the model as the scope of the Tier 3 Assessments is focussed on quantifying wellfield resilience to longer-term stresses such as future drought and increased water demands rather than sub-daily peaking. Overall, the quality of the groundwater calibration demonstrates the suitability of the calibrated GSFLOW model for the Whitemans Creek Tier 3 Risk Assessment.

11.3 GSFLOW Model Validation

To further test the adequacy of the GSFLOW model to predicting flows within the Whitemans Creek subwatershed, an additional series of validation runs were completed with historical data. The GSFLOW model was run between WY1980 and WY1986, validation statistics are presented on Table 11.2. The model outperforms the calibration period producing daily NSEs between 0.59 and 0.72 for the six year span. Log NSEs are also superior, with daily values ranging between 0.62 and 0.68. The number of climate stations available during this period is almost three times the number available during the calibration period. The streamflow calibration statistics, and by extension the groundwater calibration plots, presented in Section 11.2 may have been able to achieve a similar or better performance if the climate network had not been scaled back over the past 25 years.

Daily and month streamflow hydrographs for the three Whitemans Creek gauges with the corresponding scatter plots are provided in Figure 11.37 through Figure 11.42. A third Whitemans Creek gauge (Kenny Creek near Burford – 02GB009) is available during this period. Good performance is observed during the summer months at this relatively flashy gauge; however, the peaks simulated during the freshet appear muted. This may be due to the tile drainage representation within the model because the tile drain mapping used to parameterize the model dates to 2015. Tile drains tend to reduce peak runoff in silty, clayey soil during the spring freshet zone (Robinson, 1990) as slow drainage over the winter ensures excess storage capacity is available within the soil to accept infiltration.

Table 11.2: Validation statistics (WY1980- WY1986) for the integrated GSFLOW model.

Gauged Basin	Daily		Monthly		Volumetric Difference
	NSE	Log NSE	NSE	Log NSE	
Horner Creek near Princeton	0.65	0.68	0.83	0.69	-12.5%
Whitemans Creek near Mount Vernon	0.72	0.62	0.79	0.61	-13.1%
Kenny Creek near Burford	0.59	0.67	0.73	0.64	-9.8%
Big Otter Creek above Otterville	0.50	0.71	0.75	0.78	-11.7%
Cedar Creek at Woodstock	0.59	0.67	0.75	0.74	-13.9%
Thames River at Innerkip	0.65	0.50	0.83	0.58	-10.0%

Spotflow measurements were collected by GRCA staff across the subwatershed during low flow conditions in August of 2015 (Section 4.3.5). Figure 11.43 compares these observations against simulated streamflow for the same period. A good match is observed at most reaches, with a slight overprediction in the lowest reach of Kenny Creek. Field observations indicated a loss of streamflow from Whitemans Creek into the groundwater system between Cleaver Road (the location of WSC gauge 02GB008) and Robinson Road (adjacent to Rest Acres Creek at Apps' Mill). Figure 11.44 presents the simulated streamflow in this reach with the two spotflow measurements in question. The integrated model closely replicates the observed losing behaviour in the Apps' Mill reach. Preliminary analysis suggests this behaviour is related to the surface water leakage into the bedrock contact aquifer. Field observations suggests that Whitemans Creek has down-cut through the Port Stanley and Catfish tills in the vicinity of Apps Mill, and that the streambed is hydraulically connected to this deep, underdrained bedrock aquifer. It is suspected that the streamflow loss into the deep system eventually emerges in the Grand River Valley to the southeast.

As a final check on the model's predictive capability, areas of average groundwater discharge were plotted against mapped wetland features (Figure 11.45). Not all mapped wetlands are expected to be groundwater fed, and additionally, wetland processes are highly transient in nature; however, on average, the predicted discharge zones correlate well with the mapped wetland features.

11.4 *GSFLOW Outputs*

GSFLOW model outputs are similar to those generated for the PRMS and MODFLOW submodels but with a number of significant enhancements. For example, over 86 different groundwater and surface water flow components can be output on a cell-by-cell basis each simulation day. Earthfx has added additional components to the output and aggregated other flow components so that local (cell-based) and subcatchment-based water balances can be easily obtained. These include process variables such as observed (interpolated) precipitation (Figure 11.46), canopy interception (Figure 11.47), potential ET (Figure 11.48), actual ET (Figure 11.49), Hortonian (infiltration excess) (Figure 11.50), cascading runoff (Figure 11.51), groundwater recharge (Figure 11.52), and groundwater discharge (Figure 11.53). These elements can then be aggregated to compute annual and monthly average water budgets for the model area and for selected subcatchments.

As an example, Figure 11.54 shows simulated heads in model layer 3 and simulated streamflow (in m^3/s) on June 1st, 2014. Groundwater levels are at or near their highs for the water year, with moderate daily streamflows volumes. Figure 11.55 shows simulated heads and simulated streamflow on September 1st 2013. Groundwater levels and streamflow are at or near their lows for the water year. Many of the lower-order streams show negligible flow.

11.5 *Figures*

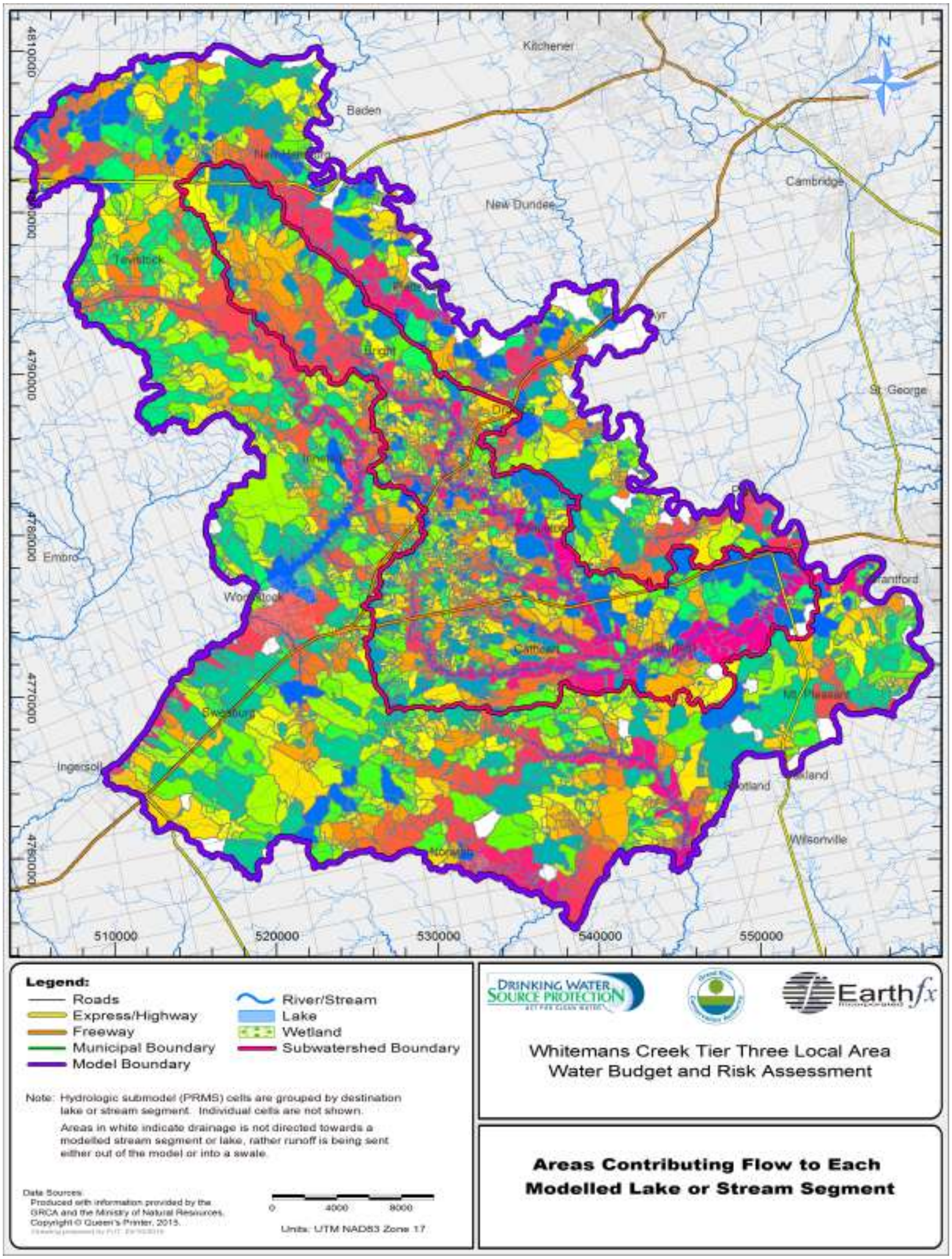


Figure 11.1: Contributing PRMS cells to each MODFLOW SFR stream reach.

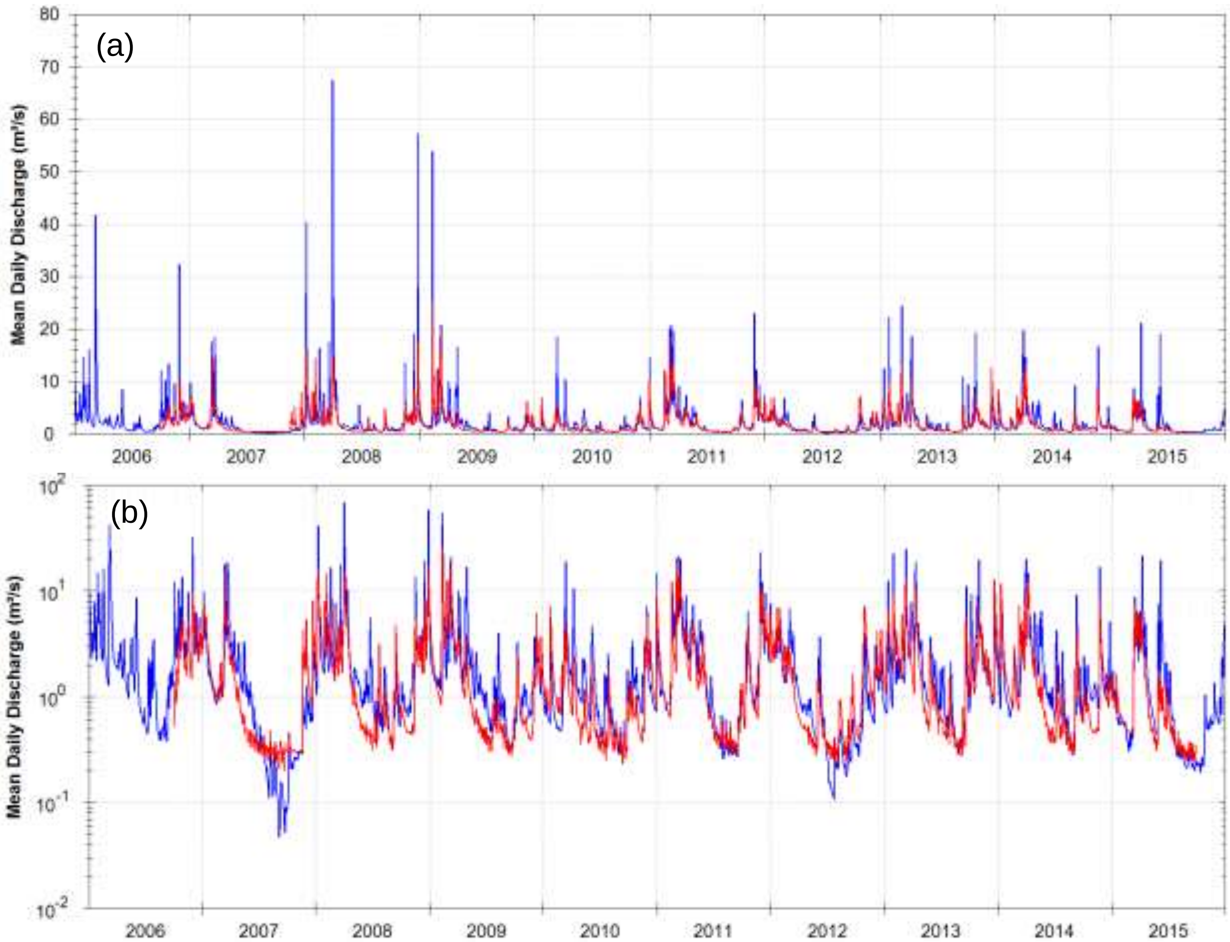


Figure 11.2: Calibration plots for Horner Creek near Princeton (02GB006); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

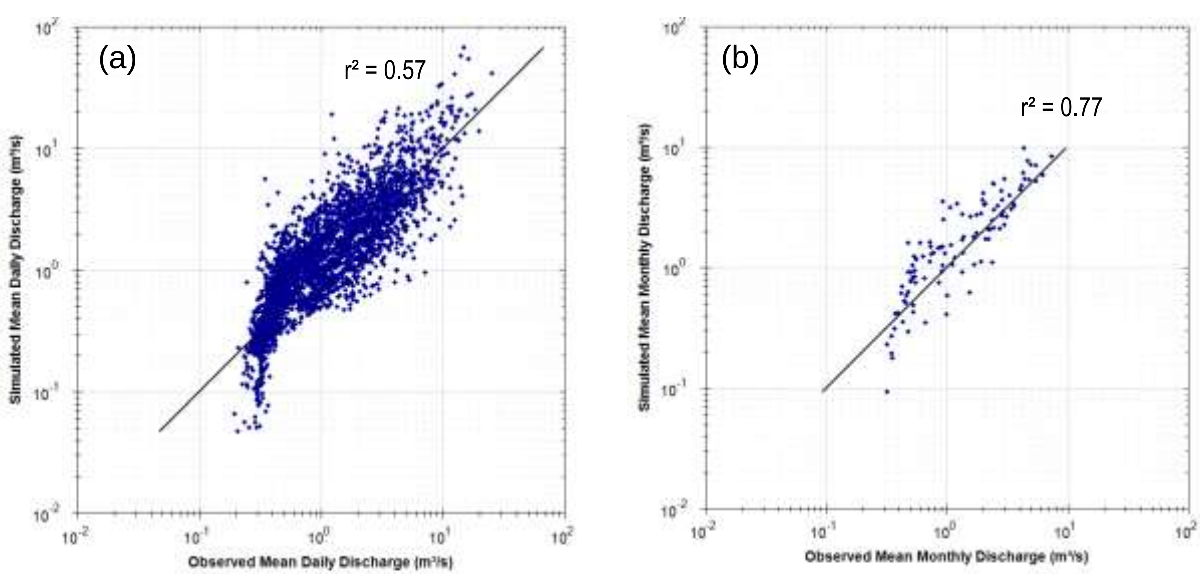


Figure 11.3: Calibration plots for Horner Creek near Princeton (02GB006); (a) daily and (b) monthly streamflow scatter plots.

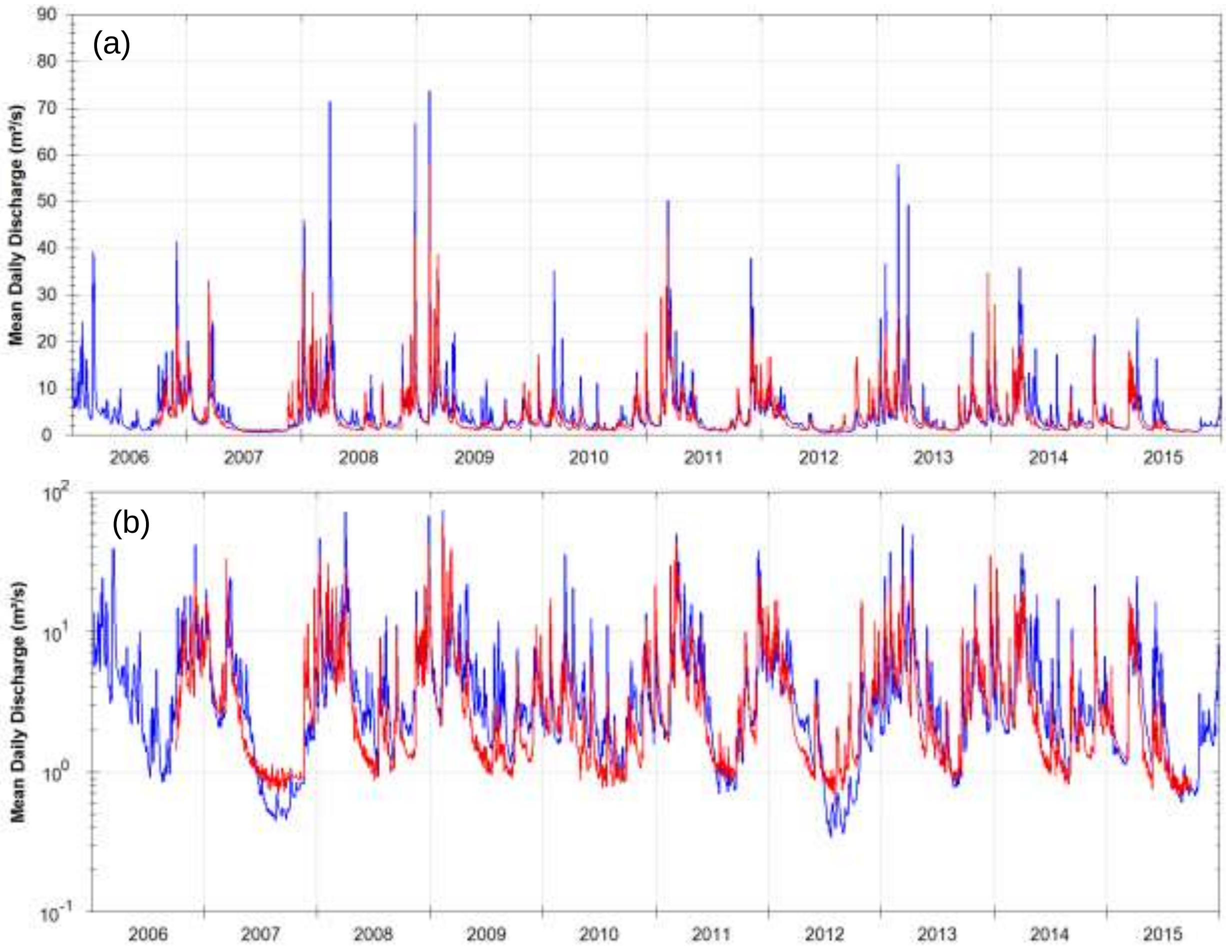


Figure 11.4: Calibration plots for Whitemans Creek near Mount Vernon (02GB008); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

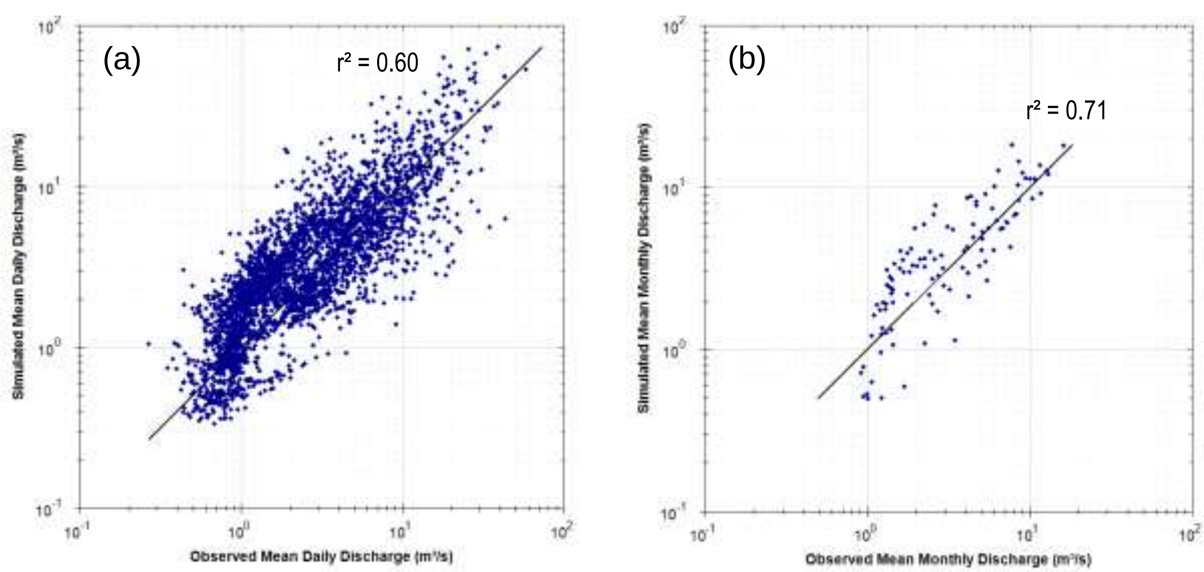


Figure 11.5: Calibration plots for Whitemans Creek near Mount Vernon (02GB008); (a) daily and (b) monthly streamflow scatter plots.

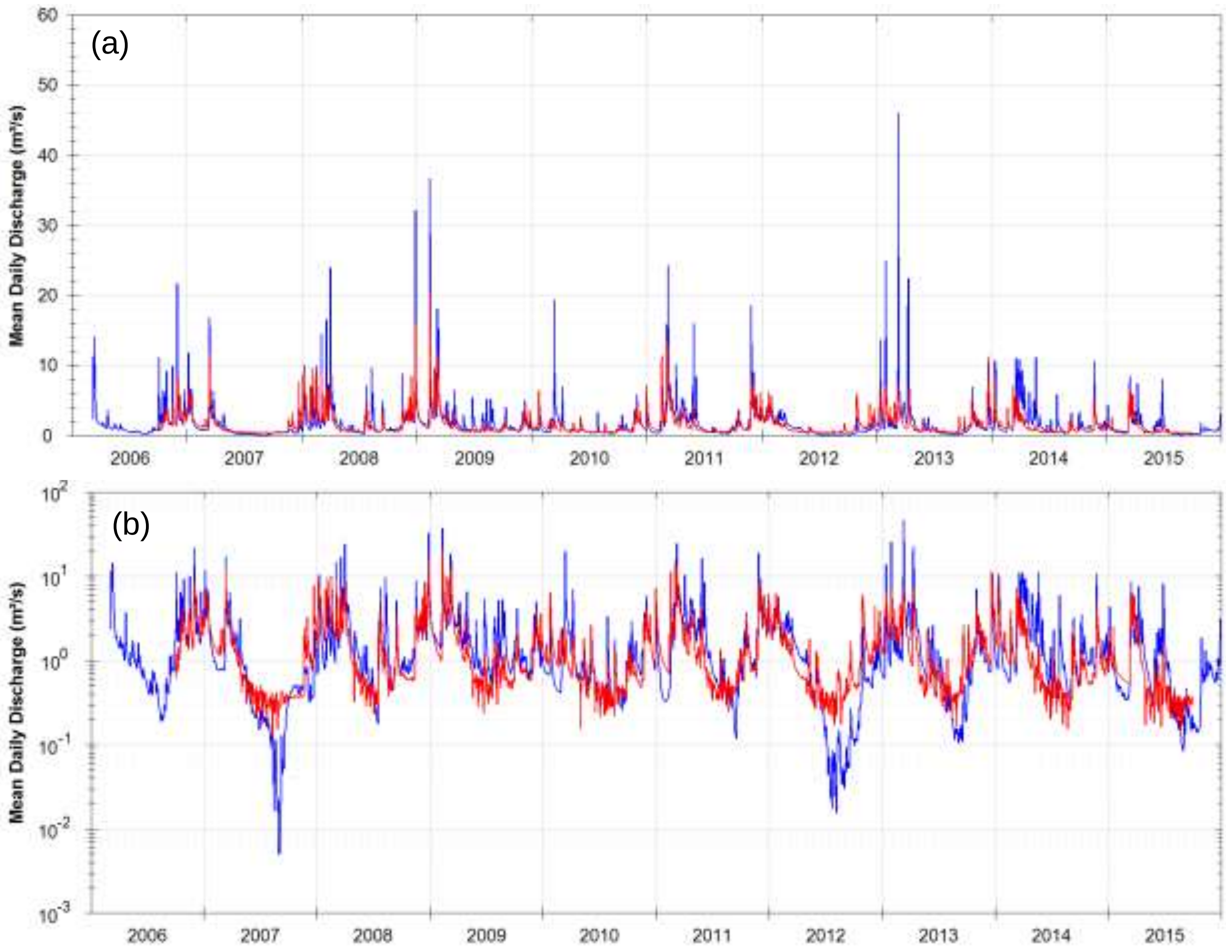


Figure 11.6: Validation plots for Big Creek near Kelvin (02GC011); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

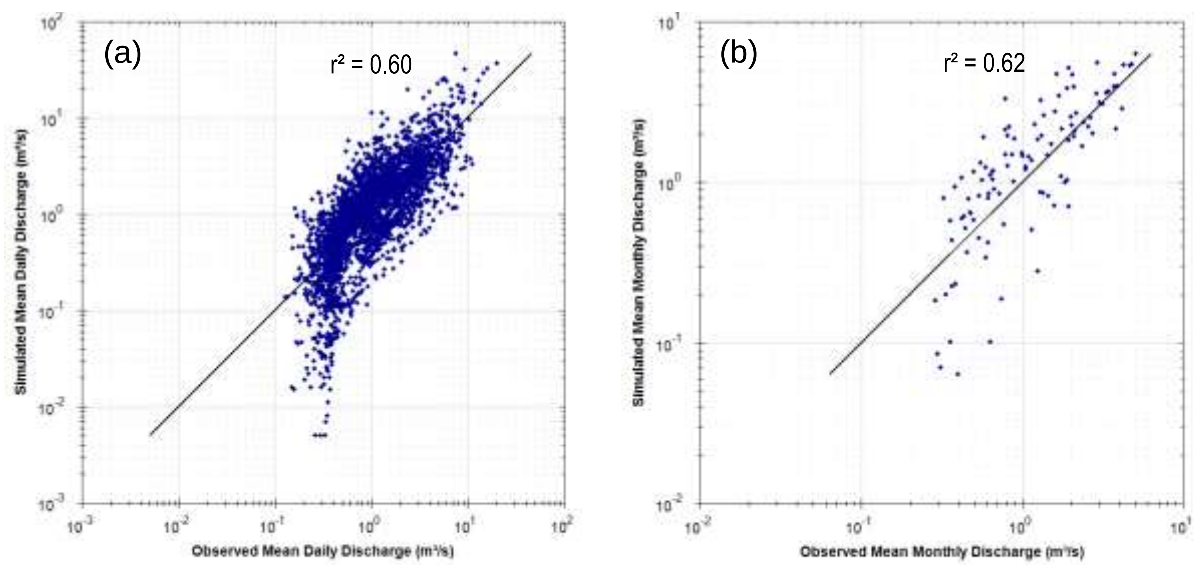


Figure 11.7: Validation plots for Big Creek near Kelvin (02GC011); a) daily and b) monthly streamflow scatter plots.

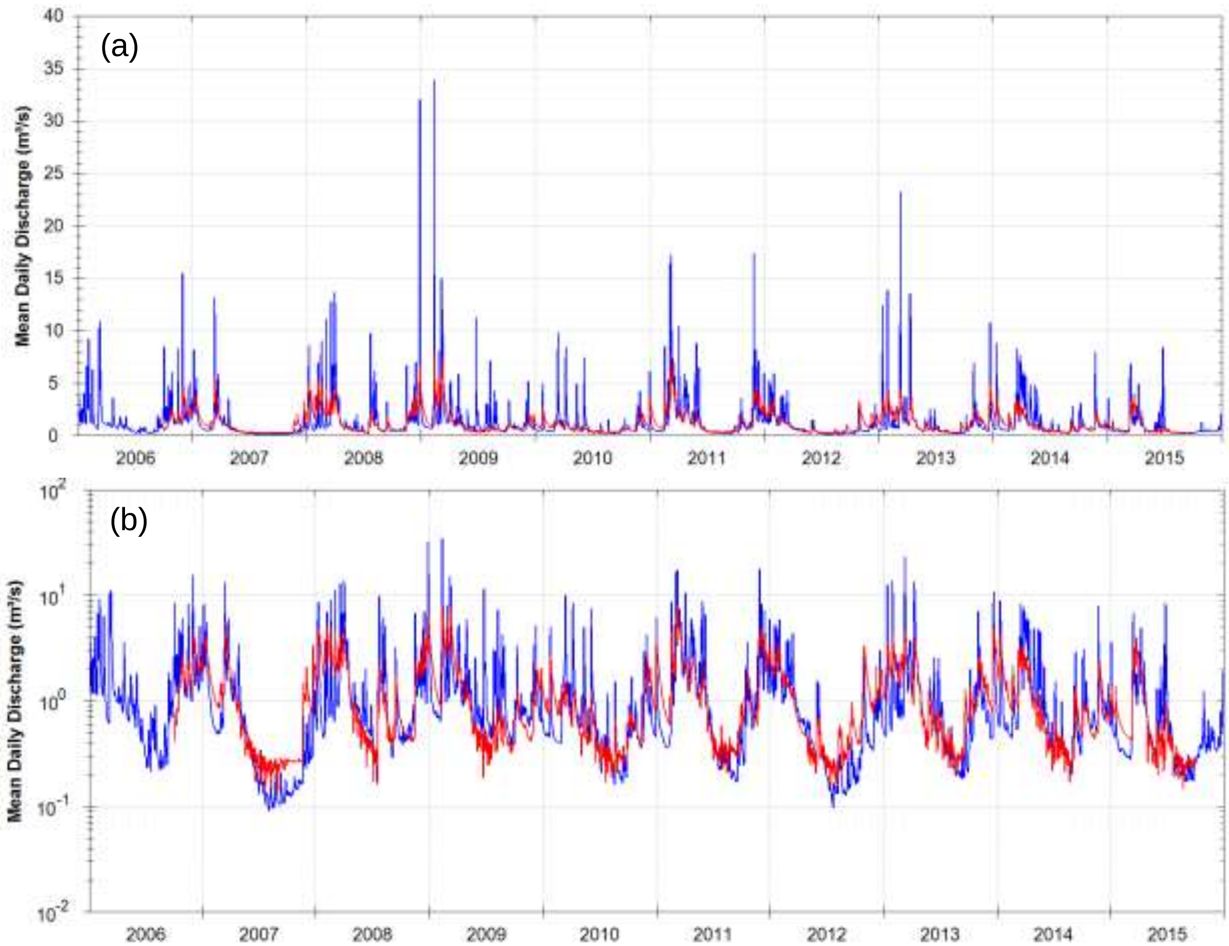


Figure 11.8: Validation plots for Big Otter Creek above Otterville (02GC017); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

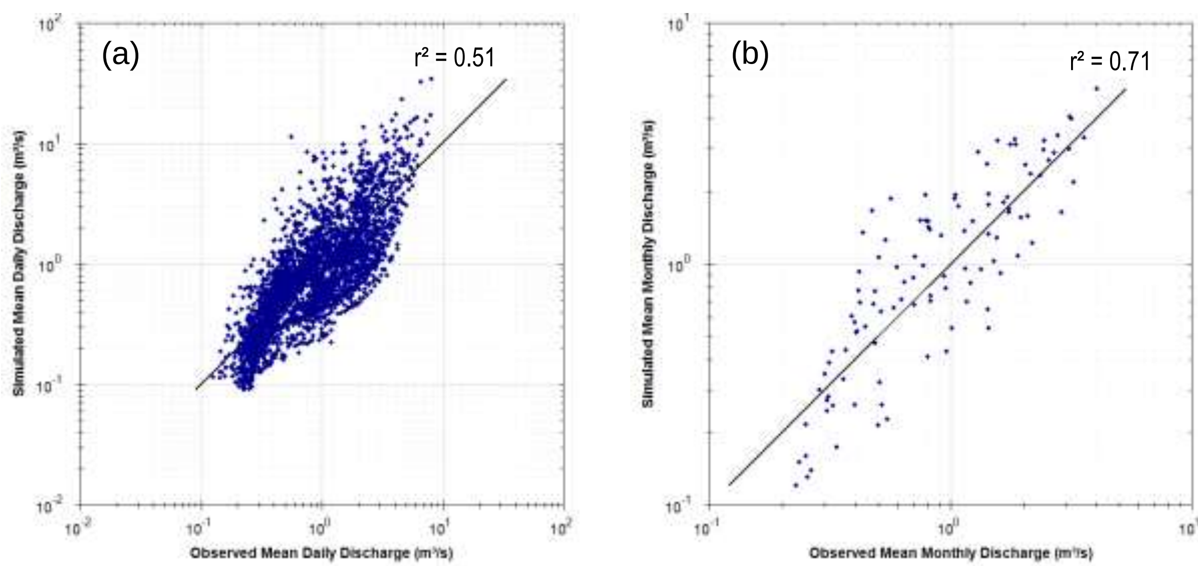


Figure 11.9: Validation plots for Big Otter Creek above Otterville (02GC017); (a) daily and (b) monthly streamflow scatter plots.

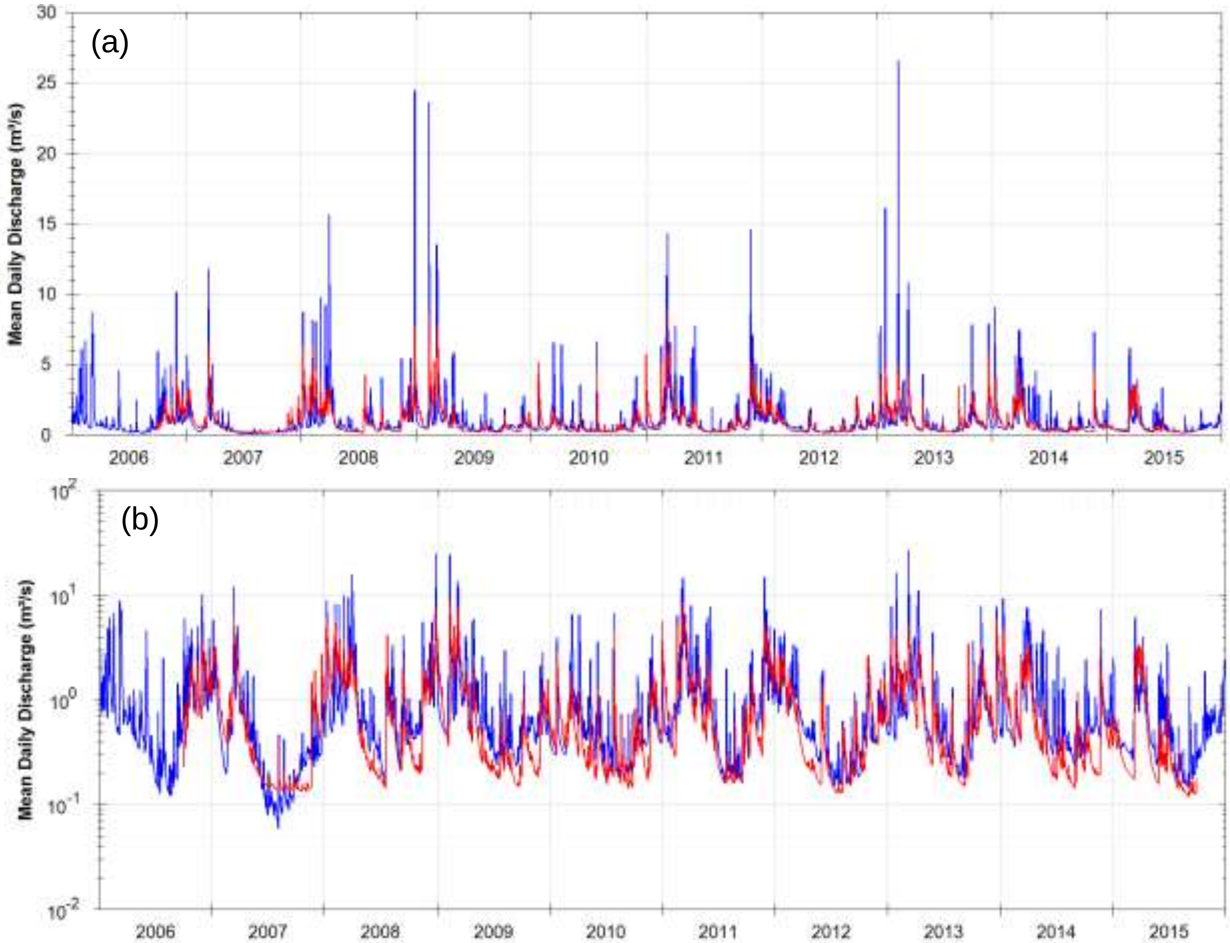


Figure 11.10: Validation plots for Cedar Creek at Woodstock (02GD011); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

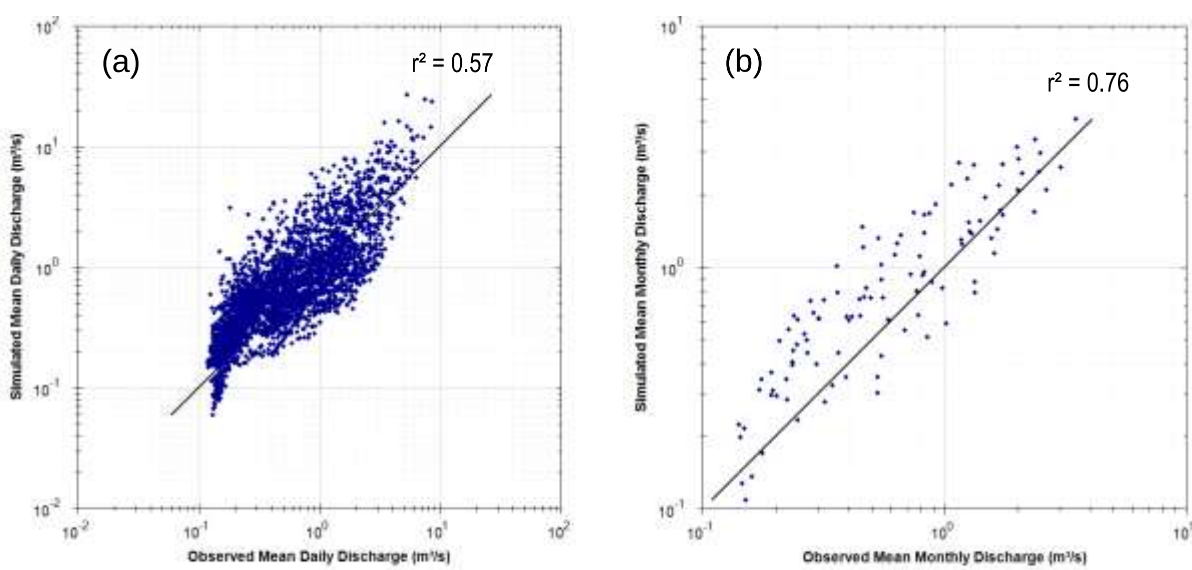


Figure 11.11: Validation plots for Cedar Creek at Woodstock (02GD011); (a) daily and (b) monthly streamflow scatter plots.

