Matrix Solutions Inc.
ENVIRONMENT & ENGINEERING

CENTRE WELLINGTON TIER THREE WATER BUDGET ASSESSMENT

GROUNDWATER FLOW MODEL DEVELOPMENT AND CALIBRATION REPORT

Report Prepared for:
GRAND RIVER CONSERVATION AUTHORITY

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Report prepared for Grand River Conservation Authority, April 2019

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EXECUTIVE SUMMARY

A Tier Two Water Budget and Subwatershed Stress Assessment was completed for the Grand River Watershed in 2009. Six subwatersheds that contain municipal water supply systems were flagged as having a moderate or significant potential for hydrologic stress from a groundwater or surface water perspective. This included the Irvine Creek Groundwater Assessment Area, which contains the communities of Fergus and Elora. Consequently, this Tier Three Assessment was initiated to evaluate the sustainability of the municipal water supply systems in Fergus and Elora. The Tier Three Assessment will assess the current and future water quantity stresses placed on municipal drinking water sources. The Study Area for the Tier Three Assessment encompasses the Township of Centre Wellington and portions of neighbouring townships of Woolwich, East Garafraxa, Mapleton, Guelph/Eramosa, Wellington North and Towns of Grand Valley and Erin.

This report summarizes the development and calibration of a groundwater flow model that was built for the Centre Wellington Tier Three Water Budget Assessment (Tier Three Assessment). The model was based on the understanding of the physical geologic, hydrologic and hydrogeologic conditions present in the Study Area, as documented in the physical characterization report (Matrix 2017a), and will be applied in later stages of the project to assess changes in water levels at municipal wells due to changes in municipal demand, land development and climate variability. This document summarizes the development and the calibration of the groundwater flow model as well as the model limitations.

Model Development

A new model of the Study Area was generated for this assessment for two primary reasons. First, there have been significant revisions to the geologic characterization since the previous numerical model (Golder 2013) was developed. Second, a review of the previously delineated municipal capture zones indicated that the modelled Study Area should be larger than the previously modelled Study Area.

The numerical groundwater flow model was developed using the FEFLOW (Finite-Element Simulation System for Subsurface Flow and Transport Processes) software code (v7.1; Diersch 2014) and was based on the conceptual hydrostratigraphic framework outlined in the physical characterization report (Matrix 2017a). The model boundaries were extended to surface water features or natural flow divides, where possible. The model includes 21 computational layers representing 16 physical hydrostratigraphic units.

Boundary conditions were included to allow water to enter or leave the model. Boundary conditions were included along the perimeter to allow water to enter the model in the bedrock aquifers in the north and to leave the model through the overburden and bedrock aquifers in the south. Boundary conditions were also applied to represent groundwater that discharges into surface water features like the Grand River, Irvine Creek, or Swan Creek. Groundwater recharge was applied using values derived from the Guelph All-Weather Storm-Event Runoff (GAWSER) watershed-based flow generation model

(Schroeter and Associates 2004), which was developed and calibrated for the Grand River Watershed (AquaResource 2009a).

Hydrogeologic properties (e.g., hydraulic conductivity and specific storage) were initially assigned to zones within the model layers based on the results of hydraulic tests (e.g., pumping tests) within the Study Area, and these values were iteratively updated within the ranges of expected values during the model calibration process.

Model Calibration

The groundwater flow model was calibrated to equilibrium conditions (steady-state), as well as a six week coordinated pumping and shutdown test involving all the Fergus and Elora wells conducted in 2012. The model was calibrated to observed baseflows from the Irvine Creek near Salem gauge and observed groundwater levels from water wells across the Study Area. Groundwater observation data was derived from lower quality wells contained in the water well information system, and 48 higher quality monitoring wells managed by the Township of Centre Wellington and others in the Study Area.

The calibration of the groundwater flow model was evaluated quantitatively and qualitatively. Quantitatively, the simulated water level elevations and baseflow measurements closely matched the observed values within an acceptable statistical range, while reproducing observed groundwater flow directions and gradients. Regionally and locally, the difference between observed and simulated water levels was minimized. The simulated water level elevations in the municipal monitoring well network were close to, or within, the observed range of values, and the model replicates the groundwater flow system's response to pumping of the municipal aquifer at those wells and the pumping wells. Simulated groundwater discharge rates agree with baseflow estimates at Irvine Creek.

Qualitatively, the simulated groundwater level contours are consistent with observed conditions, and the calibration was achieved using input parameter values that were within the expected range for the local groundwater system. Local knowledge and insight on the overburden and bedrock geology within the Study Area streamlined the model development and model calibration. Overall, the match between simulated and observed values indicates the groundwater flow model is suitably well calibrated to steady-state and transient conditions.

The ability of the model to represent observed hydrogeological conditions confirms that the hydrogeologic interpretation is reasonable and consistent with the available data. Observations providing confidence in the current interpretation include:

- Simulated groundwater levels are generally consistent with measured values. This is evident through matching of observed horizontal gradients (e.g., contour maps) and vertical gradients (e.g., at observation well pairs or multi-level installations).

- Model parameter values, such as hydraulic conductivity, are consistent with the conceptual hydrostratigraphic units (i.e., aquifers and aquitards have parameter values that are consistent with that conceptualization).

- Groundwater recharge rates are consistent with understanding of the shallow water balance (i.e., partitioning of precipitation to evapotranspiration, overland runoff, shallow interflow, and deep groundwater recharge).

- Groundwater discharge rates to surface water bodies are consistent with observed discharge rates. Cumulative discharge over a larger area (e.g., entirety of the Irvine Creek subwatershed) provides more-reliable evidence of recharge-discharge conditions over a larger area.

- The model's ability to achieve an exceptional match to observed transient water levels observed during the six week pumping and shutdown testing (Golder 2011) increases confidence in the conceptual model and parameterization.

The above calibration evidence supports the applicability of the numerical model to assess the sustainability of the municipal aquifer system.

The development and calibration of the groundwater flow model enhanced our understanding of the groundwater flow system and the quantity of water continually flowing through the groundwater system. In general, groundwater recharge from precipitation occurring within the Study Area amounts to 98% of the groundwater inflow; 88% of the water discharges to local streams, rivers, wetlands, and lakes. Permitted and non-permitted pumping in the Study Area was estimated to take 4% of the water flowing through this area. Lateral inflows represent 2% of the inflow to the Study Area.

Groundwater wells in the Study Area were estimated to pump 25% of the water that flows through the Gasport and Goat Island formations aquifers. Consequently, the majority of groundwater water (i.e., 75%) in these aquifers flows around or past the pumping wells, and discharges to surface water features, or continues to flow within bedrock aquifers beyond the Study Area.

Given this enhanced knowledge of the water budget and the calibrated groundwater flow model, the project is ready to move forward with making predictions on the sustainability of the water supplies in the Fergus and Elora area.

TABLE OF CONTENTS

LIST OF TABLES

FIGURES

APPENDICES

1 INTRODUCTION

The groundwater flow model described in this report was developed with the goal of completing the Risk Assessment portion of this Tier Three Water Budget Assessment (Tier Three Assessment). As a part of the Risk Assessment, the groundwater flow model will be used to simulate the drawdown at municipal pumping wells and evaluate potential reductions in groundwater discharge to surface water features under existing and proposed future conditions. The calibrated model will be used to assess the impact of changes in pumping and land use development on municipal wells and other water uses, such as coldwater streams and Provincially Significant Wetlands. This report presents the development and calibration of the groundwater flow model built for the municipal groundwater supplies of the Township of Centre Wellington.

1.1 Report Outline

This report documents the development and calibration of the groundwater flow model for the Centre Wellington Tier Three Water Budget Assessment, and the following summarizes the sections of this report:

- Section 2 provides a summary of the hydrogeologic framework that was outlined within the Centre Wellington Tier Three Water Budget Assessment physical characterization report (Matrix 2017a).
- Section 3 presents and discusses the construction and development of the numerical model including the model input parameters and model boundary conditions applied therein.
- Section 4 describes the calibration approach and introduces the observed datasets used in calibrating the model.
- Section 5 presents the calibration results including a discussion of the model calibration at the well field scale with emphasis on high-quality data.
- Section 6 summarizes the water budget completed for the Study Area, and the insights gained in the groundwater flow model development and calibration portions of the project.
- Section 7 outlines the data gaps identified within the Study Area.
- Section 8 describes the limitations of the groundwater flow model.
- Section 9 presents a general summary of this document.

1.2 Study Area

The Study Area (Figure 1) encompasses the Township of Centre Wellington, which contains the communities of Fergus and Elora, and portions of the neighbouring townships of Woolwich (Region of Waterloo), East Garafraxa and Town of Grand Valley (Dufferin County), and the townships of Mapleton, Guelph/Eramosa, Wellington North, and Town of Erin within Wellington County. The City of Guelph lies south of the Study Area. The Study Area was delineated at a large enough extent to allow for refinement at areas of interest such as pumping wells and surface water features, and avoid having perimeter boundary conditions influence the predictions made in the central portion of the model. The Study Area needed to be large enough to fully encapsulate the area where drawdown associated with future municipal pumping will occur, as delineated in the future Risk Assessment phase of the study. The Study Area boundaries were guided by surface water features and interpreted groundwater flow in the overburden and bedrock, discussed in Section 3.3.

Centre Wellington is completely reliant on groundwater to meet their municipal water demand. Three municipal water supply wells are located in Elora (Wells E1, E3, and E4), and six municipal wells are located in Fergus (Wells F1, F2, F4, F5, F6, and F7). All of the water supply wells are completed in bedrock and were constructed between 1935 and 2002. Specifically, Wells F1, F2, and E1 were the first wells to be drilled in 1935, 1945, and 1949, respectively. Additional wells were drilled in the years to follow with Well F4 drilled in 1972, Well F5 in 1975, Well F6 in 1989, Well E3 in 1991, Well F7 in 1999, and Well E4 in 2002.

1.3 Previous Groundwater Flow Models in the Centre Wellington Area

Previous groundwater flow models for the Township of Centre Wellington and surrounding area were designed to address one of the following key objectives: 1) improve the understanding of different portions of the groundwater system, 2) characterize the interaction between the groundwater flow system and surface water features, or 3) delineate wellhead protection areas. The flow models were developed for the specific objectives of those studies and are based on the conceptual models of groundwater flow developed at the time of the assessments. These include flow models developed in neighbouring study areas, as well as regional- and local-scale studies that encompass the Township of Centre Wellington municipal supply wells. A summary of these models follows.

Three-dimensional (3D) numerical groundwater flow models were developed for neighbouring Tier Three Assessments including the development of FEFLOW (Finite-Element Simulation System for Subsurface Flow and Transport Processes) models for the Region of Waterloo Tier Three Assessment to the south of the Study Area (Matrix and SSP&A 2014), the City of Guelph and Township of Guelph/Eramosa Tier Three Assessment to the west and southwest (Matrix 2017b), and the Orangeville, Mono, and Amaranth Tier Three Assessment (AquaResource 2011) to the northeast of the Study Area. These models were developed, calibrated, and applied to assess whether municipalities will be able to provide potable drinking water to their respective serviced populations considering existing demands, future demands associated with population growth, and reduction in recharge due to land development and drought conditions. None of these models contain all of the municipal water supply wells in Centre Wellington, so updating any of these models would not satisfy the needs of this water budget assessment.

There is overlap between the model domains for the Guelph- Guelph Eramosa Township (GET) Tier Three Assessment model, and the groundwater flow model developed for the Centre Wellington Tier Three Assessment. Each of these groundwater flow models was constructed to focus on their respective municipal water supply systems, and as such should only be used to predict conditions within their respective focus areas. Boundary conditions applied along the southern edge of the Centre Wellington Tier Three Assessment model were consistent with simulated hydraulic heads within the Guelph-GET groundwater flow model. As the two models were defined independently, boundary conditions may need to be updated periodically to simulate the drawdown associated with groundwater pumping in the Guelph-GET area on the Centre Wellington Study Area.

A regional FEFLOW groundwater model of the Grand River Watershed was developed for the Tier Two Water Budget and Subwatershed Stress Assessment (Tier Two Assessment) in 2009 (AquaResource 2009a, AquaResource 2009b) and this model included the Township of Centre Wellington Study Area. The Tier Two Assessment model built upon earlier work completed by Waterloo Hydrogeologic Inc. (WHI 2005) and was used to assess groundwater flow at the regional scale. This included estimation of the potential stress of subwatersheds and groundwater assessment areas where the Percent Water Demand (ratio of estimated water demands to available surface and groundwater supply) exceeded prescribed thresholds under current and future conditions. The hydrogeological characterization reflected by the model includes groundwater aquifers and aquitards that have a regional significance. As a result, the predicted water levels and groundwater discharge rates in the numerical model were consistent with the conceptual model of the area at the larger (e.g., subwatershed) scale. This Tier Two watershed scale model was not selected for use in the groundwater modelling portion of the Tier Three Assessment due to the regional-scale focus of the watershed scale model; however, lessons learned in the Tier Two Assessment groundwater flow model were applied in this study.

As part of the Township of Centre Wellington Groundwater Management Study (Blackport 2002a, Blackport and WHI 2002) a Visual MODFLOW numerical model was developed (WHI 2001). The model was used to delineate well field capture zones and guide areas where additional water takings could take place. This MODFLOW model was subsequently applied or refined in subsequent groundwater flow studies in the Study Area including:

- Fergus Water Supply System, Wells F1 and F2 Groundwater Under Direct Influence (GUDI) Assessment (Blackport 2002b). The results of the original MODFLOW modelling were used to aid in the GUDI of Surface Water assessment of Fergus Wells F1 and F2.

- County of Wellington Groundwater Protection Study (Golder 2006). The MODFLOW model previously developed was applied to delineate new time-of-travel capture zones and wellhead protection areas for the Centre Wellington municipal supply wells.

- Township of Centre Wellington Well Field Capacity Assessment (Golder 2013). The original (WHI 2001) MODFLOW model was refined, updated and applied to assess existing and predicted future demands and the sustainability of the municipal water supply in Centre Wellington considering potential impacts (e.g., drawdown interference and reduced stream baseflows). The model was calibrated transiently using shutdown/pumping test data from 2012, and the steady-state calibration was subsequently verified.

The model developed by Golder (2013) was considered for use in this project; however, it was not applied because of the advances made to the overburden and bedrock conceptual geologic and hydrostratigraphic models in this area since the Golder (2013) report was completed. For example, the Tier Three Assessment has capitalized on work completed in the area by the Ontario Geological Survey (OGS). Specifically, OGS geoscientist Frank Brunton provided insight into the spatial continuity of Silurian-aged bedrock units across the Study Area. These interpretations represent advancements in the conceptualization of the bedrock hydrostratigraphy presented by Golder (2013). Similarly, the Golder (2013) model included three overburden layers, whereas the current 3D overburden hydrostratigraphic model developed by Burt and Dodge (2016) includes over nine hydrostratigraphic layers. Overall, the Golder (2013) model was based on the conceptual model of the groundwater flow system available at that time. These differences in the conceptual model led to the development and calibration of a new groundwater flow model for this water budget assessment.

2 HYDROGEOLOGIC FRAMEWORK

The conceptual hydrostratigraphic model used in the development of the numerical model is presented in the Matrix (Matrix 2017a) characterization report.

2.1 Summary of Overburden Geology

Within the Study Area, overburden units deposited during the Quaternary period (2 million years before present [ybp] to 10,000 ybp) detail a record of repeated ice advance and retreat of ice lobes that originated from the Huron-Georgian Bay and the Erie-Ontario lake basins. Table 1 lists the overburden deposits (from youngest to oldest) as mapped by Karrow (1968), Cowan (Cowan 1976) and Burt and Dodge (2016). In the naming convention used by the OGS (Burt and Dodge 2016; Bajc and Shirota 2007), the first two letters in the hydrostratigraphic unit name identify if the unit is interpreted as an aquitard (AT) or an aquifer (AF), and the latter two characters correspond to the sequence of the units, with A (and 1) as the youngest sequence and F (and 3) as the oldest.

The 3D spatial extent of overburden units in the eastern half of the Study Area was conducted by Burt and Dodge (2016) and these interpretations were subsequently extended into the western half through the generation and interpretation of additional overburden cross-sections (see Matrix 2017a for details).

TABLE 1 Hydrostratigraphic Units within the Study Area

Layer Type	Hydrostratigraphic Unit Type	Interpreted Hydrostratigraphic Unit	Primary Materials
Overburden	Aquifer (AFA2)	Grand River Outwash Aquifer	Sand and gravel
	Aquitard (ATB1)	Port Bruce Stade Aquitard - Tavistock and Port Stanley Tills	Sandy, silty to clayey till
	Aquifer (AFB1)	Orangeville, Elmira, and Upper Waterloo Moraine Sands and Equivalents Aquifer	Fine to coarse sand and gravel
	Aquitard (ATB3 / ATC1 / ATC2)	Maryhill Till and Associated Glaciolacustrine Sediments, Catfish Creek Drift (Aquitard) and Lower Catfish Creek Till Aquitard	Silty to clayey till, silt, clay; Stoney, silty to sandy till
	Aquifer (AFD1)	Pre-Catfish Creek Outwash Aquifer	Sand and gravel
	Aquitard (ATE1)	Canning Drift Aquitard	Silty to clayey till, silt, clay
	Aquifer (AFF1)	Pre-Canning Aquifer	Sand and gravel
	Aquitard (ATG1)	Pre-Canning Aquitard	Stony, silty to sandy till
Bedrock	Aquifer	Contact Zone	Fractured bedrock
	Aquifer / Aquitard	Salina Group	Interbedded dolostone, mudstone and shale with lenses of evaporites
	Aquifer / Aquitard	Guelph Formation Eramosa Formation - Stone Road Member	Carbonate wackestone to mudstone (upper) and crinoidal grainstones and wackestones and reefal complexes (lower)
	Aquifer / Aquitard	Eramosa Formation - Reformatory Quarry Member	Coarsely crystalline dolostone
	Aquitard	Eramosa Formation - Vinemount Member	Finely crystalline dolostone with shaley beds
	Aquifer / Aquitard	Goat Island Formation	Finely crystalline dolostone and cross-laminated crinoidal grainstone
	Aquifer	Gasport Formation	Crinoidal grainstone-packstone with reef mounds and coquina lithofacies
	Aquitard	Lions Head, Irondequoit, Rockway and Merritton formations	Fine-crystalline mud-rich dolostone
	Aquitard	Cabot Head Formation	Silty shale

2.2 Summary of Bedrock Geology

Bedrock geology beneath the Study Area consists of dolostone and shale Paleozoic bedrock formations that overlie deeply buried Precambrian basement rocks (Armstrong and Dodge 2007). The Paleozoic bedrock formations dip regionally to the southwest (Johnson et al. 1992) and in some areas with bedrock valleys, the bedrock is buried beneath thicker Quaternary- aged overburden sediments. Paleozoic bedrock outcrops are found in the Fergus and Elora area along the banks of the Grand River valley, notably the Elora Gorge, where 20 m high vertical faces of rock are exposed.