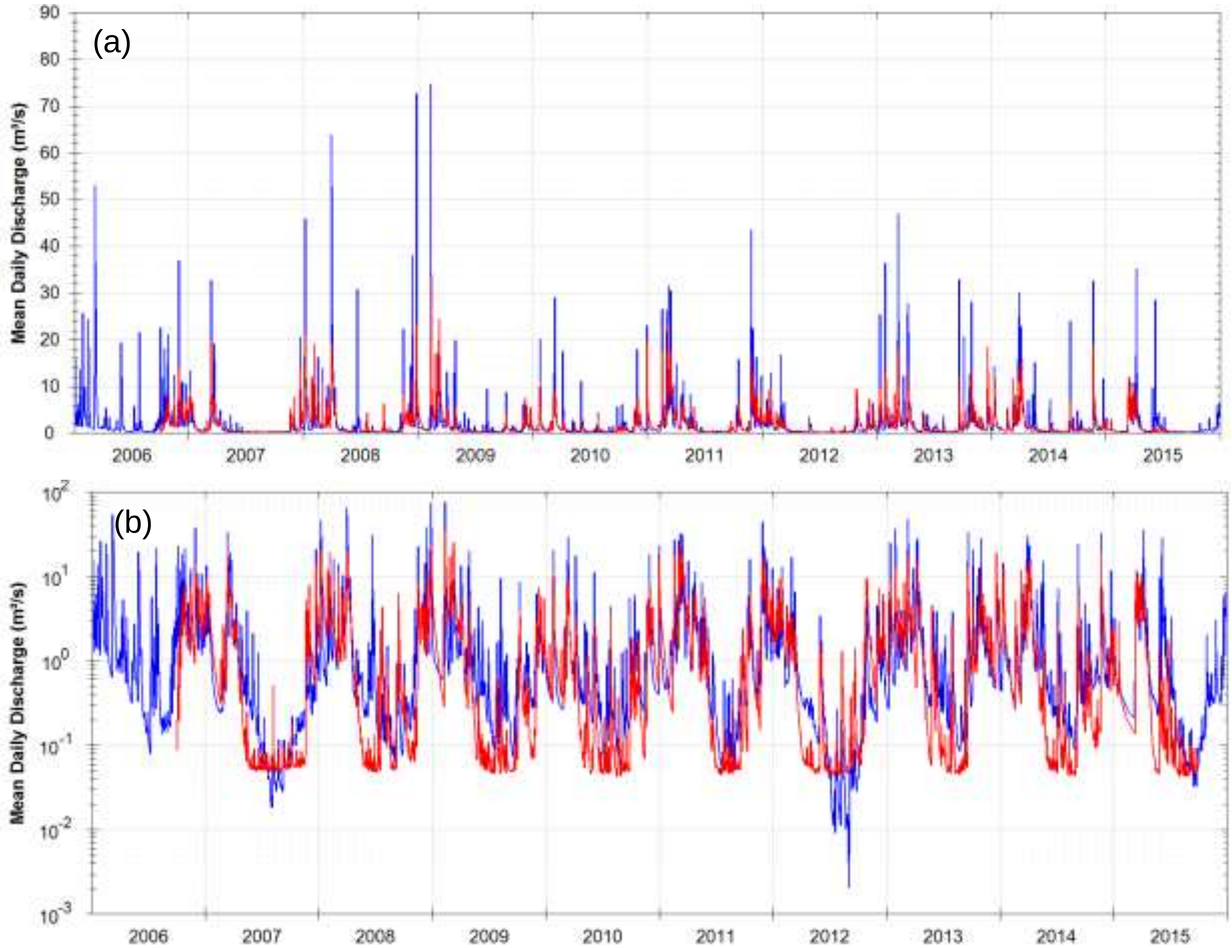


Figure 11.12: Validation plots for Thames River at Innerkip (02GD021); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.

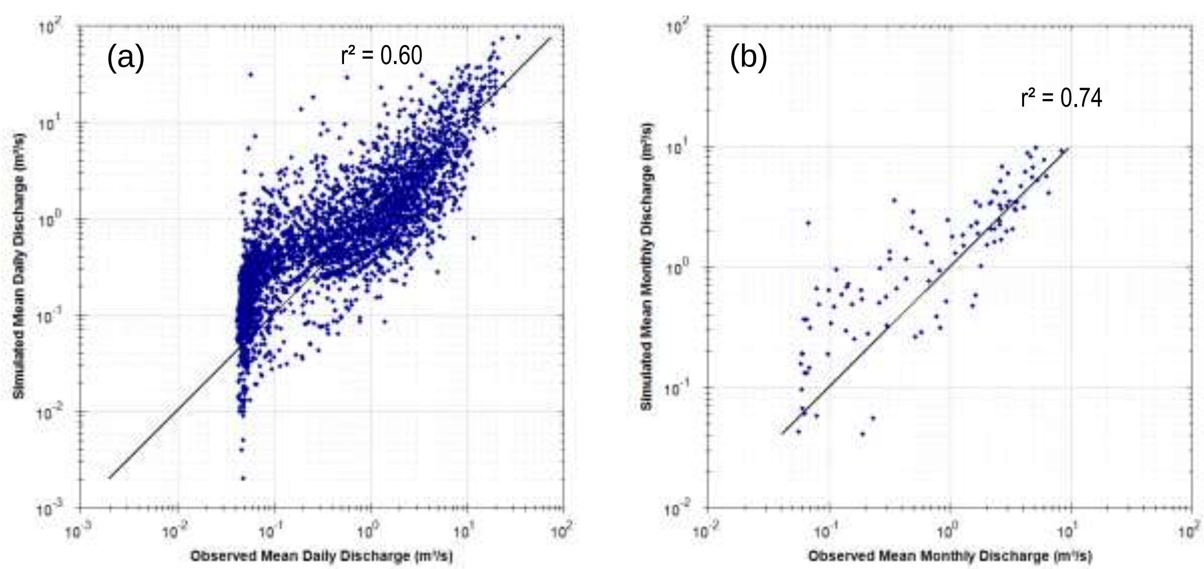
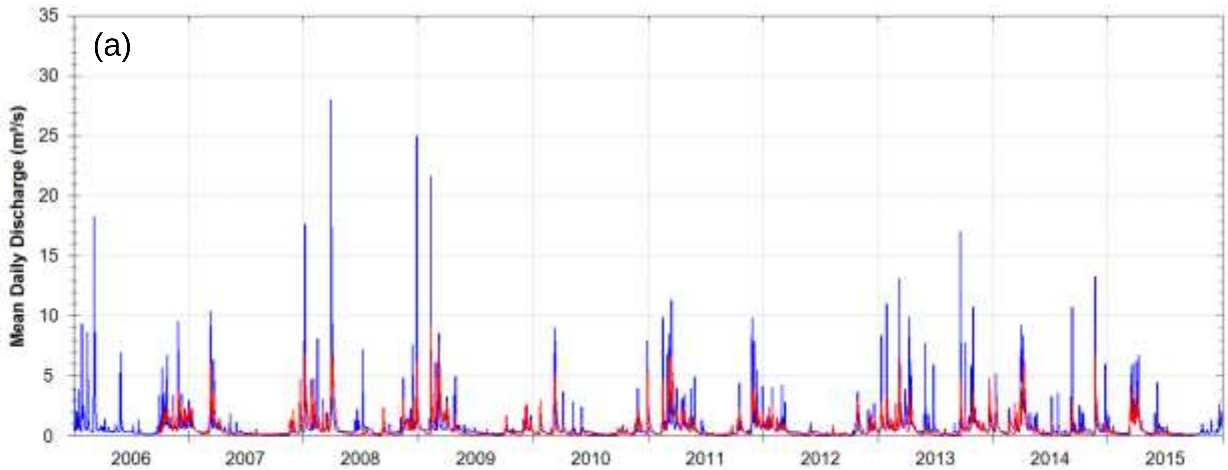


Figure 11.13: Validation plots for Thames River at Innerkip (02GD021); a) daily and b) monthly streamflow scatter plots.



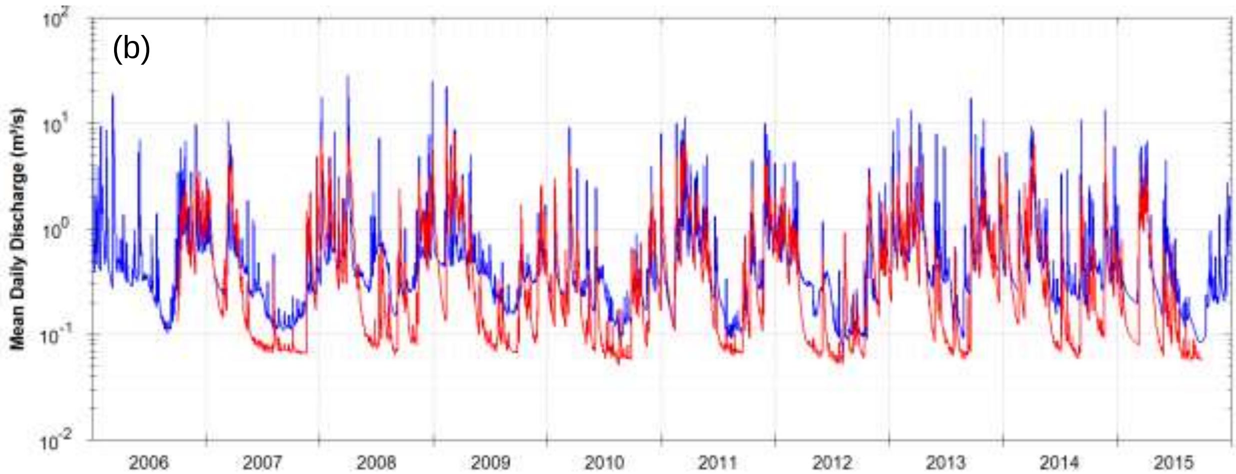
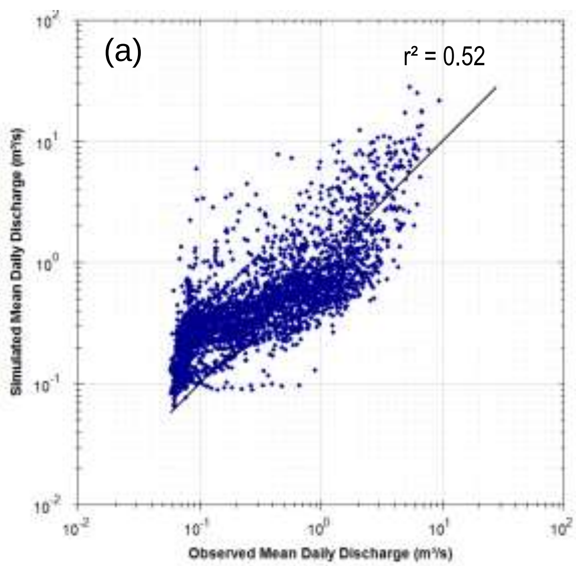


Figure 11.14: Validation plots for Avon River above Stratford (02GD026); observed (blue) versus simulated (red) (a) daily and (b) log-transformed daily streamflow.



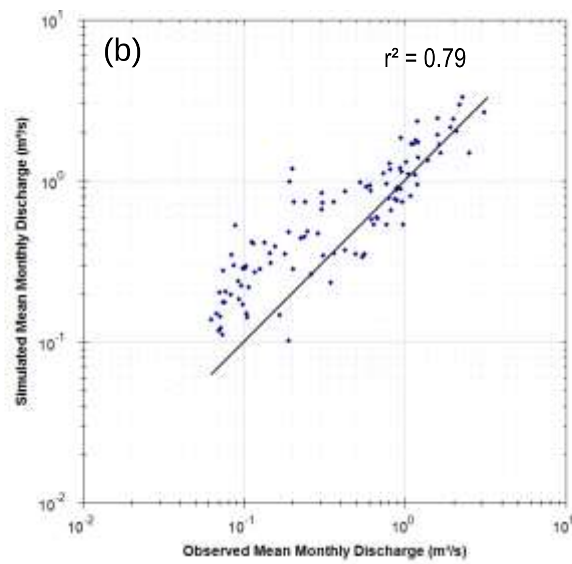


Figure 11.15: Validation plots for Avon River above Stratford (02GD026); (a) daily and (b) monthly streamflow scatter plots.

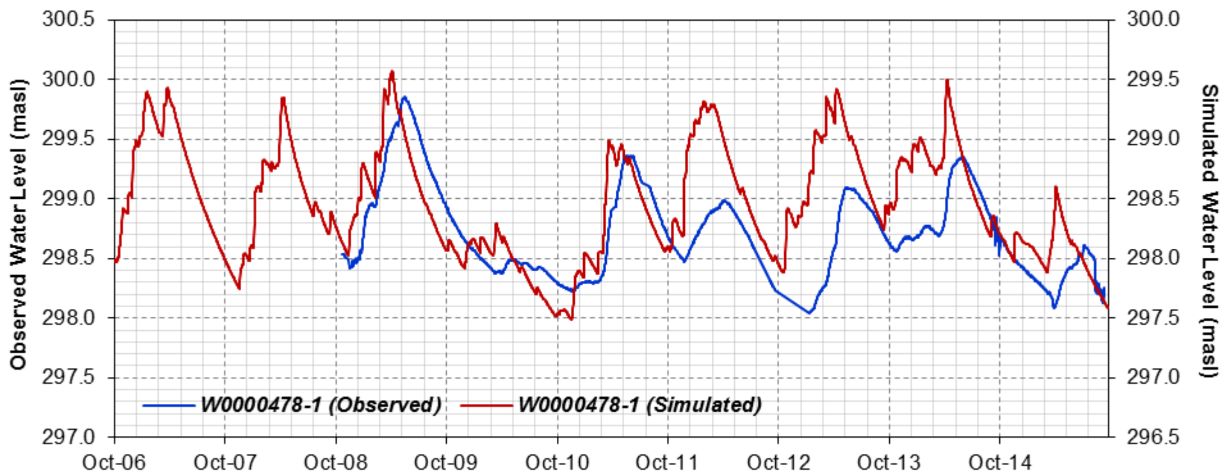


Figure 11.16: Relative water level calibration to observed head in PGMN well W0000478-1 in the Waterloo Moraine Aquifer.

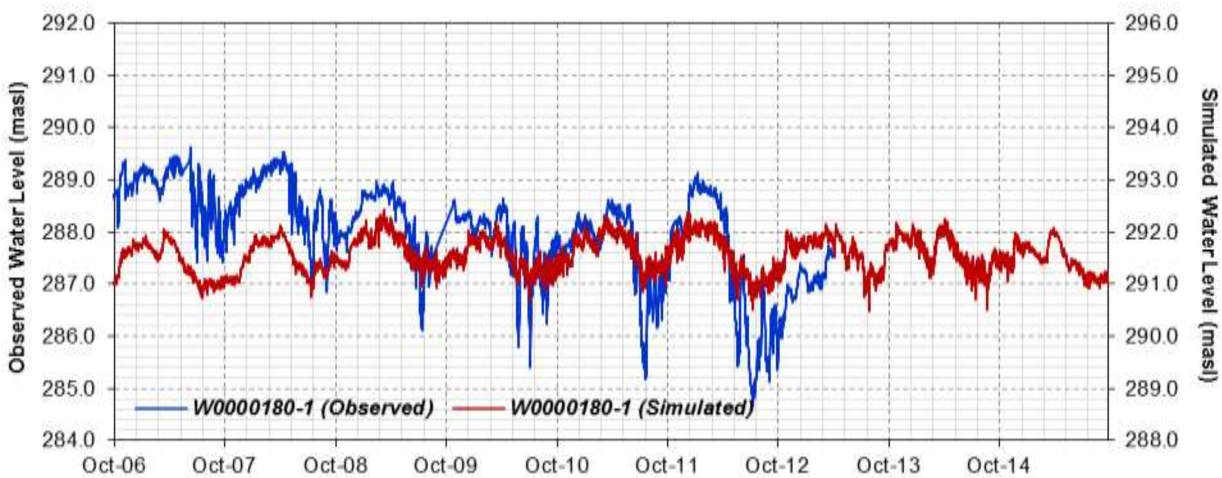


Figure 11.17: Relative water level calibration to observed head in PGMN well W0000180-1 in the Onondaga Limestone Aquifer.

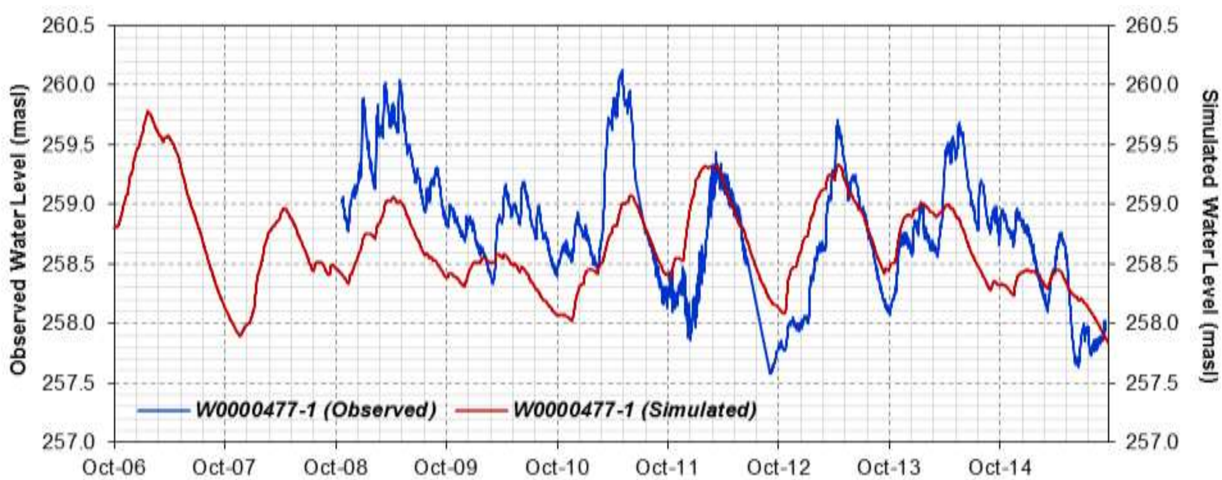


Figure 11.18: Relative water level calibration to observed head in PGMN well W0000477-1 in the Waterloo Moraine Aquifer.

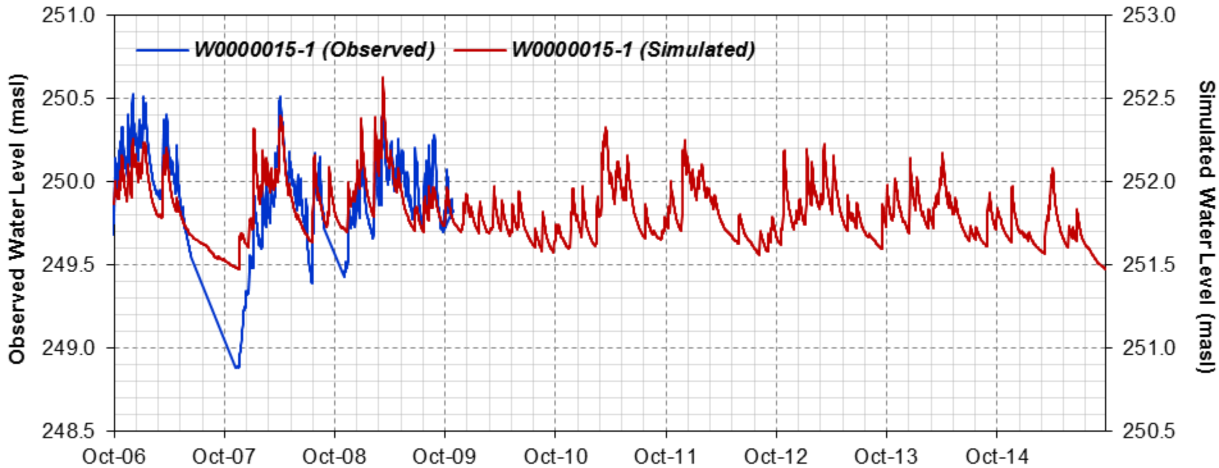


Figure 11.19: Relative water level calibration to observed head in PGMN well W0000015-1 in the Sand Plain-Outwash Aquifer.

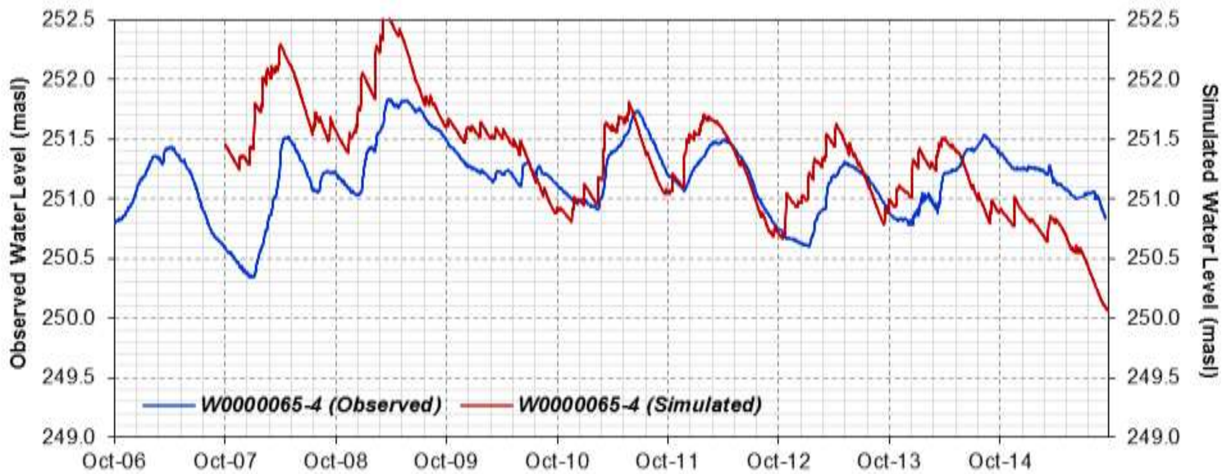


Figure 11.20: Relative water level calibration to observed head in PGMN well W0000065-1 in the Sand Plain-Outwash Aquifer.

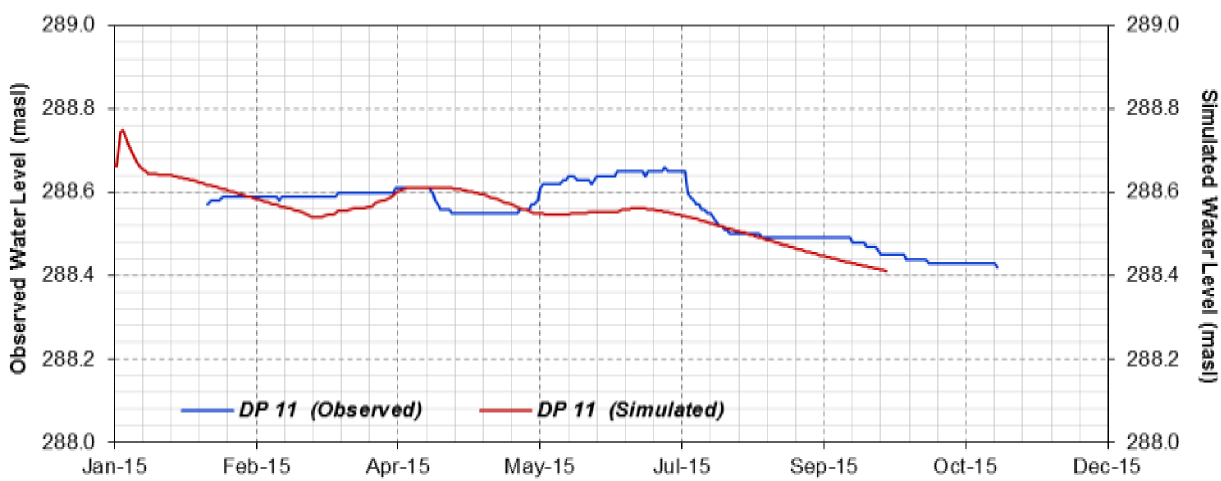


Figure 11.21: Relative water level calibration to observed head in shallow water table piezometer DP11.

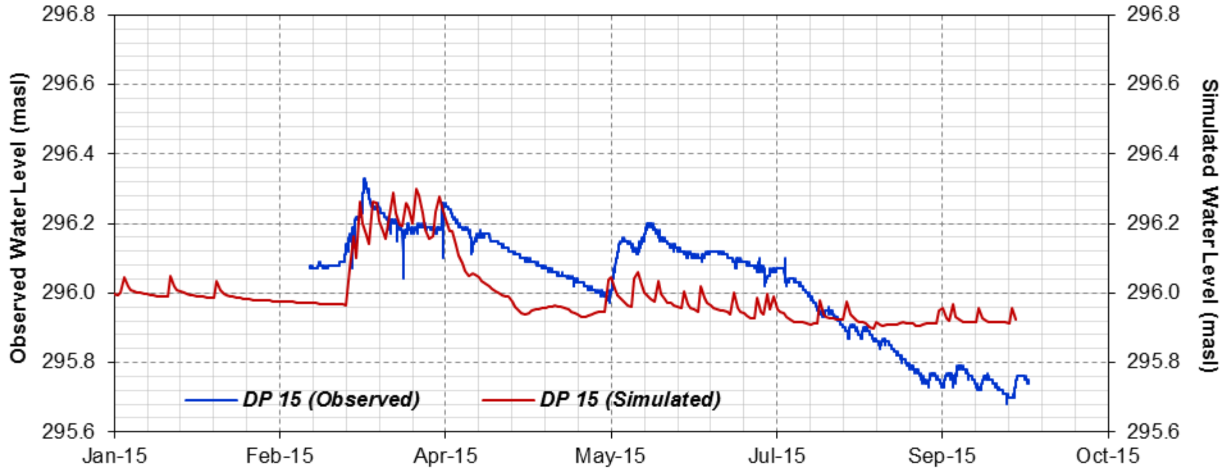


Figure 11.22: Relative water level calibration to observed head in shallow water table piezometer DP15.

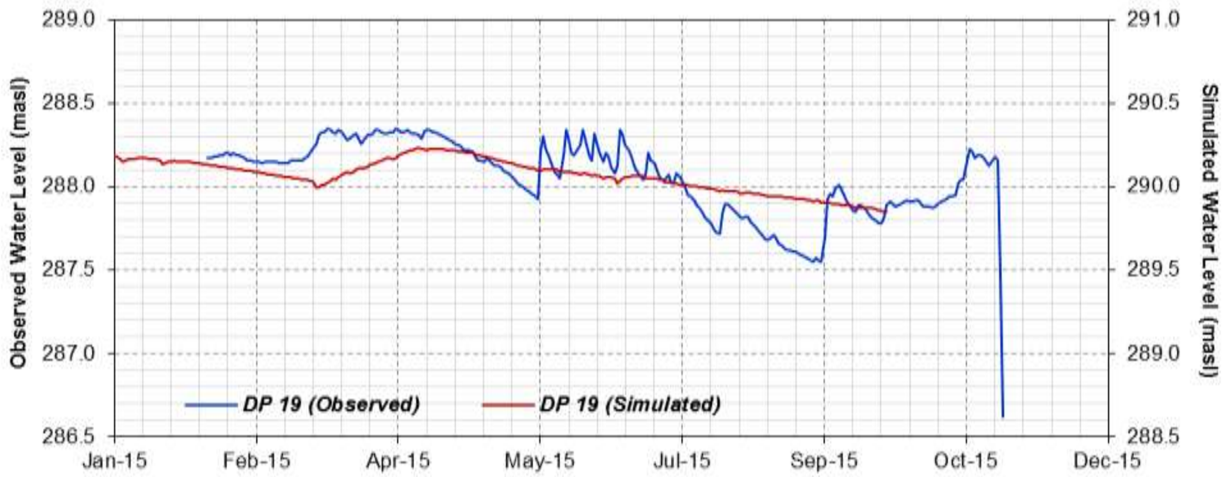


Figure 11.23: Relative water level calibration to observed head in shallow water table piezometer DP19.

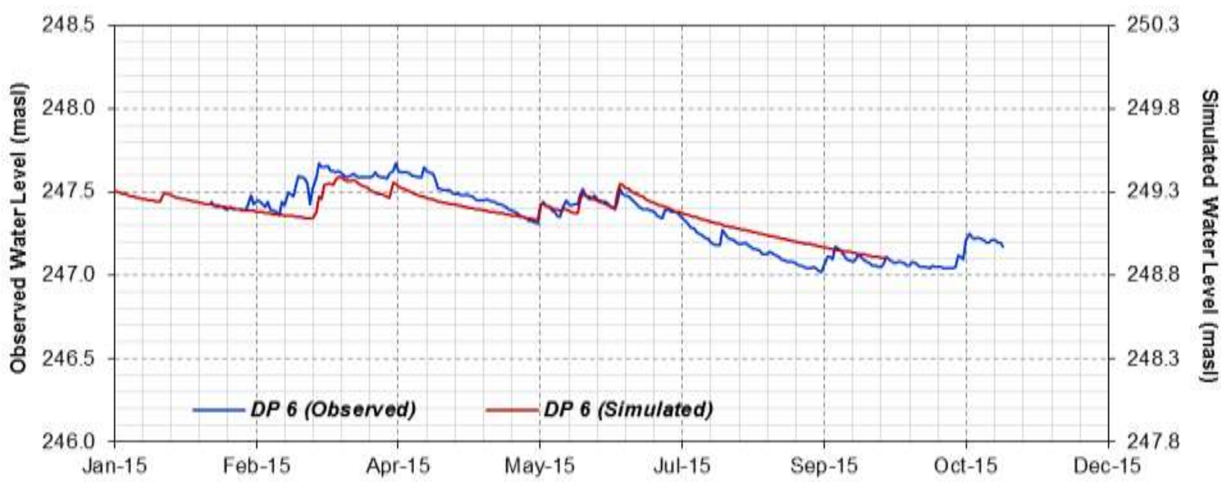


Figure 11.24: Relative water level calibration to observed head in shallow water table piezometer DP6.

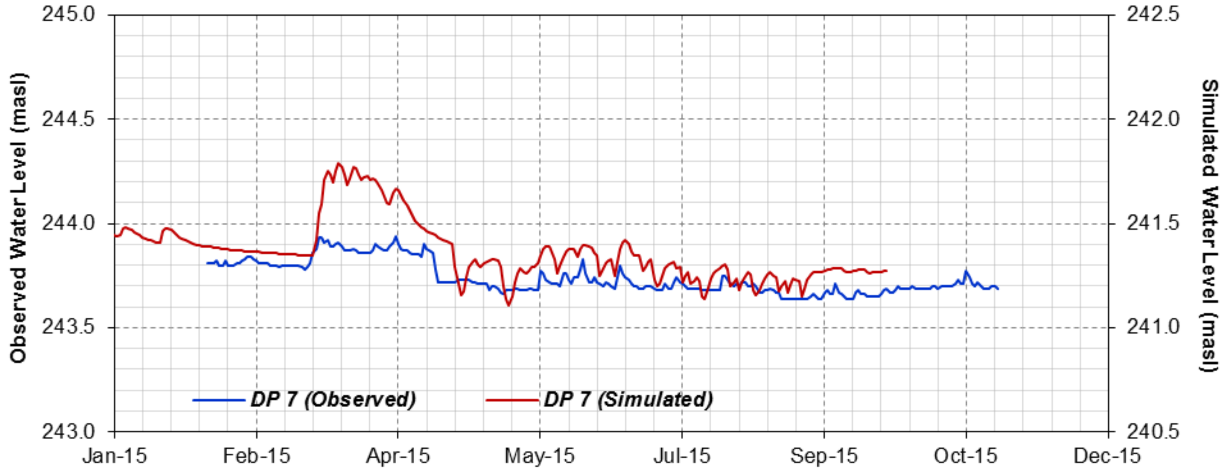


Figure 11.25: Relative water level calibration to observed head in shallow water table piezometer DP7.

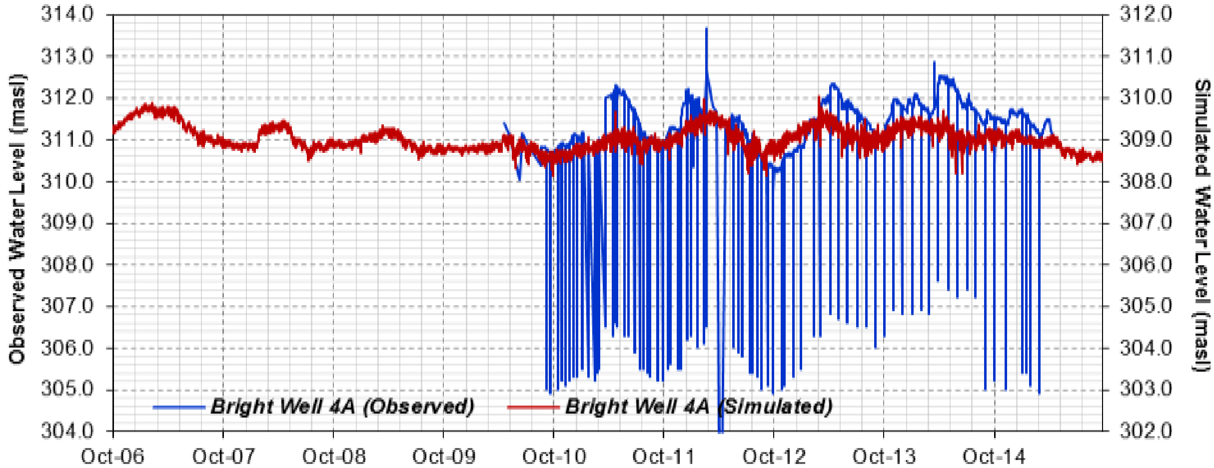


Figure 11.26: Relative water level calibration to observed head in Bright Well 4A.

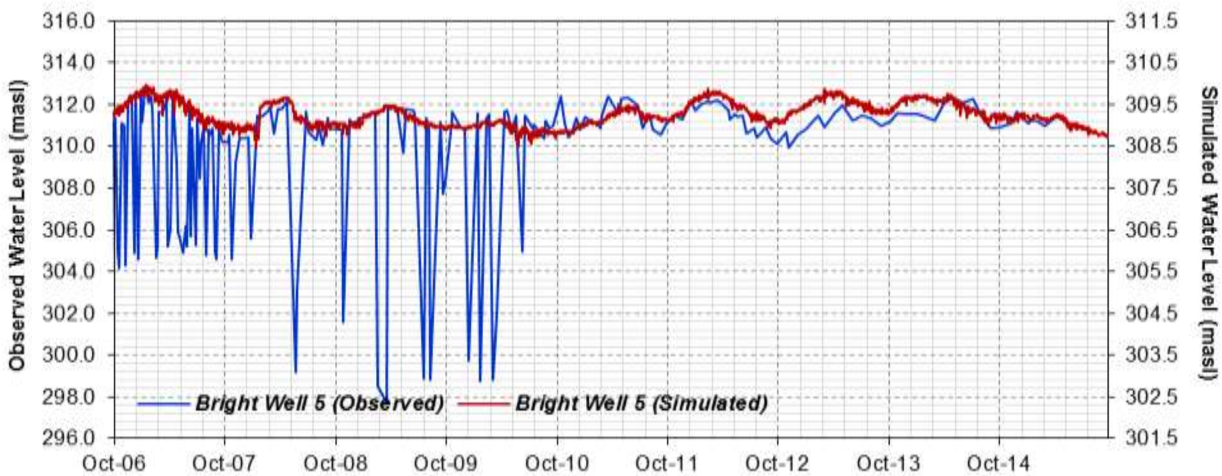


Figure 11.27: Relative water level calibration to observed head in Bright Well 5.

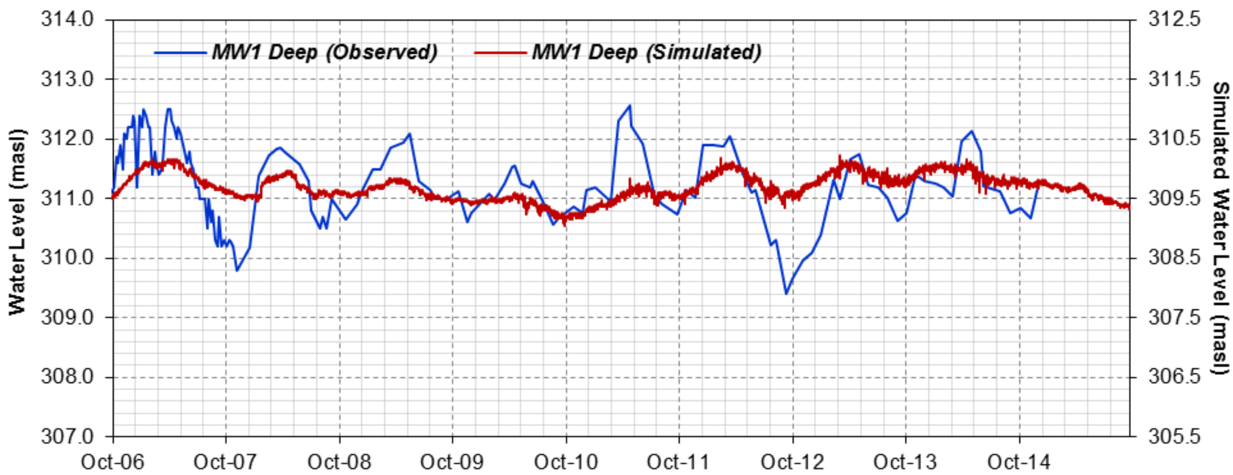


Figure 11.28: Relative water level calibration to observed head in Bright monitoring well MW1-Deep.

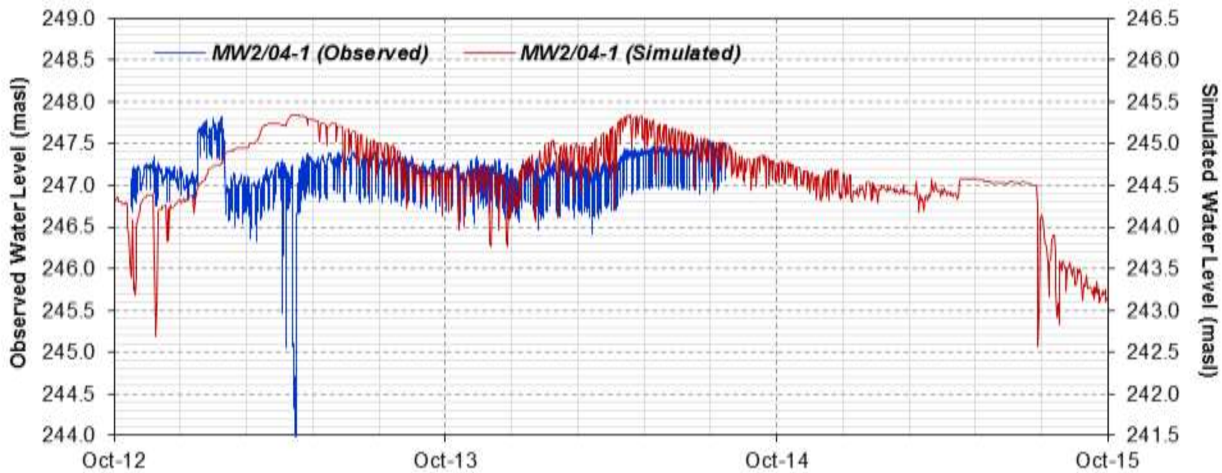


Figure 11.29: Relative water level calibration to observed head in Bethel Road monitoring well MW2/04-1 (deep).