The interpretation of the spatial distribution and continuity of bedrock beneath the Study Area was based on the bedrock conceptualization presented by the OGS (Brunton et al. 2012; Brintnell 2012; Brunton and Brintnel 2011; Brunton 2008). The updated bedrock conceptualization was developed in cooperation with OGS staff (Frank Brunton) who provided the study team with interpretations of the elevations at the top of each bedrock unit beneath the Study Area. The interpreted hydrogeologic properties associated with each of the overburden and bedrock units were assessed and units were grouped together, where possible, to form hydrostratigraphic units representing interpreted aquifer and aquitard units at the scale of the Study Area. Discussions with Elizabeth Priebe of the OGS on the properties of the hydrostratigraphic bedrock units (Priebe et al. 2017) provided insight into the assignment of hydraulic conductivity ranges in the groundwater flow model. The following paragraphs, and the physical characterization report (Matrix 2017a), provide additional details regarding the hydrostratigraphic units developed.

2.2.1 Karst Features Within the Study Area

Karst is a distinctive type of topography or terrain, formed primarily by the dissolution (chemical erosion) of carbonate rocks such as limestone or dolostone due to the movement of acidic groundwater or surface water over thousands to millions of years (Brunton and Dodge 2008). Groundwater can enlarge the openings in subsurface fractures, especially along pre-existing faults or fractures and bedding planes, creating an extensive subsurface drainage system. Fractures and zones of karstic bedrock dominate the flow of groundwater in the subsurface, but the storage of water lies in the lower-permeability rock (matrix). Karst tends to be most pronounced on the uppermost bedrock surface where bedrock is, or was exposed and along bedrock surfaces that were exposed in the past (paleokarst), but were subsequently buried by sediments, or changes in groundwater flow conditions (Worthington 2011).

Within the Study Area, small caverns, caves and well eroded fractures are visible along the banks of the Grand River, and southeast of the Study Area along the Eramosa River valley where bedrock outcrops at surface (Kunert et al. 1998, Kunert and Coniglio 2002). In these areas, water flowing over the dolostone bedrock slowly dissolves the carbonate rock enhancing existing fractures and the interconnected vuggy portions of the bedrock.

The flow profiles and downhole camera records from Wells E1, E3, E4, F1 and F5 (Lotowater 2015a, 2016b, 2016a, 2017b, 2017a, 2018) identified the depth and location of water producing zones that were described as “large fractures,” “open fractures,” “water producing features,” or “voids.” These zones are present within the Guelph, Goat Island, and Gasport formations at elevations that range from 250 to 380 m above sea level (asl). Some of these water producing zones within the municipal wells lie at the contact between bedrock formations or members, but most of these zones do not coincide with the contact between bedrock units. The size of the fracture apertures noted in the production wells varies, but some apertures are reported to be 1 to 2 cm, when rock fractures are typically on the scale of 0.001 cm. The larger size of the aperture may be due to enhanced dissolution of fractures due to the kinetic energy associated with well pumping.

The flow profile and photos from the downhole video collected in the Middlebrook Well were also reviewed to identify flow horizons and bedrock conditions within that well (Lotowater 2015b). The video recorded the thickness and depth of fractures and noted that were few fractures in the bedrock along the majority of the well, with the exception of a zone described by Lotowater (2015b) as a "cavern" in the lowermost 2 m of the well; this zone is interpreted to provide over 95% of the water that enters the well.

Frank Brunton (OGS) interprets the lowermost production zone in the Middlebrook Well, and the fracture zones noted in the municipal pumping wells are evidence of karst in the Study Area. The borehole log of DDH-05 illustrated and described in Brintnell (2012) describes fracture zones within the well as "karst" or "rubble zones." These areas with enhanced fractures exist at many boreholes within the Study Area; however, mapping the three-dimensional continuity of these zones of enhanced transmissivity is difficult due to the irregular nature of bedrock fractures and the limited extent of high quality data outside the Fergus and Elora areas. As it is difficult to map in three dimensions the locations and spatial distributions of these zones, it is difficult to capture this information within a groundwater flow model. As such, the bulk properties of the fractures and rock are simulated in the model as equivalent porous media, which represents average groundwater flow velocities through the subsurface to reflect observed conditions. This approach is valid for this study as a key objective of the study is to evaluate the sustainability of the water supply aquifer by looking at changes in the groundwater flow system over years and decades.

2.3 Conceptual Hydrostratigraphic Model

The hydrostratigraphic framework consists of eight overburden and nine bedrock units. In the overburden, there are four sand and gravel aquifers that are associated with outwash and moraine deposits and four finer-grained units (i.e., silt, clay and fine-grained till units; Table 1). In the bedrock, nine units were identified. Table 1 presents a summary of the hydrostratigraphic units in the Study Area, including a description of the hydrostratigraphic unit type and primary geologic materials.

The conceptual hydrostratigraphic framework and layer structure summarized in Table 1 was used as the basis for the development of the numerical groundwater flow model, described in Section 3. The Irondequoit, Rockway, and Merritton formations form a thin (<5 m) regional aquitard, and are underlain by the Cabot Head Formation, a low hydraulic conductivity shale unit. As there is little exchange of water between the overlying aquifers (e.g., Gasport Formation) and the underlying low hydraulic conductivity formations (i.e., Cabot Head Shale), the base of the model was simulated to coincide with the top of the Cabot Head Formation.

3 GROUNDWATER FLOW MODEL DEVELOPMENT

This section describes the development of the numerical groundwater flow model based on the conceptual hydrostratigraphic model presented in the previous section. Model selection, characteristics (e.g., boundary conditions, simulated pumping wells, and layer structure), properties (e.g., initial hydraulic conductivity estimates and storage), and the modelling process are described in this section.

3.1 Model Selection

The software code FEFLOW (v7.1; Diersch 2014) was selected to develop the numerical groundwater flow model for the Tier Three Assessment. FEFLOW is a commercially available, three-dimensional, variably saturated, finite-element groundwater modelling code. FEFLOW utilizes triangular-shaped elements allowing the numerical mesh to conform to numerous irregular (i.e., non-linear) features such as streams or wetlands. The mesh also allows for site-specific refinement of the calculation points in areas where hydraulic gradients are expected to be most pronounced. FEFLOW was selected as the preferred modelling code to develop the groundwater flow model, for the following reasons:

- ability to discretize the mesh around specific areas of interest such as pumping wells and rivers to precisely simulate observed physical features and follow complex terrains such as the steep slope along the Elora Gorge
- localized mesh discretization that requires far fewer calculation points to achieve the same level of precision as with finite difference grids (e.g., MODFLOW) that are forced to carry refinements to the model boundaries
- ability of the elements to conform to the pronounced vertical variation of aquifer/aquitard layers
- advanced boundary conditions (e.g., head boundary conditions constrained to only occur when water discharges at that location) to avoid potential impacts of non-physical boundary conditions on the simulation results.

3.1.1 Simulating Bedrock Flow

FEFLOW was selected to simulate groundwater through both fractured bedrock and overburden units within the Study Area. An “Equivalent Porous Medium” (EPM) numerical modelling approach was used whereby the bedrock fractures and matrix are treated as a continuous porous medium where discrete, individual fractures are not explicitly represented; EPM is the industry standard for simulating groundwater flow. The simulation of flow through fractures and the parent matrix, as accomplished using “Discrete Fracture Network” modelling methods, requires detailed characterization of the bedrock fractures (e.g., knowledge of number of fractures, orientation, length, connectivity, and aperture) and considerable computational effort. Given the scale of the study, it would be infeasible to use this approach in the absence of discrete fracture data at various scales across the Study Area.

Hydraulic parameters of the bedrock (e.g., conductivity) were assigned in the model based on estimates derived from previous hydrogeologic studies. Groundwater flow through the bedrock fractures and matrix could be reasonably simulated by calibrating to hydraulic head data from wells completed within the various bedrock formations.

Zones of higher hydraulic conductivity were included in the model where areas of highly fractured bedrock were interpreted, and where supported by hydrogeologic data.

3.2 Modelling Process

The numerical modelling process undertaken for this portion of the Centre Wellington Tier Three Assessment consisted of the following stages:

- Steady-State Calibration: the steady-state calibration includes varying model input parameters and boundary conditions within the model domain, within reasonable ranges based on the conceptual model, until the model-simulated water level elevations and baseflow values align with the observed values. Average groundwater recharge rates generated by the GAWSER watershed-based streamflow generation model over the 1961 to 2005 GAWSER modelling period were used as input for this calibration.

- Time-Varying (Transient) Calibration: the water level elevations from the steady-state calibration were used as the starting point for a time-varying transient calibration for a six week long set of hydraulic tests conducted in the Elora and Fergus well fields. In this calibration, hydraulic conductivity and storage values were modified until a reasonable match was achieved between the model-simulated and observed groundwater level elevations over time throughout the tests. Generally, the model parameters from the steady-state calibration produced a reasonable fit to the water level hydrographs; however, storage and hydraulic conductivity parameters were iteratively updated to improve the model-simulated fit in the transient calibration to water level hydrographs. The updated parameter values from the transient calibration were applied back into the steady-state model, to again evaluate the calibration under steady-state conditions. The transient calibration dataset consisted of monitoring wells located close to the municipal wells, whereas the steady-state calibration datasets consisted of observations spread out across the model domain. The steady-state and transient simulations were run iteratively until the discrepancies between the observed and simulated steady-state and transient observations were minimized.

When the model is considered suitably calibrated to steady-state and transient conditions, it can be applied to help evaluate potential changes in water levels and groundwater discharge under future scenarios.

3.3 Model Domain

When establishing the model domain for a groundwater flow model, it is desirable to have the model domain extend to natural groundwater flow divides whenever possible. Large rivers or topographic highs such as moraines often act as groundwater flow divides that are commonly used to establish the model domains. In addition, the model domain should be far enough away from areas where the model will be used to make predictions to minimize potential bias that may be introduced by boundary conditions around the perimeter of the model that allow water to enter the model domain.

The model domain extends approximately 22 km to the north, 8 km to the south, 11 km to the east, and 15 km to the west of the towns of Elora and Fergus (Figure 1). The domain extends farther to the north than the south because previous capture zones delineated for the Centre Wellington municipal wells extended to the north. The model was extended further north to ensure simulated drawdown does not extend to the model boundaries.

The domain boundaries coincide with Lutteral Creek along portions of the east side of the domain, a portion of Boyne Creek to the north, a portion of a Cox Creek tributary to the south, and with Mitchell's Creek, Parker Creek and Canagagigue Creek to the west. Where the boundary does not align with surface water features, it is oriented so that it is either perpendicular or parallel to interpreted overburden, shallow bedrock, and deep bedrock hydraulic head contours developed as part of the characterization effort (see Figures 16, 17, and 18 in Matrix 2017a). No-flow boundary conditions were assigned along portions of the model domain boundary oriented perpendicular to hydraulic head contours. This occurs along the east and northwest model boundary. Where the boundary is parallel to hydraulic head contours such as the north and south model boundary, groundwater constant head boundary conditions, based on interpreted hydraulic head contours, were assigned to allow water to enter and exit the model domain, respectively.

3.4 Mesh

FEFLOW is a finite-element groundwater flow modelling software package that simulates groundwater flow by solving mathematical equations governing groundwater flow at discrete points or locations within the model domain. The first step in solving a groundwater flow problem using the finite-element method is to discretize the study domain into discrete elements. The domain is replaced by a collection of nodes and elements collectively referred to as the finite-element mesh. Elements consist of three nodes joined together by line segments. Elements can be of any size, and the size and shape of each element can differ. Typically, the size of the elements is smallest in areas of the model where groundwater elevations are expected to change the most or where a high resolution of model output is desired (e.g., at pumping wells). Numerical properties used to represent hydrostratigraphic units (e.g., hydraulic conductivity values) are assigned to each element. Boundary conditions representing known conditions (e.g., wells, lakes, streams, groundwater recharge) are assigned to finite-element nodes.

The finite-element mesh developed for the Study Area (Figure 2) contained approximately 160,000 triangular prismatic elements in each of the 20 model layers, equating to a total of approximately 3.2 million elements. “Slices” defined the top and bottom of each model layer, and each slice in the model had approximately 81,000 nodes for a total of 1.7 million nodes within the model.

The mesh was refined in areas where it was important to have an enhanced definition of groundwater flow and the potentiometric surface. This includes refinements surrounding watercourses, water bodies, pumping wells (Figure 2), high quality observation wells, and along the Elora Gorge and the interpreted buried bedrock valley that cuts below Fergus and Elora.

Average element edge lengths of approximately 40 m were applied along the Irvine River and the central and southern parts of the Grand River with additional refinement along the Elora Gorge (25 m). Watercourses located further away from Fergus and Elora had element edge lengths of approximately 50 m, and refinement of 60 m was applied around the perimeter of the Belwood Reservoir. The mesh spacing in the area of the buried bedrock valley was approximately 70 m, and element edge lengths of approximately 20 m were applied around municipal and non-municipal pumping wells and high quality monitoring wells (Figure 2). Outside of these features, the mesh in the central portion of the model domain had a spacing of approximately 160 m, which increased to approximately 200 m along the outer reaches of the model domain.

3.5 Model Layer Type

FEFLOW was run in variably-saturated mode to simulate both the saturated and unsaturated groundwater zones simultaneously. The evaluation focused on saturated zone numerical results, which were evaluated in detail as part of the model calibration and in analysis of the model results.

FEFLOW simulates unsaturated and saturated groundwater flow using the Richard’s equation. In situ, unsaturated groundwater flow is a non-linear process that is dependent upon antecedent pore water pressure-saturation and relative hydraulic conductivity-saturation relationships. These constitutive relationships define the ability of water to move through the unsaturated zone (conductivity) and the ability of that water to be released from storage due to a decline in the water table position (pressure-saturation). Several models exist that mathematically describe this relationship. The most commonly used models include van Genuchten (van Genuchten 1980), which was applied in this study, and Brooks and Corey (1964).

To increase numerical stability of the model, two simplifications were applied to the van Genuchten model. First, the parameters of the van Genuchten model were modified to linearize the relationship between the relative hydraulic conductivity and effective saturation and second, effects of hysteresis (i.e., saturation’s dependence on the previous wetting/drying history of the material) were ignored. These simplifications are industry standard (Huyakorn et al. 1986) to avoid some of the non-linearities within the unsaturated zone. These simplifications do not affect computations within the saturated zone but rather they facilitate efficient solution of the water table position.

3.6 Hydrostratigraphic Layer Structure

The numerical model was subdivided into 21 layers (Figure 3, Table 2) based on the hydrostratigraphic layers outlined in Section 2.1. Model layers were split into two or more layers where additional vertical refinement was desired (i.e., Guelph Formation and Goat Island Formation).

TABLE 2 Model Representation of Hydrostratigraphic Units

Model Layer	Hydrostrati-graphic Layer	Hydrostratigraphic Unit	General Lithology
1	1	Upper Overburden Aquifer (AFA2)	Grand River Outwash: sands and gravels
2	2	Upper Overburden Aquitard (ATB1)	Tavistock and Port Stanley Tills: sandy, silty to clayey
3	3	Moraine Sand and Gravel Aquifers and Equivalents (AFB1)	Fine to coarse sand and gravel
4	4	Maryhill and Catfish Creek Tills and Glaciolacustrine Sediment (ATB3 / ATC1 / ATC2)	Silty to clayey till, silt, clay; Stoney, silty to sandy till
5	5	Pre-Catfish Sand and Gravel Outwash (AFD1)	Outwash sands and gravels
6	6	Canning Drift (ATE1)	Silty to clayey till, silt, clay
7	7	Pre-Canning Sands (AFF1)	Pre-Canning sands and gravels
8	8	Pre-Canning Till (ATG1)	Overburden aquitard. Pre-Canning stony, silty to sandy till
9	9	Upper fractured bedrock	Contact zone, fractured bedrock aquifer
10	10	Salina Group	Bedrock aquifer/aquitard. Interbedded dolostone, mudstone and shale with lenses of evaporites
11-14	11	Guelph Formation and Eramosa Formation - Stone Road Member	Bedrock aquifer/aquitard. Carbonate wackestone to mudstone (upper/ Hanlon Mbr) and crinoidal grainstones and wackestones and reefal complexes (lower/ Wellington Mbr)
15	12	Eramosa Formation - Reformatory Quarry Member	Bedrock aquifer. Coarsely crystalline dolostone
16	13	Eramosa Formation - Vinemount Member	Bedrock aquitard. Finely crystalline dolostone with shaley beds
17-19	14	Goat Island Formation	Bedrock aquifer. Finely crystalline dolostone and cross-laminated crinoidal grainstone
20	15	Gasport Formation	Bedrock aquifer. Crinoidal grainstone-packstone with reef mounds and coquina lithofacies
21	16	Lions Head, Irondequoit, Rockway, and Merritton formations	Bedrock aquitard. Fine-crystalline mud-rich dolostone

The numerical model requires continuous hydrostratigraphic layers, and as such, if a hydrostratigraphic unit was interpreted to pinch out, the associated numerical model layer decreased to a minimum thickness (i.e., 0.2 m) and the properties of the overlying or underlying hydrostratigraphic unit with appreciable thickness (exceeding the minimum thickness) were applied. For example, where the overburden layers pinch out along the Elora Gorge, the overburden layers were assigned a minimum layer thickness (10 cm) and the properties of the layer below (Guelph Formation) were applied along the sides and base of the Gorge.

The base of the FEFLOW model is a no-flow boundary and as such, groundwater flow at this depth is interpreted to be horizontal. As discussed in Section 2.2, the base of the model is represented by the top surface of the Cabot Head Formation shale.

3.7 Boundary Conditions

Boundary conditions represent the interaction between the areas within and beyond the numerical model domain. Boundary conditions are applied in groundwater flow models to approximate the regional groundwater flow patterns and major groundwater fluxes within the Study Area. Boundary conditions that can be applied in the model consist of three types:

- Constant head boundary conditions. The value of hydraulic head is assigned to specific node within the model, and the amount of discharge into or out of the model node fluctuates to satisfy the head condition. Physically, these boundary conditions are commonly used to simulate areas where aquifer potentials are expected to remain at a constant level. This is commonly applied to simulate flow into and out of large rivers, lakes, or around the perimeter of the model domain where water enters or exits the model domain.

- Specified flux boundary conditions. A flux value is assigned to specific model nodes, and the hydraulic head at the node is allowed to fluctuate to meet that flux condition. These boundary conditions are also called constant flux boundaries and are used to represent groundwater extraction or injection wells, or recharge to the groundwater system. No-flow boundaries are one type of specified flux boundary where the rate of lateral flow across the boundary is assumed to be negligible or equal to zero. In general, no-flow boundaries are applied to simulate groundwater divides or impermeable geologic units.

- Head-dependent boundary conditions are boundaries where a flux across a boundary is calculated based on an assigned head value at a specific model node. The flux value is dependent on the difference between a specified head and the calculated heads in the surrounding model cells. These head dependent flow boundary conditions are often used to represent flow into a drain or into or out of a river, or along the perimeter of the model where water enters or exits the model domain.

Boundary conditions applied in the model include groundwater recharge (provided from the calibrated GAWSER model developed in the Tier Two Assessment; AquaResource 2009a), flow into and out of surface water features (i.e., streams, rivers, lakes, and wetlands), groundwater pumping wells, and lateral flow into and out of the model along the outer model perimeter. Figure 4 illustrates the spatial distribution of boundary conditions assigned at ground surface (left map) and overburden (right map), and Figure 5 illustrates the perimeter boundary conditions applied in the bedrock layers of the FEFLOW groundwater model (see Section 3.7.1).

3.7.1 Perimeter Regional Groundwater Flow Boundary Conditions

The model domain was delineated to correspond to natural groundwater flow boundaries (groundwater divides) wherever feasible; however, natural groundwater flow divides were located far from Elora and Fergus which led to the assignment of boundary conditions to allow water to enter and exit the model domain. To determine appropriate lateral boundary conditions for the model, water level contours in the overburden and bedrock were reviewed (Matrix 2017a) and where water level contours suggested that natural flow boundaries exist (groundwater divides), or where the direction of groundwater flow is parallel to the model boundary, no-flow boundaries were applied (note: no-flow boundaries are located where there are no other boundaries specified along the boundary of the model domain in Figures 4 and 5). In other cases, constant head boundary conditions were assigned to simulate the flow of water in or out of the model domain using hydraulic head values from nearby wells completed at various depths to guide the assignment of constant head values.

3.7.1.1 Lateral Boundary Conditions in the Overburden

Overburden aquifers are thick in the northwestern portion of the Study Area, along the northeastern boundary along the Orangeville Moraine. In this area, groundwater flows into the model domain in the overburden aquifers (Layers 3, 5, and 7) via constant head boundary conditions (Figure 4; right map). In addition, in the south and southeastern portions of the Study Area coinciding with the Elmira Moraine and coarse-grained outwash deposits, flow leaves the model in overburden aquifers (Layers 3, 5, and 7) via constant head boundary conditions (Figure 4; right map). The water level elevations applied at these constant head boundary conditions were guided by overburden water level mapping conducted in this area (Matrix 2017a), and hydraulic head values reported in nearby water well records completed in the different overburden units.

3.7.1.2 Lateral Boundary Conditions in the Bedrock

Groundwater flow in the bedrock system generally travels from the north and northeast portion of the model domain to the south (and a lesser extent west), with discharge into streams (i.e., the Grand River) and the Belwood Reservoir within the model domain.

In the northern portion of the model domain (Figure 5), constant head boundary conditions were assigned to the contact zone (Layer 9; Figure 5, left map), Goat Island and Gasport formation (Layers 17 to 20; Figure 5, right map), along the northern model boundary to allow water to flow into the model.

The same constant head boundary conditions were applied in the northeastern portion of the model domain near Marsville (Figure 5, right map).

The Salina Group is thickest along the western model boundary, and groundwater flow is simulated to leave the model domain via constant head boundary conditions exclusively within this unit in areas along the western boundary (Figure 5, left map).

The lower portion of the Guelph Formation (Layers 13 and 14) is interpreted to have a modest transmissivity, so constant heads were applied in those layers as well as the contact zone (Layer 9), Goat Island and Gasport formations (Layers 17 to 20) along portions of the southern model boundary to allow water to exit the model (Figure 5).

All of the water level elevations applied at constant head boundary conditions in the model domain were guided by the bedrock water level mapping (Matrix 2017a) and water level elevation values reported in water well records completed in those bedrock units near the boundary conditions.

3.7.2 Surface Water Boundary Conditions

The interaction between groundwater and surface water was simulated in the FEFLOW groundwater flow model using boundary conditions. Based on the model-simulated groundwater elevations and water levels in the respective surface water features, groundwater may discharge into the surface water body, or water may flow out of the surface water feature into the underlying aquifer. The calibration analyses considered steady-state conditions and transient conditions, but in both cases, the constant heads representing the surface water features remained constant.

3.7.2.1 Lakes / Reservoirs

Two water bodies located within the Tier Three Assessment area were modelled using constant head boundary conditions. The simulated stage elevations for the Belwood and Woolwich Reservoirs were 421 m asl and 363 m asl respectively; both of these values were derived using Grand River Conservation Authority's (GRCA) reservoir elevation data (GRCA 2017a, 2017b).

3.7.2.2 Rivers and Creeks

Boundary conditions representing surface water features are intended to represent locations with sustained, saturated groundwater discharge (e.g., baseflow). As such, boundary conditions were not applied to represent every watercourse in the Tier Three Assessment area. Figure 4 illustrates the rivers and creeks that were simulated as boundary conditions in the model domain. In general, creeks with a Strahler Order equal to 3 or greater were simulated in the models, as well as all rivers that were interpreted by the Ontario Ministry of Natural Resources (MNR) or GRCA to host coldwater fish communities.

Boundary conditions representing surface water features were assigned in the model using constant head boundary conditions to nodes along the river or stream. The head specified in the model was equal to the estimated surface water elevation at that location, as represented in a 2 m-resolution digital elevation model (DEM) for the Study Area.

3.7.2.3 Wetlands

Wetlands within the Study Area are a combination of wetlands that receive groundwater discharge, and those that release water from the base of the wetland into the underlying groundwater flow system. Detailed characterization of the functions of wetlands within wetland complexes has not taken place so a conservative approach was undertaken. Constant head boundary conditions were applied to all MNR-evaluated wetlands, which allowed water to be removed from the groundwater flow system (i.e., groundwater discharge to the wetland), but constraints were assigned to prohibit water from flowing out of the wetland into the underlying groundwater flow system. In addition, wetland complexes mapped by the GRCA with an areal extent greater than 35,000 m^2 were also simulated in the model. The constant head values applied in the wetland boundary conditions were obtained from the high resolution (2 m) DEM.

3.7.3 Recharge

Groundwater recharge is the portion of precipitation remaining after water is evapotranspired or transferred to streams via overland flow and interflow above the groundwater system. Groundwater recharge rates are influenced by the infiltrability of the ground surface; land use or vegetation; the depth, hydraulic conductivity and soil water storage characteristics of surficial overburden layers; and slope of the topography. Typically, the largest amounts of recharge occur in areas of high relief, notably in areas where coarse-grained sediments are mapped at surface.

Recharge rates used in the FEFLOW model were obtained from the calibrated GAWSER watershed-based flow generation model (AquaResource 2009a; AquaResource and SSP&A 2014). GAWSER is a subwatershed-scale, deterministic, lumped-parameter, transient-mode, streamflow generation model. Model inputs are precipitation and air temperature, and outputs of the model include streamflow hydrographs of stormflow and baseflow components (Schroeter & Associates 2004). The GAWSER model was calibrated to baseflow, or low-flow conditions, so the estimated overall average recharge rate across the model are considered reliable for use in the groundwater flow model.

The GAWSER model was calibrated to the available data in the Tier Two Assessment (AquaResource 2009a), and updated as part of the Tier Three Assessments completed for the City of Guelph and Township of Guelph/Eramosa (Matrix 2017b) and Region of Waterloo (AquaResource and SSP&A 2014). The GAWSER model calibration was not updated in this study as the only streamflow gauge located outside the Grand River within our Study Area is the Irvine Creek in Salem gauge, and only minor changes in land cover within the Irvine Creek subwatershed area have taken place since the completion of the Tier Two Assessment that would require model calibration updates.

The local precipitation and air temperature data inputs required for the GAWSER model were derived from two Environment Canada climate stations. Climate data for the majority of the Study Area were the Fergus Shand Dam and Elora Research Stations. A third station in Mount Forest was used to characterize the climate in the westernmost portion of the Study Area. Recharge rates produced from the GAWSER model were mapped to the elements in the FEFLOW model using area-weighted averaging. Urban land uses in Fergus and Elora were not explicitly defined in the GAWSER model, so the recharge rates were reduced based on the estimated imperviousness of various development types that range from zero reduction (parks, natural areas) and up to 90% reduction in recharge on industrial zones.

Across the FEFLOW model domain, the average recharge is approximately 130 mm/y. Recharge applied in the model (Figure 6) ranges from 0 mm/y on surface water features such as Belwood Reservoir and portions of the Grand River, Swan Creek, and Cox Creek to over 500 mm/y on surficial sand deposits such as the Orangeville Moraine in the northeast and Elmira Moraine in the southwest.

There were minor adjustments made in the FEFLOW model to the GAWSER-derived recharge rates to account for uncertainty on the recharge rates in the lower range of the spectrum. For example, the groundwater recharge rates applied to portions of the Tavistock Till in northwestern portions of the Study Area was increased from approximately 20 to 50 mm/y to improve the baseflow calibration in Irvine Creek. Recharge of 50 mm/y on fine-grained tills is within the expected range for this material type in this area of the Grand River Watershed.

3.7.4 Pumping Wells

Large permitted water takers and other pumping wells within the model domain were simulated using specified flux boundary conditions. The pumping rates in the model were held constant within the steady-state simulation, and fluctuated on an ongoing basis within the transient simulation. For wells that penetrate more than one model layer, the groundwater flux into the well from each node of a bedrock well or well screen in an overburden well was automatically computed in FEFLOW based on the transmissivity of each element. The following subsections outline the pumping wells simulated within the groundwater flow model.

3.7.4.1 Permitted Water Takings

As noted in Section 3.4, the mesh was refined around the municipal pumping wells to more accurately simulate the groundwater flow in the vicinity of the wells. A total of 31 municipal and non-municipal permitted groundwater takings were represented in the numerical model (Table 3). The locations of these demands represented in the model are illustrated on Figure 7. For the municipal wells, the average annual (2016) reported pumping rates were applied in the model for the steady-state calibration. Pumping rates applied to represent the non-municipal permitted water takings were applied using the rates reported in the Water Taking Reporting System (WTRS) and other data sources (see Table 3 for details). Additional details on the pumping rates applied are provided in the Matrix (2017a) characterization report. Surface water permits noted in Matrix 2017a were not represented in the groundwater flow model.

TABLE 3 Summary of Model-Simulated Pumping Wells and Rates

Permit Type	Well Name or Permit #	Easting	Northing	Average Annual Consumptive Rate (m^3/d)	Data Source for Consumptive Demand
Municipal	Fergus - F1	550408	4839508	1,094	2016 Centre Wellington Data
	Fergus - F2	550597	4839941	---	
	Fergus - F4	550021	4840803	889	
	Fergus - F5	551830	4839069	131	
	Fergus - F6	549223	4841523	475	
	Fergus - F7	548180	4839697	820	
	Elora - E1	545849	4837406	1,195	
	Elora - E3	547140	4835867	569	
	Elora - E4	545447	4834897	249	
	Arthur - Well 7b	535311	4853283	335	2016 Annual Summary Report
	Arthur - Well 8a	538526	4852003	316	
	Arthur - Well 8b	538508	4852020	317	
	Marsville - Well 1	562182	4852976	25	2016 Annual Summary Report
Non-Municipal Permitted	1733-8QKR4S	557767	4835969	42	2015 WTRS
	2633-9XARF2_1	551512	4843928	2.3	2015 WTRS
	2633-9XARF2_2	551512	4843819	2.3	
	3277-7RDSJW_1	552675	4846378	114	2016 Pumping Data
	3277-7RDSJW_2	552662	4846325	3	
	3347-84VQV5_1	537484	4838121	1,791	2015 WTRS
	3347-84VQV5_2	537461	4837989	1,800	
	3347-84VQV5_3	537435	4838042	669	
	3347-84VQV5_4	537548	4838114	519	
	4348-9NYNX3	538344	4835742	301	Max Permitted Rate x Consumptive Use Factor
	5817-8JQN3B_1	551146	4844524	2.3	2015 WTRS
	5817-8JQN3B_2	551159	4844481	2.3	
	5874-955TM9_1	552769	4847410	42	2015 WTRS and Data Provided by Permit Holder
	5874-955TM9_2	552437	4846991	8	
	8304-6XWRVZ_1	549400	4838965	17	2014 WTRS
	8304-6XWRVZ_2	549409	4838788	8	
	8304-6XWRVZ_3	549546	4838999	16	
	8813-9NYQXV	542421	4833563	135	2015 WTRS

3.7.4.2 Non-Permitted Water Takings

Domestic Water Takings

Boundary conditions were also included in the model domain to account for domestic water takings within the Fergus, Elora, and Salem areas. As it is not feasible to simulate each domestic water taker as a unique pumping well in the model, domestic water demands in a clustered area were represented using a single surrogate pumping well in the numerical model. A total of 18 surrogate wells were included in the model domain representing the distribution of domestic well clusters within approximately 1 km of a municipal well, with reference to the Township's privately-serviced GIS datasets. Fourteen wells were added to the model in the vicinity of the Fergus and Elora areas, and four wells represented domestic water demands in the communities surrounding the Belwood Reservoir and Inverhaugh in the southwest. The total demand simulated in the model from these 18 wells was 943 m^3/d (see Figure 7 for locations). The demand value was derived by multiplying an average pumping rate of 0.251 m^3/d per person (ECCC 2017) by the approximate number of people per household in Centre Wellington (2.6; Statistics Canada 2017) by the number of households (or equivalents) within a neighbourhood area. The number of households per neighbourhood was estimated by querying wells in un-serviced areas and the total water taking was estimated to be 829 m^3/d. This value was refined and updated to 943 m^3/d using input from *Save Our Water*, who conducted independent analyses of un-serviced households, businesses and institutions.

Simulated pumping at individual surrogate wells range from 3 to 173 m^3/d, depending on the number of wells in the neighbourhood cluster. Each surrogate well was simulated to be an open hole bedrock well that was open from the overburden/bedrock contact zone aquifer to the Upper Goat Island Formation as is typical of many wells in the Fergus and Elora areas. The wells were assumed to represent fully consumptive water takings, whereby water is removed from the deep bedrock and not returned to the same source in a reasonable period of time. Some wells in the area are shallow and draw from the upper contact zone and return water to that same aquifer via septic systems; however, this assessment aimed to err on the conservative side when evaluating the water budget.

Agricultural Water Demands

Agricultural water demands were included in the model domain where they were found within a 3 km buffer surrounding the Fergus and Elora municipal wells. A 3 km area was selected as it was assumed that takings in this area have the greatest potential to impact the water levels in the municipal wells, with lesser hydrogeologic impacts expected with increasing distance from the municipal wells. Livestock operations, well locations and depths, and estimated livestock water demands were evaluated by Wellington Source Water Protection and provided to Matrix for inclusion in the numerical model. Agricultural properties with livestock operations were identified using Municipal Property Assessment Corporation (MPAC) parcel fabric spatial data, MPAC property codes, and Southwestern Ontario Orthophotography Project 2015 imagery. Properties were considered where they were larger than 1,500 m^2 and where information on the properties was available through the *Nutrient Management Act*.

A total of 37 wells in 34 livestock operations were identified and incorporated into the groundwater flow model. Well locations and depths were obtained by linking the water taking location to the Ministry of the Environment and Climate Change (MOECC) Water Well Record database in a Geographic Information System. Where livestock properties had no commercial, domestic, or livestock wells in the MOECC database, well locations were specified based on the barn location or centroid of the parcel if a barn was not present. Open hole depths were estimated for well records that lacked this information by averaging open hole depths from wells found within a 1 km radius of the well.

Consumptive livestock water use was estimated using water use data provided by Ontario Ministry of Agriculture and Rural Affairs (OMAFRA) and distributed to livestock properties based on details contained in the Nutrient Management Strategies and Nutrient Management Plans. The total water demand associated with the 37 livestock wells was estimated to be 316 m^3/d and ranged from 0.03 to 41 m^3/d at individual wells. A few wells were located in close proximity to one another so the takings were simulated as one well in the numerical model. As such, a total of 33 pumping wells were added to the model to represent the livestock takings located near the Fergus and Elora municipal wells.