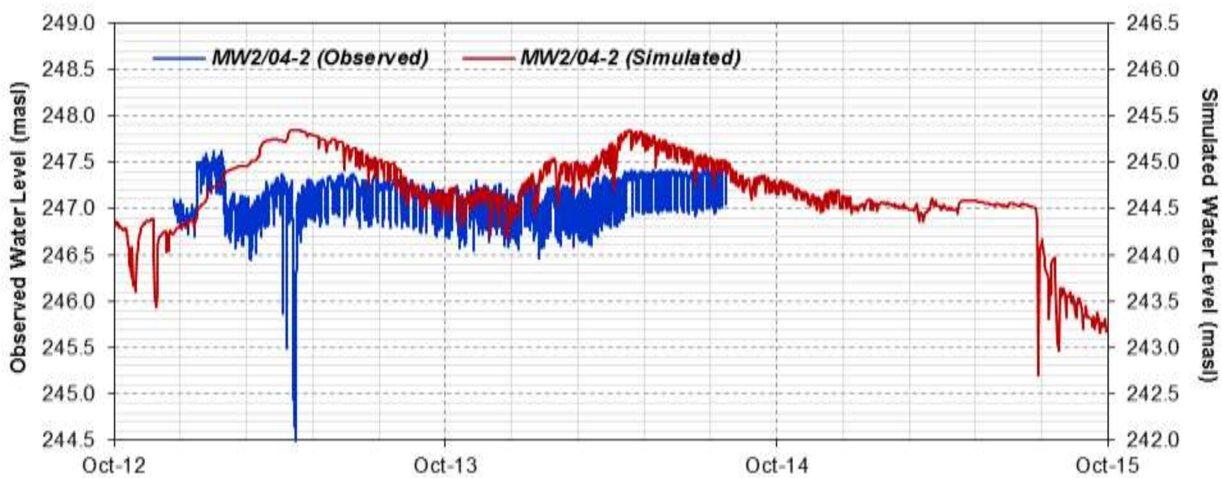


Figure 11.30: Relative water level calibration to observed head in Bethel Road monitoring well MW2/04-2 (shallow).

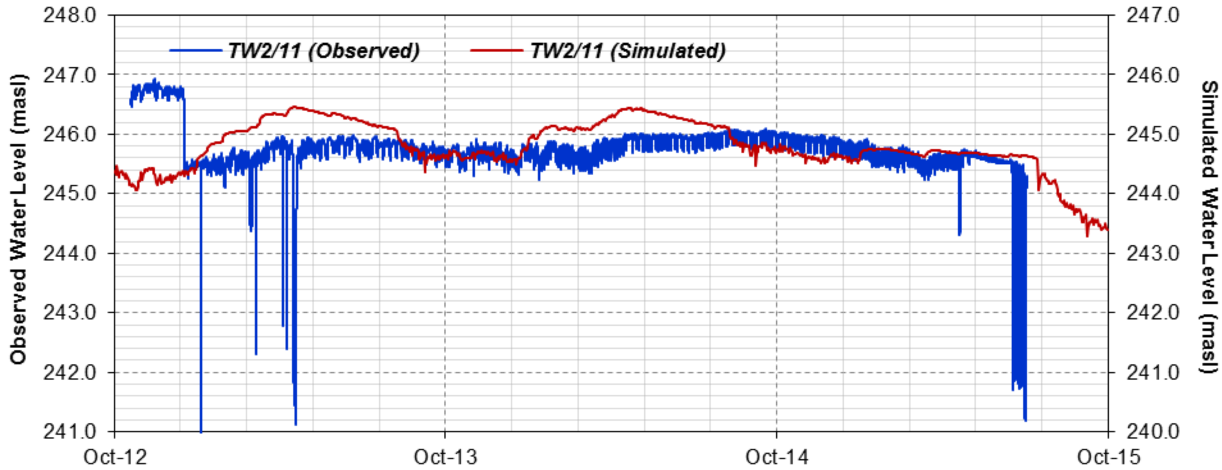


Figure 11.31: Relative water level calibration to observed head in Bethel Road monitoring well TW2/11.

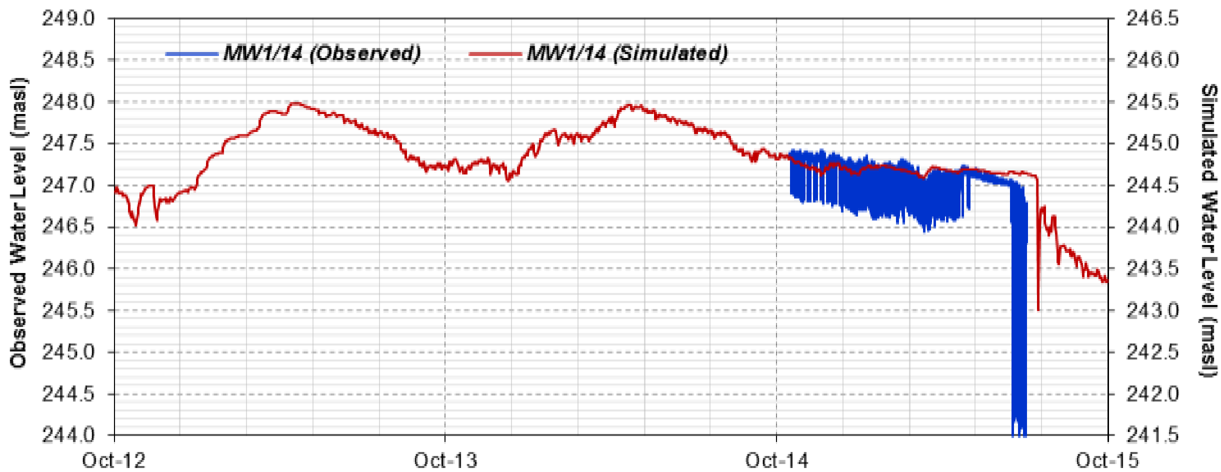


Figure 11.32: Relative water level calibration to observed head in Bethel Road monitoring well MW1/14.

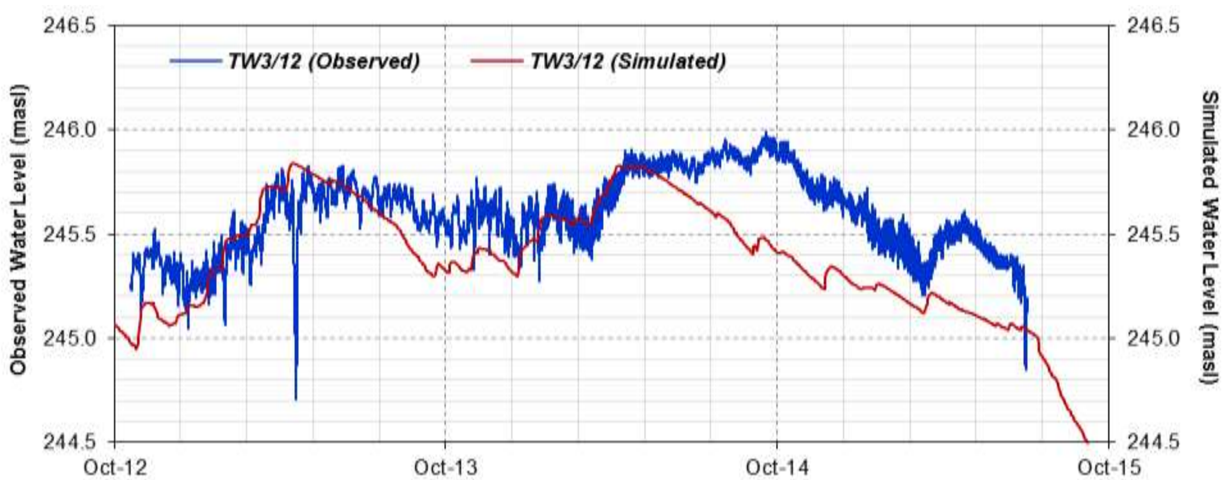


Figure 11.33: Relative water level calibration to observed head in Bethel Road monitoring well TW3/12.

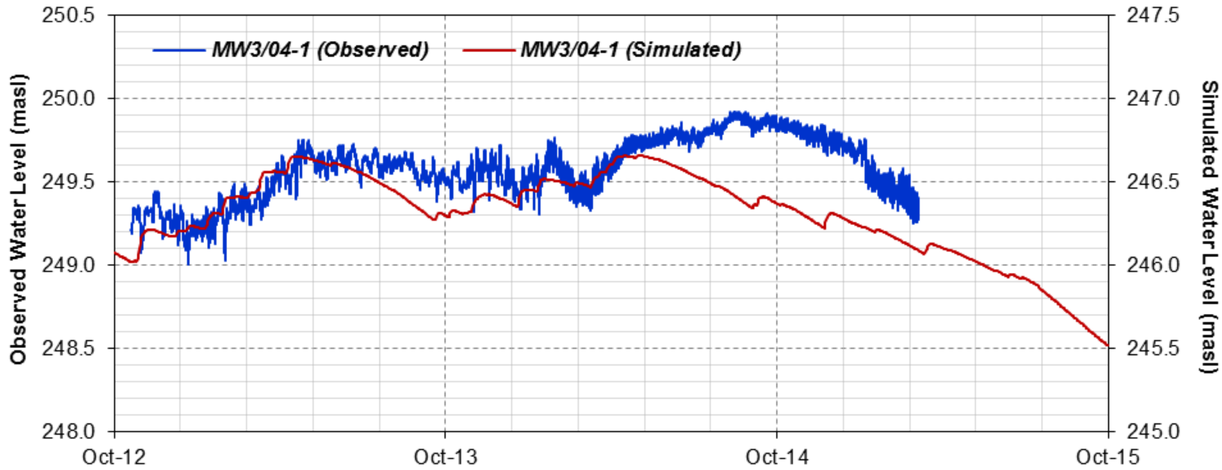


Figure 11.34: Relative water level calibration to observed head in Bethel Road monitoring well MW3/04-1 (deep).

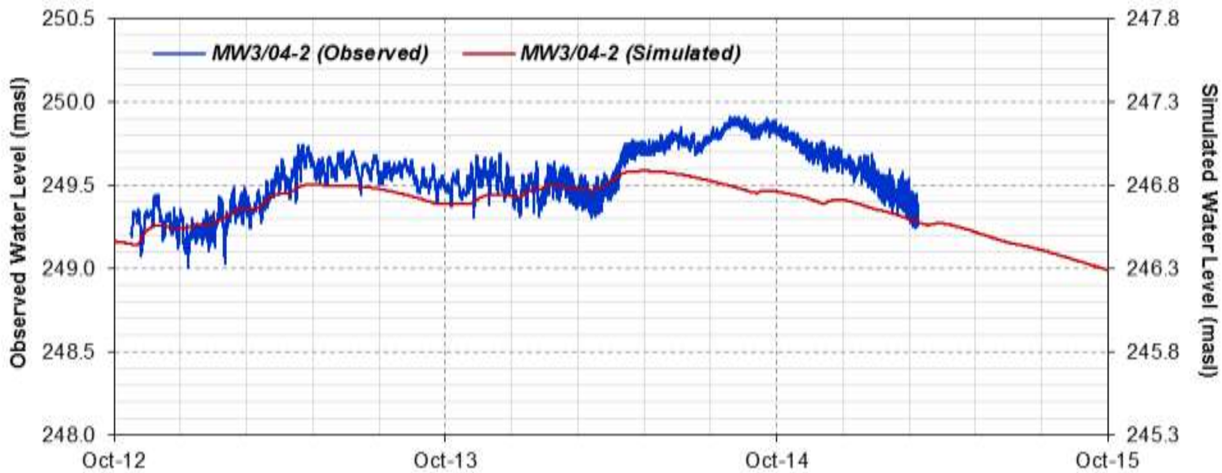


Figure 11.35: Relative water level calibration to observed head in Bethel Road monitoring well MW3/04-2 (intermediate).

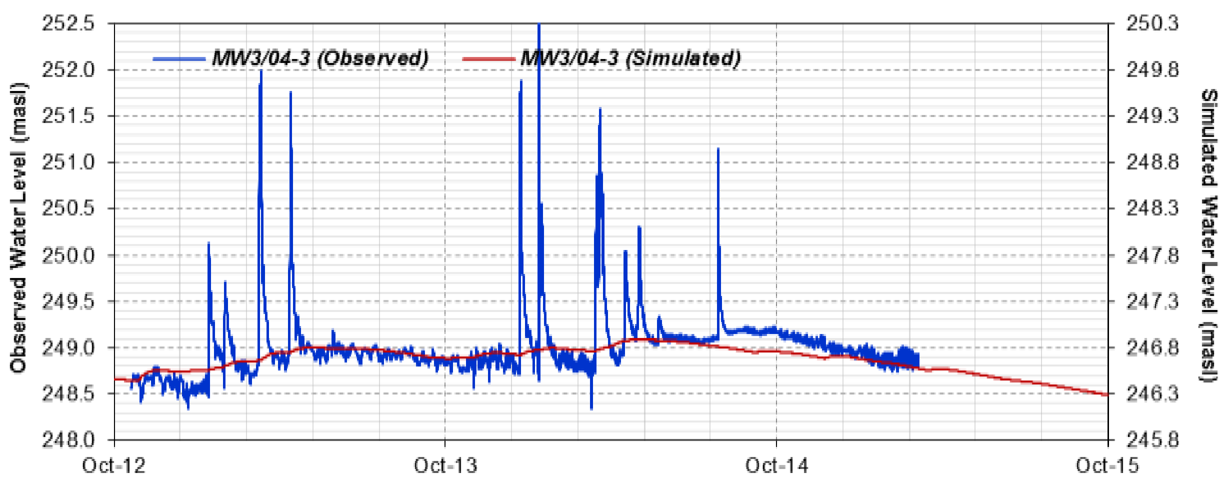


Figure 11.36: Relative water level calibration to observed head in Bethel Road monitoring well MW3/04-3 (shallow).

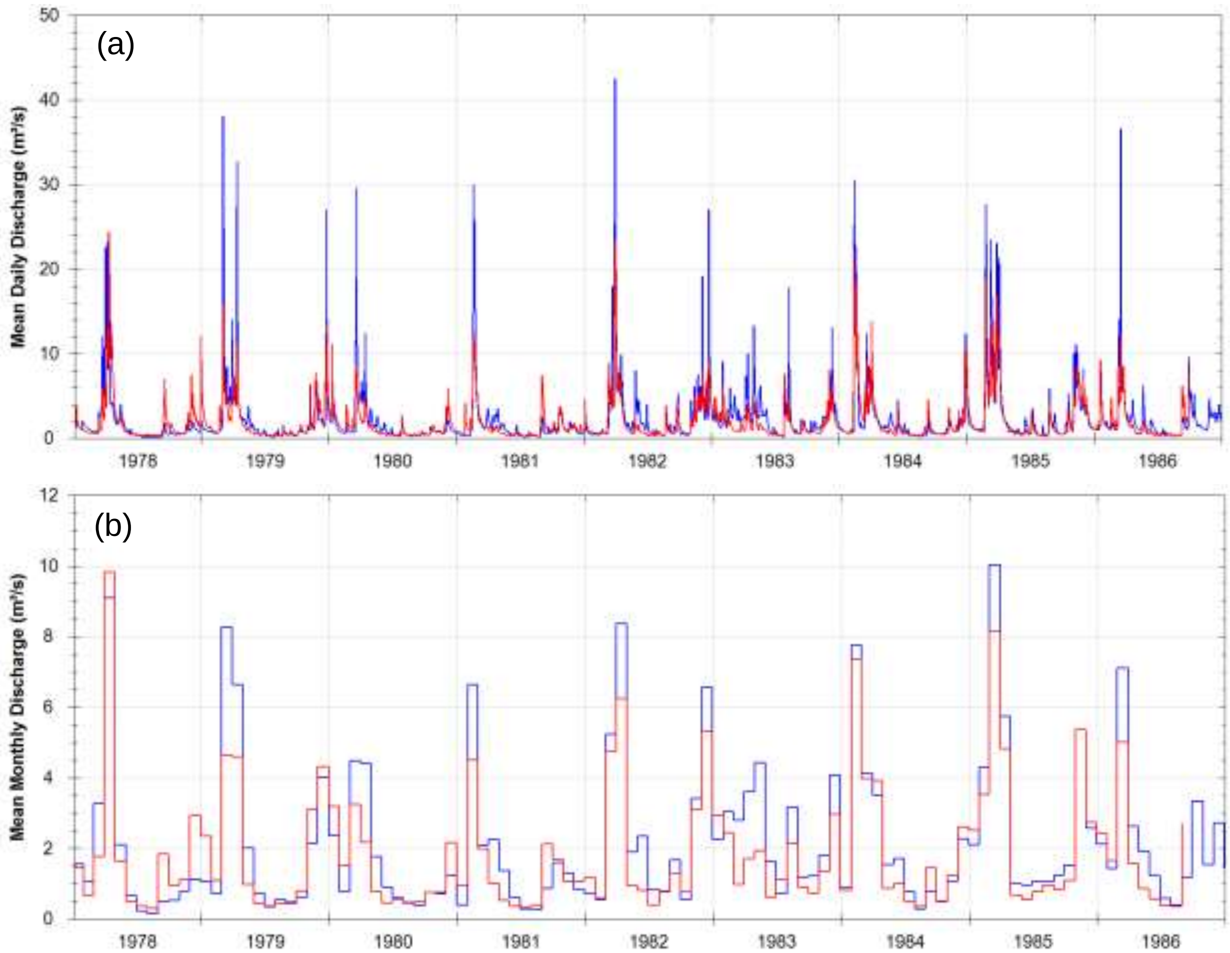


Figure 11.37: Validation plots for Horner Creek near Princeton (02GB006); observed (blue) versus simulated (red) (a) daily streamflow and (b) monthly streamflow.

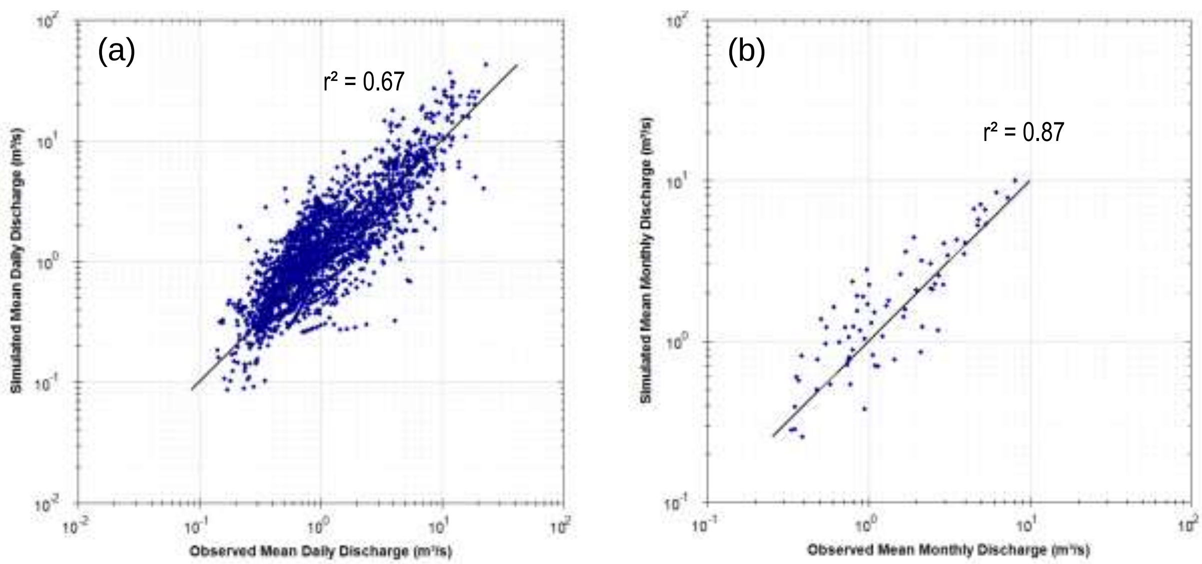


Figure 11.38: Validation plots for Horner Creek near Princeton (02GB006); (a) daily and (b) monthly streamflow scatter plots.

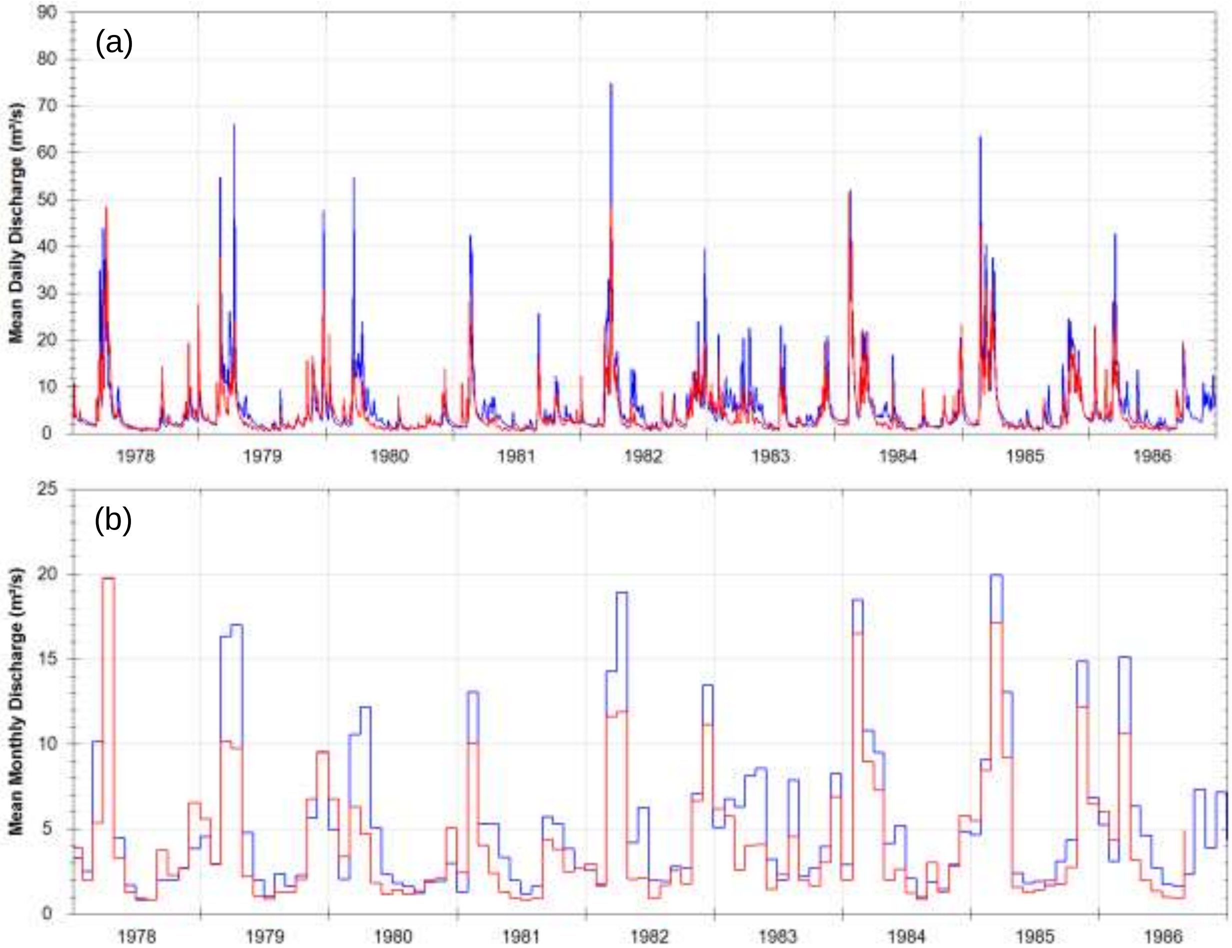


Figure 11.39: Validation plots for Whitemans Creek near Mount Vernon (02GB008); observed (blue) versus simulated (red) (a) daily streamflow and (b) monthly streamflow.

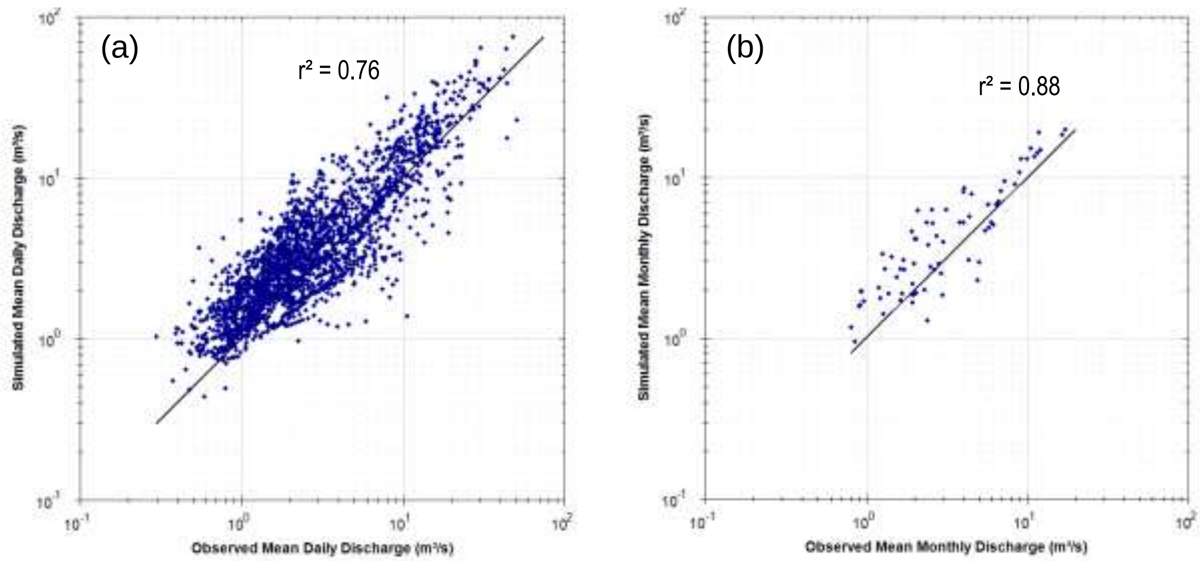


Figure 11.40: Validation plots for Whitemans Creek near Mount Vernon (02GB008); (a) daily and (b) monthly streamflow scatter plots.

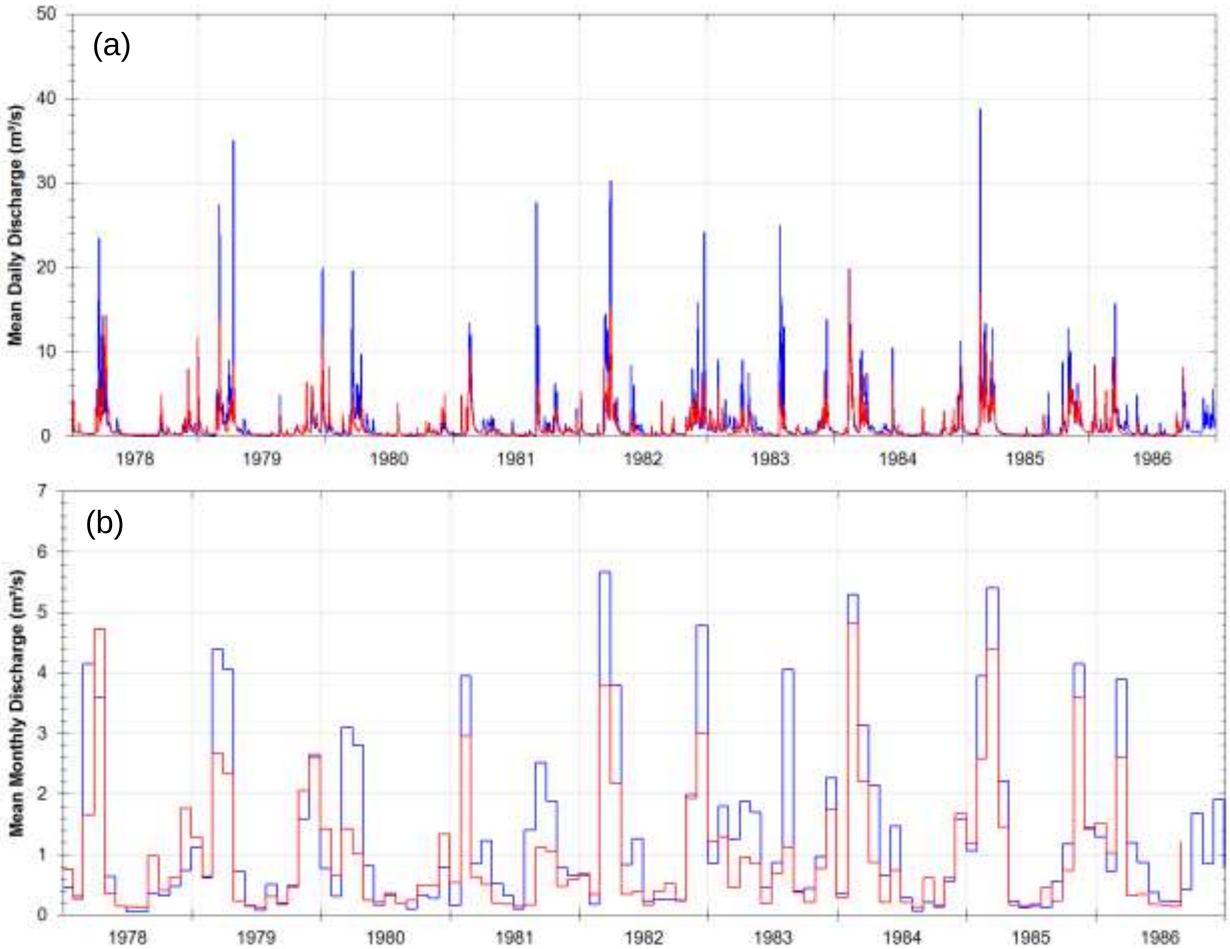


Figure 11.41: Validation plots for Kenny Creek near Burford (02GB009); observed (blue) versus simulated (red) (a) daily streamflow and (b) monthly streamflow.

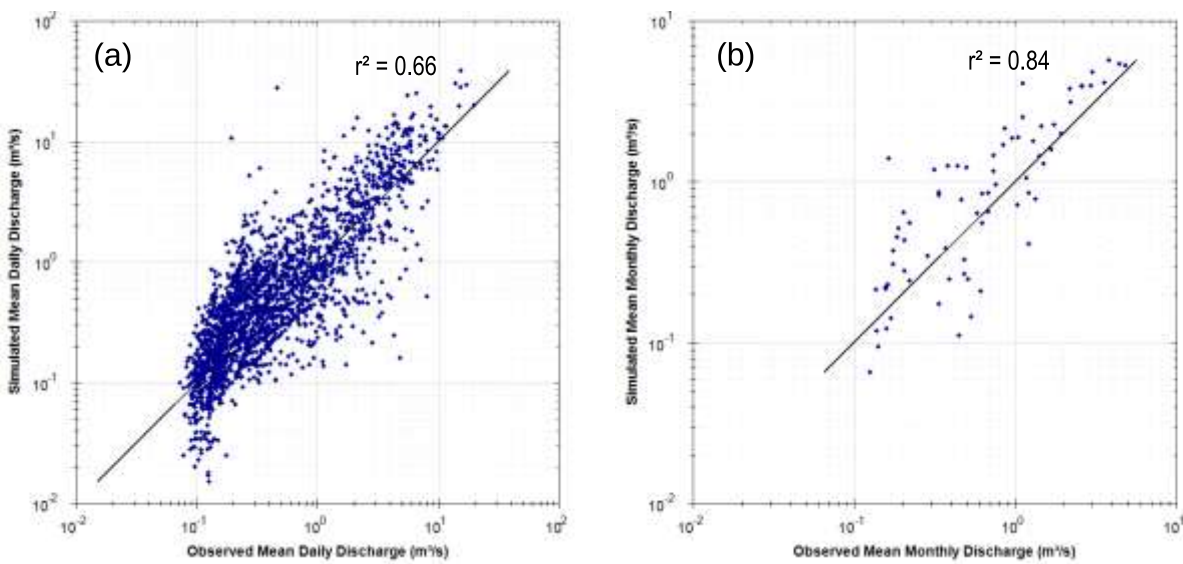


Figure 11.42: Validation plots for Kenny Creek near Burford (02GB009); (a) daily and (b) monthly streamflow scatter plots.

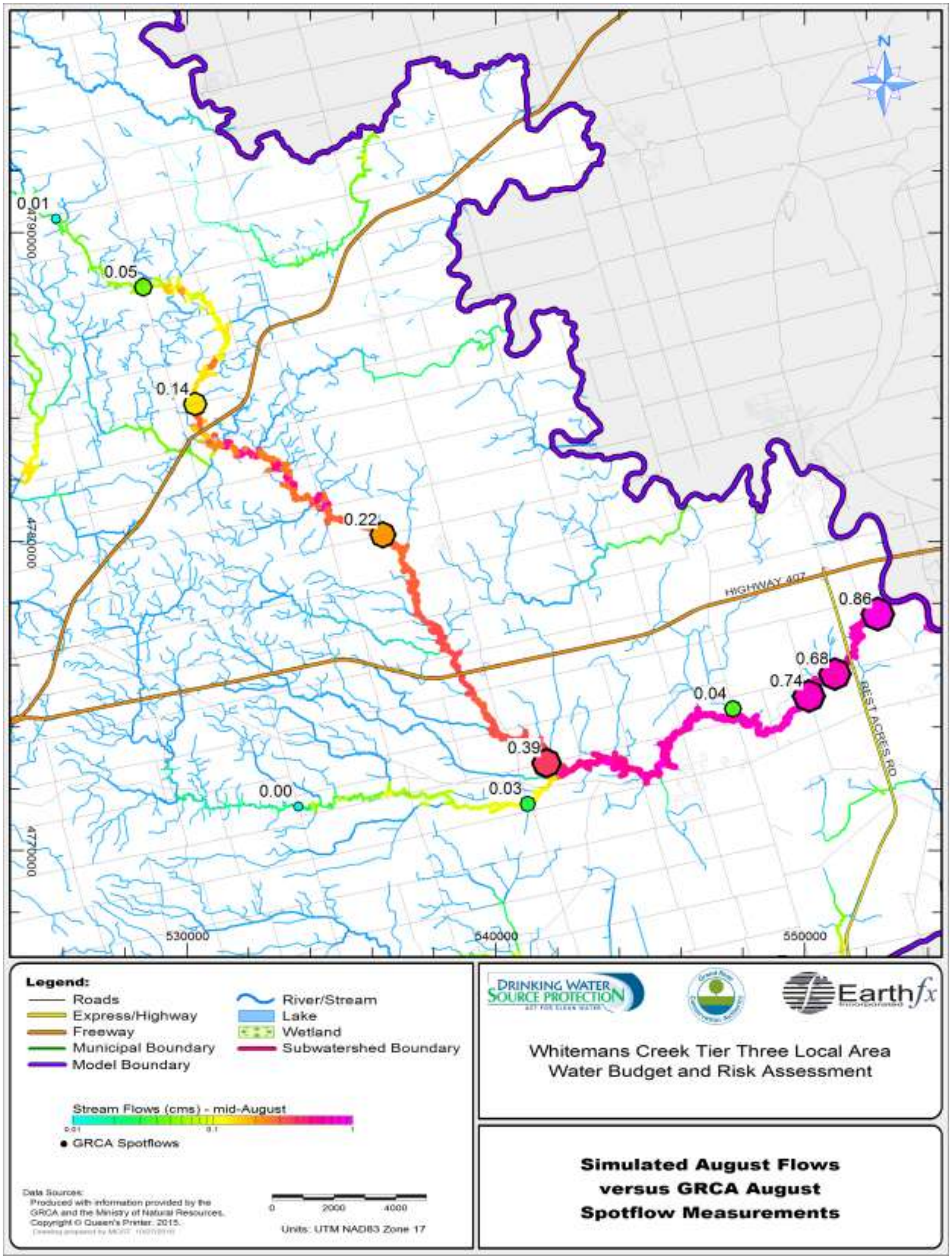


Figure 11.43: Simulated mid-August streamflow compared with August 2015 spotflow observations.

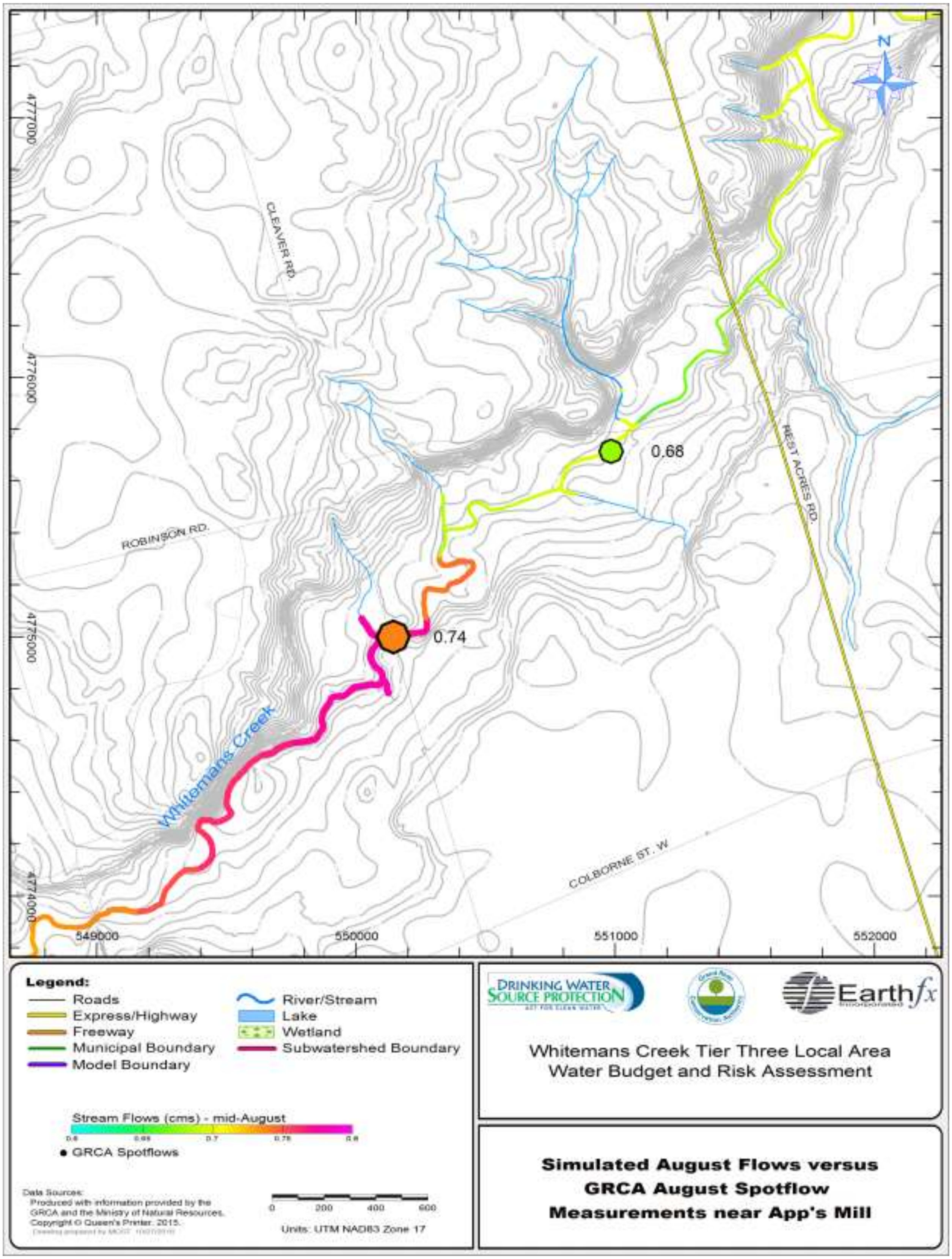


Figure 11.44: Simulated mid-August streamflow compared with August 2015 spotflow observations near Apps' Mill.

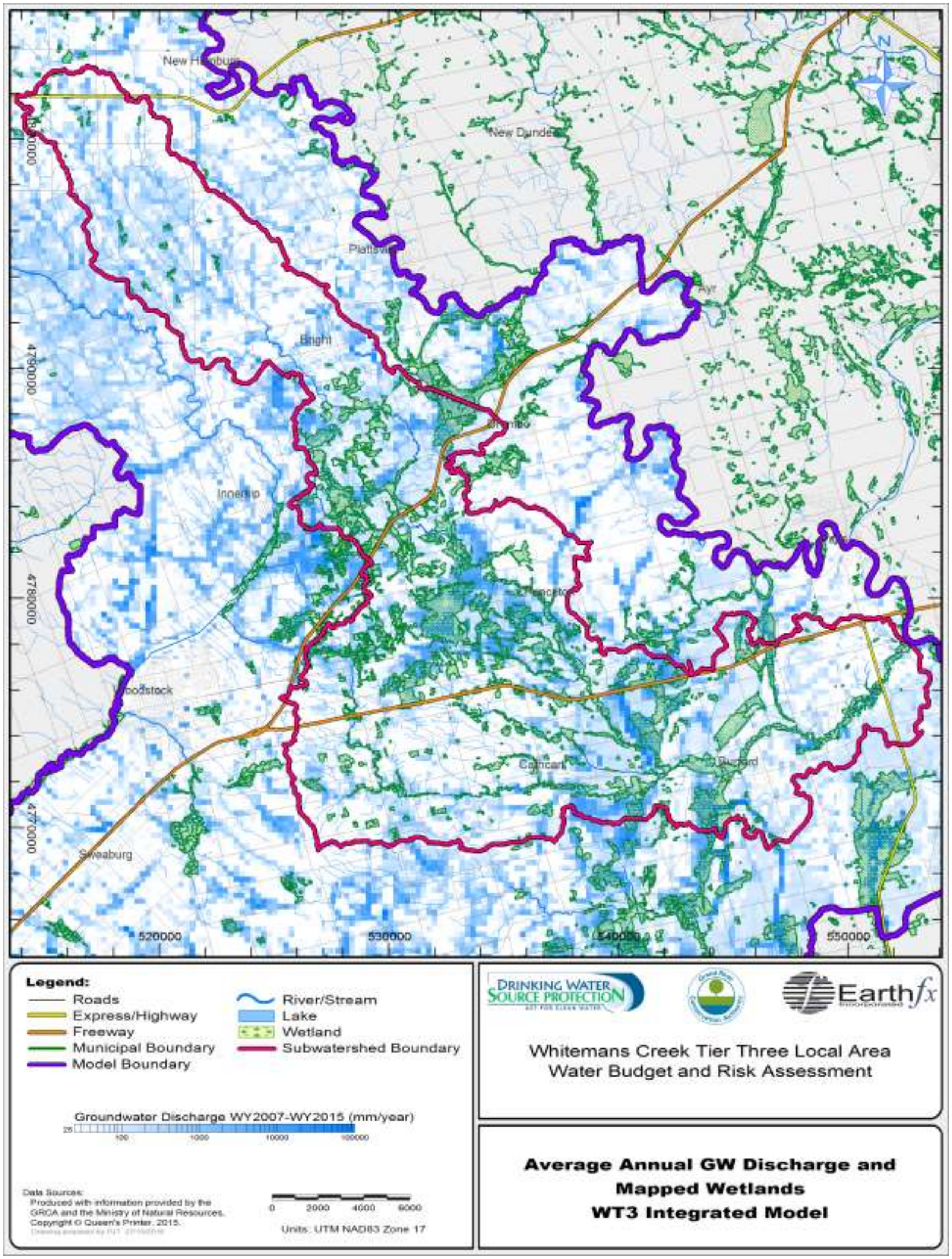


Figure 11.45: Distribution of groundwater discharge from the integrated GSFLOW model (WY2007-WY2015) compared with the extent and location of mapped wetlands.

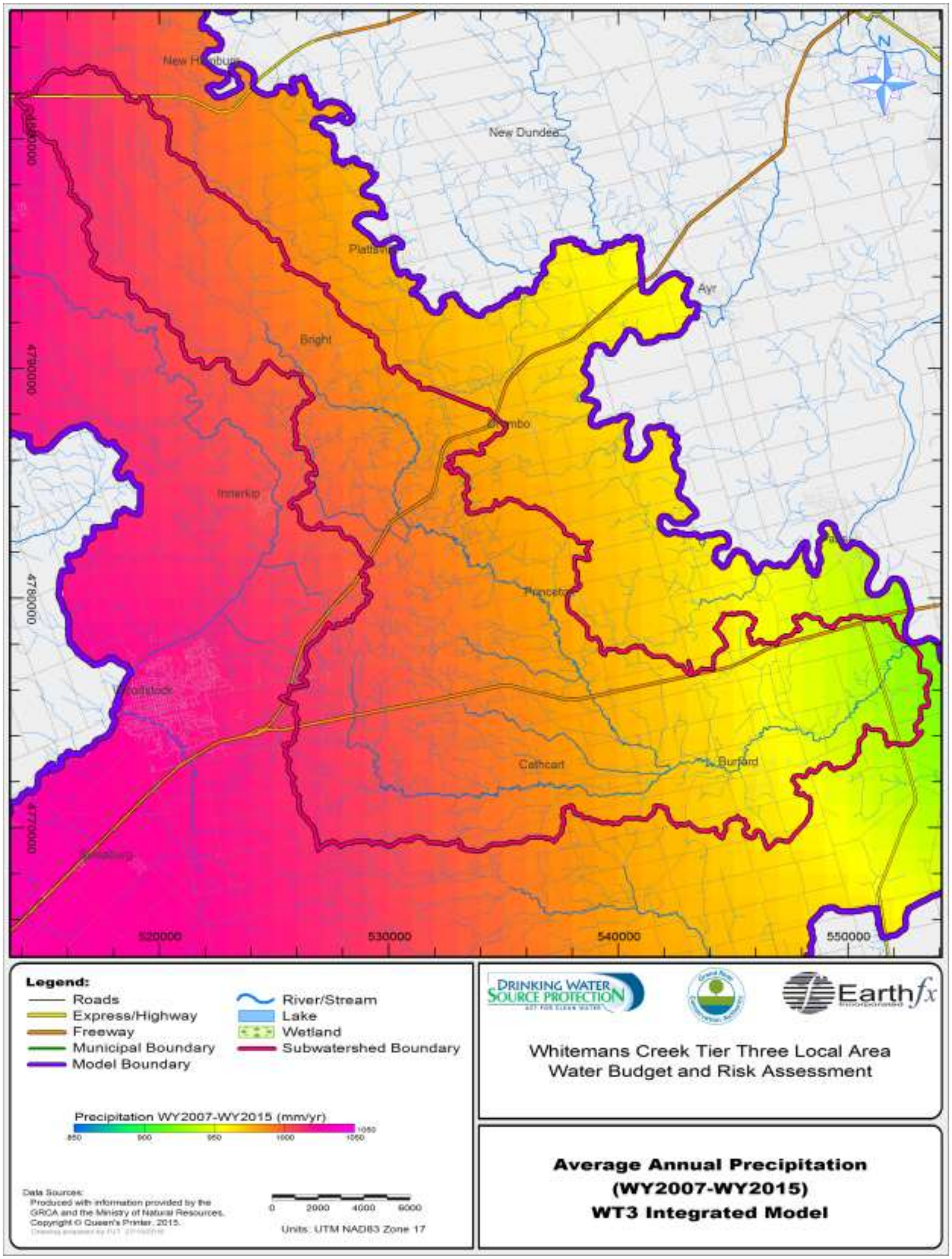


Figure 11.46: Average distribution of annual precipitation as input into the integrated GSFLOW model (WY2007- WY2015).

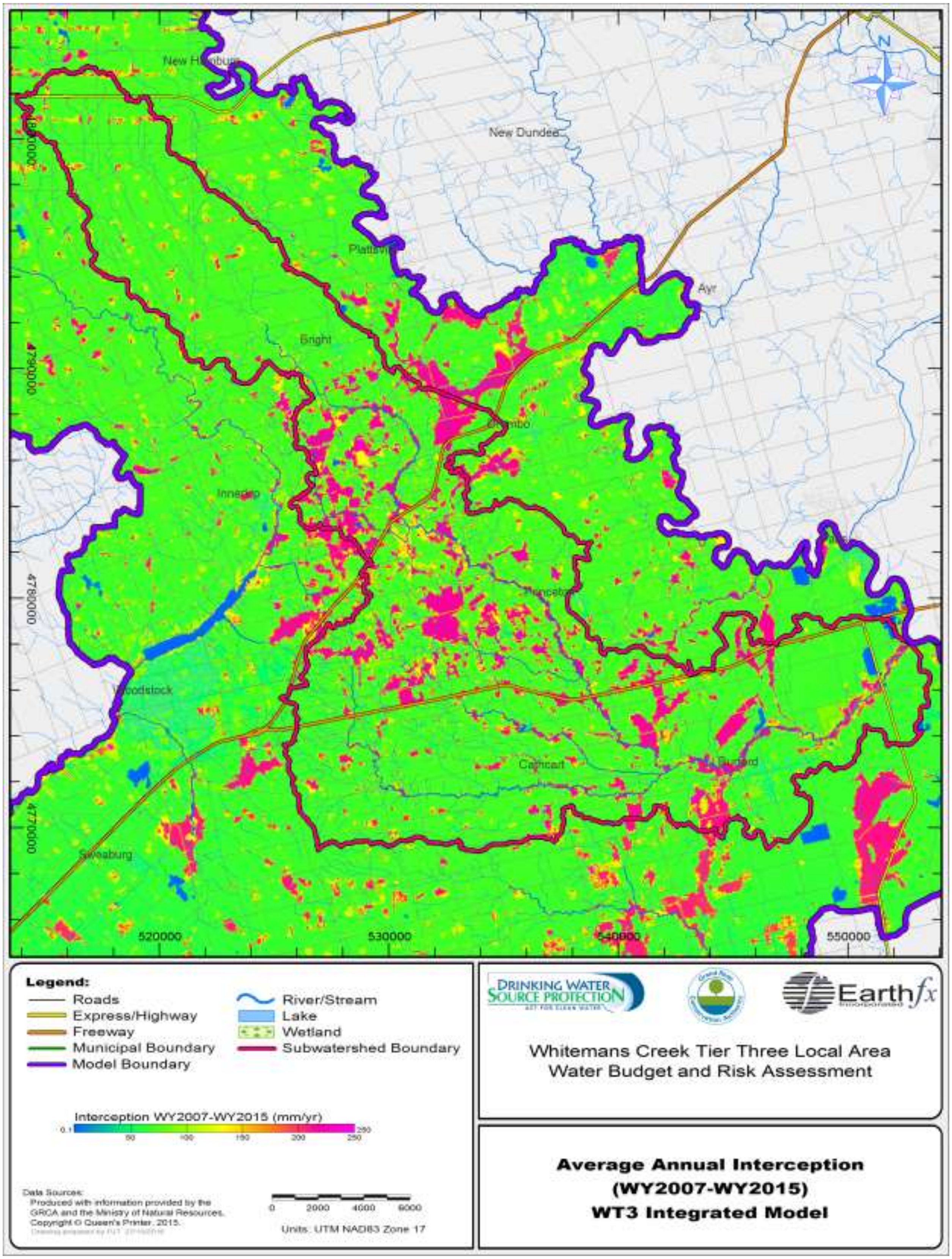


Figure 11.47: Average distribution of annual canopy interception as simulated by the integrated GSFLOW model (WY2007- WY2015).

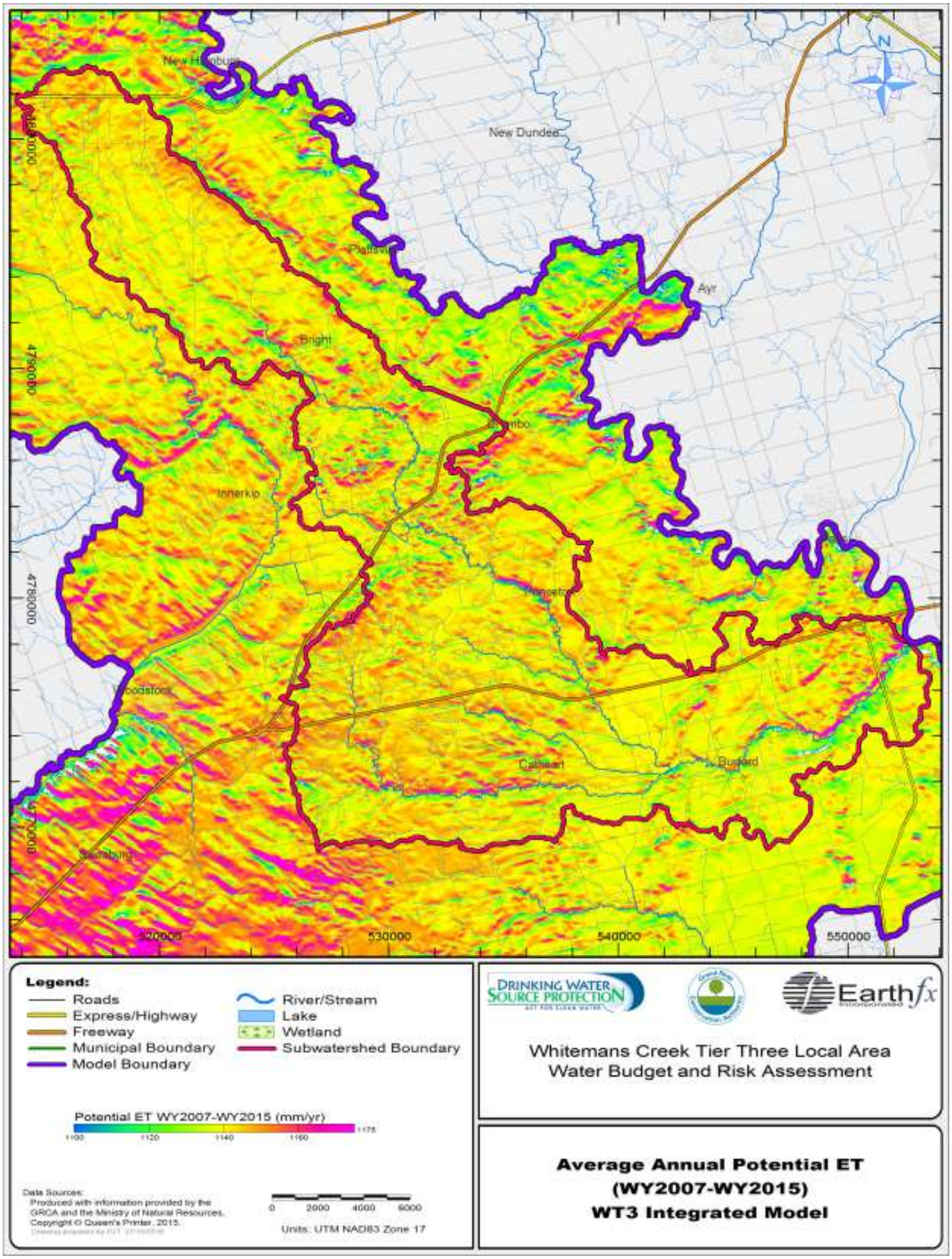


Figure 11.48: Average distribution of annual potential evapotranspiration as simulated by the integrated GSFLOW model (WY2007- WY2015).

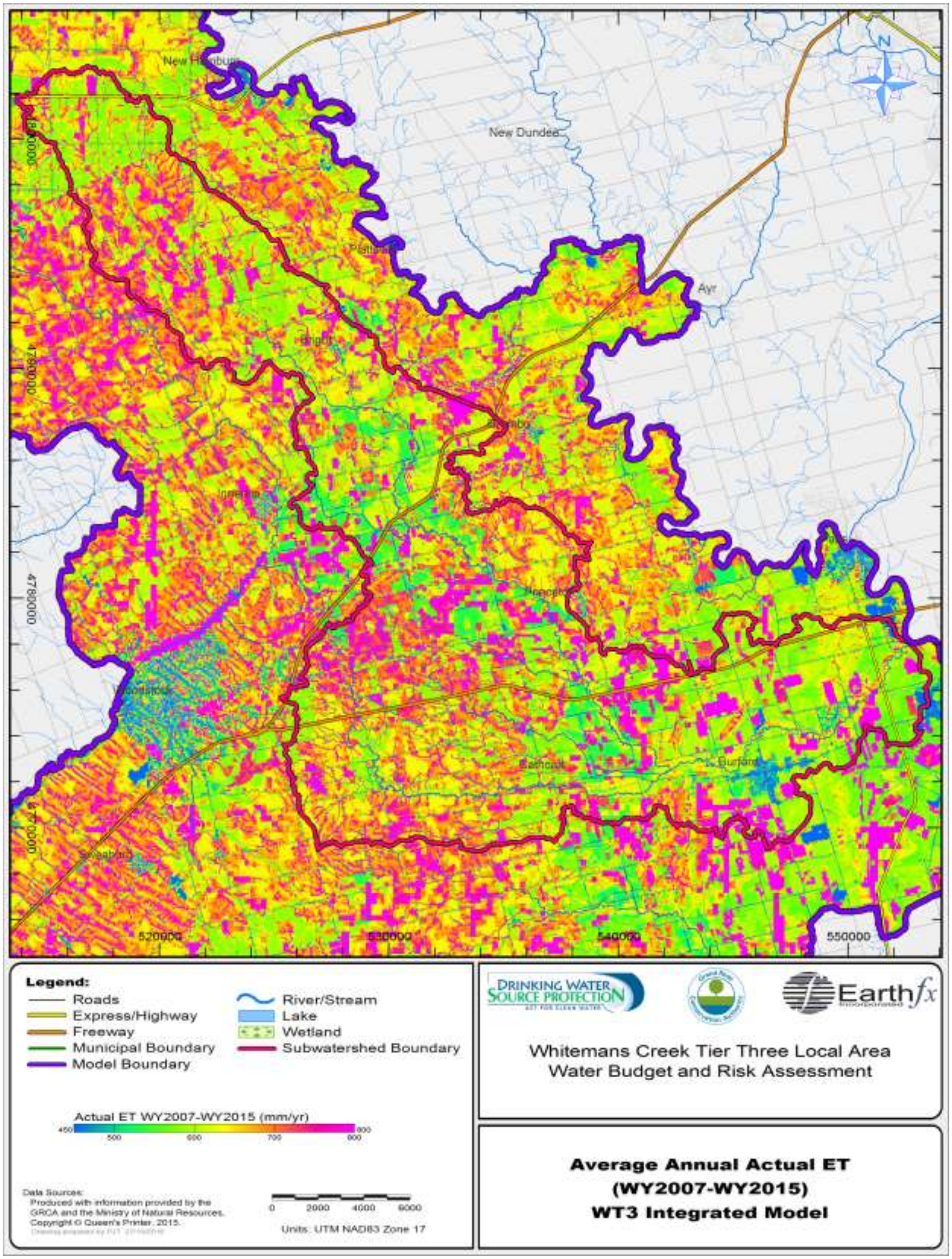


Figure 11.49: Average distribution of annual actual evapotranspiration as simulated by the integrated GSFLOW model (WY2007- WY2015).

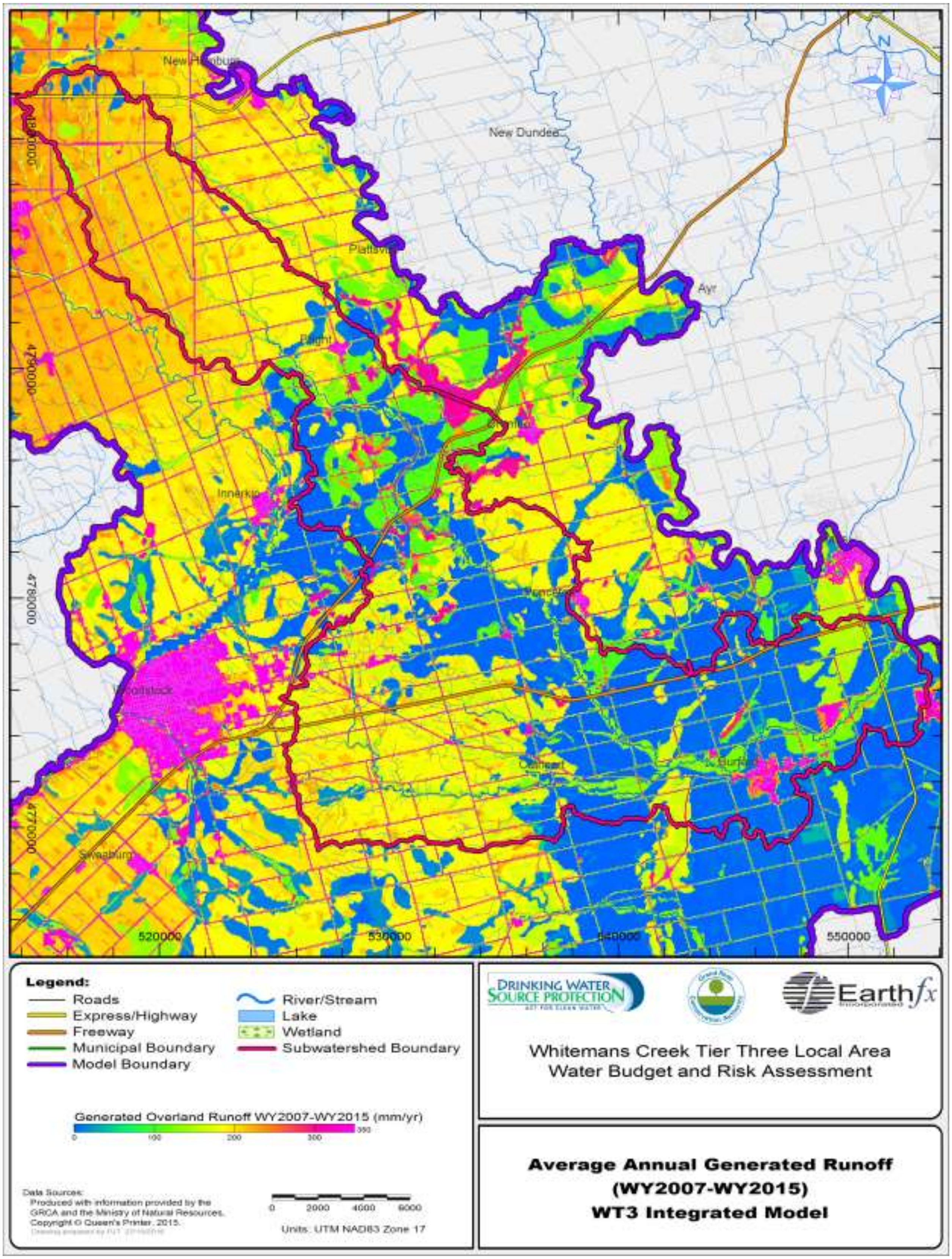


Figure 11.50: Average distribution of annual generated runoff as simulated by the integrated GSFLOW model (WY2007- WY2015).

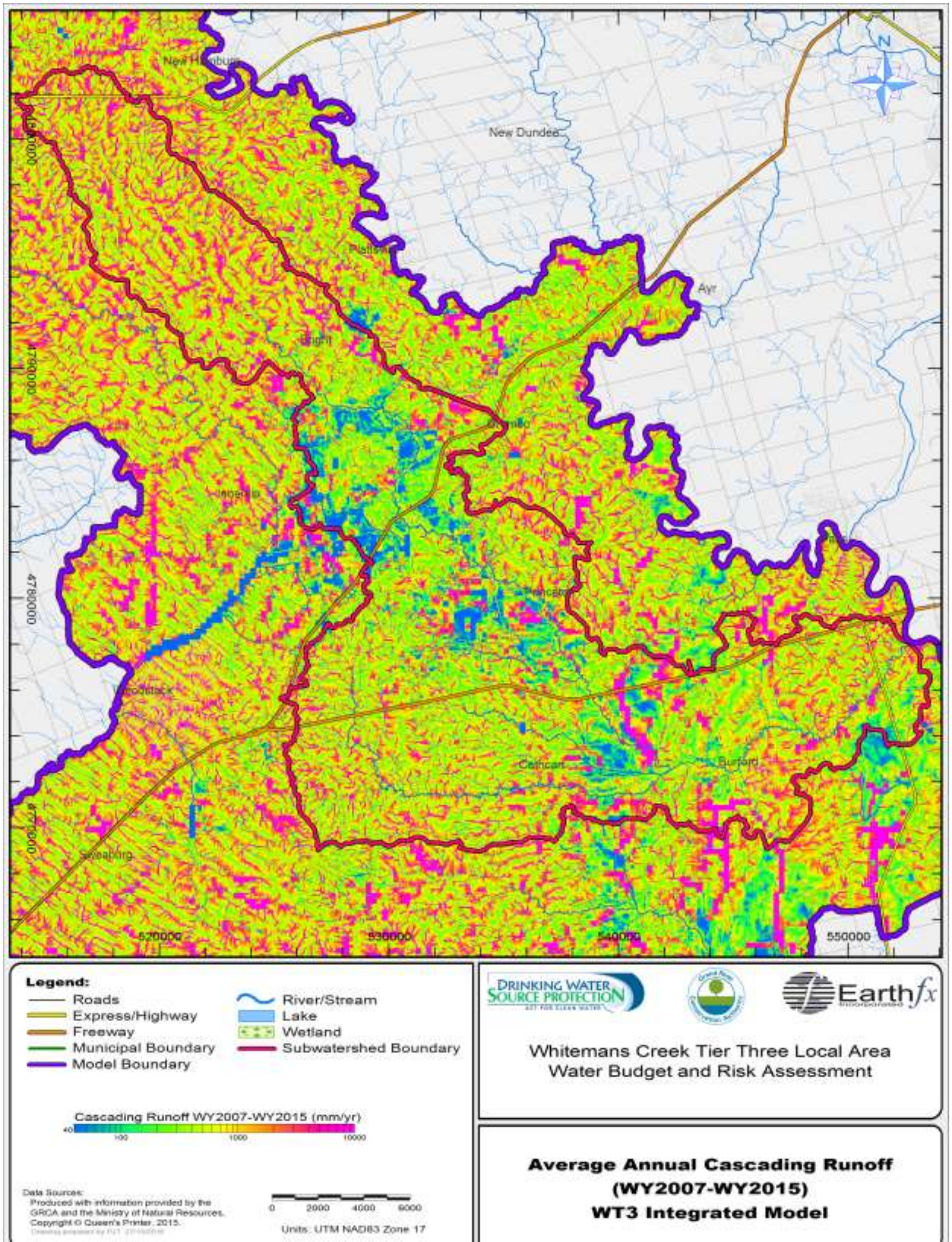


Figure 11.51: Average distribution of annual cascading runoff as simulated by the integrated GSFLOW model (WY2007- WY2015).

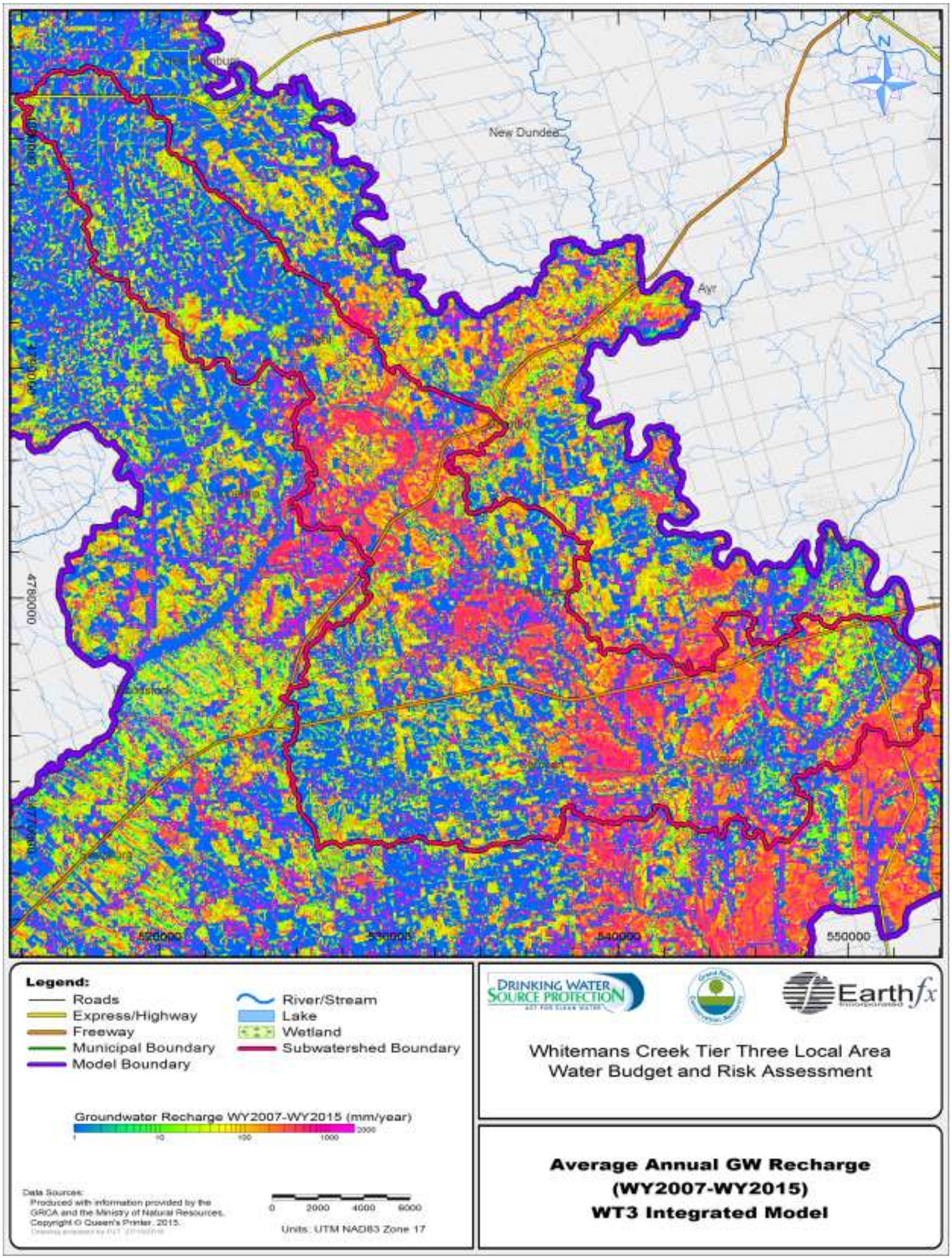


Figure 11.52: Average distribution of annual groundwater recharge as simulated by the integrated GSFLOW model (WY2007- WY2015).

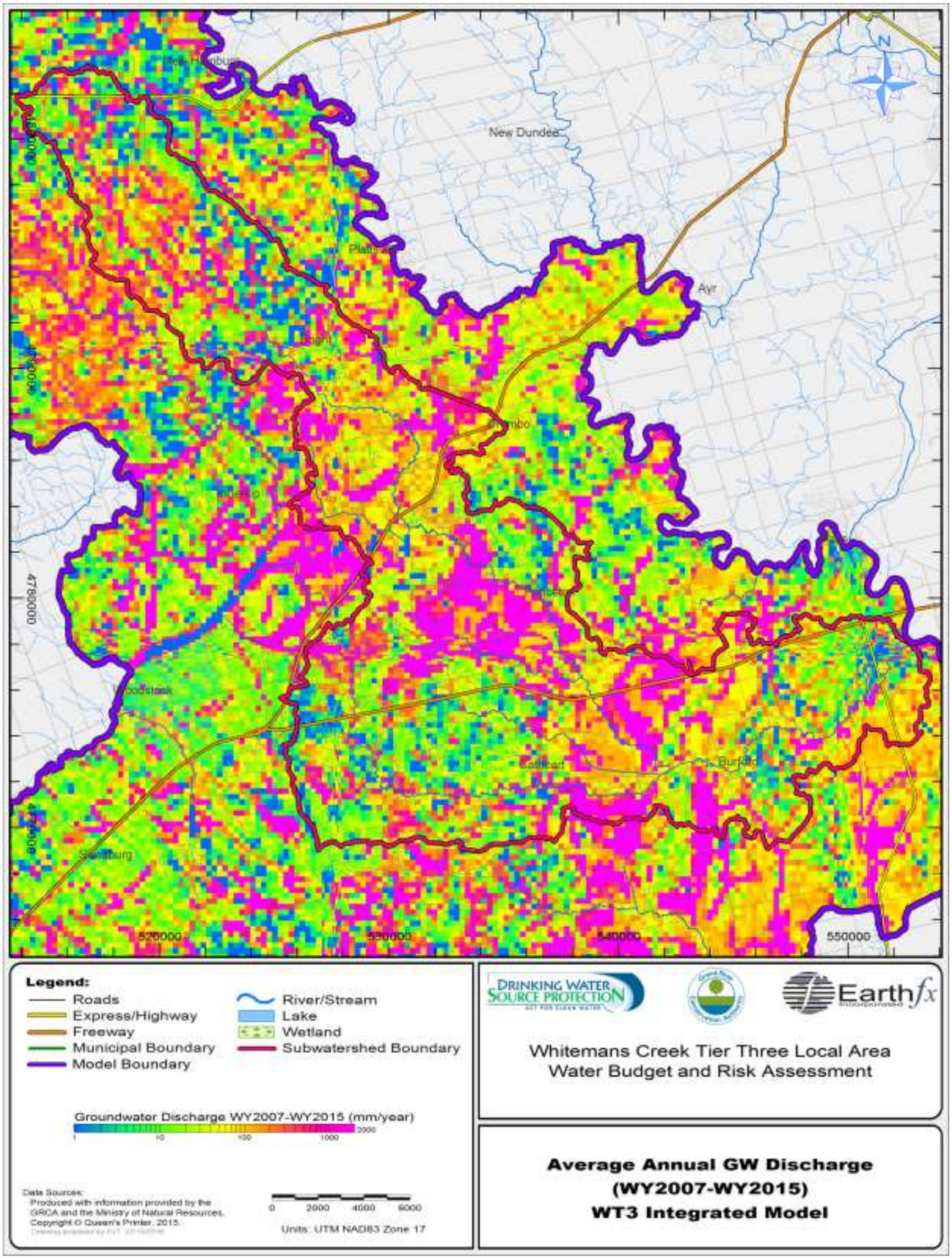


Figure 11.53: Average distribution of annual groundwater discharge as simulated by the integrated GSFLOW model (WY2007- WY2015).

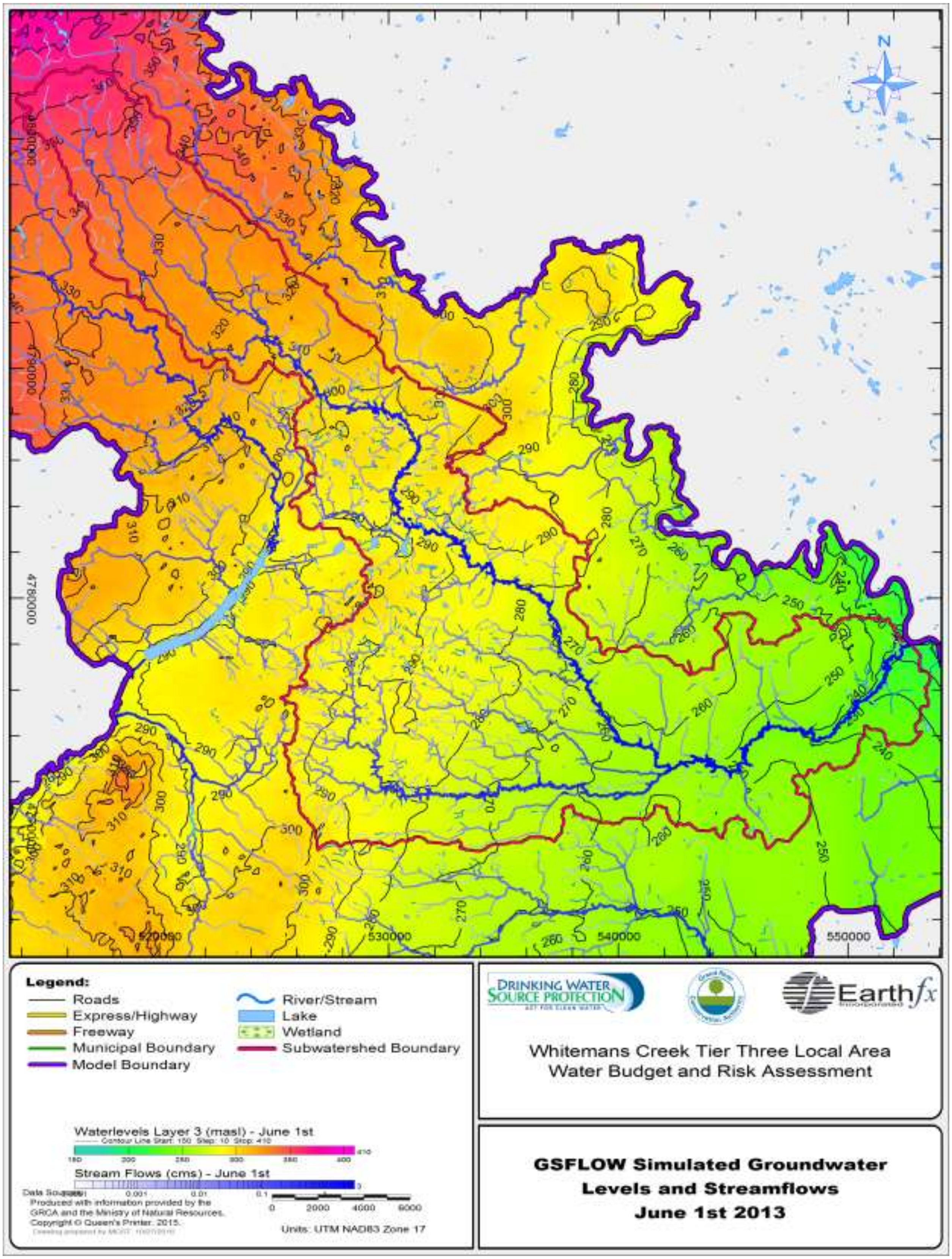


Figure 11.54: Simulated heads in model layer 3 and simulated streamflow on June 1st, 2013.