Outside of the 3 km buffer, the water takings associated with a large poultry operation located near Ponsonby were also simulated in the model with three bedrock pumping wells. The estimated water takings associated with this poultry operation are described in the physical characterization report (Matrix 2017a) and estimated at 280 m^3/d. Due to the pumping rate estimated, this water taking was included in the model despite its location outside the 3 km buffer area.

3.8 Model Properties

The primary hydrogeologic properties assigned within the FEFLOW model for simulation of steady-state (average annual) and transient (time-varying) conditions include hydraulic conductivity and specific storage. Hydraulic conductivity is a property of sediment or rock that describes the relative ease with which water can move through pore spaces or fractures, and it has an impact on the model-calculated hydraulic head distribution. Storage parameters are not used in a steady-state simulation; however, under transient conditions, specific yield and specific storage control the timing and response of the groundwater system to external stresses.

3.8.1 Hydraulic Conductivity Values

Hydraulic conductivity is the primary variable that controls the calculated hydraulic head distribution throughout the model domain (based on boundary condition values). In developing a groundwater model, initial estimates of hydraulic conductivities are specified and refined through the calibration process to achieve an acceptable fit of simulated hydraulic heads to observed heads. The spatial variability of hydraulic conductivity within the model domain was represented using hydraulic conductivity zones. The initial conductivity estimates and variability within these zones were defined based on the conceptual understanding of the geologic/hydrostratigraphic units and their hydrogeologic properties (e.g., clay-rich tills were assigned lower conductivity values than silt or sand-rich tills).

A number of hydraulic tests (e.g., pumping, packer, step and slug tests) were conducted on municipal, private, or monitoring wells in the Centre Wellington area, and analyses of field data provided estimates of hydraulic conductivity values for various hydrostratigraphic units. The hydraulic conductivity values derived from these tests were summarized in Table 12 of Matrix (2017a) characterization report and were used to help guide the distribution of conductivity zones and constrain the estimates within particular geologic formations in the model. Where only field-derived transmissivity estimates were available, estimates of conductivity were made using the transmissivity and the thickness of the tested screen or open borehole interval. The final range of field-derived conductivity values for each hydrostratigraphic unit is summarized in Table 4. When field data were unavailable, conductivity values were guided by literature values (Freeze and Cherry 1979; Anderson and Woessner 1992) for materials with similar lithological descriptions. The thickness of the geologic units was used to further guide the conductivity zone distribution.

The range of field-measured hydraulic conductivity values for hydrostratigraphic units in the area are summarized in Table 4. The vertical hydraulic conductivity was set to be 10% of the horizontal hydraulic conductivity for all layers, except for one small area in the overburden between Wells E1 and E3 where a higher anisotropy value was applied to account for interpreted interbeds of coarse- and fine-grained material within the Pre-Catfish Creek Outwash Aquifer that is infilling the bedrock valley south of the Grand River. Updating this unit in this area helped the calibration in this area.

TABLE 4 Field-Derived Hydraulic Conductivity Estimates from Tests in the Study Area

Model Layer	Unit	Horizontal Hydraulic Conductivity (m/s)
		Range of Field-derived Values
1 to 8	Overburden	6×10^{-9} to 1×10^{-4}
9	Upper fractured bedrock	2.7×10^{-5}
10	Salina Group	n/a
11 to 14	Guelph Formation	1×10^{-8} to 8×10^{-4}
15	Eramosa Formation - Reformatory Quarry Member	n/a
16	Eramosa Formation - Vinemount Member	n/a
17 to 18	Goat Island	6×10^{-7} to 8×10^{-4}
19	Gasport Formation	5×10^{-6} to 9×10^{-6}
20	Lions Head, Irondequoit, Rockway and Merritton formations	n/a

n/a - field-measured values not available for this unique unit

3.8.2 Specific Storage Parameters

Storage estimates assigned in the groundwater flow model were estimated using limited field-derived values where it was known that a single bedrock formation was tested (i.e., not a value that may represent a range of tested formations). This included testing completed on the Guelph Formation (Priebe et al. 2017) where storativity was estimated to be 1.1×10^{-4}, which equated to a specific storage value of 3.2×10^{-5} m^{-1}.

Given the absence of field-based data, literature values, and values applied in Tier Three Assessment models in neighbouring study areas were used to guide storage parameterization. Literature values of specific storage for overburden units were noted range from 2.0×10^{-2} for clay up to 4.9×10^{-5} for sand-rich gravels (Anderson and Woessner 1992). Literature values of specific storage for bedrock were reported to range from 3.3×10^{-6} to 6.9×10^{-5} m^{-1} for fissured bedrock, to less than 3.3×10^{-6} m^{-1} for competent bedrock (Anderson and Woessner 1992). For comparison, a value of 1×10^{-6} m^{-1} was applied to represent specific storage in the Silurian bedrock units in the numerical models developed for the City of Guelph and Guelph/Eramosa Township (Matrix 2017b), and the Region of Waterloo Tier Three Assessments (Matrix and SSP&A 2014).

4 MODEL CALIBRATION PROCESS

Numerical groundwater flow models are typically calibrated by systematically adjusting the model input parameters and boundary conditions to determine the optimum match (within an acceptable margin of error) between the simulated results and field observations. The model's ability to represent observed conditions is assessed qualitatively to assess trends in water levels and distribution of groundwater discharge and quantitatively to achieve acceptable statistical measures of calibration.

The model calibration process in this study included a steady-state calibration, and a transient calibration to 6 weeks of groundwater monitoring and pumping data during the shutdown/pumping tests conducted in Elora and Fergus. The calibration process is iterative and calibrating to various datasets helped refine the understanding of the groundwater flow system and decreased the uncertainty with the model input parameters.

The numerical modelling process for this Tier Three Assessment consists of the following stages:

- **Steady-State Calibration -** the model input parameters and boundary conditions were adjusted to obtain reasonable fit to the range of observed groundwater level elevations and baseflow values. Average groundwater recharge rates generated by the GAWSER model over the 1961 to 2005 GAWSER modelling period, were used as input to the groundwater flow model (see Section 4.1 for additional details).

- **Transient Calibration** - model parameters and the head solution from the steady-state calibrations were used as the starting point for the transient calibration. The transient calibration involved simulation of a 6 week long pumping and shutdown test conducted in the Fergus and Elora wells. The model parameters from the steady-state model produced a reasonable fit to all of the water level hydrographs; however, storage and hydraulic conductivity parameters were iteratively updated to improve the model-simulated fit in the transient calibrations to water level hydrographs (see Figures 12 and 13 and Appendices A and B for observed water level hydrographs). The updated parameter values from the transient calibrations were then applied back into the steady-state models, to re-evaluate the calibration under steady-state conditions. The transient calibration datasets typically had observations near the municipal wells that were tested, whereas the steady-state calibration datasets consisted of observations spread out across a broader area. The steady-state and transient models were iteratively run until sets of parameter values were achieved that minimized the discrepancies between the observed and simulated steady-state and transient observations. Section 4.2 provides additional details regarding the transient calibration, and Appendix C illustrates the calibrated hydraulic conductivity values.

4.1 Steady-State Calibration

During the steady-state calibration process, model input parameters and boundary conditions were adjusted to obtain a reasonable fit to the range of head values reported in the MOECC water well information system (WWIS), as well as higher quality data associated with wells that are monitored by the Township of Centre Wellington and others. The model was also calibrated to gauged baseflow values on Irvine Creek. The calibration was an iterative process of updating input parameters and boundary conditions until there was a match among the simulated hydraulic heads and groundwater discharge values and the observed values.

4.2 Transient Calibration

The transient calibration was another step in the model calibration process whereby the calibrated model output was compared to changes in water levels over time at several monitoring wells within the Fergus and Elora area. This transient simulation was undertaken to replicate the change in water levels resulting from groundwater pumping from the Fergus and Elora wells during the shutdown and pumping tests that took place between September 17, 2012, and October 28, 2012. The transient calibration involved simulating a 6-week period of time that was subdivided into 84 12-hour stress periods, which represent periods in the model where the groundwater pumping and recharge rates were held constant. As noted above, if the simulated response to pumping within the monitoring wells did not match observed responses, spatially variable zones of hydraulic conductivity and specific storage values within each model layer were updated until the model-simulated values aligned well with observed steady-state and transient values. Changes to input parameters made during the transient calibration were incorporated back into the steady-state model so both models have the same input parameters. Groundwater recharge rates were held constant throughout the calibration period using the average annual groundwater recharge rates.

4.3 Calibration Datasets

Establishing a dataset of observations to be used for model calibration is one of the first steps in the development of a groundwater model. The calibration dataset developed comprised all higher quality data located across the model domain as well as all available data of lesser quality. The sections below outline the targets (i.e., wells and estimated flow data) used in the calibration of the groundwater flow model.

4.3.1 Surface Water Dataset

Baseflow is the portion of streamflow that is derived from groundwater discharge. Supplemental sources of baseflow may include managed discharge from reservoirs, discharge from wastewater treatment plants, and flow diversions from outside the watershed. The baseflow measured at a stream gauge, or at one snapshot in time by spot streamflow measurements, includes the component of groundwater discharge, plus other inputs. Recognizing this, as well as the natural seasonal and climatic variability within the groundwater component of streamflow, there is a degree of uncertainty associated with baseflow calibration targets.

To characterize baseflow within and near the model domain, streamflow records from three stream gauges were assessed as part of the characterization phase of the study (Matrix 2017a), including Irvine Creek near Salem (02GA005), Speed River near Armstrong Mills (02GA040), and Eramosa Above Watson Road (02GA012). Of the three stream gauges assessed, only the baseflow estimates for Irvine Creek near Salem gauge were used as a baseflow calibration target (Figure 8) as Irvine Creek and its tributaries are the only gauged surface water features that lie completely within the model domain. Stream gauge data for the main Grand River (e.g., West Montrose gauge) was not included as the hydrologic response at the gauge is influenced by the dam operations at the Belwood Reservoir that are changed on a regular basis. The other two rivers and associated tributaries could not be used as calibration points as large portions of their catchment area are either partially, or fully, located outside the model domain.

The proportion of baseflow at the Irvine Creek gauge near Salem was evaluated using a baseflow separation algorithm using streamflow data from 2007 to 2014 (BFLOW; Arnold et al. 1995; Arnold and Allen 1999). Baseflow was estimated to range seasonally from 0.2 to 1.6 m^3/d with an average annual value of 0.7 m^3/d, which was the target value used in the calibration of the steady-state groundwater flow model. Additional details regarding streamflow characterization can be found in the Matrix (2017a) characterization report.

4.3.2 Steady-State Hydraulic Head Dataset

In the Centre Wellington area, the steady-state head calibration targets were classified as higher and lower quality datasets, based on the number of observed hydraulic head measurements collected within a given well. Wells were defined as higher quality observations when observed head data was collected manually or electronically at more than one snapshot in time. Lower quality data generally were reflective of one head measurement collected at the time the well was drilled. Higher quality hydraulic head data in this study was generally defined as water level or head data that was recorded under controlled or known conditions. Hydraulic head data reported in private wells during the 2012 six week Fergus and Elora pumping test was only collected during the test, and as such, the data are considered higher quality for the pumping test period. In contrast, hydraulic head data observed in Centre Wellington's six high quality monitoring wells has been collected with data loggers on an ongoing basis for several years in surveyed wells, so there is a higher degree of confidence in this dataset.

The goal for establishing a hydraulic head calibration dataset for the groundwater flow model was to achieve a spatial distribution of calibration targets that covered as much of the model domain as possible, while also ensuring that sufficient high quality calibration targets were available close to the Fergus and Elora municipal well fields to capture enhanced, local-scale water level trends and gradients.

Approximately 4,100 water level elevations in wells were used as steady-state calibration targets in the groundwater flow model (Figure 8). Of this, water levels associated with 48 municipal and non-municipal wells were considered to be higher quality data targets, and the remainder were considered lower quality targets derived from water well records in the WWIS. These datasets are described in greater detail in the following sections.

Observed water levels from the WWIS have an expected range of uncertainty of approximately 10 m (i.e., the observed value may be 5 m higher or lower than the value reported in the WWIS). The variability in water level observations is associated with: 1) variability of the water level relative to the time of measurement (i.e., seasonal or annual differences); 2) measurement timing (i.e., levels may not have recovered to static conditions); 3) measurement error or recording errors; 4) well location errors; and 5) measurement point elevation errors. Errors in elevations, either ground surface, screen/open borehole information, or water levels, can also result in monitoring data being assigned erroneously to particular units. As a result, it is common to see scatter with this type of data: individual values have an associated degree of uncertainty, but the trends illustrated by multiple data points are expected to be reasonable.

4.3.2.1 Higher Quality Datasets – Centre Wellington Monitoring Wells

This project focuses on replicating groundwater conditions within and near Fergus and Elora, and as such priority consideration was given to high-quality wells within these areas throughout the steady-state model calibration. The Township of Centre Wellington regularly monitors water levels at all eight active municipal wells (i.e., Wells F1, F4, F5, F6, F7, E1, E3, and E4), and two open bedrock intervals in Fergus Well F2, which is not currently in use. The packer within Well F2 is used to isolate flow into the well from to the bedrock units below the packer.

In addition, water levels from nine monitoring wells (MW1A/B/C-12, MW2A/B/C-11, MW3A/B/C-11, MW4A/B/C-12, MW5A/B/C-11, MW6A/B/C-12, MW-Well 4, MW-Well 17, and MW-Well 19) are regularly monitored by Centre Wellington (Figure 8 and 9). Six of these wells are multi-level wells that monitor deep bedrock units (“A”; Goat Island and Gasport Formation), upper bedrock (“B”; Guelph Formation) and overburden (“C”) intervals, for a total of 18 unique water level monitoring points. Hydraulic head data for these wells represent the highest quality data within the Study Area. Hydrographs illustrating historical water level elevations over time in these wells are found in the physical characterization report (see Appendix D of Matrix 2017a); however, historical manual water level elevations for Well F2 and water level elevations from a pressure transducer for Well 19 were not included in the physical characterization report (Matrix 2017a), but are included in Appendix A of this report.

The aim of the steady-state calibration was to simulate a water level elevation (head) that was within the historic range of observed water level elevations within the higher quality wells. This included water level elevation ranges for 48 monitoring points. This was especially important at the municipal wells where observed water levels are reflective of the instantaneous pumping rate at the time of the observation and not necessarily a longer term trend.

4.3.2.2 *Higher Quality Datasets – Other Data Sources*

In addition to the Township of Centre Wellington, other well owners, and permit to take water holders have collected higher quality water level data across the Study Area (Figures 8 and 9). Average water levels from a total of 17 wells from these sources were included as higher quality calibration targets and include data contributions from the Township of Wellington North (Arthur; 4 wells) GRCA (1 well), Highland Pines Campground (4 wells), and Nestlé Waters Canada (8 wells). The water level datasets provided to the project team are described in the physical characterization report (Matrix 2017a).

The water level data associated with the GRCA Ennotville Well was not available when the physical characterization report was drafted (Matrix 2017a), but the data was compiled and included in Appendix A. This overburden well is located in the southeastern portion of the Study Area (Figure 8).

4.3.2.3 *Lower Quality Datasets – Water Well Information System*

Figure 8 illustrates the location of water well records (WWIS wells) with static water level observations included in the steady-state calibration dataset. These model calibration targets extend across the entire model domain; however, there can be high uncertainty associated with the individual observations. These uncertainties arise from errors in the reported location of the wells, elevation of the well, and water level measurement techniques. In addition, the observed static water levels correspond to the drill date of the well, which in the urban areas of Centre Wellington, may represent water level conditions that are not indicative of present-day pumped water levels. As a result, the MOECC water well records should be considered suitable for use in identifying regional trends in observations, but they are not accurate indicators of an exact water level at a discrete location at the present day.

4.3.3 Transient Hydraulic Head Dataset

As mentioned previously, the transient calibration included the replication of water level drawdown and recovery resulting from the shutdown and pumping tests that occurred over a six week period in 2012 at the Elora and Fergus wells (Golder 2013). Water level elevations were recorded using data loggers at 42 monitoring points during this testing period; these data were used as transient calibration targets and included the following:

- 31 municipal monitoring points within 18 wells (Figure 9) that are part of Centre Wellington's groundwater monitoring program
- 10 domestic water wells (Wells 1, 14, 15, 20, 21, 28, 29, 30, 32, and 33; Figure 9)
- Middlebrook Well (Figure 9)

Observed water level datasets for ten domestic wells were digitized from the Golder report (2013) as digital data were unavailable and used as part of the transient calibration. These digitized observed water level hydrographs are provided in Appendix A of this report.

5 GROUNDWATER FLOW MODEL CALIBRATION RESULTS

The following sections outline the steady-state and transient calibration results achieved in this project. The steady-state model contained pumping rates, calibration targets and groundwater recharge rates representative of the 2016 calendar year.

5.1 Quantitative Assessment of Model Performance

The model input parameter and boundary conditions applied in the model and described in Section 3.8 of this report produced a good match to the observed water level elevations for high and low quality calibrations across the model domain.

To quantitatively evaluate the calibration of a groundwater flow model, a statistical comparison of the differences between simulated and observed water levels at points throughout the model domain is often undertaken. The following list outlines the statistical metrics often applied to evaluate the calibration of a groundwater flow model, and the values achieved in this project.

Normalized Root Mean Square (NRMS) Error = 3.6%. This percentage value allows the goodness-of-fit in one model to be compared to another, regardless of the scale of the model. Typically, a model is considered representative with a 10% NRMS (Spitz and Moreno 1996); however, the NRMS error is dependent on the range of observed water levels.

Root Mean Squared (RMS) Error = 6.2 m. The RMS is similar to a standard deviation, providing a measure of the degree of scatter about the 1:1 best-fit line. This magnitude of residual is reasonable as an error of ± 5 m is generally expected due to errors or uncertainties in well elevation, well coordinates, and seasonal variations in water level elevations that are inherent in the water well record dataset.