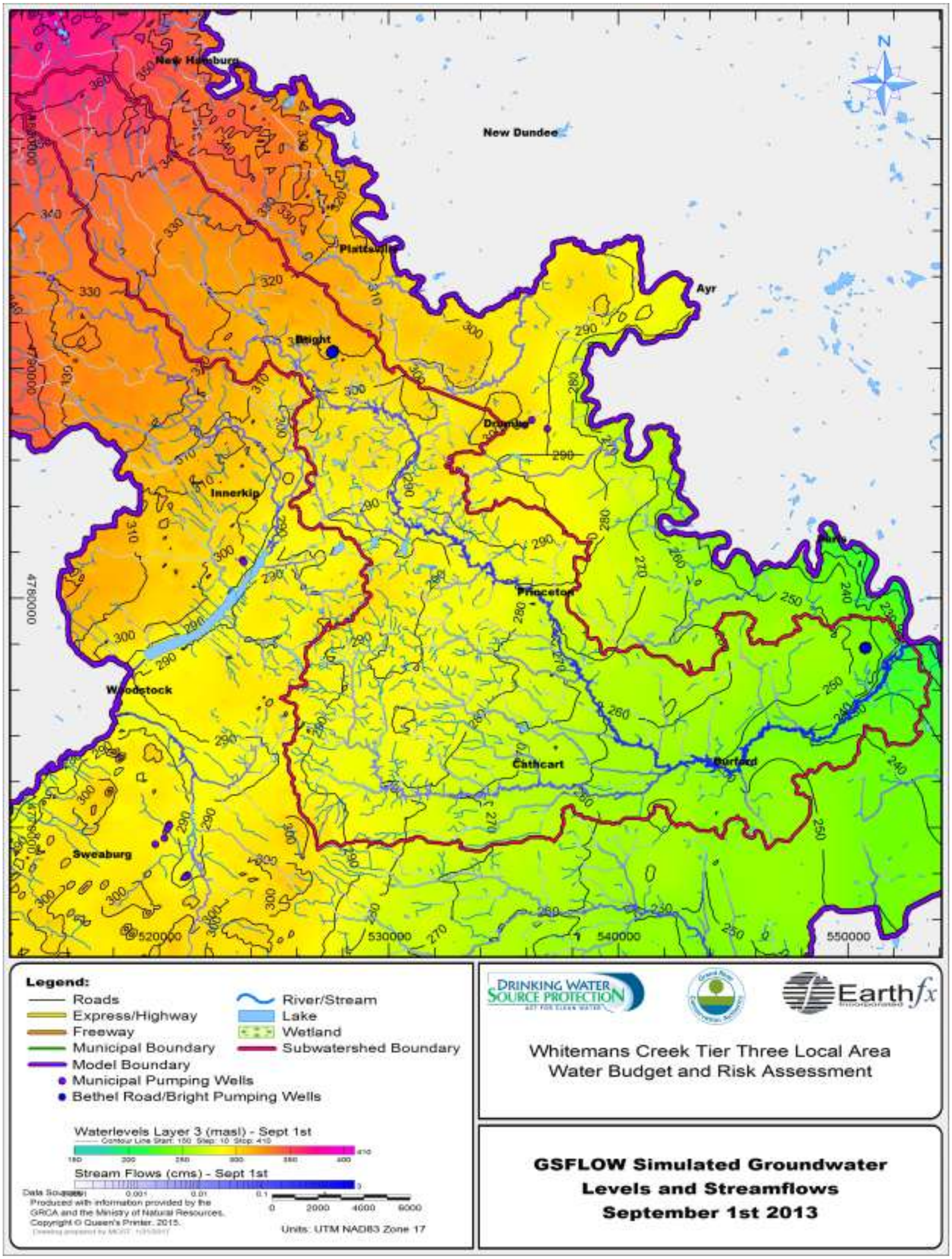


Figure 11.55: Simulated heads in model layer 3 and simulated streamflow on September 1st, 2013.

12 Conclusions

The objective of this Tier 3 study is to assess the municipal groundwater supplies operated by the County of Oxford in the Village of Bright, and for the Bethel Road wellfield servicing the Town of Paris. Previous studies have shown that the Whitemans Creek subwatershed is drought-sensitive and has been subject to frequent Low Water Response declarations. The water resources of the subwatershed play a critical role in sustaining high value agricultural activities and supporting an environmentally-sensitive cold water fishery. The OMNRF Surface Water Monitoring Centre has funded additional work under this study to improve the understanding of the long-term sustainability of the subwatersheds and to investigate drought response, agricultural water use, and low-water mitigation strategies.

To achieve the water budgeting and water quantity risk assessment objectives of the Tier 3 Assessment, Earthfx completed an extensive data synthesis and regional characterization. This work was conducted to support a model-based evaluation of water use (both current and future) and drought sensitivity within the Whitemans Creek subwatershed. The hydrologic and hydrogeologic conditions in the Whitemans Creek subwatershed are known to be highly variable and previous studies indicate that there is a significant interaction between the groundwater and surface water systems. To address this complexity, a fully integrated surface and groundwater model was developed for this study to best characterize the daily interactions as well as longer-term seasonal and inter-annual changes in surface and subsurface flows and storage under a wide range of climatic and water use conditions. The Tier 3 Assessment model was developed using the U.S. Geological Survey GSFLOW integrated model computer code (Markstrom *et al*., 2008). GSFLOW is constructed from two proven submodels: MODFLOW and PRMS.

The water resources of the subwatershed play a critical role in sustaining high value agricultural activities and supporting an environmentally sensitive cold water fishery. As an extension to this project, an irrigation demand module was developed and calibrated to run within the integrated model in order to compute realistic agricultural water takings under a wide range of climate conditions.

Following data compilation and conceptual data review, model development began with the construction of a stand-alone hydrologic submodel (PRMS) and a stand-alone groundwater flow (MODFLOW) submodel. The PRMS submodel model computes a separate soil water balance for each cell on a 60-m grid and routes overland runoff to streams and lakes using a cascading flow algorithm. Hydrologic data including streamflow, climate, soil property, land-use, and topographic data were assembled and used to assign initial estimates for model parameters. The PRMS pre-calibration was done by refining the model parameter values to best match observed daily streamflow at multiple gauges. A longer-term simulation was conducted to obtain initial estimates of average groundwater recharge for use in the groundwater submodel pre-calibration.

A steady-state groundwater flow submodel was constructed for the study area incorporating insights and data from the hydrologic, geologic and hydrostratigraphic conceptual model. Key features of the study area hydrogeology were carried forward into the numerical representation. The groundwater submodel was subdivided vertically into 12 numerical model layers, where each layer was occupied by one or more of the 17 mapped hydrostratigraphic units. Preliminary calibration of the groundwater submodel proceeded under steady-state conditions, adjusting hydraulic parameters to best match 6,030 static water level measurements from across the study area.

Upon achieving satisfactory calibrations with the stand alone submodels, the two submodels were coupled within the integrated GSFLOW model framework. A 10-year simulation period - from October 1, 2006 to September 30, 2015 – was selected for calibrating the GSFLOW model. The transient model outputs were compared against time-series data compiled from groundwater and surface water monitoring locations across the study area, including observation wells, stream gauges, and shallow piezometers installed under the Tier 3 Assessment field program. The calibrated model was able to provide a good match to the complex patterns in the observed streamflow and groundwater level monitoring data at both the subwatershed and local wellfield scales. The quality of the model calibration was demonstrated through the use of calibration statistics, which indicated a good fit to the available groundwater and surface water data, as well as visual checks using hydrographs and contour maps. Results suggest that the hydrologic and hydrogeologic processes are well represented in the model.

The calibrated GSFLOW model presented in this report represents a solid foundation for undertaking the Tier 3 Risk Assessment for the Whitemans Creek subwatershed. Furthermore, the extended Irrigation Demand Module that was developed as part of this study lends itself to a number of opportunities for evaluating water resource issues and agricultural water use within the Whitemans Creek subwatershed.

Phase 2 of this study involves the application of the Tier 3 model to conduct the Local Area Risk Assessment as required under the Clean Water Act of 2006. Results of the Phase 2 work are documented in a separate study report.

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Appendix A Active Surface Water Permits

Table A-1: Active surface water permits within the Whitemans Creek subwatershed

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
00-P-1081	Horner Creek	Agricultural	Other - Agricultural	530371	4784002	5237	30	430	0	0
00-P-1081	Pond	Agricultural	Other - Agricultural	530001	4783928	5237	30	430	0	0
00-P-1082	Pond	Agricultural	Other - Agricultural	526076	4784164	5237	30	430	0	0
0111-6DCMBG	Whiteman's Creek	Agricultural	Other - Agricultural	540796	4773608	1159	8	25	0	0
0184-7GJNVU	Sebok Pond	Agricultural	Field and Pasture Crops	526060	4787030	1488	30	122	0	0
0273-9A6LN4	Horner Creek	Agricultural	Tobacco	538209	4776915	1409	40	154	17	968
0345-9DWSBK	Pond on an intermittent tributary of Horner Creek	Agricultural	Other - Agricultural	551183	4775268	10100	50	1384	536	2741
0370-8NXLJ5	Pond 1	Agricultural	Field and Pasture Crops	538221	4773556	955	80	209	40	714
03-P-2339	Pond	Agricultural	Tobacco	551091	4775302	10100	40	1107	79	1637
0556-9J6SA9	Pond 1 (Big)	Agricultural	Tobacco	529492	4786848	818	22	49	490	490
0556-9J6SA9	Pond 2 (Small)	Agricultural	Tobacco	529632	4786958	409	22	25	245	245
0732-9Y8K6R	Whitemans Creek	Agricultural	Tobacco	543550	4773543	1681	180	829	0	0
0732-9Y8K6R	Pond	Agricultural	Tobacco	543545	4773539	1681	180	829	48	5178
0786-9EGSNK	Whiteman's Creek	Agricultural	Field and Pasture Crops	543377	4773064	912	180	450	0	0
1066-6H5J49	On-stream pond on a tributary of Whiteman's Creek	Agricultural	Field and Pasture Crops	535987	4777804	1079	10	30	0	0
1132-9DNSGT	Horner Creek Site #1	Agricultural	Tobacco	530589	4785464	756	21	43	0	0
1132-9DNSGT	Horner Creek Site #2	Agricultural	Tobacco	531130	4786089	756	21	43	0	0
1463-6PPQQR	Horners Creek	Agricultural	Sod Farm	536090	4780350	912	195	487	0	508
1676-6BVR3P	Whiteman's Creek (Horner Creek)	Agricultural	Tobacco	551782	4776861	2589	40	284	0	0
2016-8GZPT7	Whiteman's Creek	Agricultural	Tobacco	538417	4774208	524	60	86	0	0

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
2241-9YXNY4	Pond #1	Agricultural	Field and Pasture Crops	540456	4772877	1728	180	852	0	0
2241-9YXNY4	Pond #2	Agricultural	Field and Pasture Crops	540214	4772898	1728	180	852	0	0
2743-6FUJ5L	Horner Creek	Agricultural	Field and Pasture Crops	537206	4778447	1719	25	118	0	0
2767-6APJF9	Whitemans Creek	Agricultural	Tobacco	543377	4773064	999	180	493	0	0
3370-6H6RNJ	Horner Creek	Agricultural	Tobacco	537521	4777623	1623	12	53	0	0
4243-6APPKL	Whiteman's Creek	Agricultural	Tobacco	550825	4775691	2750	35	264	0	0
4561-96SQVQ	Horner Creek	Agricultural	Field and Pasture Crops	530410	4787920	2046	30	168	0	0
4633-63DQLG	Whitemans Creek	Agricultural	Tobacco	545277	4772548	2272	16	100	0	0
4672-9SZJWX	Whiteman's Kenny Creek	Agricultural	Tobacco	539278	4775096	700	20	38	0	0
5488-7VBQMC	horner creek	Agricultural	Field and Pasture Crops	533333	4782267	2455	50	336	1	458
5812-8PRLZF	Whiteman's Creek	Agricultural	Field and Pasture Crops	545532	4773223	2376	42	273	0	0
6052-9RGR3G	Whiteman's Creek Lot 13, Concession 3	Agricultural	Tobacco	552370	4777613	2210	16	97	12	1670
6268-8K7J9K	Horner Creek	Agricultural	Tobacco	530488	4785365	1080	20	59	15	749
63-P-0711	On-stream Pond	Agricultural	Field and Pasture Crops	544258	4776464	1080	125	370	4	764
6654-6DTM5D	Tributary to Whiteman's Creek	Agricultural	Field and Pasture Crops	546388	4775189	1172	10	32	0	0
6733-8WXQXF	Horner Creek	Agricultural	Field and Pasture Crops	530371	4784002	5237	30	430	48	1000
6881-6DCLKL	Whiteman's Creek	Agricultural	Tobacco	539278	4775096	751	20	41	48	600
6881-6DCLKL	Onstream Pond	Agricultural	Tobacco	539224	4775189	1020	20	56	0	0
7218-6LBMK3	Whiteman's Creek	Agricultural	Tobacco	538203	4777051	928	60	153	0	0
73-P-0097	Horner Creek	Agricultural	Other - Agricultural	530847	4785782	1092	5	15	0	0
7411-6DCM29	Whitemans Creek	Agricultural	Field and Pasture Crops	540175	4773621	1545	30	127	0	0
7411-6DCM29	Location 2 Whitemans Creek	Agricultural	Field and Pasture Crops	540024	4773881	1545	30	127	0	0
7411-6DCM29	Location 3 Whitemans Creek	Agricultural	Field and Pasture Crops	539732	4774352	1545	30	127	0	0
7411-6DCM29	Location 4 Whitemans Creek	Agricultural	Field and Pasture Crops	540062	4773830	1545	30	127	0	0
7520-8H6Q4N	Whiteman's Creek	Agricultural	Tobacco	538479	4773246	1640	60	270	0	0
7835-78PKXV	Whitemans Creek	Agricultural	Field and Pasture Crops	540721	4773594	955	30	78	0	0

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
8315-869NKJ	Horners Creek	Agricultural	Field and Pasture Crops	533917	4781415	1443	50	198	10	2182
8655-6BGSP6	Horner Creek	Agricultural	Tobacco	538669	4776161	1999	35	192	0	0
99-P-1008	Ponds	Agricultural	Other - Agricultural	530000	4780800	7855	9	194	0	0
99-P-1082	Horner Creek	Agricultural	Tobacco	530410	4787920	2046	30	168	0	0
99-P-1122	Pond	Agricultural	Other - Agricultural	529523	4785289	1227	10	34	0	0
99-P-1125	Pond	Agricultural	Other - Agricultural	532070	4786409	1227	10	34	0	0

Table A-2: Active surface water permits within the model area

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
00-P-1081	Horner Creek	Agricultural	Other - Agricultural	530371	4784002	5237	30	430	0	0
00-P-1081	Pond	Agricultural	Other - Agricultural	530001	4783928	5237	30	430	0	0
00-P-1082	Pond	Agricultural	Other - Agricultural	526076	4784164	5237	30	430	0	0
00-P-1374	Konigshofer Farm On-Stream Pond	Agricultural	Other - Agricultural	527859	4763846	2618	30	215	0	0
0111-6DCMBG	Whiteman's Creek	Agricultural	Other - Agricultural	540796	4773608	1159	8	25	0	0
0184-7GJNVU	Sebok Pond	Agricultural	Field and Pasture Crops	526060	4787030	1488	30	122	0	0
0231-7BRK2W	Online pond on Mount Pleasant Creek	Agricultural	Field and Pasture Crops	554851	4770206	1839	20	101	5	650
0273-9A6LN4	Horner Creek	Agricultural	Tobacco	538209	4776915	1409	40	154	17	968
0345-9DWSBK	Pond on an intermittent tributary of Horner Creek	Agricultural	Other - Agricultural	551183	4775268	10100	50	1384	536	2741
0370-8NXLJ5	Pond 1	Agricultural	Field and Pasture Crops	538221	4773556	955	80	209	40	714
03-P-2339	Pond	Agricultural	Tobacco	551091	4775302	10100	40	1107	79	1637
0556-9J6SA9	Pond 1 (Big)	Agricultural	Tobacco	529492	4786848	818	22	49	490	490
0556-9J6SA9	Pond 2 (Small)	Agricultural	Tobacco	529632	4786958	409	22	25	245	245

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
0617-A4TKLX	Pond on a tributary of Big Creek	Agricultural	Tobacco	542094	4770209	3787	40	415	2	651
0732-9Y8K6R	Whitemans Creek	Agricultural	Tobacco	543550	4773543	1681	180	829	0	0
0732-9Y8K6R	Pond	Agricultural	Tobacco	543545	4773539	1681	180	829	48	5178
0767-A4JKNT	Big Creek	Agricultural	Tobacco	544548	4763609	328	50	45	0	0
0786-9EGSNK	Whiteman's Creek	Agricultural	Field and Pasture Crops	543377	4773064	912	180	450	0	0
1066-6H5J49	On-stream pond on a tributary of Whiteman's Creek	Agricultural	Field and Pasture Crops	535987	4777804	1079	10	30	0	0
1132-9DNSGT	Horner Creek Site #1	Agricultural	Tobacco	530589	4785464	756	21	43	0	0
1132-9DNSGT	Horner Creek Site #2	Agricultural	Tobacco	531130	4786089	756	21	43	0	0
1345-83FHK7	Arthur Road Pond	Agricultural	Field and Pasture Crops	553871	4773236	1980	64	347	0	0
1380-7L6RS4	Patterson Creek	Agricultural	Field and Pasture Crops	554993	4774505	2750	130	979	34	1216
1463-6PPQQR	Horners Creek	Agricultural	Sod Farm	536090	4780350	912	195	487	0	508
1635-7UCQQN	Intermittent Tributary to Big Creek	Agricultural	Field and Pasture Crops	538715	4770031	1363	20	75	0	0
1676-6BVR3P	Whiteman's Creek (Horner Creek)	Agricultural	Tobacco	551782	4776861	2589	40	284	0	0
1813-96VPT6	Lee Pond #1	Agricultural	Field and Pasture Crops	541190	4769259	1309	180	646	1180	3092
1813-96VPT6	Lee Pond #2	Agricultural	Field and Pasture Crops	541171	4768519	1309	180	646	0	0
1813-96VPT6	Lee Pond #3	Agricultural	Field and Pasture Crops	540994	4768503	1309	180	646	0	0
2016-8GZPT7	Whiteman's Creek	Agricultural	Tobacco	538417	4774208	524	60	86	0	0
2033-7STRCS	By-Pass Pond #1 recharged by Mud Creek	Agricultural	Field and Pasture Crops	543505	4779464	1364	60	224	12	1361
2033-7STRCS	By-Pass Pond #2 recharged by Mud Creek	Agricultural	Field and Pasture Crops	544083	4779833	1364	60	224	0	0
2241-9YXNY4	Pond #1	Agricultural	Field and Pasture Crops	540456	4772877	1728	180	852	0	0
2241-9YXNY4	Pond #2	Agricultural	Field and Pasture Crops	540214	4772898	1728	180	852	0	0
2743-6FUJ5L	Horner Creek	Agricultural	Field and Pasture Crops	537206	4778447	1719	25	118	0	0
2767-6APJF9	Whitemans Creek	Agricultural	Tobacco	543377	4773064	999	180	493	0	0
3370-6H6RNJ	Horner Creek	Agricultural	Tobacco	537521	4777623	1623	12	53	0	0
3540-8D7PXB	Cedar Creek	Commercial	Golf Course Irrigation	521049	4773231	144	184	73	4	578
3540-8D7PXB	Unnamed Pond	Commercial	Golf Course Irrigation	521202	4773332	736	184	371	21	245

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
4058-6MHK5G	Pond on Big Otter Creek	Agricultural	Field and Pasture Crops	537874	4757911	1671	30	137	0	0
4243-6APPKL	Whiteman's Creek	Agricultural	Tobacco	550825	4775691	2750	35	264	0	0
4458-9GYMGY	Mount Pleasant Creek	Agricultural	Tobacco	554856	4770203	1091	90	269	0	0
4478-7CEQXH	Big Creek	Agricultural	Field and Pasture Crops	545277	4760026	1035	30	85	0	0
4561-96SQVQ	Horner Creek	Agricultural	Field and Pasture Crops	530410	4787920	2046	30	168	0	0
4633-63DQLG	Whitemans Creek	Agricultural	Tobacco	545277	4772548	2272	16	100	0	0
4647-9XHHLL	Whitemans Creek	Agricultural	Tobacco	554667	4772580	1090	25	75	12	1898
4672-9SZJWX	Whiteman's Kenny Creek	Agricultural	Tobacco	539278	4775096	700	20	38	0	0
5185-62NL5E	Tributary connected to McKenzie Creek	Agricultural	Other - Agricultural	551790	4765248	700	60	115	0	0
5250-9RXLGZ	Van Torre Pond	Agricultural	Tobacco	537255	4757339	1819	50	249	0	0
5488-7VBQMC	horner creek	Agricultural	Field and Pasture Crops	533333	4782267	2455	50	336	1	458
5812-8PRLZF	Whiteman's Creek	Agricultural	Field and Pasture Crops	545532	4773223	2376	42	273	0	0
6003-7FRQTL	Pittock Resevoir on Thames River "A" (Apr4 to May1	Agricultural	Field and Pasture Crops	524909	4782060	1226	7	24	0	0
6003-7FRQTL	Pittock Resevoir on Thames River "B" (May15 to May	Agricultural	Field and Pasture Crops	524909	4782060	1635	13	58	0	0
6003-7FRQTL	Pittock Resevoir on Thames River "C" (Jun1 to Oct	Agricultural	Field and Pasture Crops	524909	4782060	307	50	42	0	0
6052-9RGR3G	Whiteman's Creek Lot 13, Concession 3	Agricultural	Tobacco	552370	4777613	2210	16	97	12	1670
6172-6DSQJU	Big Creek	Agricultural	Field and Pasture Crops	541383	4766367	955	14	37	0	0
6236-6CKPFG	Cedar Creek	Commercial	Golf Course Irrigation	520974	4773292	144	184	73	5	245
6236-6CKPFG	Holding Pond (Reservoir)	Commercial	Golf Course Irrigation	521285	4773350	736	184	371	0	0
6268-8K7J9K	Horner Creek	Agricultural	Tobacco	530488	4785365	1080	20	59	15	749
63-P-0711	On-stream Pond	Agricultural	Field and Pasture Crops	544258	4776464	1080	125	370	4	764
6654-6DTM5D	Tributary to Whiteman's Creek	Agricultural	Field and Pasture Crops	546388	4775189	1172	10	32	0	0
6733-8WXQXF	Horner Creek	Agricultural	Field and Pasture Crops	530371	4784002	5237	30	430	48	1000
6745-6GMQJB	Big Creek 1	Agricultural	Tobacco	545401	4761719	544	15	22	0	0
6745-6GMQJB	Big Creek 2	Agricultural	Tobacco	545279	4761500	544	15	22	0	0
6837-A4BLMA	Welland River	Commercial	Golf Course Irrigation	531835	4760591	535	183	268	0	0

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
6881-6DCLKL	Whiteman's Creek	Agricultural	Tobacco	539278	4775096	751	20	41	48	600
6881-6DCLKL	Onstream Pond	Agricultural	Tobacco	539224	4775189	1020	20	56	0	0
70-P-0447	Otter Creek, Otter Creek which recharges	Agricultural	Tobacco	534758	4759841	305	7	6	0	0
7218-6LBMK3	Whiteman's Creek	Agricultural	Tobacco	538203	4777051	928	60	153	0	0
73-P-0097	Horner Creek	Agricultural	Other - Agricultural	530847	4785782	1092	5	15	0	0
7411-6DCM29	Whitemans Creek	Agricultural	Field and Pasture Crops	540175	4773621	1545	30	127	0	0
7411-6DCM29	Location 2 Whitemans Creek	Agricultural	Field and Pasture Crops	540024	4773881	1545	30	127	0	0
7411-6DCM29	Location 3 Whitemans Creek	Agricultural	Field and Pasture Crops	539732	4774352	1545	30	127	0	0
7411-6DCM29	Location 4 Whitemans Creek	Agricultural	Field and Pasture Crops	540062	4773830	1545	30	127	0	0
7520-8H6Q4N	Whiteman's Creek	Agricultural	Tobacco	538479	4773246	1640	60	270	0	0
75-P-2021	North Branch Pond	Commercial	Aquaculture	521371	4805481	655	365	655	0	0
75-P-2021	South Branch Pond 1	Commercial	Aquaculture	521407	4805211	490	365	490	0	0
75-P-2021	South Branch Pond 2	Commercial	Aquaculture	521560	4805203	490	365	490	0	0
7784-6H4NAH	On-stream pond on Harley Creek	Agricultural	Tobacco	538859	4769801	1220	90	301	0	0
7835-78PKXV	Whitemans Creek	Agricultural	Field and Pasture Crops	540721	4773594	955	30	78	0	0
79-P-2026	on-stream pond	Agricultural	Other - Agricultural	554451	4771133	681	0	0	0	0
8153-734RB2	Irrigation Reservoir	Commercial	Golf Course Irrigation	525383	4784710	1590	185	806	45	1313
8315-869NKJ	Horners Creek	Agricultural	Field and Pasture Crops	533917	4781415	1443	50	198	10	2182
8381-9PAMF3	Pond 1 Front	Agricultural	Other - Agricultural	541500	4764176	690	30	57	0	0
8381-9PAMF3	Pond 2 Back	Agricultural	Other - Agricultural	541607	4763723	690	30	57	0	0
8588-6LEREE	Pond connected to Mount Pleasant Creek	Agricultural	Field and Pasture Crops	554190	4771741	818	4	9	0	0
8655-6BGSP6	Horner Creek	Agricultural	Tobacco	538669	4776161	1999	35	192	0	0
8770-A4THMH	Big Creek	Agricultural	Tobacco	545241	4760834	1855	60	305	37	1295
99-P-1008	Ponds	Agricultural	Other - Agricultural	530000	4780800	7855	9	194	0	0
99-P-1022	Pond	Agricultural	Other - Agricultural	538464	4794069	2725	36	269	0	0
99-P-1082	Horner Creek	Agricultural	Tobacco	530410	4787920	2046	30	168	0	0

MOE Permit Number	Source	Purpose	Specific Use	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
99-P-1089	Artisian Supply (2 ponds)	Agricultural	Other - Agricultural	536777	4791457	1091	10	30	0	0
99-P-1089	By Pass	Agricultural	Other - Agricultural	535928	4791084	873	6	14	0	0
99-P-1089	On Stream	Agricultural	Other - Agricultural	535772	4791831	873	2	5	0	0
99-P-1122	Pond	Agricultural	Other - Agricultural	529523	4785289	1227	10	34	0	0
99-P-1125	Pond	Agricultural	Other - Agricultural	532070	4786409	1227	10	34	0	0
99-P-1133	Pond	Agricultural	Fruit Orchards	527859	4764222	1909	20	105	0	0
99-P-1134	Pond	Agricultural	Fruit Orchards	526016	4763790	1909	20	105	0	0
99-P-1139	Otter Creek	Agricultural	Other - Agricultural	534141	4759407	35	24	2	0	0

Appendix B Active Groundwater and Mixed Source Permits

Table B-1: Active groundwater and mixed surface water/groundwater permits within the Whitemans Creek subwatershed

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
0042-8GRREW	Home Farm Well	Tobacco	Agricultural	Ground Water	547050	4770650	5040	24	331	124	4800
00-P-2055	Dugout pond	Other - Agricultural	Agricultural	Ground Water	538262	4773563	955	0	0	0	0
00-P-2255	Dugout pond	Other - Agricultural	Agricultural	Ground Water	548443	4773518	2720	25	186	0	0
00-P-2339	Well Points	Field and Pasture Crops	Agricultural	Ground Water	547153	4770544	3816	40	418	20	3180
00-P-2372	Dugout pond	Tobacco	Agricultural	Ground Water	544607	4771512	2292	24	151	27	736
00-P-2458	Dugout pond	Other - Agricultural	Agricultural	Ground Water	545596	4778594	1364	15	56	0	0
00-P-2517	dugout pond	Other - Agricultural	Agricultural	Ground Water	547575	4774297	546	0	0	0	0
00-P-2518	dugout pond	Other - Agricultural	Agricultural	Ground Water	547783	4773505	546	0	0	0	0
00-P-2684	Dugout pond	Other - Agricultural	Agricultural	Ground Water	544114	4772213	2180	0	0	10	1966
00-P-2751	one dugout pond	Tobacco	Agricultural	Ground Water	545471	4770536	2180	0	0	0	0
00-P-2751	three quarry ponds	Tobacco	Agricultural	Ground Water	545869	4769989	2180	0	0	0	0
00-P-2764	well	Golf Course Irrigation	Commercial	Ground Water	544173	4774858	102	0	0	0	0
00-P-2764	Dugout pond	Golf Course Irrigation	Commercial	Ground Water	544049	4775087	1718	0	0	2	168
0188-9X7KYD	Pond	Tobacco	Agricultural	Ground Water	538811	4772117	982	90	242	0	0
01-P-2070	sandpoint	Field and Pasture Crops	Agricultural	Ground Water	548170	4770886	1637	0	0	0	0
0303-83LPN8	West Pond	Field and Pasture Crops	Agricultural	Ground Water	528666	4788076	951	16	42	18	8768
0534-9NDPJE	Pond	Field and Pasture Crops	Agricultural	Ground Water	540601	4774303	3764	180	1856	60	3494
0550-6BTRD6	Well WWR 1305235	Field and Pasture Crops	Agricultural	Ground Water	533014	4777874	196	312	168	8	144
0550-6BTRD6	Well WWR 1304883	Field and Pasture Crops	Agricultural	Ground Water	533059	4777871	524	312	448	20	38
0550-6BTRD6	Well WWR 1304499	Field and Pasture Crops	Agricultural	Ground Water	533078	4777889	131	312	112	9	44

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
0550-6BTRD6	Pond	Field and Pasture Crops	Agricultural	Ground Water	533271	4777715	3208	10	88	0	0
0786-9EGSNK	Pond	Field and Pasture Crops	Agricultural	SW/GW	542967	4774142	912	180	450	0	0
1066-6H5J49	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536390	4777569	1079	10	30	0	0
1071-5Y2MU3	Pond	Field and Pasture Crops	Agricultural	Ground Water	546079	4771004	3764	180	1856	0	0
1123-9NNN3B	Norwich Well 2 (Tag A011226)	Municipal	Water Supply	Ground Water	532640	4759396	1633	365	1633	0	0
1125-9L9Q27	Pond #1	Field and Pasture Crops	Agricultural	Ground Water	545471	4770536	3800	30	312	0	0
1125-9L9Q27	Pond #2	Field and Pasture Crops	Agricultural	Ground Water	545132	4771123	3800	30	312	87	2880
1125-9L9Q27	Pond #3	Field and Pasture Crops	Agricultural	Ground Water	546108	4770536	3800	30	312	26	2880
1167-5YVFZ2	Dugout Pond	Tobacco	Agricultural	Ground Water	540969	4770453	1637	50	224	3	360
1344-6AJNNR	Pond	Tobacco	Agricultural	Ground Water	539959	4776053	2946	90	726	7	1022
1523-8NQL6U	Pond #2	Sod Farm	Agricultural	SW/GW	533894	4778190	1013	180	499	10	608
1523-8NQL6U	Well #3	Sod Farm	Agricultural	Ground Water	533389	4778888	1310	180	646	0	0
2301-9D5M9J	Pond	Tobacco	Agricultural	Ground Water	549693	4774364	1296	40	142	294	955
2351-8S6PBV	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	549589	4774455	2592	35	249	294	1728
2486-856GX2	Pond A	Field and Pasture Crops	Agricultural	Ground Water	545565	4769761	2350	45	290	192	3276
2486-856GX2	Pond B	Field and Pasture Crops	Agricultural	Ground Water	545683	4769725	2350	45	290	58	2304
2486-856GX2	Pond C	Field and Pasture Crops	Agricultural	Ground Water	545903	4769968	2350	45	290	0	0
2526-8LRLRH	Well 1	Golf Course Irrigation	Commercial	Ground Water	543598	4776353	102	214	60	0	0
2526-8LRLRH	Ponds 1 and 2	Golf Course Irrigation	Commercial	Ground Water	543615	4776355	1718	214	1008	68	583
2715-5Z6QVP	TW1-01	Other - Commercial	Commercial	Ground Water	532087	4786336	131	365	131	0	0
2725-8HMPXS	Art Da Silva Princeton	Field and Pasture Crops	Agricultural	Ground Water	538433	4778513	2448	20	134	54	8700
2743-6FUJ5L	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536753	4778857	931	6	15	0	0
2767-6APJF9	Pond	Tobacco	Agricultural	SW/GW	543073	4774080	999	180	493	0	0
3066-9CKH6G	Dugout Pond	Tobacco	Agricultural	Ground Water	536466	4775533	3475	35	333	0	0
3101-9L5J95	Well 1	Other - Agricultural	Agricultural	Ground Water	549126	4775562	818	149	334	0	0

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
3101-9L5J95	Well 2	Other - Agricultural	Agricultural	Ground Water	549096	4775571	818	149	334	0	0
3101-9L5J95	Well 3	Other - Agricultural	Agricultural	Ground Water	549111	4775582	818	149	334	0	0
3101-9L5J95	Well 4	Other - Agricultural	Agricultural	Ground Water	549130	4775591	818	149	334	0	0
3168-9ZZPLW	Pond	Tobacco	Agricultural	Ground Water	541278	4772419	888	15	36	0	0
3243-642M69	Pond	Tobacco	Agricultural	Ground Water	538281	4771345	2488	90	613	33	5178
3257-9PMLN8	Pond	Field and Pasture Crops	Agricultural	Ground Water	546851	4769542	3764	180	1856	44	3456
3300-68ESHK	Pond	Field and Pasture Crops	Agricultural	Ground Water	542769	4776661	3764	180	1856	0	0
3411-64SLMD	Pond 1	Field and Pasture Crops	Agricultural	SW/GW	548475	4773541	1364	10	37	0	0
3411-64SLMD	Pond 2	Fruit Orchards	Agricultural	SW/GW	548144	4773454	219	10	6	0	0
3411-64SLMD	Pond 3	Market Gardens / Flowers	Agricultural	SW/GW	548151	4773460	131	12	4	0	0
3411-64SLMD	Well	Fruit Orchards	Agricultural	Ground Water	548169	4773753	219	10	6	0	0
3468-9PNPGA	6 Sandpoints	Tobacco	Agricultural	Ground Water	552165	4775780	2589	40	284	0	0
3502-7V8R6S	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	545525	4771836	982	30	81	0	0
3538-62FNDS	Pond	Field and Pasture Crops	Agricultural	Ground Water	547759	4777528	2177	14	84	0	0
3730-9KRNC8	Middle Pond	Sod Farm	Agricultural	Ground Water	544781	4774763	6378	180	3145	194	4449
3730-9KRNC8	West Pond	Sod Farm	Agricultural	Ground Water	543756	4775003	6408	180	3160	127	4637
3730-9KRNC8	East Pond	Sod Farm	Agricultural	Ground Water	545080	4774979	6378	180	3145	2055	3666
3863-7GFR3N	Pond	Field and Pasture Crops	Agricultural	Ground Water	544917	4775897	2184	90	539	0	0
4182-975J6G	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	539695	4770919	2046	180	1009	275	2046
4205-9MHPAE	James Pond #1	Field and Pasture Crops	Agricultural	Ground Water	547673	4774220	546	30	45	480	480
4205-9MHPAE	James Pond #2	Field and Pasture Crops	Agricultural	Ground Water	547822	4773487	546	30	45	480	480
4211-7UGL6P	Guido Pond	Field and Pasture Crops	Agricultural	Ground Water	542989	4775974	2455	180	1211	25	2402
4355-8JFQJL	Well "One" (WWR #39996)	Other - Agricultural	Agricultural	Ground Water	548436	4775248	630	40	69	8	375
4471-9Y8JS6	Casing	Field and Pasture Crops	Agricultural	Ground Water	543819	4773666	2620	120	861	37	5178
4471-9Y8JS6	Pond	Field and Pasture Crops	Agricultural	Ground Water	544053	4773602	1310	12	43	0	0

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
4504-5XZKJ6	Dugout Pond	Tobacco	Agricultural	Ground Water	538400	4778552	591	20	32	0	0
4505-6LSMZX	Dugout pond	Tobacco	Agricultural	Ground Water	537550	4775321	1114	150	458	0	0
4506-5WZSJD	Wellpoints (3) 150 IGPM from all sources combined	Field and Pasture Crops	Agricultural	Ground Water	543628	4772241	409	60	67	0	0
4547-69FMNG	Pond	Field and Pasture Crops	Agricultural	SW/GW	542117	4774753	2146	12	71	0	0
4647-9XHHLL	Pond	Tobacco	Agricultural	SW/GW	544520	4773032	1090	25	75	0	0
4672-9SZJWX	Dugout Pond (on farm)	Tobacco	Agricultural	Ground Water	539401	4775195	200	3	2	0	0
4704-6EMHSP	Pond	Field and Pasture Crops	Agricultural	Ground Water	537603	4772082	1250	4	14	2	625
5005-6QZLV4	Pond #1	Tobacco	Agricultural	SW/GW	540473	4777189	913	20	50	0	0
5087-9QJR28	Pond	Tobacco	Agricultural	Ground Water	538290	4771238	2488	90	613	0	0
5128-8Q8J96	Irrigation Pond	Sod Farm	Agricultural	Ground Water	535554	4778758	240	180	118	2	192
5156-9Q3HZH	Well	Field and Pasture Crops	Agricultural	Ground Water	547360	4776021	1309	120	430	0	0
5156-9Q3HZH	Pond	Field and Pasture Crops	Agricultural	Ground Water	547392	4775945	3928	120	1291	96	9494
5278-7BTL2D	Madero Pond	Field and Pasture Crops	Agricultural	Ground Water	526550	4784000	1488	30	122	5	819
5342-9BLMDB	Bedrock Well	Nursery	Agricultural	Ground Water	542420	4773932	216	180	107	0	0
5342-9BLMDB	Pond	Nursery	Agricultural	Ground Water	542392	4773899	688	120	226	6	458
5382-6CRQBW	Dugout Pond	Sod Farm	Agricultural	Ground Water	540665	4775585	1181	30	97	0	0
5388-9RNQ88	Pond 1 (Lot 18)	Field and Pasture Crops	Agricultural	Ground Water	532790	4786694	2455	60	404	0	0
5388-9RNQ88	Pond 2 (Lot 17)	Field and Pasture Crops	Agricultural	Ground Water	533450	4787025	2455	60	404	0	0
5488-7VBQMC	pond	Field and Pasture Crops	Agricultural	SW/GW	533505	4782573	2455	50	336	4	458
5546-5ZSJ5M	Pond 2. Lot 17	Tobacco	Agricultural	Ground Water	533443	4787033	2455	60	404	10	1079
5812-8PRLZF	Pond	Field and Pasture Crops	Agricultural	SW/GW	545930	4773526	2376	42	273	24	792
5815-5Z5L66	Pond	Field and Pasture Crops	Agricultural	Ground Water	542327	4776194	3764	180	1856	0	0
5836-9EANY5	Pond	Field and Pasture Crops	Agricultural	Ground Water	546614	4769558	3494	90	862	2325	28390
63-P-0711	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	544417	4775975	1080	0	0	4	764

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
63-P-1123	Dugout pond	Tobacco	Agricultural	Ground Water	539044	4772860	2771	150	1139	0	0
6420-9EYK9K	Pond #1	Field and Pasture Crops	Agricultural	Ground Water	544923	4775902	912	180	450	0	0
6635-9XEM7J	Pond	Other - Agricultural	Agricultural	SW/GW	540448	4774656	1522	120	500	0	0
66-P-0534	Dugout Pond	Tobacco	Agricultural	Ground Water	539556	4776318	1308	0	0	0	0
6728-9FMJXV	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	547119	4776127	3928	120	1291	0	0
6733-8WXQXF	Pond	Field and Pasture Crops	Agricultural	SW/GW	526076	4784164	5237	30	430	444	2500
6782-98DHDL	Pond 1 (Lot: 18, Con: 1)	Other - Agricultural	Agricultural	Ground Water	535256	4779757	2318	20	127	40	2318
6782-98DHDL	Pond 2 (Lot: 17, Con:1)	Other - Agricultural	Agricultural	Ground Water	535416	4779730	2318	20	127	12	1855
6881-6DCLKL	Dugout Pond	Tobacco	Agricultural	Ground Water	539150	4775110	1020	20	56	0	0
69-P-0199	Dugout pond	Other - Agricultural	Agricultural	Ground Water	540476	4772932	1364	0	0	0	0
69-P-0203	Dugout pond	Tobacco	Agricultural	Ground Water	545254	4775626	999	0	0	0	0
69-P-0374	Excavation Pit	Other - Agricultural	Agricultural	Ground Water	553183	4774740	3805	0	0	0	0
7104-9CLK8A	South Pond	Other - Agricultural	Agricultural	Ground Water	529304	4788559	2040	150	838	31	405
7104-9CLK8A	North Pond	Other - Agricultural	Agricultural	Ground Water	528999	4789790	1224	90	302	0	0
7287-A57RWG	VanDeWalle 8th	Field and Pasture Crops	Agricultural	Ground Water	544892	4770554	1264	180	623	91	4150
7377-8JXJFS	Pond	Field and Pasture Crops	Agricultural	Ground Water	550740	4775473	2864	20	157	48	2500
73-P-0097	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	531006	4784951	1092	5	15	0	0
7454-8WYLSF	Franken Pond	Field and Pasture Crops	Agricultural	Ground Water	542297	4776525	3764	153	1578	101	1964
7467-84BQEE	Well 4	Municipal	Water Supply	Ground Water	527587	4790760	327	365	327	6	126
7467-84BQEE	Well 4A	Municipal	Water Supply	Ground Water	527587	4790765	327	365	327	84	230
7467-84BQEE	Well 5	Municipal	Water Supply	Ground Water	527515	4790696	243	365	243	15	122
7506-5TXH8B	Dugout Pond #1	Tobacco	Agricultural	Ground Water	538709	4772821	3840	120	1262	0	0
7506-5TXH8B	Dugout Pond #2	Tobacco	Agricultural	Ground Water	538494	4776870	3840	120	1262	0	0
7607-63RPKH	Pond	Field and Pasture Crops	Agricultural	Ground Water	546614	4769558	5237	210	3013	78	4368
7680-64CJKY	Pond	Sod Farm	Agricultural	Ground Water	533461	4778832	3475	180	1714	671	9926

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
7680-64CJKY	Well #1	Sod Farm	Agricultural	Ground Water	533395	4778824	1310	180	646	314	1094
7680-64CJKY	Well #2	Sod Farm	Agricultural	Ground Water	533420	4778827	1310	180	646	158	1094
77-P-2000	Pond	Other - Agricultural	Agricultural	Ground Water	545446	4771840	982	0	0	0	0
7847-62ENT9	Pond	Field and Pasture Crops	Agricultural	Ground Water	545894	4770754	3273	180	1614	103	3276
79-P-2024	Pond	Other - Agricultural	Agricultural	Ground Water	538545	4777869	916	0	0	0	0
8025-82TRZT	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	537332	4775409	952	24	63	8	834
8120-7VBQVQ	old	Field and Pasture Crops	Agricultural	Ground Water	534524	4780464	3273	50	448	15	1718
8120-7VBQVQ	new	Field and Pasture Crops	Agricultural	Ground Water	534287	4781034	3273	50	448	2	1527
8142-642JS2	Pond	Field and Pasture Crops	Agricultural	Ground Water	536591	4776571	3090	180	1524	0	0
8242-8KDKUR	Pond 1	Tobacco	Agricultural	Ground Water	539911	4775827	1950	30	160	137	1850
8242-8KDKUR	Pond 2	Tobacco	Agricultural	Ground Water	540092	4775484	1950	30	160	210	1850
8242-8KDKUR	Pond 3	Tobacco	Agricultural	Ground Water	540568	4775908	1950	30	160	216	1850
8242-8KDKUR	Pond 4	Tobacco	Agricultural	Ground Water	540510	4775321	1950	30	160	192	1850
8242-8KDKUR	Pond 5	Tobacco	Agricultural	Ground Water	540365	4775223	1950	30	160	178	1850
8314-65JLCU	Dugout Pond	Tender Fruit	Agricultural	Ground Water	537586	4772671	128	120	42	0	0
8340-8L2KYR	Pond	Field and Pasture Crops	Agricultural	Ground Water	547827	4773453	952	24	63	4	467
8545-A48Q8C	P52 (TW 1/05) [A026040]	Municipal	Water Supply	Ground Water	550781.63	4777851.5	1296	365	1296	57	744
8545-A48Q8C	P51 (PW 1/12) [A002048]	Municipal	Water Supply	Ground Water	550768	4777831	1310	365	1310	17	1077
8545-A48Q8C	P53 (PW 2/12) [A002049]	Municipal	Water Supply	Ground Water	550782	4777834	1310	365	1310	17	473
8545-A48Q8C	P54 (PW 4/12) [A002052]	Municipal	Water Supply	Ground Water	550746	4777821	1310	365	1310	47	371
8565-95RL8P	Pond	Other - Agricultural	Agricultural	Ground Water	546798	4770069	5042	90	1243	78	1890
8587-8GPKDT	Wilson Farm Well	Tobacco	Agricultural	Ground Water	547250	4770150	5040	24	331	154	4800
8618-8JJNN9	Pond 1	Other - Agricultural	Agricultural	Ground Water	541233	4775178	2043	150	840	145	2043
8618-8JJNN9	Pond 2	Other - Agricultural	Agricultural	Ground Water	541106	4774871	2043	150	840	45	1321

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
8643-9ZZQER	Pond	Tobacco	Agricultural	SW/GW	541054	4770810	1780	15	73	0	0
8655-6BGSP6	Pond	Tobacco	Agricultural	SW/GW	537904	4776109	1999	35	192	0	0
8770-82HQU7	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	550184	4774187	2619	100	718	103	2316
88-P-2077	Wells(PW1, PW2, PW3, PW4, PW5)	Other - Agricultural	Agricultural	Ground Water	546832	4770289	3272	0	0	0	0
93-P-2049	Pond	Field and Pasture Crops	Agricultural	Ground Water	541646	4775323	1364	30	112	0	0
99-P-1097	Dugout pond	Tobacco	Agricultural	Ground Water	529736	4786634	1364	10	37	0	0
99-P-2127	Dugouts	Other - Agricultural	Agricultural	Ground Water	540621	4771906	2128	0	0	0	0
99-P-2139	Dugout	Tobacco	Agricultural	Ground Water	552840	4774269	1091	0	0	0	0
99-P-2142	Well	Tobacco	Agricultural	Ground Water	549631	4773202	546	0	0	0	0
99-P-2154	Well	Other - Agricultural	Agricultural	Ground Water	547033	4769638	2	0	0	0	0

Table B-2: Active groundwater and mixed surface water/groundwater permits within the model

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
0042-8GRREW	Home Farm Well	Tobacco	Agricultural	Ground Water	547050	4770650	5040	24	331	124	4800
00-P-1105	8 Well Points	Other - Agricultural	Agricultural	Ground Water	537059	4757925	982	25	67	0	0
00-P-1240	Gravel Pit	Other - Construction	Construction	Ground Water	509580	4803190	200	30	16	1	76
00-P-1244	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	535849	4758927	1125	15	46	0	0
00-P-2028	Dugout pond	Tobacco	Agricultural	Ground Water	552527	4770178	1091	0	0	9	230
00-P-2055	Dugout pond	Other - Agricultural	Agricultural	Ground Water	538262	4773563	955	0	0	0	0
00-P-2073	Dugout pond	Other - Agricultural	Agricultural	Ground Water	542044	4763215	1637	30	135	0	0
00-P-2084	Dugout pond	Tobacco	Agricultural	Ground Water	544374	4768141	1309	30	108	0	0
00-P-2089	Dugout pond	Other - Agricultural	Agricultural	Ground Water	538982	4759223	1703	20	93	0	0
00-P-2098	Dugout pond	Other - Agricultural	Agricultural	Ground Water	539484	4758842	1937	25	133	0	0
00-P-2108	Dugout pond	Other - Agricultural	Agricultural	Ground Water	545345	4764071	1454	90	358	0	0
00-P-2178	Dugout pond	Tobacco	Agricultural	Ground Water	547136	4767200	1159	0	0	0	0
00-P-2180	Dugout pond	Tobacco	Agricultural	Ground Water	547084	4767947	2619	60	430	0	0
00-P-2180	Sandpts.	Tobacco	Agricultural	Ground Water	547084	4767972	2619	60	430	0	0
00-P-2181	Dugout pond	Tobacco	Agricultural	Ground Water	548021	4767268	2619	60	430	0	0
00-P-2238	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	541247	4762087	2455	16	108	0	0
00-P-2239	Dugout pond	Other - Agricultural	Agricultural	Ground Water	539291	4760923	2455	24	161	0	0
00-P-2247	Dugout pond	Market Gardens / Flowers	Agricultural	Ground Water	553181	4767874	1472	50	202	0	0
00-P-2255	Dugout pond	Other - Agricultural	Agricultural	Ground Water	548443	4773518	2720	25	186	0	0
00-P-2328	Dugout pond	Tobacco	Agricultural	Ground Water	539155	4769095	1500	5	21	0	0
00-P-2339	Well Points	Field and Pasture Crops	Agricultural	Ground Water	547153	4770544	3816	40	418	20	3180
00-P-2371	Dugout pond	Tobacco	Agricultural	Ground Water	545084	4770151	2292	12	75	27	736
00-P-2372	Dugout pond	Tobacco	Agricultural	Ground Water	544607	4771512	2292	24	151	27	736
00-P-2458	Dugout pond	Other - Agricultural	Agricultural	Ground Water	545596	4778594	1364	15	56	0	0

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00-P-2517	dugout pond	Other - Agricultural	Agricultural	Ground Water	547575	4774297	546	0	0	0	0
00-P-2518	dugout pond	Other - Agricultural	Agricultural	Ground Water	547783	4773505	546	0	0	0	0
00-P-2547	dugout pond	Tobacco	Agricultural	Ground Water	537774	4759025	2180	0	0	11	968
00-P-2612	Dugout pond	Other - Agricultural	Agricultural	Ground Water	554101	4773052	1104	0	0	0	0
00-P-2684	Dugout pond	Other - Agricultural	Agricultural	Ground Water	544114	4772213	2180	0	0	10	1966
00-P-2692	DUGOUT POND	Other - Agricultural	Agricultural	Ground Water	547212	4768772	1637	0	0	0	0
00-P-2722	dugout pond	Tobacco	Agricultural	Ground Water	551332	4770698	1500	0	0	16	1500
00-P-2748	one dugout pond	Other - Agricultural	Agricultural	Ground Water	551932	4767719	1964	0	0	0	0
00-P-2751	one dugout pond	Tobacco	Agricultural	Ground Water	545471	4770536	2180	0	0	0	0
00-P-2751	three quarry ponds	Tobacco	Agricultural	Ground Water	545869	4769989	2180	0	0	0	0
00-P-2764	well	Golf Course Irrigation	Commercial	Ground Water	544173	4774858	102	0	0	0	0
00-P-2764	Dugout pond	Golf Course Irrigation	Commercial	Ground Water	544049	4775087	1718	0	0	2	168
00-P-2779	one dugout pond	Tobacco	Agricultural	Ground Water	558910	4770435	2615	0	0	0	0
0163-856HNA	Carrita Pond #1	Field and Pasture Crops	Agricultural	Ground Water	551454	4771051	2350	45	290	93	2402
0175-8CSQJW	East Gravel Pit	Other - Construction	Construction	SW/GW	509580	4803190	200	365	200	1	170
0182-9ZQQXF	Dugout Pond	Tobacco	Agricultural	Ground Water	539704	4759709	1588	50	218	72	1542
0188-9X7KYD	Pond	Tobacco	Agricultural	Ground Water	538811	4772117	982	90	242	0	0
01-P-1208	Well	Heat Pumps	Miscellaneous	Ground Water	520358	4775866	953	365	953	0	0
01-P-2067	one dugout pond	Tobacco	Agricultural	Ground Water	552071	4770764	3000	0	0	0	0
01-P-2069	One well (WWR #1300676)	Tobacco	Agricultural	Ground Water	548950	4767000	4419	0	0	0	0
01-P-2070	sandpoint	Field and Pasture Crops	Agricultural	Ground Water	548170	4770886	1637	0	0	0	0
01-P-2242	wellpoint	Field and Pasture Crops	Agricultural	Ground Water	547535	4769093	2816	0	0	0	0
01-P-2262	dugout	Tobacco	Agricultural	Ground Water	544992	4759581	1440	0	0	0	0
0222-9QLSMJ	Dugout Pond	Tobacco	Agricultural	Ground Water	550957	4772541	3276	50	449	44	3276
0261-9LGLWG	Pond 2	Field and Pasture Crops	Agricultural	Ground Water	554821	4767585	1637	12	54	0	0

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0271-9TDJK2	P1	Campgrounds	Water Supply	Ground Water	520697	4778311	44	214	26	0	0
0271-9TDJK2	P3	Campgrounds	Water Supply	Ground Water	521262	4778622	94	214	55	0	0
0271-9TDJK2	P4	Campgrounds	Water Supply	Ground Water	519598	4777854	82	214	48	0	0
0282-8XER2W	Well 5	Municipal	Water Supply	Ground Water	510880	4764680	3273	365	3273	1315	2978
02-P-1061	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536418	4759627	961	60	158	27	771
02-P-1069	#1 Pond connected to stream	Field and Pasture Crops	Agricultural	Ground Water	535675	4758787	1308	18	65	0	0
02-P-1069	8 sandpoint wells	Field and Pasture Crops	Agricultural	Ground Water	535242	4758412	654	20	36	0	0
02-P-1071	Dugout Pond	Tobacco	Agricultural	Ground Water	537631	4757625	1681	40	184	0	0
02-P-1108	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536414	4758449	981	6	16	0	0
0303-83LPN8	West Pond	Field and Pasture Crops	Agricultural	Ground Water	528666	4788076	951	16	42	18	8768
0352-8SFKQF	Park Well #1	Municipal	Water Supply	Ground Water	513584	4796502	1296	365	1296	68	1022
0352-8SFKQF	Park Well #2A	Municipal	Water Supply	Ground Water	513616	4796513	2765	365	2765	102	1971
0352-8SFKQF	Park Well #3	Municipal	Water Supply	Ground Water	513621	4796534	4320	365	4320	1147	2439
0366-6ARRS5	Dugout	Field and Pasture Crops	Agricultural	Ground Water	549213	4768911	5236	14	201	32	3273
0387-967L92	Pond	Other - Agricultural	Agricultural	SW/GW	546493	4763238	1940	122	648	0	0
03-P-1062	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536891	4758226	1392	30	114	7	600
03-P-2016	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	547390	4766257	2182	10	60	0	0
03-P-2050	Pond	Field and Pasture Crops	Agricultural	Ground Water	539655	4760585	960	60	158	0	0
03-P-2087	Dugout Pond	Tobacco	Agricultural	Ground Water	544447	4765570	955	16	42	37	1899
03-P-2089	Pond	Field and Pasture Crops	Agricultural	Ground Water	541130	4768309	1828	8	40	0	0
03-P-2094	Dugout Pond	Tobacco	Agricultural	Ground Water	544732	4764690	2030	30	167	0	0
03-P-2126	Pond	Field and Pasture Crops	Agricultural	Ground Water	539057	4756367	1054	7	20	0	0
03-P-2144	Pond	Field and Pasture Crops	Agricultural	Ground Water	537763	4761070	918	30	75	0	0
03-P-2165	Pond	Tobacco	Agricultural	Ground Water	545007	4766015	650	30	53	0	0
03-P-2252	Pond	Field and Pasture Crops	Agricultural	Ground Water	543386	4762641	1528	50	209	0	0

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03-P-2252	Well	Field and Pasture Crops	Agricultural	Ground Water	543416	4762696	99	12	3	0	0
03-P-2330	PW1	Aggregate Washing	Industrial	Ground Water	552457	4779301	691	300	568	0	0
03-P-2330	PW3	Aggregate Washing	Industrial	Ground Water	552220	4779189	493	300	405	0	0
0461-9MPQF2	Well 4	Heat Pumps	Miscellaneous	Ground Water	519389	4775327	284	365	284	0	0
0461-9MPQF2	Well 6	Heat Pumps	Miscellaneous	Ground Water	519361	4775255	302	365	302	0	0
0463-9HQMWC	Pond	Tobacco	Agricultural	SW/GW	545007	4780254	1294	30	106	24	1250
0476-8DAT6N	Irrigation Well	Other - Agricultural	Agricultural	Ground Water	549011	4767124	2318	50	318	63	2300
0476-9KXLDH	Pond 1	Field and Pasture Crops	Agricultural	Ground Water	544113	4765222	955	15	39	1290	1812
0476-9KXLDH	Pond 2	Field and Pasture Crops	Agricultural	Ground Water	544469	4765227	955	15	39	0	0
0512-8GRL9P	Pfleger Farm Well	Field and Pasture Crops	Agricultural	Ground Water	547500	4769089	2520	12	83	38	1900
0534-9NDPJE	Pond	Field and Pasture Crops	Agricultural	Ground Water	540601	4774303	3764	180	1856	60	3494
0545-9Y8L5U	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	545046	4767115	1050	20	58	0	0
0550-6BTRD6	Well WWR 1305235	Field and Pasture Crops	Agricultural	Ground Water	533014	4777874	196	312	168	8	144
0550-6BTRD6	Well WWR 1304883	Field and Pasture Crops	Agricultural	Ground Water	533059	4777871	524	312	448	20	38
0550-6BTRD6	Well WWR 1304499	Field and Pasture Crops	Agricultural	Ground Water	533078	4777889	131	312	112	9	44
0550-6BTRD6	Pond	Field and Pasture Crops	Agricultural	Ground Water	533271	4777715	3208	10	88	0	0
0568-82WQS8	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	545889	4764886	2566	30	211	65	2299
0617-A4TKLX	Dugout Pond	Tobacco	Agricultural	Ground Water	540734	4769856	3787	40	415	10	651
0640-9S2RQ4	VanDeWalle 9th	Field and Pasture Crops	Agricultural	Ground Water	544573	4768996	5237	210	3013	36	3713
0677-9MQP9B	Surmanski Pond	Field and Pasture Crops	Agricultural	Ground Water	546973	4768593	3456	180	1704	2957	3456
0723-9QBLKM	Five (5) Well Points	Aquaculture	Commercial	Ground Water	546349	4765234	2628	365	2628	818	818
0767-A4JKNT	Dugout Pond	Tobacco	Agricultural	Ground Water	544833	4763830	1915	50	262	6	1130
0786-9EGSNK	Pond	Field and Pasture Crops	Agricultural	SW/GW	542967	4774142	912	180	450	0	0
0824-9QSSCA	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	538423	4769154	1363	10	37	0	0
0876-8JVS26	391	Field and Pasture Crops	Agricultural	Ground Water	552527	4770178	1126	120	370	54	950

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0876-8JVS26	157	Field and Pasture Crops	Agricultural	Ground Water	553436	4773455	1126	120	370	59	950
1066-6H5J49	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536390	4777569	1079	10	30	0	0
1071-5Y2MU3	Pond	Field and Pasture Crops	Agricultural	Ground Water	546079	4771004	3764	180	1856	0	0
1123-9NNN3B	Norwich Well 2 (Tag A011226)	Municipal	Water Supply	Ground Water	532640	4759396	1633	365	1633	0	0
1123-9NNN3B	Norwich Well 4 (WWR 4705010)	Municipal	Water Supply	Ground Water	534041	4759555	2290	365	2290	171	941
1123-9NNN3B	Norwich Well 5 (Tag A011222)	Municipal	Water Supply	Ground Water	532627	4759400	821	365	821	245	425
1125-9L9Q27	Pond #1	Field and Pasture Crops	Agricultural	Ground Water	545471	4770536	3800	30	312	0	0
1125-9L9Q27	Pond #2	Field and Pasture Crops	Agricultural	Ground Water	545132	4771123	3800	30	312	87	2880
1125-9L9Q27	Pond #3	Field and Pasture Crops	Agricultural	Ground Water	546108	4770536	3800	30	312	26	2880
1167-5YVFZ2	Dugout Pond	Tobacco	Agricultural	Ground Water	540969	4770453	1637	50	224	3	360
1206-9NELFY	Farkas 8th	Field and Pasture Crops	Agricultural	Ground Water	544710	4769416	1242	30	102	0	0
1206-9NELFY	Farkas 9th	Field and Pasture Crops	Agricultural	Ground Water	544304	4768975	1242	30	102	0	0
1268-9QJS9H	Pond	Field and Pasture Crops	Agricultural	Ground Water	544080	4776907	4582	180	2260	106	4375
1315-7SAPKH	5 Well Points	Field and Pasture Crops	Agricultural	Ground Water	548018	4766262	1448	100	397	0	0
1315-7SAPKH	#2 Pond	Field and Pasture Crops	Agricultural	SW/GW	547694	4766138	504	100	138	0	0
1344-6AJNNR	Pond	Tobacco	Agricultural	Ground Water	539959	4776053	2946	90	726	7	1022
1402-8KNNTU	Pond 2	Field and Pasture Crops	Agricultural	Ground Water	547150	4767164	1159	30	95	64	927
1420-6FSNZ5	Dugout Pond with an overflow connection to an unna	Golf Course Irrigation	Commercial	Ground Water	556775	4773204	273	75	56	0	0
1436-96GKU3	Haverkamp Pond	Other - Agricultural	Agricultural	SW/GW	539493	4758808	1937	120	637	0	0
1482-9TWMBH	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	525332	4781434	2209	30	182	0	0
1508-9YPPW9	Wells (6)	Field and Pasture Crops	Agricultural	Ground Water	550471	4772335	1146	30	94	0	0
1508-9YPPW9	Pond	Field and Pasture Crops	Agricultural	Ground Water	550646	4772235	3930	30	323	0	0
1523-8NQL6U	Pond #2	Sod Farm	Agricultural	SW/GW	533894	4778190	1013	180	499	10	608
1523-8NQL6U	Well #3	Sod Farm	Agricultural	Ground Water	533389	4778888	1310	180	646	0	0
1546-6L4HU9	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	542421	4765107	1159	20	64	0	0

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1585-6RPQXC	Well PW 1	Golf Course Irrigation	Commercial	Ground Water	521772	4779269	2455	195	1312	238	1575
1585-6RPQXC	Pond 1	Golf Course Irrigation	Commercial	SW/GW	521647	4779376	1363	195	728	189	1270
1622-82BPKX	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	547823	4767176	2618	90	646	88	2592
1644-8KMJ6Z	Pond	Other - Agricultural	Agricultural	Ground Water	537774	4759025	968	20	53	27	968
1645-74YKVX	Well A	Other - Water Supply	Water Supply	Ground Water	516615	4768338	318	365	318	10	97
1645-74YKVX	Well B	Other - Water Supply	Water Supply	Ground Water	516568	4768417	318	365	318	0	0
1664-63LPSX	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	538862	4762594	450	210	259	0	0
1763-63ZS2Y	Pond	Tobacco	Agricultural	Ground Water	543483	4764306	992	40	109	18	992
2011-94MQP5	North Pond	Field and Pasture Crops	Agricultural	Ground Water	539091	4760223	1364	60	224	0	0
2033-7STRCS	Dugout Pond #1	Field and Pasture Crops	Agricultural	Ground Water	543556	4779790	1364	60	224	0	0
2040-63RPDY	Dugout	Tobacco	Agricultural	Ground Water	542638	4777577	3540	60	582	0	0
2104-8K4QEE	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	546363	4767442	765	30	63	99	765
2160-68ESPW	Pond	Tobacco	Agricultural	Ground Water	547806	4764901	2726	25	187	8	927
2231-6B6QH9	Brant Farm (L21 C14)	Tobacco	Agricultural	SW/GW	538955	4759948	645	150	265	0	0
2231-6B6QH9	Home (L1 C5)	Tobacco	Agricultural	SW/GW	536511	4757345	645	150	265	5	600
2231-6B6QH9	Hill (L3 Block A Gore)	Tobacco	Agricultural	SW/GW	537344	4757564	645	150	265	0	0
2301-9D5M9J	Pond	Tobacco	Agricultural	Ground Water	549693	4774364	1296	40	142	294	955
2323-63ZRHF	Pond	Field and Pasture Crops	Agricultural	Ground Water	540846	4767945	1590	45	196	0	0
2351-8S6PBV	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	549589	4774455	2592	35	249	294	1728
2353-6C8K6W	Pond	Field and Pasture Crops	Agricultural	Ground Water	555934	4770577	267	60	44	0	0
2378-972PWH	Catry Pond	Other - Agricultural	Agricultural	SW/GW	537631	4757625	1681	40	184	0	0
2410-6LDHXS	Well	Other - Agricultural	Agricultural	Ground Water	538433	4764465	1309	30	108	0	0
2410-6LDHXS	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	538417	4764412	1309	30	108	0	0
2413-9M4MYG	Ireland Pond	Field and Pasture Crops	Agricultural	Ground Water	539141	4767305	1091	30	90	8	960
2486-856GX2	Pond A	Field and Pasture Crops	Agricultural	Ground Water	545565	4769761	2350	45	290	192	3276

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2486-856GX2	Pond B	Field and Pasture Crops	Agricultural	Ground Water	545683	4769725	2350	45	290	58	2304
2486-856GX2	Pond C	Field and Pasture Crops	Agricultural	Ground Water	545903	4769968	2350	45	290	0	0
2507-9YMJN5	Dugout pond	Tobacco	Agricultural	Ground Water	537796	4758621	1472	365	1472	5	968
2526-8LRLRH	Well 1	Golf Course Irrigation	Commercial	Ground Water	543598	4776353	102	214	60	0	0
2526-8LRLRH	Ponds 1 and 2	Golf Course Irrigation	Commercial	Ground Water	543615	4776355	1718	214	1008	68	583
2531-9KTQ2U	Beachville Well #1 (WWR 4703620)	Municipal	Water Supply	Ground Water	513678	4770166	657	365	657	47	121
2586-9NFQMG	Pond Lot: 3, Con: 10	Field and Pasture Crops	Agricultural	Ground Water	548460	4766711	3764	180	1856	0	0
2586-9NFQMG	Pond Lot: 3, Con: 11	Field and Pasture Crops	Agricultural	Ground Water	548083	4767618	3928	180	1937	0	0
2624-82QMAP	Sandpoints	Field and Pasture Crops	Agricultural	Ground Water	547084	4767972	2618	90	646	132	2360
2677-5ZXQZF	Well DaSilva	Other - Agricultural	Agricultural	Ground Water	549291	4771186	5237	42	603	58	5237
2715-5Z6QVP	TW1-01	Other - Commercial	Commercial	Ground Water	532087	4786336	131	365	131	0	0
2725-8HMPXS	Art Da Silva Princeton	Field and Pasture Crops	Agricultural	Ground Water	538433	4778513	2448	20	134	54	8700
2743-6FUJ5L	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	536753	4778857	931	6	15	0	0
2767-6APJF9	Pond	Tobacco	Agricultural	SW/GW	543073	4774080	999	180	493	0	0
2846-5ZTGGT	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	546874	4768914	4032	210	2320	131	3931
2862-7R4Q66	Pond #1	Field and Pasture Crops	Agricultural	SW/GW	558117	4769563	1800	50	247	5	1500
3003-9U3KA9	Dugout Pond	Tobacco	Agricultural	Ground Water	545442	4767240	1527	30	126	0	0
3066-9CKH6G	Dugout Pond	Tobacco	Agricultural	Ground Water	536466	4775533	3475	35	333	0	0
3101-9L5J95	Well 1	Other - Agricultural	Agricultural	Ground Water	549126	4775562	818	149	334	0	0
3101-9L5J95	Well 2	Other - Agricultural	Agricultural	Ground Water	549096	4775571	818	149	334	0	0
3101-9L5J95	Well 3	Other - Agricultural	Agricultural	Ground Water	549111	4775582	818	149	334	0	0
3101-9L5J95	Well 4	Other - Agricultural	Agricultural	Ground Water	549130	4775591	818	149	334	0	0
3104-6CCS2G	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	539493	4770223	851	150	350	45	850
3168-9ZZPLW	Pond	Tobacco	Agricultural	Ground Water	541278	4772419	888	15	36	0	0
3186-9C9QBM	Pond	Field and Pasture Crops	Agricultural	Ground Water	541910	4778367	3240	30	266	0	0

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3243-642M69	Pond	Tobacco	Agricultural	Ground Water	538281	4771345	2488	90	613	33	5178
3257-9PMLN8	Pond	Field and Pasture Crops	Agricultural	Ground Water	546851	4769542	3764	180	1856	44	3456
3300-68ESHK	Pond	Field and Pasture Crops	Agricultural	Ground Water	542769	4776661	3764	180	1856	0	0
3337-5XES2F	North Pond	Field and Pasture Crops	Agricultural	Ground Water	540373	4767258	1909	90	471	0	0
3337-5XES2F	South Pond	Field and Pasture Crops	Agricultural	Ground Water	540467	4767209	955	90	235	0	0
3347-9A5LKP	PW1	Aggregate Washing	Industrial	Ground Water	552265	4779087	691	300	568	0	0
3347-9A5LKP	PW3	Aggregate Washing	Industrial	Ground Water	552119	4779144	493	300	405	0	0
3347-9A5LKP	Ponds	Aggregate Washing	Industrial	Ground Water	552257	4778936	5892	300	4843	0	0
3411-64SLMD	Pond 1	Field and Pasture Crops	Agricultural	SW/GW	548475	4773541	1364	10	37	0	0
3411-64SLMD	Pond 2	Fruit Orchards	Agricultural	SW/GW	548144	4773454	219	10	6	0	0
3411-64SLMD	Pond 3	Market Gardens / Flowers	Agricultural	SW/GW	548151	4773460	131	12	4	0	0
3411-64SLMD	Well	Fruit Orchards	Agricultural	Ground Water	548169	4773753	219	10	6	0	0
3430-8JVQ9W	North Pond	Other - Agricultural	Agricultural	Ground Water	533117	4786138	951	16	42	0	0
3430-8JVQ9W	South Pond	Other - Agricultural	Agricultural	Ground Water	533911	4785692	951	20	52	0	0
3467-8JQKB3	Pond	Other - Agricultural	Agricultural	Ground Water	543445	4762640	951	30	78	0	0
3468-9PNPGA	6 Sandpoints	Tobacco	Agricultural	Ground Water	552165	4775780	2589	40	284	0	0
3502-7V8R6S	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	545525	4771836	982	30	81	0	0
3523-A57PJF	VanDeWalle Home	Field and Pasture Crops	Agricultural	Ground Water	545394	4768824	1264	180	623	62	4368
3527-9NSKF3	James Dick West Brantford Pit Supply Pond	Aggregate Washing	Industrial	Ground Water	554442	4774498	5876	275	4427	1978	4406
3532-A4SK3G	Well	Field and Pasture Crops	Agricultural	Ground Water	540485	4767291	240	180	118	0	0
3532-A4SK3G	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	540389	4767320	60	365	60	0	0
3538-62FNDS	Pond	Field and Pasture Crops	Agricultural	Ground Water	547759	4777528	2177	14	84	0	0
3576-8UUQD4	Pond #1	Other - Agricultural	Agricultural	Ground Water	544150	4763730	756	150	311	5	314
3615-9UKNUD	Dugout Pond	Nursery	Agricultural	Ground Water	526563	4761532	171	145	68	36	108
3650-7KEKC2	PW1	Communal	Water Supply	Ground Water	528211	4781108	120	365	120	29	290

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3650-7KEKC2	PW2	Communal	Water Supply	Ground Water	528320	4781116	120	365	120	29	268
3671-9ZGPHB	Innerkip Well 1	Municipal	Water Supply	Ground Water	523631	4781657	1728	365	1728	175	858
3671-9ZGPHB	Innerkip Well 2	Municipal	Water Supply	Ground Water	523682	4781563	1296	365	1296	167	617
3714-7BCMU5	Well	Municipal	Water Supply	Ground Water	513200	4801900	546	365	546	56	135
3730-9KRNC8	Middle Pond	Sod Farm	Agricultural	Ground Water	544781	4774763	6378	180	3145	194	4449
3730-9KRNC8	West Pond	Sod Farm	Agricultural	Ground Water	543756	4775003	6408	180	3160	127	4637
3730-9KRNC8	East Pond	Sod Farm	Agricultural	Ground Water	545080	4774979	6378	180	3145	2055	3666
3745-6H6Q2Q	Dugout Pond	Tobacco	Agricultural	Ground Water	537796	4758621	1104	20	60	0	0
3757-8KEPA4	10th Concession Dugout Pond	Other - Agricultural	Agricultural	Ground Water	548000	4768507	3487	65	621	0	0
3760-8KDJB9	Well 1	Municipal	Water Supply	Ground Water	536233	4787747	272	365	272	0	0
3760-8KDJB9	Well 2A	Municipal	Water Supply	Ground Water	536874	4787383	337	365	337	69	315
3760-8KDJB9	Well 3	Municipal	Water Supply	Ground Water	535867	4787554	720	365	720	161	510
3826-7UENDN	Steinmetz Pond	Field and Pasture Crops	Agricultural	Ground Water	547829	4766694	2455	150	1009	86	2839
3826-9YMHR2	Azevedo Pond	Field and Pasture Crops	Agricultural	SW/GW	553165	4772180	1824	30	150	0	0
3863-5WSMFE	Well	Other - Agricultural	Agricultural	Ground Water	540488	4767300	86	90	21	0	0
3863-5WSMFE	Pond	Field and Pasture Crops	Agricultural	Ground Water	540371	4767304	45	90	11	0	0
3863-7GFR3N	Pond	Field and Pasture Crops	Agricultural	Ground Water	544917	4775897	2184	90	539	0	0
4002-5Y2HNQ	Pond	Field and Pasture Crops	Agricultural	Ground Water	548003	4768449	3928	180	1937	0	0
4008-6YUQ6G	Mt. Pleasant Well #1	Municipal	Water Supply	Ground Water	554814.13	4771001	2290	365	2290	101	1560
4008-6YUQ6G	Mt. Pleasant Well #2	Municipal	Water Supply	Ground Water	554806.13	4771018	2290	365	2290	602	2082
4182-975J6G	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	539695	4770919	2046	180	1009	275	2046
4205-9MHPAE	James Pond #1	Field and Pasture Crops	Agricultural	Ground Water	547673	4774220	546	30	45	480	480
4205-9MHPAE	James Pond #2	Field and Pasture Crops	Agricultural	Ground Water	547822	4773487	546	30	45	480	480
4211-7UGL6P	Guido Pond	Field and Pasture Crops	Agricultural	Ground Water	542989	4775974	2455	180	1211	25	2402

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4213-9XCNZG	Well 1	Aquaculture	Commercial	Ground Water	537182	4794563	266	365	266	0	0
4254-6GGH6E	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	538515	4761066	2581	45	318	0	0
4262-8JFR7X	Pond	Other - Agricultural	Agricultural	Ground Water	550284	4767633	908	40	100	3	954
4316-9XKJSY	Home Pond (Lot 1 Concession 5)	Tobacco	Agricultural	SW/GW	536511	4758958	645	150	265	0	0
4316-9XKJSY	Hill Pond (Lot 3 Block A, Concession Gore)	Tobacco	Agricultural	SW/GW	537344	4757564	645	150	265	0	0
4316-9XKJSY	Brant Farm Pond (Lot 21, Concession 14)	Tobacco	Agricultural	SW/GW	538955	4759948	645	150	265	0	0
4355-8JFQJL	Well "One" (WWR #39996)	Other - Agricultural	Agricultural	Ground Water	548436	4775248	630	40	69	8	375
4452-9PJHUJ	Pond #1	Field and Pasture Crops	Agricultural	SW/GW	543186	4763864	818	45	101	16	684
4452-9PJHUJ	Pond # 2	Field and Pasture Crops	Agricultural	SW/GW	543700	4763644	818	30	67	2	390
4452-9PJHUJ	Pond # 3	Field and Pasture Crops	Agricultural	SW/GW	543669	4763792	818	30	67	4	600
4471-9Y8JS6	Casing	Field and Pasture Crops	Agricultural	Ground Water	543819	4773666	2620	120	861	37	5178
4471-9Y8JS6	Pond	Field and Pasture Crops	Agricultural	Ground Water	544053	4773602	1310	12	43	0	0
4487-6YPSAM	Airport Municipal Well	Municipal	Water Supply	Ground Water	553900	4775032	2290	365	2290	209	2359
4504-5XZKJ6	Dugout Pond	Tobacco	Agricultural	Ground Water	538400	4778552	591	20	32	0	0
4505-6LSMZX	Dugout pond	Tobacco	Agricultural	Ground Water	537550	4775321	1114	150	458	0	0
4506-5WZSJD	Wellpoints (3) 150 IGPM from all sources combined	Field and Pasture Crops	Agricultural	Ground Water	543628	4772241	409	60	67	0	0
4547-69FMNG	Pond	Field and Pasture Crops	Agricultural	SW/GW	542117	4774753	2146	12	71	0	0
4626-84YG85	Front Pond # 1	Field and Pasture Crops	Agricultural	SW/GW	539291	4760917	1146	25	78	22	1080
4626-84YG85	Back Pond # 2	Field and Pasture Crops	Agricultural	SW/GW	539655	4760592	1146	25	78	17	1080
4647-9XHHLL	Pond	Tobacco	Agricultural	SW/GW	544520	4773032	1090	25	75	0	0
4672-9SZJWX	Dugout Pond (on farm)	Tobacco	Agricultural	Ground Water	539401	4775195	200	3	2	0	0
4682-9KXHWS	Pond 1	Field and Pasture Crops	Agricultural	Ground Water	545282	4764360	966	15	40	8	1812
4704-6EMHSP	Pond	Field and Pasture Crops	Agricultural	Ground Water	537603	4772082	1250	4	14	2	625
4776-5YUR3R	Dugout	Tobacco	Agricultural	Ground Water	541427	4777695	5905	60	971	0	0