Mean Error (ME) = -0.6 m. The mean error is a measure of whether, on average, simulated water levels are higher or lower than those observed (ideally it should be close to zero). This statistic indicates that on average, the simulated water levels are lower than observed by 0.7 m, indicating that a good balance has been achieved between water levels higher and lower than simulated. This further indicates that the regional trends in water levels are well simulated.

Mean Absolute Error (MAE) = 4.7 m. The mean absolute error is a measure of the average deviation between observed and simulated water levels. This magnitude of residual is reasonable as an error of ± 5 m is generally accepted to be inherent in the use of water well record data, reflecting inaccuracies in well elevation, coordinates, and measurements.

5.1.1 Steady-state Calibration to Hydraulic Heads

The fit of the calibration is presented visually for the higher quality monitoring wells and the lower quality domestic water well data as outlined in the following sections.

5.1.1.1 *Calibration to Higher Quality Wells*

The calibration to the higher quality wells is illustrated on Figure 10. The range of observed water level elevations at the well are illustrated on the graph with a thick blue line and they represent the range of observed water level elevations for the full period of record available for each well. The highest quality wells are the pumping and monitoring wells that are monitored on an ongoing basis by Centre Wellington using electronic data loggers. The period of record for each of the higher quality wells varied on a well by well basis and is summarized below:

- Centre Wellington municipal wells: 2011 to December 2016 for Well F5; 2010 to December 2016 for the remainder of pumping wells; and 2008 to December 2016 for Well F2
- Centre Wellington monitoring wells: 2012 to June 2017 for Well 19 and 2012 to June 2016 for the remainder of the monitoring wells
- Nestlé-provided well data: late 2015 to early 2017 (plus 2011-2012 data that predates purchase of the lands by Nestlé)
- Highland Pines data: early 2000s to fall 2015
- Arthur data: 2005 to 2017

The variation in the water level elevations is largest in the pumping wells and monitoring wells located close to the pumping wells and in the same bedrock aquifers, as the water levels change rapidly as the pumping wells cycle on and off. The aim of the model calibration was to match the simulated water level elevations to the range of observed values. The simulated steady-state water level elevations are illustrated on Figure 10 with a yellow circle. The simulated water level elevation lies within the range of observed values for all wells except the following:

- Ennotville Well: this well is an overburden well located south of Fergus. The range in observed water level elevations at the well is approximately 2 m, and the simulated water level elevation is 1.4 m higher than the observed range. The discrepancy is interpreted to be due to local variations in the thickness of the overburden aquifer or aquitard units that are not represented in the groundwater flow model.

- Well 19: this municipal bedrock monitoring well is located northwest of municipal Well E4. The range in observed water level elevations at the well is approximately 4 m, and the simulated water level elevation is 11.3 m higher than the observed range. The discrepancy is interpreted to be due to local heterogeneities in the bedrock near this well that are not represented in the model.

- MW1A-12 and MW2A-11: these high quality municipal bedrock monitoring wells are interpreted to be completed within the Goat Island Formation. The range in observed water level elevations at MW1A-12 and MW2A-11 are 9.1 m and 7.7 m, which is 0.9 m and 0.1 m higher than each well’s observed range, respectively. Similar to Well 19, these small differences are interpreted to be due to local heterogeneities that are not represented in the numerical model.

- MW5B-11 and MW6B-12: these high quality municipal bedrock monitoring wells are interpreted to be completed within the Guelph Formation. The simulated water levels for MW5B-11 and MW6B-12 are 0.7 m and 0.4 m higher than each well's observed range, respectively. This small difference is interpreted to be due to local heterogeneities that are not represented in the numerical model.

- MW1C-12, MW2C-11, and MW3C-11: these three wells are high quality monitoring wells completed in the lower portion of the overburden. The simulated values for MW1C-12, MW2C-11, and MW3C-11 are approximately 2, 4, and 8 m lower than the range of observed values, respectively. These discrepancies are attributed to local variations not captured in the model. These may include heterogeneities in the overburden units or hydraulic connections to smaller wetlands or ponds that may raise the water levels on a local scale.

- MW4C-11, MW5C-11, and MW6C-11: in contrast to MW1C-12, MW2C-11, and MW3C-11, these three overburden wells, have simulated water level elevations that are higher than the range of observed values by approximately 2, 6, and 3 m, respectively. Again, these small discrepancies are attributed to local variations that are not captured in the model, such as spatial distribution of overburden units, groundwater recharge rates, or surface water features.

- OW2 and one of the private wells monitored by Nestlé on Wellington Road 7 have simulated values that lie outside the range of observed values; however, the simulated head for OW2 is within 1 m of the range of observed head values. The private well has an open (uncased) section through the bedrock and so it is not clear which bedrock zone to attribute the monitoring point within the model. Given this uncertainty, the discrepancy between the simulated and observed values is considered acceptable.

- The "East Section" well is located in the Pine Meadows (Highland Pines) area, which sits on the east side of Belwood Reservoir. The well is completed in the bedrock and has a range of observed values that are over 7 m lower than simulated. The discrepancy between the simulated and observed is attributed to local variations in the bedrock near the well, which are not represented in the model. The simulated water levels in the other Pine Meadows and Highland Pines wells lie within the range of observed values.

- Well WN-MW1-00 is an overburden monitoring well for the municipal wells located in Arthur in the northwest corner of the model domain. The well has a simulated water level that is 0.5 m higher than the observed range. This small discrepancy is attributed to local variations that are not captured in the model, such as spatial distribution of overburden units, groundwater recharge rates, or surface water features.

5.1.1.2 Calibration to Lower Quality Wells

Figures 11a, b, and c illustrate the differences between simulated and observed water level elevations in high quality wells, lower quality overburden wells, and lower quality bedrock wells, across the Study Area, respectively. On all three charts, a 1:1 fit (solid diagonal) line and 5 m offset (dashed diagonal) lines are shown to help illustrate the relative fit.

A few areas exist in the model where there are greater deviations in the simulated and observed conditions suggesting the local hydrogeologic conditions are more complex than the model represents; however, the majority of the hydraulic heads lie within 5 m of the observed values suggesting the model replicates the regional groundwater flow within the expected margin of error for MOECC water wells collected over a 60-year period. Figures D1 to D5 in Appendix D illustrate the residuals (difference between simulated and observed values) for the calibration targets across the Study Area on a hydrostratigraphic unit basis. Residuals for the overburden, contact zone, Guelph, Goat Island, and Gasport formations show a fairly uniform distribution of over and under prediction of values, which are expected when the hydraulic head data is collected over many seasons and years, and is of variably quality. Many of the large residuals illustrated on Figures D1 to D5 are associated with lower quality data points.

5.1.1.3 Cumulative Probability Plots

Cumulative probability plots provide another method to assess the difference between observed and simulated water levels (i.e., the residual). Following the guidance of Spitz and Moreno (1996) and Hill (1998), the residuals from a calibration should be normally distributed, confirming that there is no systematic bias in the model results. Where residuals do not follow a normal distribution there may be structural uncertainties in the model, which introduce a limitation to the degree of calibration that is possible.

Figures 11d and 11e illustrate the cumulative probability plots for higher quality and lower quality calibration targets, respectively. Approximately 83% of the higher quality residuals in Figure 11d approximate a straight line, following a normal distribution. Where residuals fall outside of the normal distribution (i.e., outliers), this suggests that these observed water levels may represent small-scale heterogeneities (e.g., bedrock fractures). Achieving a better fit to these points may not be possible given the current model conceptualization.

Similarly, the majority of the lower quality residuals in Figure 11e also approximate a straight line when plotted on a normal probability axis. The outliers identified in this figure may suggest the presence of small-scale heterogeneities in the field; however, they also may highlight lower quality targets where there may be errors in the reported well locations and depths, errors in how the water levels were measured, and spatial differences caused by water levels that may have been collected in different years or seasons, or under different pumping regimes. These types of errors are common among calibration targets derived from water well records.

5.1.2 Steady-state Calibration to Baseflow Estimate

Simulated baseflow of Irvine Creek was calculated in the steady-state groundwater flow model by summing the total groundwater discharge to stream boundary conditions for all calculation locations located upstream of the Irvine Creek near Salem gauge. During calibration, the local hydraulic conductivity values, conductance values, and the river or drain stage were updated to improve the fit between the model-simulated and observed baseflow values.

Calibration was conducted to match simulated and observed discharge. The model-simulated groundwater discharge upstream of the Irvine Creek near Salem gauge was 0.6 m^3/d, and the observed baseflow value ranged from 0.2 to 1.6 m^3/d (annual average 0.7 m^3/d). The fit to observed flows along Irvine Creek is considered good, as the model-simulated baseflow value lies within the range of observed values. The agreement with the observed baseflow values suggests the estimated recharge rates and water balance are reasonable.

5.1.3 Transient Calibration to Hydraulic Heads

The calibration to the water level data collected during the six week pumping and shutdown test is illustrated on a series of hydrographs (Figures 12 and 13) and discussed in the following sections. On all figures, the solid line denotes the simulated drawdown achieved during the transient calibration and the dots on the figures denote the observed drawdown collected within the wells during the six week pumping and shutdown test. The lower portion of each graph illustrates the cumulative pumping from all municipal wells in Fergus (purple line) and the cumulative pumping of all municipal wells in Elora (blue line). The pumping rates applied in the model were averaged over a 12-hour period. As such, if a well was pumped for only an hour or two within a 12-hour period, the short-term spike in observed drawdown was not captured in the model. Many of the wells cycle on and off at short intervals; this explains the discrepancies between the simulated and observed values observed on some hydrographs. The drawdown illustrated on the left hand Y axis of all graphs is referred to as “relative drawdown,” as the pumping wells in the area were all cycling on and off when the test began. Because of this, it was not possible to establish the static water level from which to record drawdown. Rather, drawdown was measured from the water level at the onset of the test. The goal of the transient calibration was to achieve a reasonable match between the simulated and observed drawdown values during the 6 week pumping and shutdown test.

Figure 12a illustrates the simulated and observed water level elevations over time during the transient test within the three Elora pumping wells (Wells E1, E3, and E4). The data logger installed within Well E1 was faulty, and this is why the observed water levels in the well appear to remain constant throughout the test. As such, the upper left hand graph of Figure 12a illustrates the simulated drawdown within the well throughout the test.

The calibration to drawdown within Wells E3 and E4 are also illustrated on Figure 12a, and in both cases there is an excellent match between the model-simulated and observed drawdown values, especially in the early portion of the test, which correlated to the testing and shutdown of the Elora Wells. The interaction with the cycling on and off of the Fergus Wells in the later period of the test is also well simulated.

Figure 12b illustrates the calibration within Wells F1, F2, F4, and F5 in Fergus. The simulated drawdown within Well F1 in the early portions of the test when the Elora Wells were pumping is less than observed; however, the response in the well to the pumping within Well F1 and other wells within Fergus in the latter portions of the test are well simulated. Observed water levels within Well F2 (below the packer) were restricted to the latter 3 weeks of the test, but the model-simulated drawdown correlates well to the observed drawdown values. Similarly, the magnitude and the timing of the simulated drawdown within Wells F4 and F5 align very well with the observed values at these pumping wells.

Figure 12c illustrates the calibration within Wells F6 and F7 in Fergus. Again the model-simulated values at the well are a close match to the observed values throughout the test with excellent agreement in the latter stages when the Fergus wells were the focus of the shutdown and pumping tests. The scatter of high and low observed drawdown values in Well F7 between September 17 and October 15 are due to the 12-hour averaging of pumping rates in the Fergus and Elora wells across this period.

Figure 13 illustrates the calibration within the high quality monitoring wells across the Centre Wellington area using the same formatting as that applied to the pumping well hydrographs illustrated on Figure 12. The upper two hydrographs on Figure 13a illustrate the simulated and observed drawdown over time within MW1A-12 and MW1B-12, located in Elora near Well E3. The A and B horizons of this multi-level well are located in the lower portion of the Goat Island Formation and the upper portion of the Guelph Formation, respectively. The simulated drawdown at MW1-12 is similar to the observed, although the simulated drawdown is underpredicted in the deep (MW1A-12) and shallower (MW1B-12) bedrock system. Overall, the match to the calibration dataset at this well is reasonable.

The two lower hydrographs on Figure 13a illustrate the simulated and observed drawdown over time within MW2A-11 and MW2B-11, located in the northern portion of Elora near Well E1. The A and B horizons for this multi-level well are located in the lower portion of the Goat Island Formation and the upper portion of the Guelph Formation, respectively. The calibration in both wells is reasonable but different to MW1-12; the simulated drawdown at MW2-11 is slightly overpredicted in the deep bedrock (MW2A-11) and slightly overpredicted in the upper bedrock (MW2B-11).

The two upper hydrographs on Figure 13b illustrate the simulated and observed drawdown over time in MW3-11, located in the eastern reaches of Fergus near Well F5. The two lower hydrographs on Figure 13b illustrate the transient calibration in MW4-12, which is located in the northwestern reaches of Fergus near Well F7. Both the A monitoring horizons are located in the Goat Island Formation; MW3A-11 is located in the lower Goat Island (Niagara Falls Member) and MW4A-12 is located in the upper Goat Island (Ancaster Member). Both of the B monitoring horizons are completed in the upper portion of the Guelph Formation. As illustrated on Figure 13b, the match between observed and simulated values in MW3A-11 and MW3B-11 is very good, with a very similar response to pumping between the two wells despite being vertically separated by approximately 70 m.

Within MW4-12, the simulated drawdown at the well is underpredicted in both the upper and lower bedrock horizons throughout the test. Specifically, during the pumping test when the Fergus wells are turned on, approximately 8 m and 5.5 m of drawdown were observed in the MW4-12A and MW4-12B monitoring horizons (Figure 13b). Simulated drawdown over this period was approximately 4 and 2 m at the same monitoring horizons. The discrepancies between the simulated and observed drawdown values are interpreted to be due to the zone of elevated hydraulic conductivity that the monitoring well and Well F7 lie within. A lower hydraulic conductivity zone was mapped less than 500 m west of MW4-12, so it is possible that if the lower hydraulic conductivity zone in the bedrock was shifted east such that MW4-12 would lie within that zone, the simulated drawdown would be greater and better replicate the observed drawdown during the pumping test. As the high hydraulic conductivity zone around the municipal well is limited in spatial extent, and was not carried broadly outside the Fergus area, this discrepancy is not considered significant from an overall water budget or modelling perspective.

Figure 13c illustrates the simulated and observed drawdown over time in MW5-11 and MW6-12, which are located near one another in northeast Fergus near Wells F6 and F4. MW5A-11 is located in the Gasport Formation and MW6A-12 is located in the upper Goat Island (Ancaster Member), while the B monitoring horizon in both wells is located in the upper Guelph Formation (Hanlon Member). As illustrated on all four hydrographs, the match between the simulated and observed drawdown in all four monitoring horizons is very good.

Figure 13d illustrates a selection of other higher quality monitoring wells that were part of the transient calibration. The upper left hand hydrograph of Figure 13d illustrates the simulated and observed drawdown values within the monitoring horizon above the packer in Well F2, within the Guelph Formation. As illustrated, the simulated values are a reasonable match to the observed points. The upper right hydrograph on Figure 13d illustrates the simulated and observed drawdown within the Middlebrook Well. Again, the match between the simulated and observed values at this well is very good. The lower two hydrographs on Figure 13d illustrate the simulated and observed drawdown values over time in Centre Wellington’s Well 19, which is located approximately 1 km northwest of Well E4, and 1 km east of the Middlebrook Well. The match achieved between the simulated and observed drawdown values at this well was very good. Lastly, the calibration at Well 1, a domestic water supply well monitored during the pumping and shutdown test, is illustrated in the lower right hydrograph on Figure 13d. The simulated drawdown achieved during the Fergus area shutdown was a close match to the observed values.

Appendix B contains the simulated and observed hydrographs for all the remaining wells that were monitored in the pumping test. Each of the six higher quality Centre Wellington monitoring wells has a monitoring port in the lower overburden. As noted on the hydrographs in Appendix B, there is very little hydraulic response in these monitoring horizons throughout the pumping tests suggesting the upper portion of the Guelph is a competent aquitard that limits the connection between the shallow overburden aquifers and deeper municipal bedrock aquifers.

5.1.4 Model Verification

Following the model calibration to both steady-state and transient conditions, the model's ability to replicate the groundwater flow system in the Elora area was tested using an independent dataset. This step was undertaken to assess how well the model replicates the complex groundwater flow system and artesian conditions in the vicinity of the Middlebrook Well. An additional transient simulation was undertaken to replicate the hydraulic responses to the 2004 pumping test undertaken at the Middlebrook Well (Gartner Lee 2005). For this model simulation, the Middlebrook Well was simulated to withdraw water at a rate of 1,633 m^3/d for a 30-day period, and the responses in the residential wells documented in the Gartner Lee (2005) report were evaluated. The pumping within the nearby Elora municipal wells were updated to reflect the 2004 average annual pumping rates.

The observed drawdown values in the Gartner Lee (2005) report (Appendix D) were estimated from the water level hydrographs, and are listed in Table 5. Hydrographs for the W1 to W4 residential wells were included in the Gartner Lee (2005) report; however, details regarding the well depths and exact locations were not documented in the report, so the model observation points were estimated using the maps provided in the report and water well information stored in the WWIS and there is uncertainty with the wells selected. Changes in hydraulic head were collected manually and electronically within the four residential wells (W1 to W4; Table 5), as well as the Middlebrook Well, two observation wells (OW1 and GRCA-330-31B), and one mini-piezometer, located near Cascade Creek (see Gartner Lee 2005 for map). The estimated drawdown values observed in the various monitoring points during the test are outlined on Table 5.