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4780-83DHNS	well 1	Communal	Water Supply	Ground Water	514956	4767125	319	365	319	76	167
4780-83DHNS	well 2	Communal	Water Supply	Ground Water	514995	4767071	319	365	319	7	133
4856-9XMHQ7	Dugout Pond	Tobacco	Agricultural	Ground Water	545816	4760560	802	20	44	0	0
5005-6QZLV4	Pond #1	Tobacco	Agricultural	SW/GW	540473	4777189	913	20	50	0	0
5005-6QZLV4	Pond #3	Tobacco	Agricultural	SW/GW	539870	4778053	913	20	50	0	0
5072-7T3L4E	dugout pond	Field and Pasture Crops	Agricultural	Ground Water	526535	4782614	613	36	60	0	0
5087-9QJR28	Pond	Tobacco	Agricultural	Ground Water	538290	4771238	2488	90	613	0	0
5128-8Q8J96	Irrigation Pond	Sod Farm	Agricultural	Ground Water	535554	4778758	240	180	118	2	192
5156-9Q3HZH	Well	Field and Pasture Crops	Agricultural	Ground Water	547360	4776021	1309	120	430	0	0
5156-9Q3HZH	Pond	Field and Pasture Crops	Agricultural	Ground Water	547392	4775945	3928	120	1291	96	9494
5278-7BTL2D	Madero Pond	Field and Pasture Crops	Agricultural	Ground Water	526550	4784000	1488	30	122	5	819
5281-5RWJEK	P1	Campgrounds	Water Supply	Ground Water	520697	4778311	44	214	26	1	34
5281-5RWJEK	P3	Campgrounds	Water Supply	Ground Water	521262	4778622	94	214	55	6	112
5281-5RWJEK	P4	Campgrounds	Water Supply	Ground Water	519598	4777854	82	214	48	5	129
5305-9ZRJZZ	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	549536	4766715	2590	90	639	16	1812
5333-7GLRU3	Pond	Field and Pasture Crops	Agricultural	Ground Water	545948	4768361	3494	90	862	197	3494
5342-9BLMDB	Bedrock Well	Nursery	Agricultural	Ground Water	542420	4773932	216	180	107	0	0
5342-9BLMDB	Pond	Nursery	Agricultural	Ground Water	542392	4773899	688	120	226	6	458
5378-967JY3	Lee Pond	Field and Pasture Crops	Agricultural	Ground Water	537567	4769285	1920	30	158	21	1092
5382-6CRQBW	Dugout Pond	Sod Farm	Agricultural	Ground Water	540665	4775585	1181	30	97	0	0
5388-9RNQ88	Pond 1 (Lot 18)	Field and Pasture Crops	Agricultural	Ground Water	532790	4786694	2455	60	404	0	0
5388-9RNQ88	Pond 2 (Lot 17)	Field and Pasture Crops	Agricultural	Ground Water	533450	4787025	2455	60	404	0	0
5488-7VBQMC	pond	Field and Pasture Crops	Agricultural	SW/GW	533505	4782573	2455	50	336	4	458
5546-5ZSJ5M	Pond 1. Lot 18	Tobacco	Agricultural	Ground Water	523775	4786691	2455	60	404	13	1244
5546-5ZSJ5M	Pond 2. Lot 17	Tobacco	Agricultural	Ground Water	533443	4787033	2455	60	404	10	1079

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5546-9A6QXF	Kegels Pond (#1)	Other - Agricultural	Agricultural	Ground Water	551561	4766392	674	12	22	0	0
5566-7VAKWQ	Dogout Pond	Tobacco	Agricultural	Ground Water	538464	4794067	2725	36	269	0	0
5567-5YGP7H	Pond	Field and Pasture Crops	Agricultural	Ground Water	550722	4772139	819	150	337	0	0
5606-9XEJ5X	Miller Pond	Field and Pasture Crops	Agricultural	Ground Water	550790	4772083	840	20	46	0	0
5657-96NPYR	Pond	Other - Agricultural	Agricultural	Ground Water	546432	4762150	2181	122	729	0	0
5707-95QHJR	Pond	Field and Pasture Crops	Agricultural	Ground Water	546231	4764554	1746	90	431	359	1728
5782-6AYNCF	Pond	Sod Farm	Agricultural	Ground Water	540738	4778018	591	20	32	1	566
5805-8L7NUX	Pond	Tobacco	Agricultural	SW/GW	552736	4769399	2343	45	289	0	0
5812-8PRLZF	Pond	Field and Pasture Crops	Agricultural	SW/GW	545930	4773526	2376	42	273	24	792
5815-5Z5L66	Pond	Field and Pasture Crops	Agricultural	Ground Water	542327	4776194	3764	180	1856	0	0
5836-9EANY5	Pond	Field and Pasture Crops	Agricultural	Ground Water	546614	4769558	3494	90	862	2325	28390
6003-7FRQTL	Pond (Jun 1 to Oct 30)	Field and Pasture Crops	Agricultural	SW/GW	526148	4781762	307	50	42	6	1226
6022-9J8LSJ	Pond	Tobacco	Agricultural	Ground Water	552611	4769316	2280	50	312	0	0
6164-8K8NMY	Home Farm Pond	Field and Pasture Crops	Agricultural	Ground Water	544803	4769051	3276	28	251	32	1449
6164-8K8NMY	Back 50 Pond	Field and Pasture Crops	Agricultural	Ground Water	545330	4768475	3276	28	251	25	2326
6213-85ZQTQ	Pond	Field and Pasture Crops	Agricultural	Ground Water	539965	4760192	2245	40	246	20	1954
6331-8SRLGP	Dug Out Pond 1	Field and Pasture Crops	Agricultural	Ground Water	553094	4767736	682	40	75	209	682
6331-8SRLGP	Dug Out Pond 2	Field and Pasture Crops	Agricultural	Ground Water	552041	4768287	682	40	75	0	0
63-P-0711	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	544417	4775975	1080	0	0	4	764
63-P-0962	Pond	Field and Pasture Crops	Agricultural	Ground Water	540994	4768503	1309	0	0	34	2621
63-P-0975	Pond	Other - Agricultural	Agricultural	Ground Water	545063	4768296	2180	0	0	66	3839
63-P-0980	Pond 1	Other - Agricultural	Agricultural	Ground Water	545191	4767132	2062	0	0	10	1490
63-P-1009	Pond	Tobacco	Agricultural	Ground Water	545537	4762753	1944	0	0	0	0
63-P-1123	Dugout pond	Tobacco	Agricultural	Ground Water	539044	4772860	2771	150	1139	0	0
63-P-2591	Pond	Field and Pasture Crops	Agricultural	Ground Water	552091	4768969	2273	180	1121	0	0

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6420-9EYK9K	Pond #1	Field and Pasture Crops	Agricultural	Ground Water	544923	4775902	912	180	450	0	0
6432-8QGJNL	One Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	538982	4759223	1703	60	280	259	1558
6521-9Y7P6L	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	545073	4763175	827	25	57	0	0
6566-98UN74	Well	Fruit Orchards	Agricultural	Ground Water	542703	4765118	682	180	336	379	591
6566-98UN74	Pond	Other - Agricultural	Agricultural	Ground Water	543468	4764990	1920	180	947	620	1920
6635-9XEM7J	Pond	Other - Agricultural	Agricultural	SW/GW	540448	4774656	1522	120	500	0	0
6642-95ZKEP	Dugout Pond	Tobacco	Agricultural	Ground Water	545130	4767164	2566	30	211	726	1254
6670-9GARTH	Pond #1	Field and Pasture Crops	Agricultural	Ground Water	554198	4767598	1817	60	299	39	1817
6670-9GARTH	Pond #2	Field and Pasture Crops	Agricultural	Ground Water	554255	4767715	1817	60	299	30	1817
66-P-0319	Pond 1	Other - Agricultural	Agricultural	Ground Water	549215	4768907	1399	0	0	0	0
66-P-0534	Dugout Pond	Tobacco	Agricultural	Ground Water	539556	4776318	1308	0	0	0	0
6726-62MQ4V	Dugout Pond	Tobacco	Agricultural	Ground Water	552135	4772527	2873	120	945	2	55
6728-9FMJXV	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	547119	4776127	3928	120	1291	0	0
6733-8WXQXF	Pond	Field and Pasture Crops	Agricultural	SW/GW	526076	4784164	5237	30	430	444	2500
6745-6GMQJB	Dugout Pond 1	Tobacco	Agricultural	Ground Water	545360	4761653	544	12	18	0	0
6745-6GMQJB	Dugout Pond 2	Tobacco	Agricultural	Ground Water	545352	4761498	544	12	18	0	0
6770-6LNRWP	Bedrock Well	Other - Industrial	Industrial	Ground Water	522183	4772178	60	365	60	11	102
6770-6LNRWP	Municipal Ditch A	Aggregate Washing	Industrial	SW/GW	522233	4771992	979	25	67	1	390
6770-6LNRWP	Municipal Ditch B	Aggregate Washing	Industrial	SW/GW	522233	4771992	59	290	46	2	39
6772-65CNKN	Pond	Field and Pasture Crops	Agricultural	Ground Water	544249	4761699	1146	180	565	0	0
6780-8J5NMD	Well 1 (6 well points)	Other - Agricultural	Agricultural	Ground Water	548360	4768685	1090	90	269	41	1909
6782-98DHDL	Pond 1 (Lot: 18, Conc: 1)	Other - Agricultural	Agricultural	Ground Water	535256	4779757	2318	20	127	40	2318
6782-98DHDL	Pond 2 (Lot: 17, Conc:1)	Other - Agricultural	Agricultural	Ground Water	535416	4779730	2318	20	127	12	1855
67-P-0146	Pond 1	Other - Agricultural	Agricultural	Ground Water	539384	4770090	1200	0	0	0	0

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67-P-0469	Ponds	Other - Agricultural	Agricultural	Ground Water	554299	4767531	1817	0	0	0	0
6834-6G6N5Q	Dugout Pond	Tobacco	Agricultural	Ground Water	545442	4767240	1527	30	126	0	0
6834-876RSV	Well 3	Other - Miscellaneous	Miscellaneous	Ground Water	519185	4775190	655	365	655	0	0
6881-6DCLKL	Dugout Pond	Tobacco	Agricultural	Ground Water	539150	4775110	1020	20	56	0	0
69-P-0199	Dugout pond	Other - Agricultural	Agricultural	Ground Water	540476	4772932	1364	0	0	0	0
69-P-0203	Dugout pond	Tobacco	Agricultural	Ground Water	545254	4775626	999	0	0	0	0
69-P-0374	Excavation Pit	Other - Agricultural	Agricultural	Ground Water	553183	4774740	3805	0	0	0	0
7013-9A5REL	Kegels Pond (#2)	Field and Pasture Crops	Agricultural	Ground Water	550525	4766730	674	12	22	0	0
7045-6BVJS4	Dugout	Other - Agricultural	Agricultural	Ground Water	548563	4766072	3516	5	48	0	0
7054-98EQAG	Pond	Tender Fruit	Agricultural	Ground Water	543463	4764551	1831	80	401	191	1343
7063-7YTHKC	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	553365	4766943	1908	104	544	112	1801
70-P-0394	Pond	Other - Agricultural	Agricultural	Ground Water	546239	4764570	3358	0	0	0	0
7104-9CLK8A	South Pond	Other - Agricultural	Agricultural	Ground Water	529304	4788559	2040	150	838	31	405
7104-9CLK8A	North Pond	Other - Agricultural	Agricultural	Ground Water	528999	4789790	1224	90	302	0	0
7107-9JXQEA	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	542020	4766961	296	10	8	0	0
7127-96VNNR	DeReus Pond	Field and Pasture Crops	Agricultural	Ground Water	536516	4759192	955	60	157	0	0
7143-9R6S9A	Palinkas Pond	Field and Pasture Crops	Agricultural	Ground Water	552837	4766795	1543	25	106	0	0
7188-9DSSBQ	Sandpoints	Other - Agricultural	Agricultural	Ground Water	551224	4773909	2589	50	355	0	0
7270-9QUN29	Dugout	Field and Pasture Crops	Agricultural	Ground Water	542032	4762882	491	125	168	0	0
7287-A57RWG	VanDeWalle 8th	Field and Pasture Crops	Agricultural	Ground Water	544892	4770554	1264	180	623	91	4150
7337-9BEKTG	Rob's Pond	Field and Pasture Crops	Agricultural	Ground Water	542407	4766228	690	30	57	0	0
7337-9BEKTG	Mom's Pond	Field and Pasture Crops	Agricultural	Ground Water	542809	4765644	690	30	57	0	0
7377-8JXJFS	Pond	Field and Pasture Crops	Agricultural	Ground Water	550740	4775473	2864	20	157	48	2500
73-P-0097	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	531006	4784951	1092	5	15	0	0
73-P-0546	Well MOE W.W.R. # 6503959	Communal	Water Supply	Ground Water	522504	4805921	131	200	72	3	21

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
7402-5TLS4Y	6 Sandpoints	Tobacco	Agricultural	Ground Water	551224	4773909	2589	12	85	0	0
7454-8WYLSF	Franken Pond	Field and Pasture Crops	Agricultural	Ground Water	542297	4776525	3764	153	1578	101	1964
7465-8W3J89	Well #1	Field and Pasture Crops	Agricultural	Ground Water	538067	4756177	1533	12	50	86	1632
7467-84BQEE	Well 4	Municipal	Water Supply	Ground Water	527587	4790760	327	365	327	6	126
7467-84BQEE	Well 4A	Municipal	Water Supply	Ground Water	527587	4790765	327	365	327	84	230
7467-84BQEE	Well 5	Municipal	Water Supply	Ground Water	527515	4790696	243	365	243	15	122
7506-5TXH8B	Dugout Pond #1	Tobacco	Agricultural	Ground Water	538709	4772821	3840	120	1262	0	0
7506-5TXH8B	Dugout Pond #2	Tobacco	Agricultural	Ground Water	538494	4776870	3840	120	1262	0	0
7546-8C6SS5	Thornton Well 1	Municipal	Water Supply	Ground Water	520436	4770139	9100	365	9100	517	5452
7546-8C6SS5	Thornton Well 3	Municipal	Water Supply	Ground Water	520346	4769939	2700	365	2700	146	1942
7546-8C6SS5	Thornton Well 5	Municipal	Water Supply	Ground Water	520443	4770104	5900	365	5900	285	5102
7546-8C6SS5	Thornton Well 8	Municipal	Water Supply	Ground Water	520161	4769565	3200	365	3200	1246	2705
7546-8C6SS5	Thornton Well 11	Municipal	Water Supply	Ground Water	519864.9 1	4769353	3900	365	3900	1905	3528
7546-8C6SS5	Tabor Well 2	Municipal	Water Supply	Ground Water	521208	4767905	10000	365	10000	4273	8640
7546-8C6SS5	Tabor Well 4	Municipal	Water Supply	Ground Water	521084	4767838	10000	365	10000	4831	9555
7546-8C6SS5	Southside Well 6	Municipal	Water Supply	Ground Water	520363	4774395	4500	365	4500	1046	3150
7546-8C6SS5	Sutherland Park Well 7	Municipal	Water Supply	Ground Water	521638	4777358	3900	365	3900	358	2121
7546-8C6SS5	Hart Springs Well 9	Municipal	Water Supply	Ground Water	520766	4772950	1300	365	1300	7	675
7546-8C6SS5	Bond Well 12	Municipal	Water Supply	Ground Water	519659	4767518	3275	365	3275	0	0
7607-63RPKH	Pond	Field and Pasture Crops	Agricultural	Ground Water	546614	4769558	5237	210	3013	78	4368
7607-63RPKH	Well	Field and Pasture Crops	Agricultural	Ground Water	546278	4769498	262	210	151	0	0
7622-9ZGJC2	Pond	Field and Pasture Crops	Agricultural	Ground Water	540458	4767700	795	21	46	1	253
7680-64CJKY	Pond	Sod Farm	Agricultural	Ground Water	533461	4778832	3475	180	1714	671	9926
7680-64CJKY	Well #1	Sod Farm	Agricultural	Ground Water	533395	4778824	1310	180	646	314	1094
7680-64CJKY	Well #2	Sod Farm	Agricultural	Ground Water	533420	4778827	1310	180	646	158	1094

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
7684-9C6QCQ	Pond	Tobacco	Agricultural	Ground Water	539886	4769228	1909	30	157	0	0
7687-7HPPAA	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	550577	4767039	1417	40	155	0	750
7743-8JRPWC	Drilled well (#195698)	Tobacco	Agricultural	Ground Water	557289	4770613	123	50	17	0	0
7743-8JRPWC	Dugout pond	Tobacco	Agricultural	Ground Water	557289	4770613	1800	50	247	10	1800
7784-6H4NAH	Dugout Pond	Tobacco	Agricultural	Ground Water	539639	4769207	1220	90	301	1	850
7788-9EAMFN	Pond	Tobacco	Agricultural	Ground Water	552686	4770497	1637	40	179	15	409
77-P-2000	Pond	Other - Agricultural	Agricultural	Ground Water	545446	4771840	982	0	0	0	0
7820-9QSRRZ	Dugout Pond	Tobacco	Agricultural	Ground Water	551846	4772542	2873	120	945	0	0
7830-8JXLSW	Pond	Field and Pasture Crops	Agricultural	Ground Water	539344	4769934	3494	90	862	480	3494
7847-62ENT9	Pond	Field and Pasture Crops	Agricultural	Ground Water	545894	4770754	3273	180	1614	103	3276
7856-698QJY	Well #1	Cooling Water	Industrial	Ground Water	543171	4765079	1310	365	1310	895	26938
7856-698QJY	Well #2	Cooling Water	Industrial	Ground Water	543780	4765030	1310	365	1310	1451	34182
79-P-2024	Pond	Other - Agricultural	Agricultural	Ground Water	538545	4777869	916	0	0	0	0
79-P-2046	Well	Other - Industrial	Industrial	Ground Water	558098	4775775	393	0	0	0	0
79-P-2062	Pond	Other - Agricultural	Agricultural	Ground Water	546486	4765770	1473	0	0	0	0
8025-82TRZT	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	537332	4775409	952	24	63	8	834
8110-9R7P7Q	Pond	Field and Pasture Crops	Agricultural	Ground Water	545368	4768038	1700	210	978	0	0
8120-7VBQVQ	old	Field and Pasture Crops	Agricultural	Ground Water	534524	4780464	3273	50	448	15	1718
8120-7VBQVQ	new	Field and Pasture Crops	Agricultural	Ground Water	534287	4781034	3273	50	448	2	1527
8125-7F9QM7	Plant Pond	Aggregate Washing	Industrial	SW/GW	548250	4780875	24600	365	24600	2693	7658
8142-642JS2	Pond	Field and Pasture Crops	Agricultural	Ground Water	536591	4776571	3090	180	1524	0	0
8153-734RB2	Irrigation Well	Golf Course Irrigation	Commercial	Ground Water	525383	4784710	1571	185	796	151	13016
8153-734RB2	Clubhouse Well	Communal	Water Supply	Ground Water	525383	4784710	14	200	7	0	0
8153-734RB2	OW3 (Snack Bar)	Golf Course Irrigation	Commercial	Ground Water	525383	4784710	4	180	2	0	0

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
8153-734RB2	OW4 (Maintenance)	Golf Course Irrigation	Commercial	Ground Water	525383	4784710	2	200	1	0	0
8188-642PGD	Pond	Tobacco	Agricultural	SW/GW	524465	4777972	3000	60	493	0	0
8221-85JK95	Pond	Field and Pasture Crops	Agricultural	Ground Water	551881	4770490	1750	64	307	0	0
8227-5TXHSJ	Dugout Pond	Tobacco	Agricultural	Ground Water	545988	4768403	3014	120	991	0	0
8242-8KDKUR	Pond 1	Tobacco	Agricultural	Ground Water	539911	4775827	1950	30	160	137	1850
8242-8KDKUR	Pond 2	Tobacco	Agricultural	Ground Water	540092	4775484	1950	30	160	210	1850
8242-8KDKUR	Pond 3	Tobacco	Agricultural	Ground Water	540568	4775908	1950	30	160	216	1850
8242-8KDKUR	Pond 4	Tobacco	Agricultural	Ground Water	540510	4775321	1950	30	160	192	1850
8242-8KDKUR	Pond 5	Tobacco	Agricultural	Ground Water	540365	4775223	1950	30	160	178	1850
8314-65JLCU	Dugout Pond	Tender Fruit	Agricultural	Ground Water	537586	4772671	128	120	42	0	0
8316-9SWQPR	Irrigation Pond	Field and Pasture Crops	Agricultural	Ground Water	510394	4795599	150	30	12	0	0
8323-9A6LQ5	Kegels Pond (#3)	Field and Pasture Crops	Agricultural	Ground Water	552539	4766697	674	12	22	0	0
8330-87CLDW	North Pond	Field and Pasture Crops	Agricultural	Ground Water	551323	4770672	2728	64	478	14	273
8340-8L2KYR	Pond	Field and Pasture Crops	Agricultural	Ground Water	547827	4773453	952	24	63	4	467
8431-9Y7PD4	Chwastyk Pond	Field and Pasture Crops	Agricultural	Ground Water	547250	4768700	840	20	46	0	0
8468-9D8M25	Dugout Pond	Other - Agricultural	Agricultural	Ground Water	536951	4758216	1392	30	114	0	0
8503-994LJ5	Well	Field and Pasture Crops	Agricultural	Ground Water	548612	4767610	3273	21	188	0	0
8544-8JPQFK	Pond	Other - Agricultural	Agricultural	Ground Water	542881	4763933	2537	30	209	93	1438
8545-A48Q8C	P52 (TW 1/05) [A026040]	Municipal	Water Supply	Ground Water	550781.63	4777851.5	1296	365	1296	57	744
8545-A48Q8C	P51 (PW 1/12) [A002048]	Municipal	Water Supply	Ground Water	550768	4777831	1310	365	1310	17	1077
8545-A48Q8C	P53 (PW 2/12) [A002049]	Municipal	Water Supply	Ground Water	550782	4777834	1310	365	1310	17	473
8545-A48Q8C	P54 (PW 4/12) [A002052]	Municipal	Water Supply	Ground Water	550746	4777821	1310	365	1310	47	371
8556-8M5QAL	NH3 - 6507832	Municipal	Water Supply	Ground Water	523184	4801566	3543	365	3543	1557	2957
8565-95RL8P	Pond	Other - Agricultural	Agricultural	Ground Water	546798	4770069	5042	90	1243	78	1890
8587-8GPKDT	Wilson Farm Well	Tobacco	Agricultural	Ground Water	547250	4770150	5040	24	331	154	4800

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m³/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m³/d)	Mean Reported Daily Demand (m³/d)	Maximum Reported Daily Demand (m³/d)
8617-9NCQSM	Pond	Field and Pasture Crops	Agricultural	Ground Water	543410	4777971	4582	180	2260	131	3682
8618-8JJNN9	Pond 1	Other - Agricultural	Agricultural	Ground Water	541233	4775178	2043	150	840	145	2043
8618-8JJNN9	Pond 2	Other - Agricultural	Agricultural	Ground Water	541106	4774871	2043	150	840	45	1321
8643-9ZZQER	Pond	Tobacco	Agricultural	SW/GW	541054	4770810	1780	15	73	0	0
8655-6BGSP6	Pond	Tobacco	Agricultural	SW/GW	537904	4776109	1999	35	192	0	0
8663-8JVH68	Dugout Pond	Field and Pasture Crops	Agricultural	Ground Water	543515	4781354	2073	14	80	10	2300
8706-96VMS6	215 Fairfield pond	Other - Agricultural	Agricultural	Ground Water	543705	4765753	2000	150	822	19	400
8727-6G6R7D	Five sand points	Field and Pasture Crops	Agricultural	Ground Water	543834	4764909	360	120	118	1	350
8770-82HQU7	Dugout pond	Field and Pasture Crops	Agricultural	Ground Water	550184	4774187	2619	100	718	103	2316
8770-A4THMH	Dugout Pond	Tobacco	Agricultural	Ground Water	545952	4761637	1855	60	305	19	1208
8778-9DULDR	Pond	Field and Pasture Crops	Agricultural	Ground Water	545967	4767442	1642	90	405	0	0
87-P-2002	Dugout pond	Aggregate Washing	Industrial	Ground Water	549618	4767052	1640	0	0	187	1309
8840-95XR8S	Pond	Field and Pasture Crops	Agricultural	Ground Water	545097	4759632	1440	100	395	1421	1440
88-P-1036	well #1	Municipal	Water Supply	Ground Water	524500	4783800	196	365	196	0	0
88-P-1036	well #2	Municipal	Water Supply	Ground Water	524500	4783800	196	365	196	0	0
88-P-2077	Wells(PW1, PW2, PW3, PW4, PW5)	Other - Agricultural	Agricultural	Ground Water	546832	4770289	3272	0	0	0	0
90-P-1092	W-1	Municipal	Water Supply	Ground Water	524644	4783649	392	365	392	0	0
93-P-2049	Pond	Field and Pasture Crops	Agricultural	Ground Water	541646	4775323	1364	30	112	0	0
99-P-1039	Sand Points	Tobacco	Agricultural	Ground Water	535594	4758026	982	45	121	0	0
99-P-1062	Well 1	Municipal	Water Supply	Ground Water	518803	4768627	1091	365	1091	0	0
99-P-1062	Well 2	Municipal	Water Supply	Ground Water	518718	4768611	1305	365	1305	0	0
99-P-1089	Dugout pond	Other - Agricultural	Agricultural	Ground Water	535940	4790641	873	3	7	0	0
99-P-1097	Dugout pond	Tobacco	Agricultural	Ground Water	529736	4786634	1364	10	37	0	0
99-P-1239	Pond	Aggregate Washing	Industrial	Ground Water	538732	4794629	4910	180	2422	378	6828
99-P-2093	Well (4)	Other - Agricultural	Agricultural	Ground Water	539187	4757378	5995	40	657	0	0

MOE Permit Number	Source	Purpose	Specific Use	Source Classification	Easting (m)	Northing (m)	Maximum Daily Permitted Taking (m^3/d)	Number of Permitted Days per Year	Mean Annual Permitted Taking (m^3/d)	Mean Reported Daily Demand (m^3/d)	Maximum Reported Daily Demand (m^3/d)
99-P-2124	Dugout (1)	Other - Agricultural	Agricultural	Ground Water	547459	4766760	491	0	0	0	0
99-P-2124	Well Points (5)	Other - Agricultural	Agricultural	Ground Water	547854	4766867	1432	0	0	0	0
99-P-2127	Dugouts	Other - Agricultural	Agricultural	Ground Water	540621	4771906	2128	0	0	0	0
99-P-2133	Dugout (1)	Other - Agricultural	Agricultural	Ground Water	549268	4768919	965	0	0	0	0
99-P-2134	Dugout (1)	Other - Agricultural	Agricultural	Ground Water	547850	4766572	3928	0	0	0	0
99-P-2139	Dugout	Tobacco	Agricultural	Ground Water	552840	4774269	1091	0	0	0	0
99-P-2141	Dugout (1)	Other - Agricultural	Agricultural	Ground Water	544599	4765065	2291	0	0	0	0
99-P-2142	Well	Tobacco	Agricultural	Ground Water	549631	4773202	546	0	0	0	0
99-P-2150	Dugout	Other - Agricultural	Agricultural	Ground Water	548968	4768220	1448	0	0	0	0
99-P-2153	dugout	Other - Agricultural	Agricultural	Ground Water	543711	4762468	2455	0	0	0	0
99-P-2153	Dugout	Other - Agricultural	Agricultural	Ground Water	544151	4762848	2455	0	0	0	0
99-P-2154	Dugout	Other - Agricultural	Agricultural	Ground Water	546934	4769407	965	0	0	0	0
99-P-2154	Well	Other - Agricultural	Agricultural	Ground Water	547033	4769638	2	0	0	0	0

Appendix C Irrigation Demand Submodule Data Input Instructions

The Irrigation Demand module follows the standard MODFLOW input rules. The Irrigation Demand module input data area read from a file that has type "IRR" specified in the NAME File. Optional variables are shown in square brackets. All variables are free format if the option “FREE” is specified in the Basic Package input file; otherwise, the non-optional variables have 10-character fields and the optional variables are free format.

FOR EACH SIMULATION

```
0. [#Text]
```

Item 0 is optional—“#” must be in column 1. Item 0 can be repeated multiple times.

```
1. MXSOURCE, MXCROP, MXFARM, MXPARCEL, MXPARCELFARM, MXPARCELHRU,
   MXSOURCEFARM, IRROUT
```

FOR EACH STRESS PERIOD

```
2. ITMP, [NCROP, NFARM, NPARCEL, IPRN]

3. CROP_ID, CROP_IRRIG_TYPE, CROP_IRRIG_STARTMON, CROP_IRRIG_ENDMON,
   CROP_TRIGGER CROP_EFFICIENCY, CROP_MONTHLYRATE, [CROP_NAME]

4. FARM_ID, FARM_NUMPARCELS, FARM_NUMSOURCES, FARM_OPTSELECT,
   FARM_MAXAREA

5. PARCEL_ID, PARCEL_FARMID, PARCEL_CROPID, PARCEL_MAXDAYON,
   PARCEL_MINDAYBTWN

6. SOURCE_ID, SOURCE_TYPE, SOURCE_FARMID, SOURCE_MAXTAKING,
   [SOURCE_NAME]
```

C.1 Explanation of Variables Read by the Irrigation Demand Module

Text—is a character variable (199 characters) that starts in column 2. Any characters can be included in Text. The “#” character must be in column 1. Lines beginning with # are restricted to the first lines of the file. Text is written to the Listing File.

MXSOURCE—is the maximum number of irrigation sources in use during any stress period.

MXCROP—is the maximum number of crop types in use during any stress period.

MXFARM—is the maximum number of farms in use during any stress period.

MXPARCEL—is the maximum number of parcels in use during any stress period.

MXPARCELFARM—is the maximum number of parcels associated with a farm.

MXSOURCEFARM—is the maximum number of sources associated with a farm.

MXPARCELFARM—is the maximum number of PRMS cells (HRUs) associated with any parcel. This may be hard to know in advance as it is based on parcel and HRU size. A reasonable overestimation of this number should not cause memory exceedance problems.

IRROUT—is a unit number. Irrigation event data will be written to an external file. The file name must be specified in the NAME file. Cell-by-cell budgets for the sources are done within the MODFLOW WEL and SFR2 routines

ITMP—is a flag and a counter. If ITMP < 0, irrigation data from the last stress period will be reused. If ITMP > 0, then ITMP is equal to NSOURCE, the number of sources active for the stress period. Other variables, NCROP, NFARM, NPARCEL, IPRN must also be read.

NCROP—is the number of crop types in use during this stress period.

NFARM—is the number of farms in use during this stress period.

NPARCEL—is the number of parcels in use during this stress period.

IPRN—is a flag to control printing of the input data. If IPRN < 0, printing will be supressed.

MXSOURCEFARM—is the maximum number of sources associated with a farm.

MXPARCELFARM—is the maximum number of PRMS cells (HRUs) associated with any parcel. This may be hard to know in advance as it is based on parcel and HRU size. A reasonable over-estimation of this number should not cause memory exceedance problems.

CROP_ID -- unique identification number for the crop type. This number is used to link to the parcel crop identifier.

CROP_IRRIG_TYPE – an integer flag signifying whether the applied irrigation water is subject to interception by the plant canopy. If CROP_IRRIG_TYPE = 1, the applied water is subject to interception; if CROP_IRRIG_TYPE = 2, it is not subject to interception.

CROP_IRRIG_STARTMON – integer value identifying the first month for which irrigation demand is calculated for this crop type.

CROP_IRRIG_ENDMON – integer value identifying the last month in which irrigation demand is calculated for this crop type.

CROP_TRIGGER –trigger value (0.0 to 1.0) for the moisture deficit, as defined by Eq. 3. Value is compared against the moisture content, averaged over each parcel, to determine whether irrigation is needed.

CROP_EFFICIENCY – value (0.0 to 1.0) for the delivery efficiency for the crop irrigation method. If CROP_EFFICIENCY < 1, water is lost to evaporation or wind drift and does not reach the crop.

CROP_MONTHLYRATE – monthly value for the irrigation depth. Twelve values are read. Values must be in consistent MODFLOW length units.

CROP_NAME – an optional identifier not used in the calculations.

FARM_ID -- unique identification number for this farm. This number is used to link to the parcel and source identifiers.

FARM_NUMPARCELS – number of parcels associated with this farm.

FARM_NUMSOURCES – number of sources associated with this farm.

FARM_OPTSELECT – an integer flag to identify the method for selecting the "driest" parcel on the farm for irrigation. If FARM_OPTSELECT = 1, the parcel with the highest moisture deficit (Eq. 3) is selected; if FARM_OPTSELECT = 2, he parcel with the highest relative moisture deficit (Eq. 4) is selected.

FARM_MAXAREA – maximum area that can be irrigated in a day based on farm equipment. Value must be in in consistent MODFLOW length units.

PARCEL_ID -- unique identification number for the parcel

PARCEL_FARMID – identification number for the farm associated with this parcel

PARCEL_CROPID – identification number for the crop associated with this parcel

PARCEL_MAXDAYON -- maximum number of consecutive days that irrigation may occur for a HRU within this parcel. (The value should be set in conjunction with PARCEL_MINDAYBTWN, as discussed below)

PARCEL_MINDAYBTWN—minimum number of days that must pass before an HRU within this parcel can be irrigated again. The value should be adjusted based on parcel size and irrigation capacity (FARM_MAXAREA) to force cycling between all the HRUS. A high value will limit the number of irrigation event occurring on the parcel. If PARCEL_MINDAYBTWN = 0, cycling can be forced using PARCEL_MAXDAYON to prevent the same HRUs to be irrigated for too many consecutive days.

SOURCE_ID -- unique identification number for the source. For wells, this number is used to link to a well ID in the MODFLOW WEL module. For surface water diversions, this number is used to link to a segment number in the MODFLOW SFR2 module.

SOURCE_TYPE – an integer value indicating source type. If SOURCE_TYPE = 1; source is a standard MODFLOW well; if SOURCE_TYPE = 2, source is a SFR2 diversion.

SOURCE_FARMID – identification number for the farm associated with this taking.

SOURCE_MAXTAKING — is the maximum taking for the source per day. This can represent a permit limit or a pump capacity limit

SOURCE_NAME – an optional identifier not used in the calculations.

Note: There are no data input changes to the SFR2 module except to add the information for the surface water diversions as per the SFR2 documentation (Niswonger and Prudic, 2005). Note that diversion Type 2 (a fixed percent of flow is diverted) is not currently supported. Takings specified in the SFR2 input are ignored and replaced by values computed by the Irrigation Demand module.