TABLE 5 Comparison of Simulated and Observed Drawdown during the 30-day Middlebrook Pumping Test (Gartner Lee 2005)

Well Name	Estimated Observed Drawdown (m; Gartner Lee 2005)	Simulated Drawdown (m)
Middlebrook_Well	10.5	22.1
OW1	0.0	0.2
W1	0.1	1.3
W2	1.9	4.1
W4	0.9	3.4
GRCA-330-31B	1.0	1.0
MP1	0.0	0.0

The simulation results from the 30-day pumping test showed comparable simulated and observed drawdown values for some monitoring wells (i.e., OW1, GRCA-330-31B, and MP1) and an over-prediction of drawdown for other monitoring wells (i.e., Middlebrook Well, W1, W2, and W4). As discussed in previous sections, the hydraulic conductivity values in the bedrock at the base of the Middlebrook Well are interpreted to contain local karst zones, and may be locally higher at the well than simulated in the model. The model does not replicate this local feature; however, the equivalent porous media approach used in this study was able to represent the hydraulic responses in the larger groundwater flow system.

5.1.5 Overall Comments on Model Calibration

This section outlines the lessons learned or insights gained within the Fergus and Elora areas through the calibration of the groundwater flow model. Additional text is also provided in Section 6. The steady-state and transient calibration within the Fergus and Elora areas was guided by the highest quality datasets collected in the Centre Wellington pumping wells and the six multi-level monitoring wells. The transient responses observed at private domestic wells during the pumping test also helped to refine the model input parameters within the model.

The model calibration began with very broad hydraulic conductivity zones within the model that were subdivided as part of the model calibration process, where supported by hydrogeologic data or the conceptual model. The spatial distribution of hydraulic conductivity zones within the model are illustrated on Figures C1 to C5 in Appendix C. The following sections outline the rationale for updates made to the hydraulic conductivity zones within the Fergus and Elora areas as part of the steady-state and transient model calibration.

5.1.5.1 Upper Overburden Aquifer

The upper overburden aquifer represents sands that are associated with the Orangeville and Elmira Moraines, and equivalent sediments. An initial hydraulic conductivity of 5×10^{-5} m/s was estimated uniformly throughout the model layer representing this hydrostratigraphic unit and variability was introduced as part of the calibration process. Hydraulic conductivity values of 6×10^{-4} m/s and 5×10^{-4} m/s were applied to represent the sands north of Fergus near the Arthur area, and sands on the Elmira Moraine southwest of Elmira, respectively (see red areas on Figure C1). Similarly, elevated hydraulic conductivity values of 1×10^{-4} m/s and 8×10^{-5} m/s were applied to the areas east of Fergus and north of Elmira respectively. The shapes of the zones illustrated on the figure were guided by the thickness of the aquifer; in areas where sands were thin or missing, the properties of the underlying Maryhill Till were assigned (hydraulic conductivity values of approximately 1.0×10^{-7} m/s). Higher hydraulic conductivity values were also applied along streams due to weathering.

5.1.5.2 Intermediate Overburden Aquifer

The intermediate overburden aquifer represents Pre-Catfish Creek Outwash sands (Figure C2). The initial hydraulic conductivity of 5×10^{-5} m/s produced good fits with observed data in all areas where the sediments are present, with the exception of the area within the bedrock valley that crosses beneath the Grand River between Fergus and Elora. In this area, the hydraulic conductivity value was lowered to

5×10^{-6} m/s to avoid underdraining the overburden through the bedrock valley. Areas on Figure C2 that represent aquitard material (i.e., blue shading) are areas where the aquifer was not mapped to exist, so the hydraulic conductivity value representing the underlying aquitard was applied.

Zones of elevated hydraulic conductivity values on Figure C2 correspond to areas where bedrock outcrops at surface (i.e., overburden is absent). In these zones, the model layer thins (10 cm) and the elevated hydraulic conductivity values represent the upper fractured bedrock contact zone.

5.1.5.3 Lower Overburden Aquifer and Bedrock Contact Zone

The lower overburden Pre-Canning Aquifer (yellow areas on Figure C3) is discontinuous across the Study Area, and where present was simulated in the model with an initial hydraulic conductivity value of 5×10^{-5} m/s. Zones of elevated hydraulic conductivity values (5×10^{-5} m/s) on Figure C2 correspond to areas where bedrock outcrops at surface (i.e., overburden is absent). In these zones, the model layer thins (10 cm) and the elevated hydraulic conductivity values represent the upper fractured bedrock contact zone. These include bedrock outcrops along the Grand River, and Irvine, Swan, and Cox Creeks.

A 2 m thick contact zone of weathered bedrock was represented in the model with an initial hydraulic conductivity value of 5×10^{-5} m/s. This value matched the high quality hydraulic head data in the central portion of the model; however, a lower value was applied in the west, east, and southeast portions of the model to match the observed hydraulic head data in these areas (Figure C4). The hydraulic conductivity value of the contact zone (and upper Guelph Formation) around Well E1 was reduced to 5×10^{-9} m/s (Figure C4) to achieve 26 m of vertical head difference at MW2-11 observed between the lower overburden and the underlying upper Guelph Formation.

5.1.5.4 Upper Guelph Formation

Hydraulic heads in the Centre Wellington multi-level monitoring wells exhibit strong downward gradients across the upper Guelph Formation. Specifically, the change in head between the lower overburden and upper portion of the Guelph Formation (i.e., monitoring horizons B and C) ranges from 11 to 26 m across this area (note: vertical difference between B and C horizons ranges from 18 to 25 m). This head difference indicates the presence of a low hydraulic conductivity confining unit between the lower overburden and the underlying production aquifer. The notable exception is at MW1-12 where the change in head between the lower overburden and Guelph Formation is only 6 m. One hypothesis is that the B monitoring horizon for MW1-12 lies in the middle of the low hydraulic conductivity unit, rather than beneath it, as the total observed head change between the A and C monitoring horizons in MW1-12 is 21 m, which is comparable to the 26 m observed head change across the same units in nearby MW2-11.

The initial hydraulic conductivity value for the upper portion of the Guelph Formation in the Fergus and Elora area was approximately 1×10^{-7} m/s; however, as the steady-state simulations progressed, the 11 to 20 m observed vertical head differences could not be achieved until the horizontal hydraulic conductivity values for the upper Guelph Formation layers were decreased to 7×10^{-8} to 1×10^{-9} m/s (Figure C5).

5.1.5.5 Lower Guelph, Goat Island, and Gasport Formations

The difference in the estimated hydraulic head values observed in the B horizons (Guelph Formation) and A horizons (Goat Island and Gasport formations) in the Centre Wellington multilevel monitoring wells were minor (<5 m), with the exception of the 16 m observed head difference in MW1-12 (see Section 5.1.5.4). The similarity in observed hydraulic heads where the discrete monitoring horizons are separated by a vertical distance of 80 to 100 m, indicates vertical confining units are absent in this area within the lower Guelph, Goat Island and Gasport formations in the Fergus and Elora area where high quality data exist.

The hydraulic conductivity values in the lower Guelph Formation were increased from 1.0×10^{-7} to 5.0×10^{-5} m/s in the zones beneath the Grand River to allow water to move from the groundwater flow system into the Grand River, and to improve the discrepancy between simulated and observed heads in wells in this area.

As the difference in hydraulic head from the lower Guelph and Gasport formations were observed to be comparable (i.e., <5 m), the initial hydraulic conductivity values applied to represent these bedrock units were comparable and ranged from 3×10^{-6} to 5×10^{-6} m/s based on hydraulic test data and literature values. West of Elora, hydraulic conductivity values in the deeper bedrock units were increased to 5×10^{-5} m/s in the Goat Island Formation and 1×10^{-4} m/s in the Gasport Formation. These values were increased to create the artesian conditions at the Middlebrook Well in the east, and aid in the transient calibration of the municipal wells in Elora.

East of Elora, the initial hydraulic conductivity values applied were a reasonable match to the observed data, with some zones of higher conductivity values applied during transient calibration in the Goat Island and Gasport formations in the areas local to the well fields to match the drawdown responses in the pumping and monitoring wells in Elora and Fergus.

5.2 Qualitative Assessment of Model Performance

The following sections outline the qualitative measures used to assess the model calibration. Models are non-unique and as such, field-based parameter values are beneficial to assess the reasonableness of the input parameters. In addition, the following subsections outline the model-simulated water levels in the lower overburden, upper bedrock, and lower bedrock across the Study Area. These maps are compared and contrasted with the observed water level maps produced by contouring the water levels reported in the MOECC domestic water wells, as well as the additional high quality monitoring data across the Study Area (Section 4.3.2).

5.2.1 Consistency Between the Conceptual and Numerical Models

Assessing the consistency between the conceptual and the numerical groundwater flow model is a qualitative assessment that can be conducted on a groundwater flow model. The following sections compare the conceptual or field-derived values of hydraulic conductivity and storage in the Study Area with those applied in the calibrated groundwater flow model.

5.2.1.1 Calibrated Hydraulic Conductivity Values

Hydraulic conductivity estimates for the overburden units were extrapolated from field-based, local-scale values to other areas within the Study Area. Where available, these field-measured values were used as initial estimates of hydraulic conductivity in the groundwater flow model, and as described in Section 4, the values were altered to improve the match between simulated and observed water levels.

The calibrated hydraulic conductivity values applied in the model were a close match to field-derived values collected in the Study Area or Silurian bedrock formations in the Guelph or Cambridge area. Table 6 compares the field-derived estimates of hydraulic conductivity values with those applied in the calibrated groundwater flow model. The lower end of the calibrated horizontal conductivity value for the upper Guelph Formation (Hanlon Member) is lower than the field-derived range of values. This is because many of the hydraulic tests conducted within and outside the Study Area were targeting new water supply sources, and aimed to complete the wells in zones of enhanced transmissivity. The range of values cited in Table 6 is expected to be on the high side.

TABLE 6 Field-Derived and Calibrated Hydraulic Conductivity Values

Model Layer	Unit	Horizontal Hydraulic Conductivity (m/s)		
		Field-derived Values from Studies in Centre Wellington	Field-derived Values from Studies Outside CW*	Calibrated Values
1 to 8	Overburden	6×10^{-9} to 1×10^{-4}	n/a	5.0×10^{-9} to 5.7×10^{-4}
9	Upper fractured bedrock	2.7×10^{-5}	n/a	5.0×10^{-9} to 5.0×10^{-5}
10	Salina Group	n/a	n/a	2.50×10^{-5}
11 to 14	Guelph Fm	1×10^{-8} to 8×10^{-4}	2×10^{-7} to 9×10^{-4}	1.0×10^{-9} to 5.0×10^{-5}
15	Eramosa Fm - Reformatory Quarry Member	n/a	1×10^{-6} to 1×10^{-3}	5.0×10^{-5}
16	Eramosa Fm- Vinemount Member	n/a		5.0×10^{-8} to 8.5×10^{-6}
17 to 19	Goat Island Fm	6×10^{-7} to 8×10^{-4}	4×10^{-7} to 6×10^{-5}	5.0×10^{-8} to 8.5×10^{-5}
20	Gasport Fm	5×10^{-6} to 9×10^{-6}	6×10^{-7} to 1×10^{-3}	1.0×10^{-6} to 1.0×10^{-4}
21	Lions Head, Irondequoit, Rockway and Merritton Fm	n/a	n/a	1.0×10^{-7}

n/a - field-measured values not available for this unique unit
* from Priebe et al. 2017

As noted in Table 6, the hydraulic conductivity values applied within the calibrated groundwater flow model were within the range of expected values for the overburden and bedrock units. To illustrate the spatial distribution of hydraulic conductivity values, two cross-sections were generated through the model domain (Figure 7 presents cross-section locations) and are discussed below.

Figure 14 is a cross-sectional view of the hydraulic conductivity values applied in the groundwater flow model from Arthur in the northwest, toward Lutteral Creek in the southeast corner of the model domain. As illustrated on the figure, the upper overburden layers contain an upper aquifer unit of variable thickness underlain by Maryhill, Catfish Creek, and older tills. The thickness of aquifers across this area is relatively thin, with the thickest overburden aquifers lying in the Arthur area where the municipal wells are completed.

Figure 14 also illustrates the continuity and low hydraulic conductivity of the upper portion of the Guelph Formation. Water levels collected in all the multi-level wells in Fergus and Elora have a large (up to 26 m) vertical head difference between the lower overburden (overlying the contact zone) and the underlying upper Guelph Formation (Hanlon Member), indicating the presence of a continuous confining unit throughout this area. A horizontal hydraulic conductivity value of approximately 1×10^{-8} m/s was applied in the upper layer of the Guelph Formation, and 1×10^{-7} m/s was applied to the lower portions of the Guelph. The spatial extent of this confining unit beyond Fergus and Elora is not well understood. However, water levels collected in 2011 and 2012 in a multi-level well drilled on Highway 6 south of Fergus (MW08-T3-04) as part of the Guelph Tier Three Assessment (Golder 2011) shows approximately 3 m of head difference across the upper Guelph (Hanlon Member) suggesting the upper confining portion of the Guelph Formation thins as the formation pinches out in the eastern portions of the Study Area (Figure 14). The model-simulated difference in head between the upper Guelph (Hanlon Member) and underlying bedrock units is approximately 6 m at the well, which is considered reasonable.

Observed heads in the lower Guelph (Wellington Member), Goat Island, and Gasport have observed water levels in multi-level wells that are very similar; the difference in head between the Guelph and Gasport is observed to be less than 5 m (despite the fact these two monitoring horizons are vertically 60 to 80 m part) in many wells, indicating the absence of confining units in the lower bedrock in this area. The same trend in water levels is seen in MW08-T3-04 south of Fergus where the change in hydraulic head between the lower Guelph Formation and the Gasport Formation is less than 50 cm (presented in Appendix C of Golder 2011).

As noted in the physical characterization report (Matrix 2017a), few boreholes extend through the thick overburden into the bedrock in the area near Ariss. As such, the nature of the bedrock and groundwater flow in this area is not well understood. The Middlebrook Well, located on the west side of the Grand River, is a flowing artesian well, and flow meter and packer testing data indicates that most of the inflow to the well is derived from the lowermost 3 m of the well (Lotowater 2015b). Groundwater flow into the well above this zone was estimated to be less substantial, so the hydraulic conductivity values in the bedrock were updated to account for this. Specifically, the hydraulic conductivity values of the Ancaster Members of the Goat Island Formation were decreased, and the hydraulic conductivity value of the lowermost Goat Island layer (Niagara Falls) and the underlying Gasport Formation were increased (Figure 14). These changes led the model to simulate a steady-state water level elevation at the Middlebrook Well that is consistent with average conditions and an excellent fit to the water level response during the Elora shutdown and pumping test.

Figure 15 illustrates a cross-sectional view of the hydraulic conductivity values applied in the groundwater flow model from just outside the Elmira area in the southwest to near Marsville and the Orangeville Moraine in the northeast. As illustrated on the figure, the upper overburden units were assigned a higher hydraulic conductivity value on the right side of the cross-section to simulate the sand-rich outwash sediments associated with the Orangeville Moraine. In the west, the Maryhill and Catfish Creek Tills are laterally continuous, except where cross-cut by the Grand River. Similar to Figure 14, the hydraulic conductivity values in the Goat Island and lower Guelph Formation (Wellington Member) are lower in the west than the east but all values are within the range of field-derived values. As noted on Figure 15, the Guelph Formation thins from west to east and pinches out just east of the Study Area. The Reformatory Quarry Member of the Eramosa Formation is thin, but present in the eastern portion of the model (Figure 15). The hydraulic conductivity of the Guelph Formation (Hanlon Member) along the Grand River was increased to reflect weathering of the bedrock along this regional discharge feature. Appendix C illustrates the spatial distribution of hydraulic conductivity values applied within the model domain within the overburden aquifers and the bedrock formations.

5.2.1.2 Calibrated Storage Parameters

Table 7 lists the specific storage values applied in the calibrated transient model. As noted in Section 3.8.2, there were few field-derived estimates of specific storage within the Study Area with which to guide the model calibration. The assignments of the final calibrated values were guided to a larger extent by literature values and values applied in groundwater flow models applied in the nearby City of Guelph (AquaResource 2014) and Region of Waterloo (AquaResource and SSP&A 2014). The fit to the transient calibration data suggests the values applied are reasonable and within the expected range for the aquifer conditions.

TABLE 7 Storage Parameter Estimates Applied in the Groundwater Model

Model Layer	Unit	Calibrated Specific Storage Value (1/m)
1 to 8	Overburden	1.0×10^{-4} to 2.0×10^{-4}
9	Overburden and upper fractured bedrock (contact zone)	2.0×10^{-4}
10	Salina Group	2.5×10^{-6}
11 to 14	Guelph Formation	1.0×10^{-7} to 5.0×10^{-6}
15	Eramosa Formation - Reformatory Quarry Member	2.5×10^{-6}
16	Eramosa Formation - Vinemount Member	2.5×10^{-6}
17 to 19	Goat Island Formation	5.0×10^{-7} to 5.0×10^{-6}
20	Gasport Formation	1.0×10^{-6} to 5.0×10^{-6}
21	Lions Head, Irondequoit, Rockway and Merritton formations	7.5×10^{-7}

5.2.2 Simulated Water Levels and Potentiometric Surfaces

The quantitative assessment of the model presented in Section 5.1 above is based on individual observation point locations scattered throughout the 3D model domain. To get a more complete picture of the spatial fit between model-simulated and observed data, contours of potentiometric surfaces were compared. The physical characterization report (Matrix 2017a) presented contour maps of interpreted water levels for overburden, shallow bedrock, and deep bedrock aquifers. The maps of the interpreted (observed) water level elevations for the lower overburden and bedrock units involved interpolation of hydraulic head data from water wells; surface water features were not incorporated in the development of the surfaces where it was unclear if they should constrain deep water levels. The following sections compare those simulated potentiometric surface contours with the model-simulated contours.

Figures 16 to 18 illustrate the simulated water level elevation in the overburden, and the potentiometric surfaces in the shallow and deep bedrock, respectively. The simulated values are illustrated as coloured surfaces with 20 m contours (grey, solid lines), and the observed contours are represented with blue, dashed lines.