Some minor input data changes are needed for the standard MODFLOW well package. For data set 2 (shown below), the optional variable [option] should be replaced “AUX WELLID”, which defines an auxiliary variable, named WELLID. WELLID will be read as an integer variable for each well replacing the optional variable [xyz] after the pumping rate in data sets 4 and 6. A value of 0 should be used for non-irrigation wells. Takings specified in the WEL input for irrigation wells are ignored and replaced by values computed by the Irrigation Demand module.

```
2. MXACTW IWELCB [Option]
```

```
6. Layer Row Column Q [xyz]
```

As noted, the NAME file should have a reference to the input file for the Irrigation Demand module and a unit number for the irrigation event output, as highlighted in the example below.

```
# Whitemans Creek Tier 3 Water Budget and Risk Assessment Study - Earthfx 2016
LIST  7 WT3_2016.lst
BAS6  8 CORE\WT3.ba6
DIS   9 CORE\WT3.dis
UPW  11 CORE\WT3.upw
WEL  12 CORE\WT3.wel
IRR  21 CORE\WT3.irr
SFR  13 CORE\WT3.sfr
LAK  14 CORE\WT3.lak
UZF  19 CORE\WT3.uzf
OC   22 CORE\WT3.oc
NWT  23 CORE\WT3.nwt
DATA 90 OUTPUT\WT3.irrout
DATA(BINARY) 49 OUTPUT\WT3.flx UNFORMATTED
DATA(BINARY) 50 OUTPUT\WT3.hbn UNFORMATTED
DATA(BINARY) 70 OUTPUT\WT3.ddn UNFORMATTED
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Appendix D Additional Irrigation Rates by Crop Type

Table D.1: Irrigation estimates from Ecologistics Ltd. (1993) for vegetable crops.

Crop Type	Number of Applications per year	Volume Applied (mm per application)	Main Harvest Season (weeks)
Sweet Corn	3	30	10
Tomatoes	3	30	8
Cucumbers and Gherkins	5	30	6
Green Peas	5	30	8
Green or Wax Beans	5	30	8
Cabbage	7	30	10
Cantaloupes	1.5	30	4
Potatoes	9	30	6
Chinese Cabbage	7	30	10
Cauliflower	7	30	8
Broccoli	7	30	16
Brussel Sprouts	7	30	6
Carrots	5	30	6
Rutabagas	5	30	6
Beets	5	30	6
Radishes	7	30	16
Dry Onions	7	30	4
Green Onions and Shallots	7	30	22
Celery	7	30	6
Lettuce	7	30	6
Spinach	7	30	9
Peppers	5	30	8
Squash Zucchini and Pumpkins	5	30	10
Asparagus	3	30	6
Rhubarb	3	30	4
Other Vegetables	5	30	12

Table D.2: Irrigation estimates from Ecologistics Ltd. (1993) for fruit crops.

Crop Type	Number of Applications per year	Volume Applied (mm/application)
Tree Fruit (Apples, Pears, Cherries, Peaches, Apricots)	4	35
Berries (Strawberries, Raspberries Blueberries)	8	28
Strawberries (Nursery)	8	38

Table D.3: Irrigation estimates from Ecologistics Ltd. (1993) for field crops.

Crop Type	Number of Applications per year	Volume Applied (mm/application)
Winter Wheat	-	-
Spring Wheat	-	-
Oats	-	-
Barley	-	-
Mixed Grains	-	-
Corn	-	-
Rye	-	-
Hay	-	-
Forage seed	-	-
Canola	-	-
Soybeans	-	-
Dry Field Beans	-	-
Tobacco	2.5	30
Other	2	25

Table D.4: Irrigation estimates from Ecologistics Ltd. (1993) for specialty crops.

Crop Type		Number of Applications per year	Volume Applied (mm per application)
Nursery Products	New Stock	3	25
	Containers	100	25
Sod	Normal	21	25
	Additional Before Harvesting	2	25
Greenhouse	Flower		1060 mm/yr
	Flower Pots	250	18
	Flower Greenhouse	275	4.3
	Tomatoes	275	5
	Cucumbers	200	4
	Lettuce	275	4.3
	Vegetable Transplants	120	1.5
	Other Greenhouse Products	200	4
Other	Ginseng	0.75	25

Appendix E Drought Analysis

Additional analyses were carried out related to drought in the Whitemans Creek subwatershed. Because these are not related directly to the Tier 3 Risk Assessment, these discussions have been extracted from the original drafts of the Model Calibration report and consolidated in this Appendix.

13.1.1 Precipitation Drought Response

The relationship between low-water events and annual precipitation was investigated. Annual (calendar year) basin-averaged average precipitation is presented along with the number of low-water events per year in Figure 13.3. The number of low-water events per year was derived from a 7-day moving average streamflow series, with Level 1 and 2 occurring when flows drop below 1.1 m^3/s and 0.81 m^3/s, respectively. Level 3 events occur when stream flows drop below 0.5 m^3/s, which represents a target threshold where permanent ecological damage is possible (e.g., loss of viable habitat eliminates a significant percentage of young-of-the-year trout). Figure 13.4a shows a clear relationship between years with low precipitation and the number of days with streamflow in Whitemans Creek below the prescribed ecological minimums. Low-water events increase linearly with decreases in annual precipitation below 950 mm/yr. This suggests a direct link between precipitation droughts and ecological impairment. Level 2 and Level 3 events (which denote conditions where ecological impairment is likely) are compared with precipitation on Figure 13.4b, these events are almost certain to occur in years when annual precipitation is below 900 mm/yr.

13.2 *Drought Impacts on Groundwater Level and Storage*

The history of droughts within the Whitemans Creek subwatershed can be seen in the streamflow and precipitation records going back to 1962 and 1866, respectively (Section 4). Comparable hydrogeologic datasets include the MOECC PGMN water levels discussed above. These datasets provide an important source of information regarding the long-term trends in streamflow and groundwater levels and their respective response to drought conditions.

Depending on the duration and severity of a meteorological drought (i.e., lack of rainfall), the subsequent reduction in recharge may impact groundwater levels and streamflow. The relationship between meteorological and hydrological drought is controlled by climate and catchment characteristics (Van Loon, 2015). Figure 13.1 illustrates how a meteorological drought propagates through surface water and groundwater systems, impacting flows/fluxes. Characteristics of this relationship include: pooling, lag, attenuation, and lengthening. Pooling is cumulative effect of a combination of meteorological drought factors that contribute to the severity of the ensuing hydrologic drought such as: the magnitude of rainfall deficit, evapotranspiration rates, and the number of consecutive years over which the meteorological drought conditions prevail. The lag is related to the temporal delay in the response of the hydrologic system to meteorological drought which depends strongly on characteristics times associated with surface and subsurface flow paths. Attenuation is related to the amount of storage within the hydrologic/hydrogeologic system. In general, the response of groundwater systems to drought, as shown in in Figure 13.1, is more attenuated than that of surface water systems because they typically have larger volumes of storage available. Finally, lengthening refers to the different duration of the effects of drought between surface water and groundwater systems; lengthening is controlled both by climate and catchment characteristics.

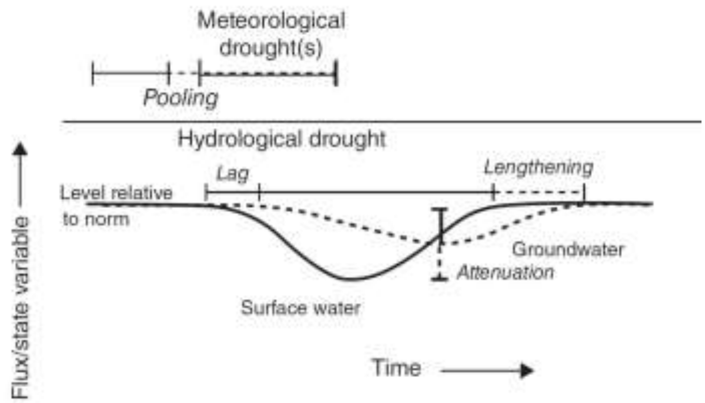

Figure 13.1: Propagation of meteorological drought to hydrological and hydrogeological drought (from Hisdal and Tallaksen, 2000).

The propagation of meteorological drought through to hydrological drought is illustrated in Figure 13.2 by precipitation, streamflow, and groundwater time series from monitoring stations in the Whitemans Creek subwatershed. The period of 2006 to 2014 was chosen as it is representative of a full range in meteorological and hydrological conditions showing the response to wet, dry and average years. Raw time series presented in Figure 13.2a show that periods of low precipitation in 2007 and 2012 correspond to reductions in streamflow and groundwater levels, with some degree of associated lag. These periods are consistent with the anomalies shown in Figure 13.2b. Anomalies are calculated as a percent difference relative to the long-term monthly mean values. The datasets have been normalized in order to be compared at a similar scale and then smoothed by applying a 3 month moving average. The temporal behaviour is consistent with the drought theory discussed above wherein the meteorological drought first propagates through the surface water system, followed by the groundwater system. Further, the effects of attenuation are manifest in the slightly smaller relative reduction in groundwater levels compared to streamflow. It should be noted that 2007 and 2012 each represent single-year meteorological drought events, after which streamflow and groundwater levels were able to recover. These data do not show the exacerbated impact of a multi-year drought. In addition, not all anomalies observed in Figure 13.2b can be explained by precipitation. For instance, additional factors such as snowfall accumulation, freshet timing and intensity, evapotranspiration and antecedent soil moisture conditions may also be controlling the timing and magnitude of the streamflow and groundwater anomalies.

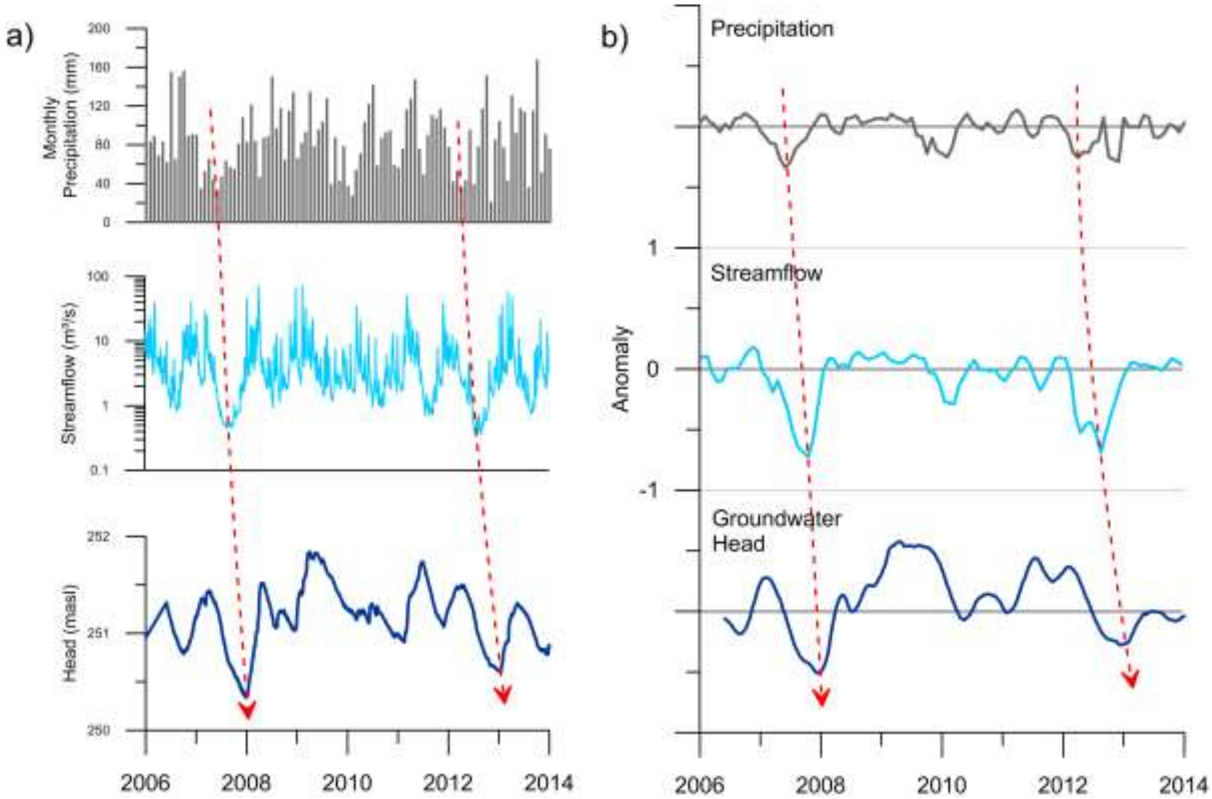

Figure 13.2: Propagation of precipitation anomalies through the surface water and groundwater systems; a) observed basin averaged monthly precipitation, streamflow observed at Whitemans Creek near Mount Vernon (02B008), and groundwater levels in the Norfolk Sand Plains (PGMN well W0000065-4); and, b) observed monthly anomalies.

Figure 13.5 presents a set of graphs comparing precipitation - annualized by water year - with the groundwater levels at the end of the corresponding water year (i.e., September 30th) for PGMN monitoring wells across the study area. The data show that regardless of geologic unit, the lowest water levels tend to correspond with years of low rainfall while the highest water levels tend to correspond with years of high rainfall. Within the Whitemans Creek subwatershed, the Sand Plain/Outwash Aquifer is the most heavily pumped (See Section 6.2.7). This pumping occurs primarily within the southern/southeastern portion of the model area where agricultural water demand is high. The end-of-year water level variation in this aquifer unit was approximately 0.75 - 1 m and was reasonably correlated to precipitation as seen in both PGMN wells W0000015-1 and W0000065-4 (Figure 13.5a and Figure 13.5b). Similar behaviour was also observed in the Maryhill Till Aquitard (W0000477-1, Figure 13.5c), albeit with a weaker correlation, despite not being a unit that has any reported pumping. Nevertheless, given its location in the southeastern region of the Whitemans Creek subwatershed, this behaviour is not surprising.

The Waterloo Moraine Aquifer is also an important aquifer for agricultural water use; however, the two PGMN wells screened in this aquifer show different behaviour relative to one another (Figure 13.5d and Figure 13.5f). For instance, W0000478-1, located in the central part of the subwatershed, is strongly correlated to precipitation and experienced a range in end-of-year water levels of approximately 0.8 m. Conversely, W0000218-3, located in the north, shows only a minor correlation to precipitation and experienced relatively small changes in water level of 0.5 m. This difference in behaviour may be explained by the higher density of agricultural water users in the central portion of the watershed as compared to the north. Water level fluctuations at W0000218-3 may have also been mitigated by recharge from the nearby Shakespeare pond. The same can be said for a deeper monitor at the same location, W0000218-4, which is screened in a confined or semi-confined portion of the Post-Catfish Aquifer. Water levels at this monitor were slightly higher than at W0000218-3; however it was also poorly correlated with precipitation and had a similar range in end-of year water levels.

In the Whitemans Creek subwatershed, the bedrock groundwater systems are not relied upon as heavily for water supply as the overburden aquifers discussed above. Time series water level fluctuations discussed in Section 5.3.4 indicate that bedrock monitor W0000016-3, completed in the Bois Blanc Formation, is in good connection to the surface and it experienced end-of-year water levels similar to those of the nearby shallow monitor W0000015-1. Here, end-of-year water levels varied over approximately 1.25 m and were relatively well correlated with precipitation. The bedrock monitor W0000218-5, located at the north end of the subwatershed, is also completed in the Bois Blanc Formation; however, water levels varied by only 0.5 m and were not well correlated to precipitation. This may be related to proximity of the wells to high density agricultural water use; however, it may also reflect a difference in storage available in these aquifer units.

It should be noted that the bedrock monitor W0000180-1 (Figure 13.5e) is likely within the zone of influence of the nearby Innerkip municipal drinking water system which pumps from the same bedrock aquifer units about 300 m to the northeast. The variability introduced by the pumping tends to dominate over any seasonal fluctuations (See Figure 5.47) making it difficult to determine how the bedrock aquifer system in this area is influenced by wet and dry years.

Figure 13.5 illustrates that, in general, wet years result in high groundwater levels and dry years result in low groundwater levels. While this is expected, the data show that some aquifer systems, especially those more heavily relied upon for agricultural supply, are more sensitive to drought than others. This is evidenced by larger variations in the end-of-year water levels and a stronger correlation to precipitation (e.g., W0000015-1, W0000016-3, W0000065-4, and W0000478-1). Although this is insightful, it does not address the importance of aquifer storage for enhancing drought resiliency. To further investigate the dependency of groundwater levels on precipitation and the importance of storage, cross-correlation analysis was performed to determine the correlation and time-lag between the two hydrologic variables. Using the time lag, inferences may be made about the storage characteristics of a particular aquifer. For example, water levels in an aquifer with more available storage will be slower to respond and experience a smaller magnitude change in response to decreases in precipitation compared to an aquifer with less available storage.

The correlation analysis was performed using time series of daily interpolated precipitation and water levels in PGMN wells W0000065-4 and W0000218. These locations were selected because they offered the most complete water level records of the PGMN wells within the study area. W0000065-4 is located in the southeastern region of the subwatershed in the unconfined Sand Plain/Outwash aquifer where there is a high density of agricultural water users. W0000218 is located in the north end of the subwatershed with no known influence from irrigation, and is screened across the Waterloo Moraine aquifer (W0000218-3), the Post-Catfish Aquifer (W0000218-4) and the Bois Blanc Formation bedrock aquifer (W0000218-5).

The cross-correlation approach has been used in previous studies to identify the impact of climate variables (i.e., precipitation and temperature) on groundwater levels in Canada (e.g., Chen *et al.,* 2002, 2004). The cross-correlation functions are defined as follows (from Chen *et al.,* 2002):

$$C_{xy}(k) = \frac{1}{n}\sum_{t=1}^{n-k}(x_t - \bar{x})(y_{t+k} - \bar{y}) \qquad (1)$$

$$r_{xy} = \frac{C_{xy}(k)}{\sigma_x \sigma_y} \qquad (2)$$

Where C_{xy} is the cross-correlogram, x and y are the datasets being compared, k is the applied lag, r_{xy} is the correlation coefficient and σ_x and σ_y are the standard deviations of each time series. Time series of precipitation and water levels were pre-processed by applying a three-month moving average to each dataset. This was done to reduce high-frequency fluctuations in the data, while preserving longer-term seasonal trends. Although individual precipitation events may impact water levels on the short time-scale, the longer term fluctuations are of more interest in the analysis of drought response. The datasets were then normalized to facilitate comparison.

Figure 13.6 and Figure 13.7 compare the normalized precipitation and groundwater levels from 2003 to 2015 for W0000065-4 and W0000218, respectively. The time series show similar trends; however, the groundwater levels are generally lagged behind precipitation. Cross-correlation analysis, shown in Figure 13.8 and summarized in Table 13.1, presents the lag time applied to the precipitation time series to achieve a maximum correlation between the two datasets. Overall, the correlation at each monitor for the entire 13-year time series was weak, suggesting that groundwater levels are controlled by many factors and that the specific role of precipitation may be variable. While groundwater recharge is known to be a function of precipitation, other factors such as storage, temperature, ET, runoff and agricultural water use also play a role in influencing water levels.

Table 13.1: Summary of cross correlation analysis between precipitation and water levels at select PGMN wells.

Well No.	Location within Whitemans Creek	Geologic Unit	Lag Time (days)	Correlation Coefficient
W0000065-4	Southeastern (Sand Plain)	Sand Plain/Outwash Aquifer	200	0.43
W0000218-3	North (Till Uplands)	Waterloo Moraine Aquifer	185	0.28
W0000218-4	North (Till Uplands)	Post Catfish Aquifer	208	0.35
W0000218-5	North (Till Uplands)	Bois Blanc Formation Aquifer	209	0.33

Closer inspection of Figure 13.6 and Figure 13.7 indicates that certain individual climate periods may be better correlated with water levels than others, particularly the drought years of WY2007 and WY2012. To explore this further, the same correlation analysis was performed on a yearly basis. Figure 13.9 and Figure 13.10 shows the correlation between precipitation and water levels at W0000065-4 and W0000218, respectively, during WY2007 and WY2012.

Strong correlations were observed at W0000218 across all screened intervals for 2007 and 2012, as shown in Figure 13.9 and summarized in Table 13.2. This indicates that the low water levels are strongly related to the lack of precipitation during these particular years. The shallowest monitor, W0000218-3, is characterized by unconfined conditions resulting in a relatively short lag-time in response to both 2007 and 2012 precipitation in addition to the largest change in water level (up to 2 m, see Section 5.3.4). The short lag time suggests that this shallow aquifer system is connected to local recharge and drainage features such as Shakespeare Pond, located immediately north of the well ,and the Avon River to the south. In addition, the large change in water level and short time lag (i.e., rapid response to precipitation) are indicative of an aquifer system with limited storage and a potentially high sensitivity to drought.

The increased lag and dampened head fluctuations (1 m to 1.25 m, see Section 5.3.4), observed in W0000218-4 and W0000218-5 relative to W0000218-3 in both 2007 and 2012, is indicative of their semi-confined condition and their connection to larger, more regional recharge/storage features, such as the Easthope Moraine located directly to the north. This type of behavior suggests that the deeper groundwater systems in this area are less vulnerable to drought in comparison to the shallow system discussed above. It should be noted that there was a difference in the drought response in the two deeper monitors for 2007 and 2012. This is attributed to the difference in drought conditions where 2007 was characterized by a relatively normal freshet followed by a very dry summer, whereas 2012 was characterized by minimal freshet followed by a slightly wetter, yet relatively dry summer. The 2007 freshet supplied recharge to the deeper aquifer units with very little recharge coming from precipitation through the summer. The increased lag associated with these deeper units is a reflection of the connectivity and storage associate with the moraine recharge features. In 2012, the regional recharge features that supply water to the deeper aquifer units were not replenished and consequently both aquifers behaved similarly, starting with relatively low water levels that continued to drain through the summer. In addition, the slightly larger lag observed in 2012 at both monitors may be the result of the smaller recharge pulse taking longer to propagate through the system.

Table 13.2: Summary of cross-correlation analysis at W0000218 for drought years 2007 and 2012.

Well No.	Geologic Unit	2007 Lag Time (days)	2007 Correlation Coefficient	2012 Lag Time (days)	2012 Correlation Coefficient
W0000218-3	Waterloo Moraine Aquifer	111	0.86	116	0.89
W0000218-4	Post Catfish Aquifer	143	0.87	188	0.91
W0000218-5	Bois Blanc Formation Aquifer	177	0.93	203	0.88

Strong correlations between water level and precipitation were also observed at W0000065-4 for both 2007 and 2012, as shown in Figure 13.10 and summarized in Table 13.3. Although W0000065-4 is screened in an unconfined system, the lag time associated with the maximum correlation between precipitation and groundwater level is generally larger than all intervals of W0000218 – even the middle (W0000218-4) and lower (W0000218-5) intervals, which are screened in deeper, confined systems. The large lag observed at W0000065-4 is likely associated with its physiographic setting. The Norfolk Sand Plain is characterized by high recharge and has the potential for large amounts of storage. As a result, it is expected that this aquifer unit has considerable drought resiliency. The slight increase in the lag observed in 2012 compared to 2007 is again attributed to the different characteristics of the drought where the lack of freshet in 2012 resulted in a smaller recharge pulse that took longer to propagate through the aquifer system.

Table 13.3: Summary of cross-correlation analysis at W0000065-4 for drought years 2007 and 2012.

Well No.	Geologic Unit	2007 Lag Time (days)	2007 Correlation Coefficient	2012 Lag Time (days)	2012 Correlation Coefficient
W0000065-4	Sand Plain/Outwash Aquifer	188	0.89	203	0.88

The cross correlation data indicate that the direct dependence of groundwater levels on precipitation is highest during periods of drought, as shown by the high correlations achieved when comparing the two variables on a yearly basis, rather than as a long time series. In addition, the data show that during a drought, water levels in aquifer systems with different hydrogeologic characteristics (i.e., unconfined, confined, and bedrock aquifers) are all strongly influenced by the lack of precipitation. However, their resiliency to drought may be strongly related to the amount of storage available in the aquifer system.

13.3 *Water Use under Drought Conditions*

Drought conditions, depending on the severity, can result in the jurisdictional imposition of voluntary or mandatory water used restrictions. This is often problematic for permitted agricultural water users because their water requirements increase during drought. Consequently, the impact of a drought on stream flows and groundwater levels may be exacerbated by an increase in irrigation demand.

Evidence for increased water use during drought is presented in Table 13.4, which lists the number of irrigation events per year over the 2011 and 2014 time period. During this period, 2011, 2013 and 2014 represent average climate years, while 2012 represents a drought year. The data show that while the average taking volume per irrigation event is consistent from year to year, the number of irrigation events is highest in 2012. (It should be further noted that irrigation events in all years may be under-reported because WTRS reporting compliance was between 66 and 73% during that time (See Section 6.2).)

There is some evidence that suggests the 2012 drought changed water use patterns in the watershed. While 2013 had fewer irrigation events than 2012, it still had a relatively high number of events despite precipitation being very similar to the 2011 and 2014 growing seasons. Figure 9.24 indicates that a large number of new wells were installed after the 2012 drought. Permitted agricultural water users may have been more liberal with their water use during the 2013 growing season to ensure a successful crop. This increase may be an artifact of an increase in water use reporting, but the data show that the fewest number of irrigation events occurred in 2014 despite having the highest percentage of reporting water users.

Table 13.4: Summary of irrigation events occurring between 2011 and 2014 within the model area and the Whitemans Creek subwatershed

Year	Annual Precipitation (mm)	Irrigation Events in Model Area	Irrigation Events in Whitemans Creek Subwatershed	Average Taking (m^3)
2011	1089	1928	703	1124
2012	899	2723	1296	1239
2013	1083	2272	1259	1180
2014	1059	1539	710	1268

Despite the significant improvements in the number of agricultural water users reporting their water usage to the WTRS database, there is still considerable uncertainty regarding non-reporting users and potential non-permitted users. These sources of uncertainty highlight the need for a specific irrigation demand tool that can estimate water use based on various hydrological parameters such as soil moisture deficit rather than relying solely on the reporting system.

13.4 *Figures*

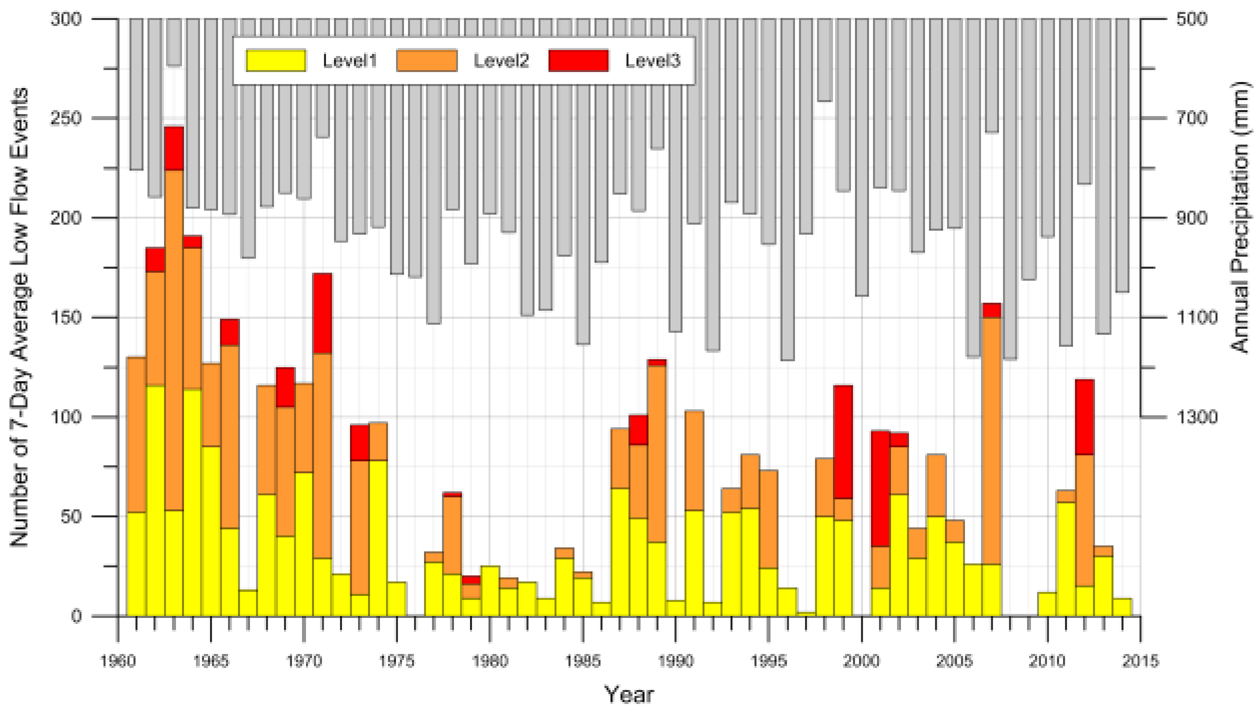

Figure 13.3: Annual basin average precipitation and the number of low-water days for each year in the 7-day average streamflow record at Whitemans Creek near Mount Vernon (02GB008).

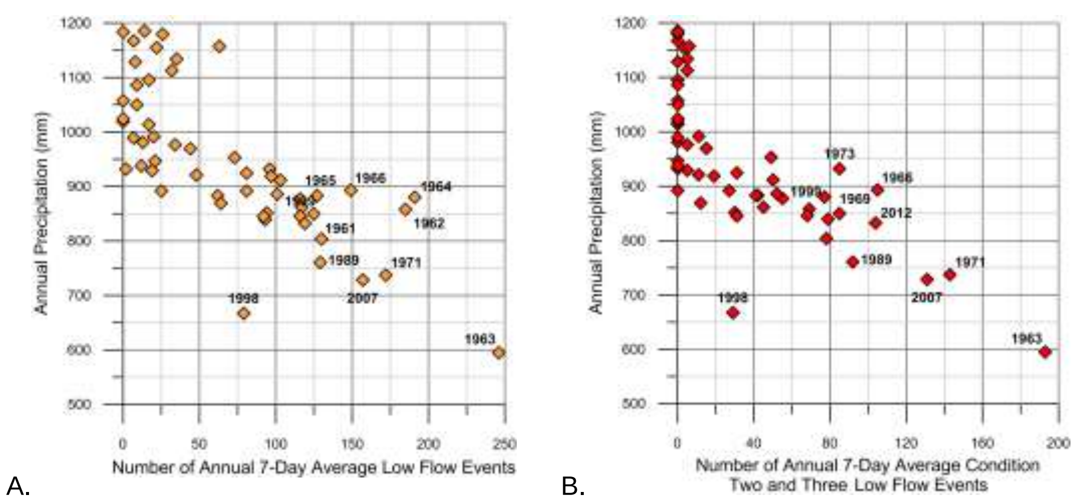

Figure 13.4: Annual basin average precipitation versus (A) total number of low water days; and, (B) number of Level 2 and Level 3 low-water days in the 7-day average streamflow record.

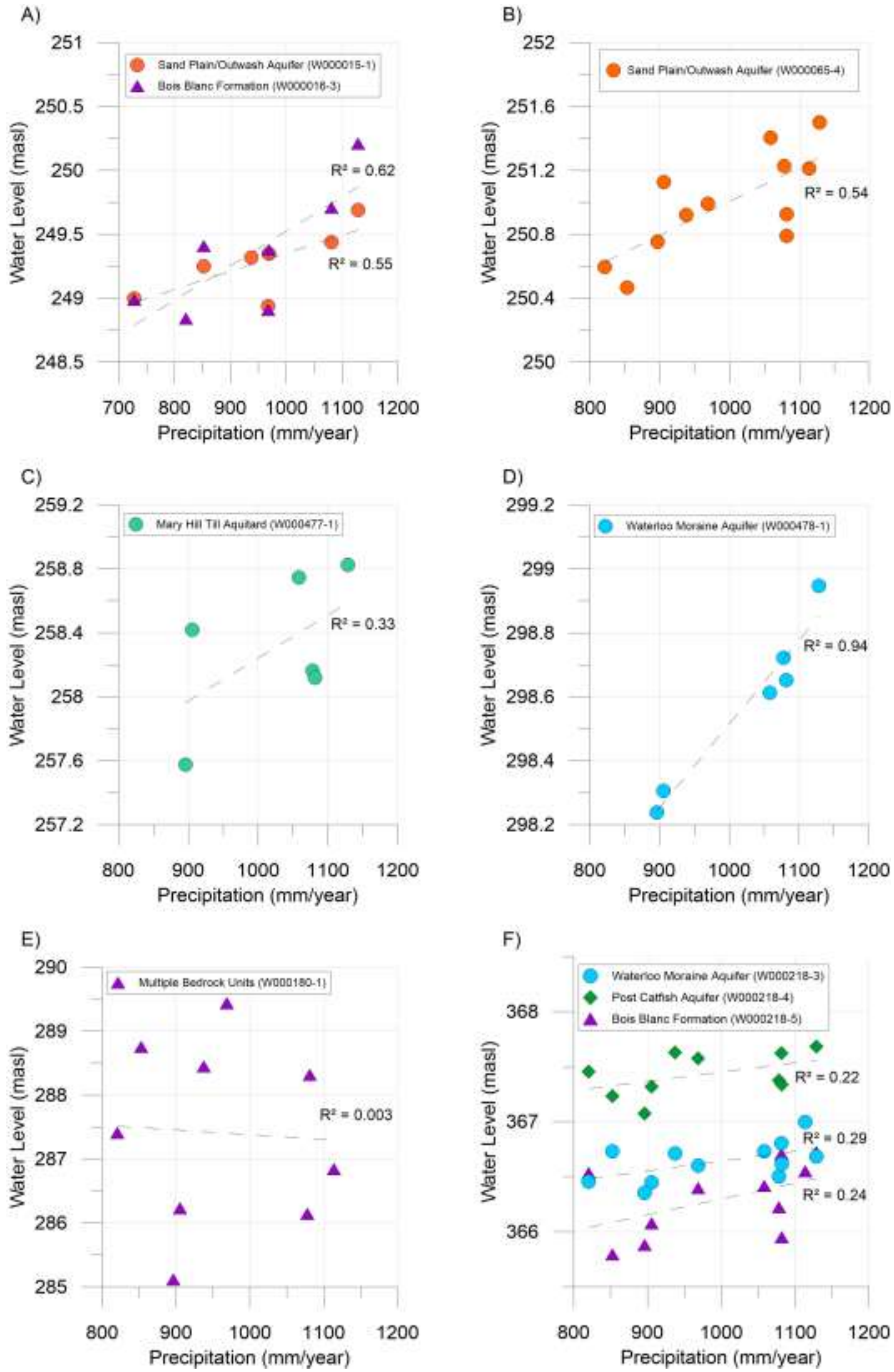

Figure 13.5: PGMN well data showing the relationship between annual precipitation and groundwater water level at the end of each respective water year.

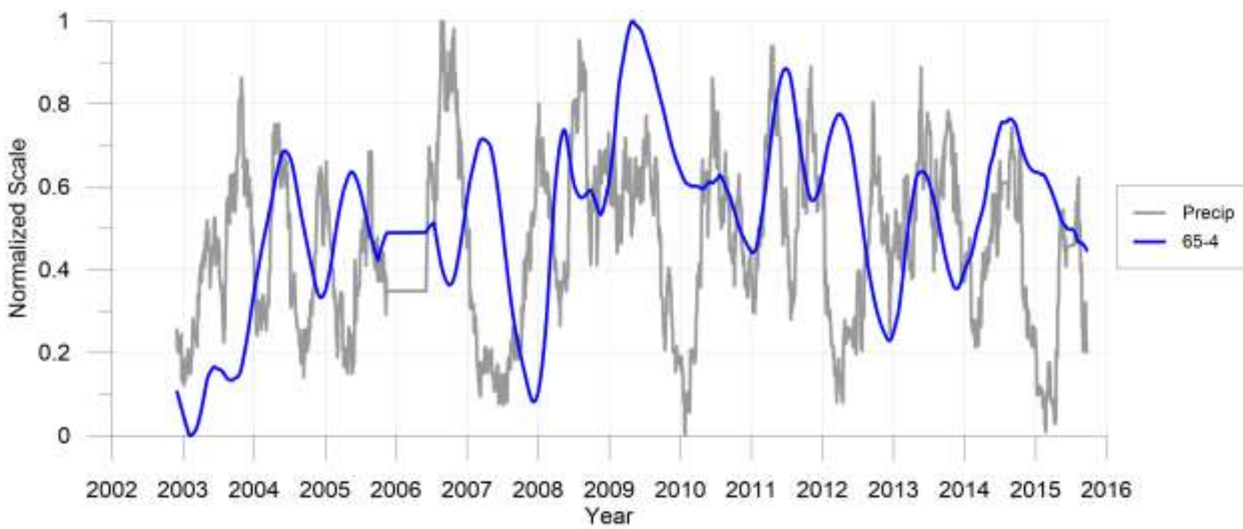

Figure 13.6: Comparison of normalized precipitation and water levels at PGMN well W000065-4

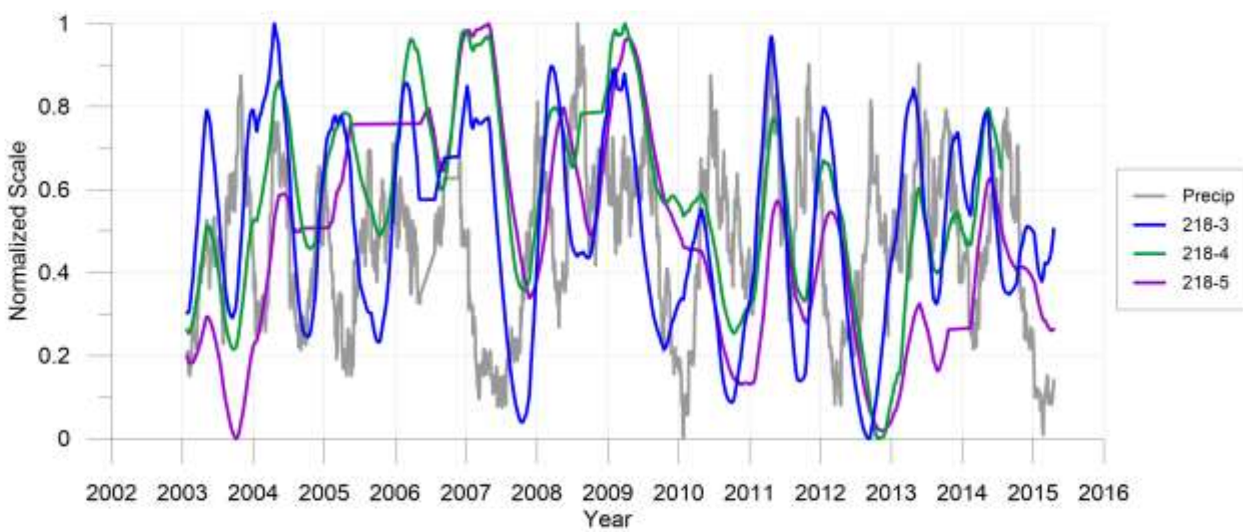

Figure 13.7: Comparison of normalized precipitation and water levels at PGMN well W0000218-3, -4, -5

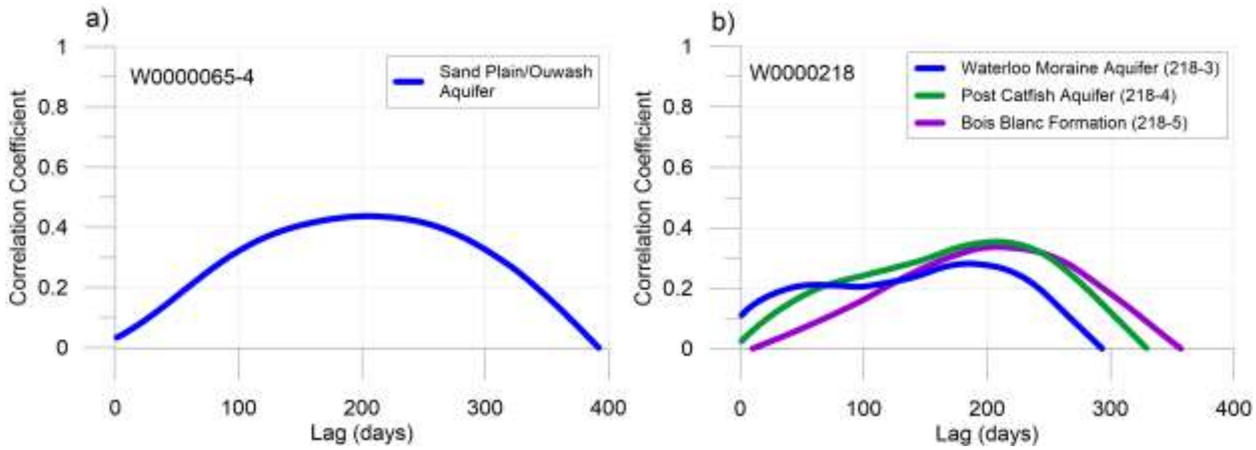

Figure 13.8: Correlation between lagged precipitation and groundwater levels at (a) W0000065-4 and (b) W0000218.

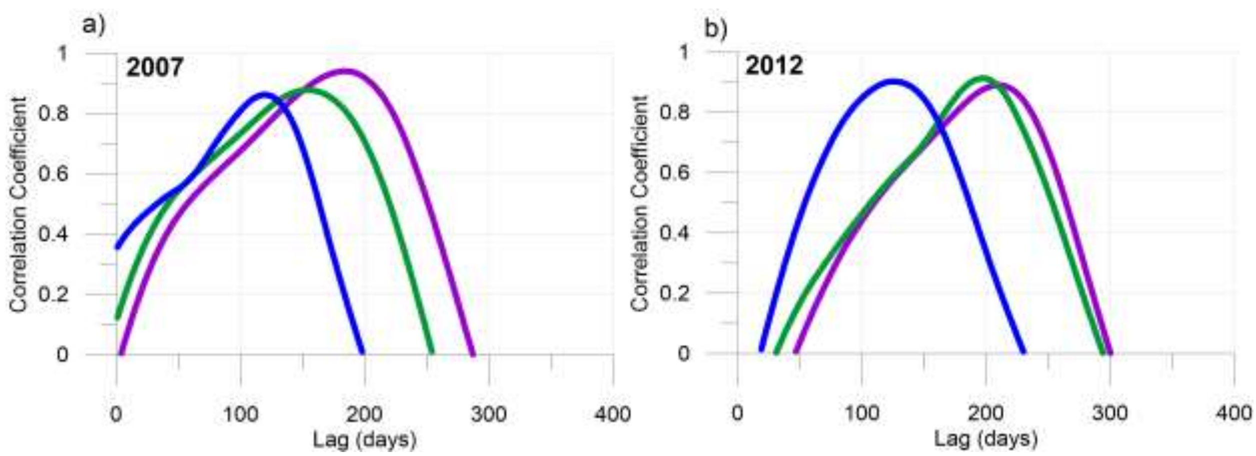

Figure 13.9: Correlation between lagged precipitation and groundwater levels for W0000218 in (a) 2007 and (b) 2012.

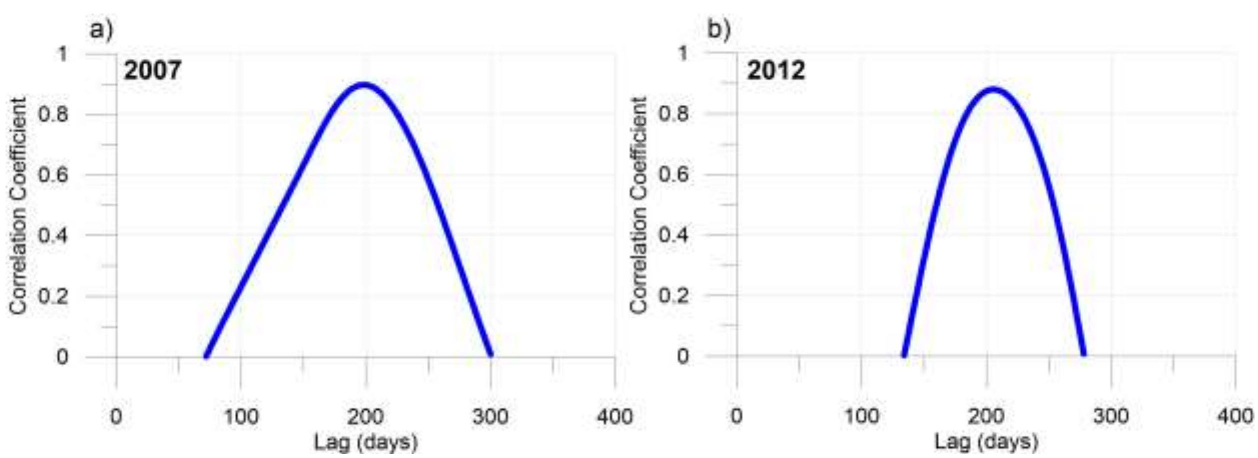

Figure 13.10: Correlation between lagged precipitation and groundwater levels for W0000065-4 in (a) 2007 and (b) 2012.