5.2.2.1 Simulated Overburden Water Level Elevations

Figure 16 illustrates the simulated water level contours produced in the steady-state groundwater flow model (in the Pre-Catfish Creek Outwash Aquifer; Model Layer 5), and the observed water level contours from wells completed in overburden aquifers. The majority of the water wells in the Study Area are completed in the bedrock aquifers, and as such, there are few data points available to create the overburden water level surface (Figure 16). As illustrated, the model-simulated and observed water table contours follow ground surface topography, with a high of 475 m asl along the northern model boundary falling to approximately 340 m asl along the Grand River at the southern extent of the model domain. The general groundwater flow direction is from north to the south with some flow to the west toward the Conestogo River. The Grand River, Belwood Reservoir, and portions of the Irvine River and Swan Creek receive groundwater discharge, as indicated by the deflections in the simulated and observed contours along these features. The simulated contours show close alignment with the observed data, especially along the south model border and around the communities of Elora and Fergus. Discrepancies were noted in the area north of Belwood Reservoir along the Grand River where the observed water levels were generated by interpolating water well data without surface water constraints. Through the calibration process, the connection between the lower overburden and the Grand River was identified and this connection was incorporated in the model. Additional small-scale discrepancies between the simulated and observed contours were also noted in some areas and may be due to the multiple overburden aquifer units.

5.2.2.2 Simulated Upper Bedrock Potentiometric Surface

Figure 17 illustrates the simulated and observed upper bedrock potentiometric surface map. Groundwater flow directions in the contact zone are similar to flow directions in the overburden. Flow is interpreted and mapped to extend from the north to the south with local deviations (i.e., within 5 km) in flow toward the Grand River. The bedrock contours are smoother than the overburden contours and are at a lower elevation due to the downward gradients across the low permeability tills present north and south of the Grand River. The match between the simulated and observed water levels is good, with some local level discrepancies. One of those is the Alma area where depth to bedrock is over 75 m and there are few water wells that extend into bedrock in this area. As such, the contoured water level elevations in this area are based on few bedrock wells of lower quality.

5.2.2.3 Simulated Lower Bedrock Potentiometric Surface

Figure 18 illustrates the simulated and observed lower bedrock potentiometric surface map. Groundwater flow directions are comparable to the upper bedrock except the simulated and observed contours are smoother across the Study Area as the influence of ground surface topography and surface water features are more subdued. In addition, the observed groundwater contours illustrated on Figure 18 in the areas outside Fergus and Elora were created using hydraulic head data stored within the WWIS and a few additional high quality wells. In these areas, water wells that extend deep into the Goat Island or Gasport formations are rare (especially in the west), so there is limited data in this area to capture heterogeneities in the bedrock surface, such as bedrock valleys. As such, actual groundwater flow directions within the deep bedrock formation may vary locally from what is presented on these maps and what the model simulates. It is acknowledged that local-scale features may exist and they have the potential to influence the local groundwater flow directions and gradients. All the available data was used within the Study Area but it is acknowledged that data and knowledge gaps exist (see Section 7). Despite these gaps, there is good agreement between the simulated and observed potentiometric surfaces within the Study Area, which increases the confidence in the use of the groundwater flow model as tool that can help make water management decisions.

5.2.3 Groundwater Discharge to Surface Water

Part of the Tier Three Risk Assessment involves examining the potential impact of increased municipal pumping on other water uses such as streams or rivers that host coldwater fish communities. Within the Study Area, streams mapped as hosting coldwater fisheries include the Grand River, Swan Creek, and Irvine Creek among others (shown on Figure 4 of the characterization report [Matrix 2017a]). Local water budgets conducted on these streams confirmed net groundwater discharge into these features, which is consistent with their characterization as coldwater streams. Without field observations, simulated flows cannot be verified; however, the baseflow calibration to the Irvine Creek gauge near Salem (Section 5.1.2) was deemed to be very good.

5.3 Overall Groundwater Model Calibration Assessment

Overall, the results summarized in this section illustrate a very good level of model calibration. The ability of the groundwater model to simulate the flow system in the Study Area was evaluated both quantitatively and qualitatively. Quantitatively, simulated hydraulic head and baseflow measurements closely match observed values to achieve a statistical calibration that meets industry standards (Spitz and Moreno 1996). The calibrated conditions are also confirmed by the ability of the model to reproduce observed flow directions and gradients. Regionally, the error based on the difference between observed and simulated water levels is minimized and there are no spatial trends in this error that are expected to impact the model predictions. Locally, the simulated heads at most of the municipal monitoring network wells were close to observed values and the model accurately predicts the flow system response to stresses due to pumping of the municipal aquifer and finally, simulated groundwater discharge rates agree with the baseflow estimates. Qualitatively, the simulated groundwater level contours and vertical hydraulic gradients are consistent with observed conditions. The calibration was achieved using input parameter values that are within the expected range or measured range for the groundwater system in the area. Overall, the match between simulated and observed values indicates the groundwater flow model is well calibrated to steady-state and transient conditions and suitable for use in making predictions regarding the sustainability of the water supplies in the Fergus and Elora area.

The ability of the model to represent observed hydrogeological conditions confirms that the hydrogeologic interpretation is reasonable and consistent with the available data. Observations providing confidence in the current interpretation include:

- Simulated groundwater levels are generally consistent with measured values. This is evident through matching of observed horizontal gradients (e.g., contour maps) and vertical gradients (e.g., at observation well pairs or multi-level installations).

- Model parameter values, such as hydraulic conductivity, are consistent with the conceptual hydrostratigraphic units (i.e., aquifers and aquitards have parameter values that are consistent with that conceptualization).

- Groundwater recharge rates are consistent with understanding of the shallow water balance (i.e., partitioning of precipitation to evapotranspiration, overland runoff, shallow interflow, and deep groundwater recharge).

- Groundwater discharge rates to surface water bodies are consistent with observed discharge rates. Cumulative discharge over a larger area (e.g., entirety of the Irvine Creek subwatershed) provides more-reliable evidence of recharge-discharge conditions over a larger area.

- The model's ability to achieve an exceptional match to observed transient water levels observed during the six week pumping and shutdown testing (Golder 2011) increases confidence in the conceptual model and parameterization.

The above calibration evidence supports the applicability of the numerical model to assess the sustainability of the municipal aquifer system.

6 GROUNDWATER FLOW SYSTEM AND WATER BUDGET INSIGHTS

The development and calibration of groundwater flow models provides insight and an enhanced understanding of how groundwater moves through the subsurface. Insights are gained regarding where the largest quantity of flow occurs, where water originates, and where water discharges to surface water features under current conditions. Much of this understanding can readily be conveyed through the presentation of a water budget, which is the accounting of the inputs and outputs associated with the flow of water through a given area.

Through the physical characterization, model development, and calibration portions of this project, groundwater flow into the deep bedrock aquifers (i.e., Goat Island and Gasport formations) was found to be dominantly derived from local precipitation that slowly infiltrates and recharges the groundwater system. While groundwater recharge rates in the northwestern portions of the Study Area on the Tavistock Till Plain are lower than other areas in the Grand River Basin, this diffuse recharge is estimated to be the dominant inflow of water (approximately 81%) into the Study Area. Most of the recharge entering the groundwater flow system ends up discharging to streams and other surface water features, with only a small fraction (4%) of the total water flowing into the area being captured by municipal or non-municipal pumping wells; the remaining water (8%) continues to flow in a southerly direction within the groundwater flow system outside the Study Area. Much of the groundwater recharging into the ground remains in the overburden and shallow bedrock aquifers and flows toward discharge locations; while a smaller portion (approximately 10%) recharges the deep bedrock (i.e., Goat Island and Gasport formations) flow system.

The approximate age of the groundwater (i.e., time it takes water to infiltrate and flow through the subsurface to a discharge location) was estimated using the groundwater flow model. Groundwater captured by the Fergus and Elora municipal wells was estimated to range from less than 50 years to over 500 years, depending on the depth of the well and casing, and the nature of the geologic units overlying the production aquifer. This relatively slow travel time through the regional aquifer suggests these wells may be more resilient to drought conditions.

6.1 Groundwater Water Budget Components

The following sections further explain details about the groundwater water budget components and the water budget rates (and percentages).

6.1.1 Groundwater Recharge

As described previously, the GRCA developed a GAWSER continuous streamflow generation model to simulate the hydrologic processes within the Grand River Watershed. The hydrologic model was developed in the late 1980s for flood forecasting purposes, and since that time the model was periodically refined as new information became available. The event-based model was converted to a continuous streamflow generation model in the late 1990s, and the model was calibrated and verified.

As part of the GRCA's Source Protection Water Budget studies (i.e., Tier Two Assessment) the GAWSER model was again updated and refined, with a specific focus on representing low flow conditions driven by groundwater recharge. The GAWSER model was further updated as part of the Tier Three studies completed for the City of Guelph and Township of Guelph/Eramosa (Matrix 2017b), and the Region of Waterloo (AquaResource and SSP&A 2014). The groundwater recharge values within the water budget were derived from the Tier Two Assessment with minor updates, noted in Section 3.7.3.

6.1.2 Groundwater Demands

Average annual demands in this study were updated (Section 3.7.4) with respect to the Tier Two Assessment pumping rates. The groundwater demand represents the cumulative groundwater extraction from permitted and non-permitted wells. Municipal and large permitted water taking rates were based on reported values provided to the Province's WTRS. Estimates of clusters of domestic water takings and agricultural water takings were based on the best available data, and have some uncertainty as they are estimated and not reported values.

With respect to the Tier Two Assessment, the Tier Three Assessment's average annual demand within the Irvine Creek subwatershed area decreased by over 50%, reflecting the additional efforts undertaken in the Tier Three Assessment to accurately capture actual water demands within the Study Area.

6.1.3 Cross-Boundary Flows (In/Out of the Model Domain)

As noted below in Section 6.2, the majority of the water flowing through the Study Area is simulated to originate from groundwater recharge within the Study Area (98%) while regional inflow to the Study Area (i.e., across the model boundary) was simulated to be minor (2%). This is typical for most subwatersheds in Ontario; as our regional topography is relatively flat there is little potential energy to drive groundwater flow over large distances (i.e., tens of kilometres).

The net magnitude of cross-boundary flows along six segments (i.e., A, B, C, D, E, and F) of the model domain boundary were evaluated in greater detail for overburden layers, upper bedrock layers (Guelph Fm.), and lower bedrock layers (Eramosa Fm. to Gasport Fm.) on Figures 19a, 19b, and 19c, respectively. Lateral flow through the overburden (Figure 19a) is simulated to be a net outflow from the model domain along the southern (segment E) and southwestern (segment D) model boundaries, where net outflows are approximately 1,500 and 1,100 m^3/day, respectively. Some of this water will discharge into nearby rivers and streams. Similarly, lateral flow through the upper bedrock (Figure 19b) is simulated to be a net outflow along the southern (segment E), southwestern (segment D) and western (segment C) model boundaries, ranging from 450 to 10,700 m^3/day. In the lower bedrock (Figure 19c), a net inflow of 250 to 2,500 m^3/day is simulated along the northern (segment B) and northeastern (segment A) model domain boundaries. Similar to flow in the shallower units, net outflows in the lower bedrock ranging from 2,450 to 3,050 m^3/day are simulated along the southwestern (segment D), southern (segment E), and southeastern (segment F) boundaries.

Although there are uncertainties with respect to the absolute amount of cross-boundary flow along each of the segments, the total net cross-boundary flow is a relatively small part of the water budget. The boundary conditions assigned to those segments of the model were estimated from reported water level elevations, and the calibration results suggest that the model's prediction of shallow and deep groundwater flow generally reflects actual conditions.

6.2 Water Budget Summary

Water budget components for the simulated groundwater flow system derived in this Tier Three Assessment and the previous Tier Two Assessment (AquaResource 2009a, 2009b) are summarized in Table 8. Values are presented as both a representative depth of water over the Study Area (expressed in units of mm/y) and as a percentage of the total groundwater inflow or outflow.

As shown in Table 8, the dominant water input to the model is groundwater recharge (i.e., surficial infiltration of precipitation) while cross-boundary flows play a comparatively smaller role. Groundwater discharge was simulated to streams, lakes, and wetlands located within the model and cross-boundary flows represent a relatively small portion of water that leaves the model domain. A small portion of the total groundwater flow system is also removed via groundwater pumping wells.

As Table 8 illustrates, similar water budget components were obtained in both the Tier Two and Tier Three Assessment groundwater flow models. The amount of water withdrawn by groundwater wells was greater in the Tier Two Assessment model and is associated with the refined level of effort that went into characterizing the water demands within this Tier Three Assessment. Cross-boundary flows were also larger in the Tier Two Assessment model due to the differences in the characterization of bedrock units.

TABLE 8 Groundwater Budget for the Study Area

In/ Out Flow	Component	Flow (mm/y)		Percentage of Total (%)	
		Tier Two	Tier Three	Tier Two	Tier Three
Inflow	Groundwater Recharge	157	138	100%	98%
	Cross-boundary Flows	-	2	-	2%
	Total	157	140		
Outflow	Net Groundwater Discharge to Surface Water Features	125	124	80%	88%
	Groundwater Demand (Pumping Wells)	12	5	8%	4%
	Cross-boundary Flows	20	11	12%	8%
	Total	157	140		

The average annual groundwater recharge rate applied in the Tier Three Assessment groundwater flow model was 138 mm/y (98%; Table 8), while inflows across the model boundary were 2 mm/y (approximately 2%). Simulated groundwater discharge to surface water features was estimated to be 124 mm/y (88%), while permitted and non-permitted groundwater pumping was 4% of the total outflow. The remaining component of groundwater outflow was cross-boundary groundwater flow, with a rate of 11 mm/y (8%; Table 8).

With respect to the deep bedrock aquifer units (i.e., Gasport and Goat Island), approximately 6% of the groundwater recharge within the model is simulated to penetrate to this aquifer, while inflow from the northern boundary of the model is less than 1% of the recharge. The spatial distribution of downward gradients across the upper Guelph Formation aquitard indicates downward flow occurs throughout the majority of the Study Area, while upward (i.e., discharge) gradients are focused beneath major river systems (e.g., Grand River). Pumping from the municipal wells enhances downward gradients locally; with the pumped volume representing about 25% of the flow through the lower Guelph, Goat Island and Gasport formation aquifers, while the remainder of the flow continues to flow downgradient or discharge to major surface water features.

7 DATA GAPS

Through the development the physical characterization of the groundwater flow system, and the development and calibration of the groundwater flow model, some areas within the Study Area were identified where the understanding of the groundwater flow system is limited due to lack of data. Data gaps represent areas where additional data could be collected to refine the geologic or hydrogeologic conceptual model and be used to enhance future versions of the groundwater flow model. The Tier Three Assessment groundwater flow model is a tool that represents the current state-of-the-knowledge of the groundwater system and can be revised periodically when new information or knowledge becomes available.

The current conceptual knowledge of the depositional environments affecting the formation of overburden or bedrock guided the development of conceptual model input parameters. Model input parameters were kept as simple as possible, with heterogeneity introduced in areas where supported by hydrogeologic data.

Groundwater flow models are simplifications of the real world environment and data gaps are present in virtually all groundwater flow modelling studies. An important question remains as to the impact of those data gaps or unknowns on the model's ability to make predictions. This Risk Assessment phase of the Tier Three Assessment will include further assessment of the impact of uncertainty on model predictions

The following sections outline the data gaps identified within the Study Area.

7.1.1 Continuity and Thickness of Bedrock Formations

The continuity and thickness of the bedrock units within the Study Area beyond the locations where bedrock cores or higher quality lithologic/geophysical data exist represent data gaps. While there are abundant water well records in the Study Area, driller's descriptions of "grey rock" or "brown limestone" do not support the confident subdivision of the carbonate bedrock units in the Study Area.

The OGS staff reviewed core data, where available within the Study Area; however, where high quality data are unavailable, bedrock units were assumed to be of uniform thickness. This assumption is based on the geologic understanding that many of these units were deposited in marine environments where we would expect a degree of spatially continuity of geologic units. Where data points are closer together, confidence in the geologic interpretation is higher, but this confidence decreases at distances from the high quality data points.

The thickness and continuity of the Gasport Formation north and west of Elora represents a data gap as the Gasport Formation lies 200 to 300 m below surface in this area, and few boreholes penetrate to this depth. Consequently, the continuity of this bedrock unit (and others) is assumed to change uniformly between the available high quality data points.

One additional area of uncertainty is an interpreted depression in the bedrock surface northwest of Elora. Overburden is thick in this area, and there are few wells penetrating to depth to characterize: a) the deep overburden and bedrock units and, b) the groundwater flow directions and vertical gradients in this area. The depth to bedrock was defined based on the available water well data in the area; however, the depth to bedrock may be higher or lower than observed and change the way the Guelph Formation is represented in this area.

7.1.2 Hydrogeologic Properties of Interpreted Bedrock Formations

In addition to knowledge gaps associated with the continuity and thickness of bedrock formations in areas outside high quality data points, there is uncertainty with respect to the interpreted hydraulic properties assigned to those bedrock units where hydraulic test data or high quality multilevel monitoring data are unavailable. In areas where high quality data are unavailable, bulk properties of the bedrock units were assumed to be similar to those in areas where the high quality observation data exist. While local level differences may occur, conditions were assumed to be uniform. Within the Study Area, high quality lithologic and water level data exist within the towns of Fergus and Elora, but as we move away from these areas to the north and south, our confidence in the interpreted hydraulic parameters of the various overburden and bedrock formations is reduced. Specifically, the data available to characterize the hydraulic properties of the upper portion of the Guelph Formation (Hanlon Member) is a data gap. This unit is a key hydrostratigraphic unit in the Study Area as it acts as an important barrier to vertical flow between the overburden and the underlying deeper bedrock formations. Field-based hydraulic test data are unavailable to help constrain the hydraulic properties of this unit, so the properties of the member were assumed through model calibration and best estimates based on the interpretation of the formation’s lithology.

There are also knowledge gaps with respect to the 3D continuity of bedrock production zones, or inferred areas of karstic bedrock. These zones were inferred to exist in discrete locations at several pumping wells, the Middlebrook Well and DDH-05 in the Study Area; however, the lateral and vertical continuity of these local-scale higher transmissivity features between boreholes represents a knowledge gap. Within this study, areas with enhanced fractures (interpreted karst) are observed and simulated in the groundwater flow model using an EPM approach. This means the individual zones were not discretely represented; rather areas with elevated hydraulic conductivity values were simulated in the model to replicate the broader hydraulic response of these features. The calibration to pumping wells and nearby monitoring wells indicates this approach is reasonable.

7.1.3 Groundwater Recharge Distribution

Groundwater recharge is the driving force of the groundwater flow system, yet it is difficult to reliably measure at a regional or well field scale. Instead, we are reliant on water partitioning simulations to estimate recharge rates; such simulations are based on well-documented physical processes, but are generally difficult to validate due to a lack of local field data. For this study, recharge was estimated from the results of a watershed-based streamflow generation model (GASWER), which utilizes physics-based computations across the watershed and is calibrated to available streamflow gauge locations. As such, it produces a realistic distribution of groundwater recharge, with a series of inherent assumptions. One such assumption is the portion of groundwater recharge that will enter the deep groundwater system and bypass local stream-gauge locations. Another is that evapotranspiration, which is simulated annually in GAWSER, remains constant over time on cropped and forested areas.

In this study, the groundwater recharge rate through the Tavistock Till in the northeastern portion of the Study Area represents an important knowledge gap, as this is interpreted to be a major source of groundwater input in the Study Area.

7.1.4 Surface Water Monitoring Data

Surface water features such as streams and lakes are typically an expression of the groundwater table above ground surface. Streamflow measurements within the Study Area are sparse, and the number of locations and the frequency of surface water monitoring are data gaps. Streamflow measurements could be used to enhance the baseflow calibration and improve our confidence in the representation of the groundwater and surface water interaction in the groundwater flow model. Increasing the number of streamflow monitoring locations could provide insight into areas where reaches are receiving significant groundwater contribution. It could also improve understanding on the spatial distribution of groundwater recharge.

7.2 Conclusions

Despite the knowledge and data gaps presented above, the groundwater flow model represents the best available understanding of the groundwater flow conditions across the Study Area at this time. During the course of this study, all available data sources were consulted to develop a conceptual understanding of the groundwater flow system. This conceptual framework was built into the hydrologic and groundwater flow models and the understanding was refined during the model calibration process.

8 GROUNDWATER MODEL LIMITATIONS

Regardless of the level of refinement of the groundwater modelling analysis, uncertainty in subsurface hydrogeologic continuity and parameters cannot be eliminated. Numerical models are approximations of the real world, natural environment and generalizations are necessary to take a complex hydrogeologic system and bring it into the numerical environment. The distribution of data points and the lesser quality of some data (e.g., geological descriptors in water well records) means that assumptions need to be made. Outside Fergus and Elora, the number of boreholes available to characterize the geology and hydrogeology in the bedrock is limited as groundwater resources have not been explored in these areas. Consequently, there is uncertainty associated with the layer structure and the properties applied in the model, especially in areas further away from the municipal wells and high quality data points. The model parameters were applied uniformly and guided by knowledge of the regional depositional environments that the overburden and bedrock units were laid down within.

The groundwater flow model was designed to incorporate the key hydrogeologic features of the regional Study Area and localized features (noted in the physical characterization report [Matrix 2017a]) beneath and surrounding Fergus and Elora. Small-scale features located outside the municipal well field areas, where higher quality wells are unavailable, are not represented in the model. As such, additional data collection, characterization, and calibration of the model may be required if predictions are requested in areas that lie outside the focus area of this study, including in the vicinity of the Middlebrook well. The groundwater flow model may be used to address water budget questions within the Fergus and Elora areas; however, additional characterization and refinement of the model may be necessary to characterize the groundwater flow system before it is applied to help address site-specific questions regarding changes in water levels or contaminant fate and transport.

As noted above, uncertainties exist within the model layer structure and parameters in the areas where the interpretations are not supported by high quality data. These uncertainties will be evaluated when applying the groundwater flow model. The groundwater flow model is suitable for use as a tool to evaluate the potential effects caused by municipal and non-municipal pumping in the Centre Wellington area. Potential effects include declines in water levels in the bedrock over periods of months to years, interference between wells, and changes to overall water budget components. The model is also suitable for use in evaluating changes in water levels and groundwater discharge under different land development scenarios and under short-term (e.g., 1-2 year) and long-term (e.g., 5-10 year) droughts.

9 SUMMARY

This report describes the development and calibration of a FEFLOW groundwater flow model developed for the Fergus and Elora Study Area. The model layers were developed from a conceptual model that was developed during the characterization phase of this study, which included interpretations of the overburden and bedrock stratigraphy from the OGS (Burt and Dodge 2016; Priebe et al. 2017).

The model was calibrated using recharge estimates developed using the GAWSER streamflow generation model. The GAWSER model estimates of recharge were used as boundary conditions to the FEFLOW groundwater flow model. The model calibration focused on matching observed baseflow at Irvine Creek, as well as observed water levels in 48 high-quality monitoring wells and to static water levels reported in the MOECC water well database. The model was also calibrated to transient conditions observed during a shutdown/pumping test in 2012; the transient calibration used high quality observation data that was collected during a six week period in late 2012. The calibration results suggest the model is well calibrated to steady-state and transient conditions. This numerical model reflects the most up-to-date hydrogeologic understanding and is effective at replicating field-observed conditions.

Groundwater flow models are important tools for municipal water managers and are ideally updated and refined periodically to reflect the evolution of the geologic or hydrogeologic conceptualization. The OGS and researchers at the G^{360} Institute for Groundwater Research are currently conducting work in this area, and it is recommended to update the model as new data becomes available from this research.

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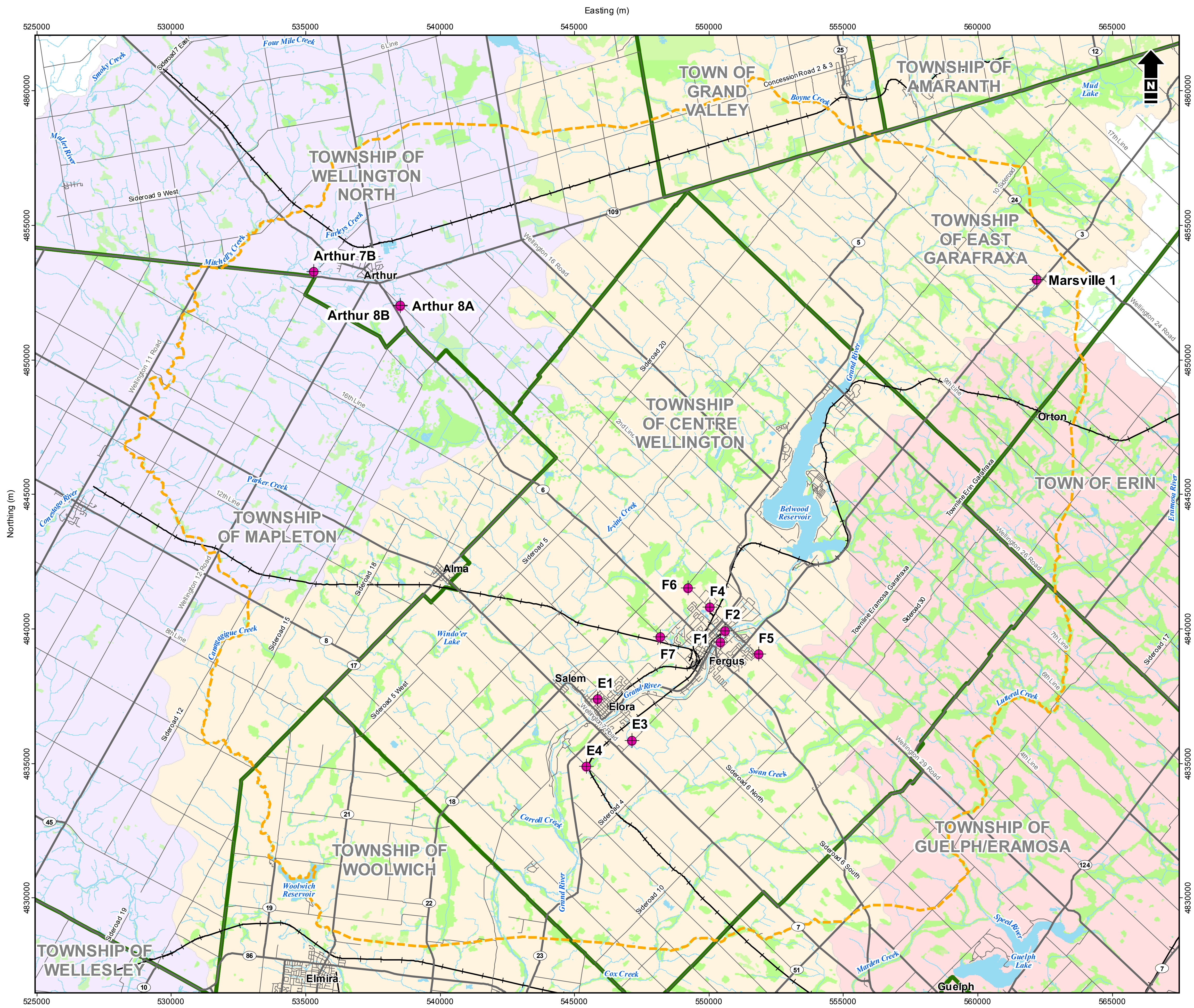

Study Area
Municipal Boundary
Wetland
Water Body
Watercourse
Highway
Road
Railroad Trail
Municipal Well within the Study Area

Subwatershed Boundary

Conestogo River
Grand River
Speed River

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministry of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000

1,400 0 1,400 2,800 m

NAD 1983 UTM Zone 17N

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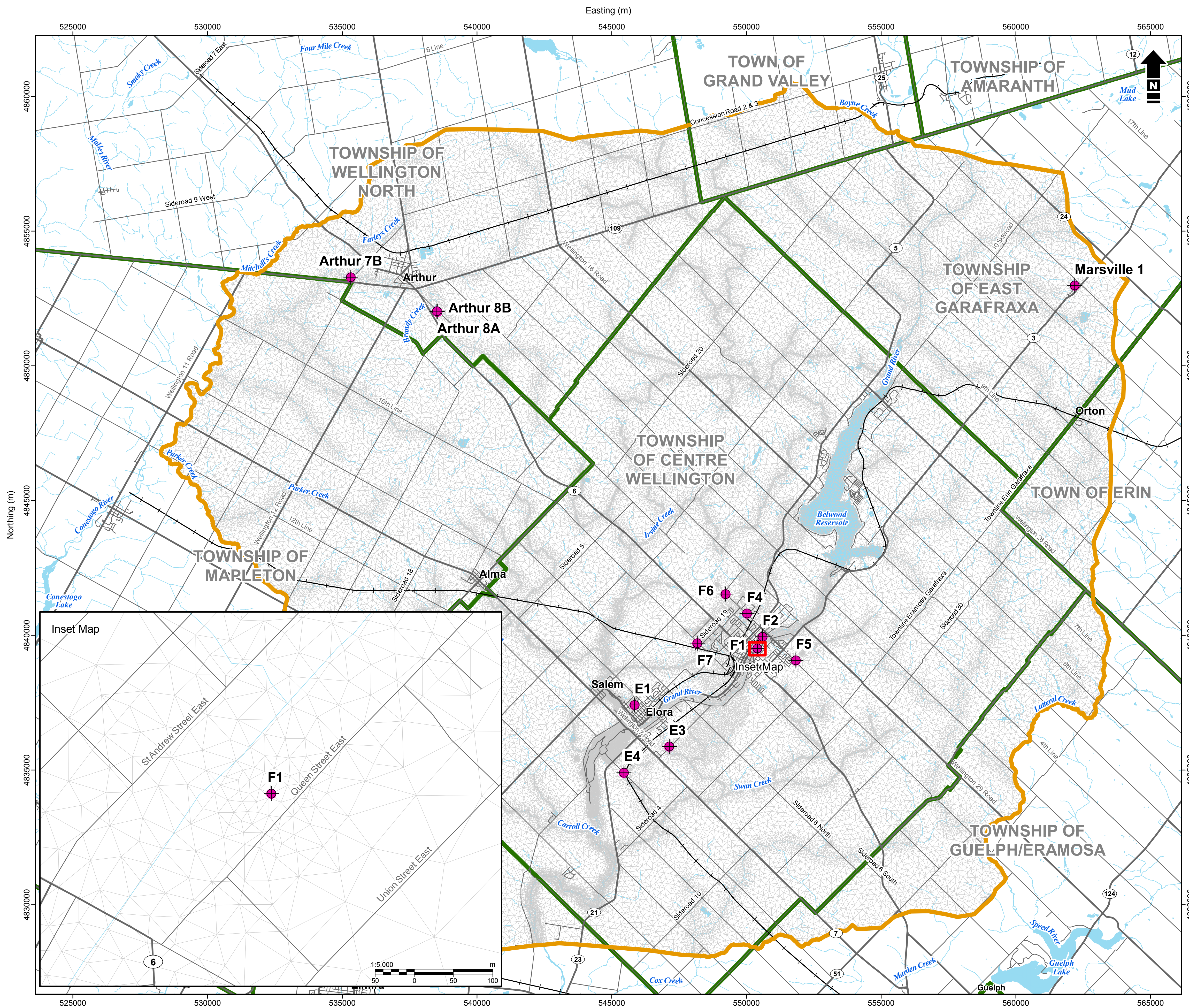
Centre Wellington Tier Three Model Development and Calibration Report

Study Area

Date:	Project:	Technical:	Reviewer:	Drawn:
10 Jan 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 1



Study Area
Finite Element Mesh
Municipal Boundary
Water Body
Watercourse
Highway
Road
Railroad Trail
Municipal Well

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Finite Element Mesh

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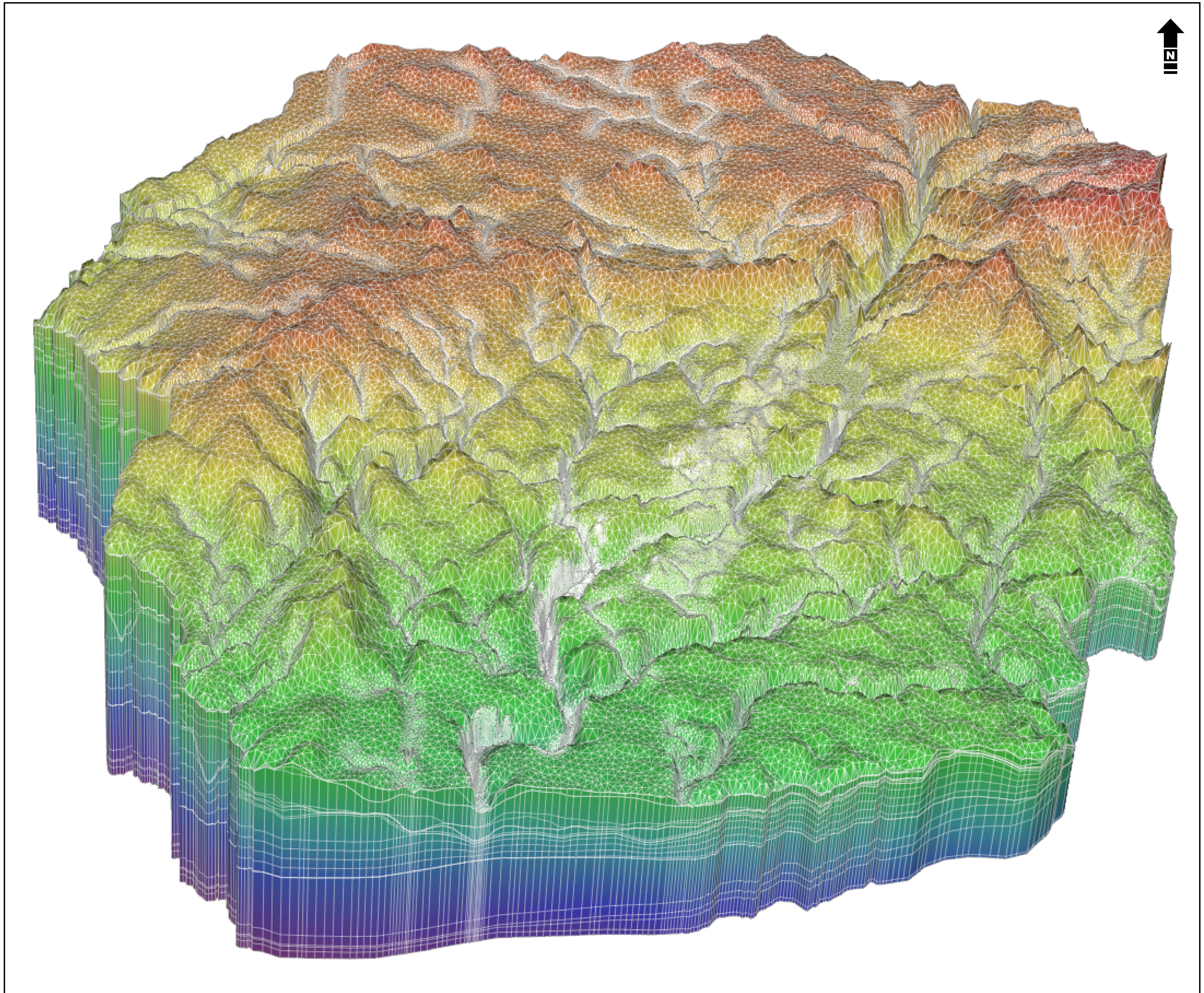
04 May 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 2



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3D View of the Groundwater Flow Model

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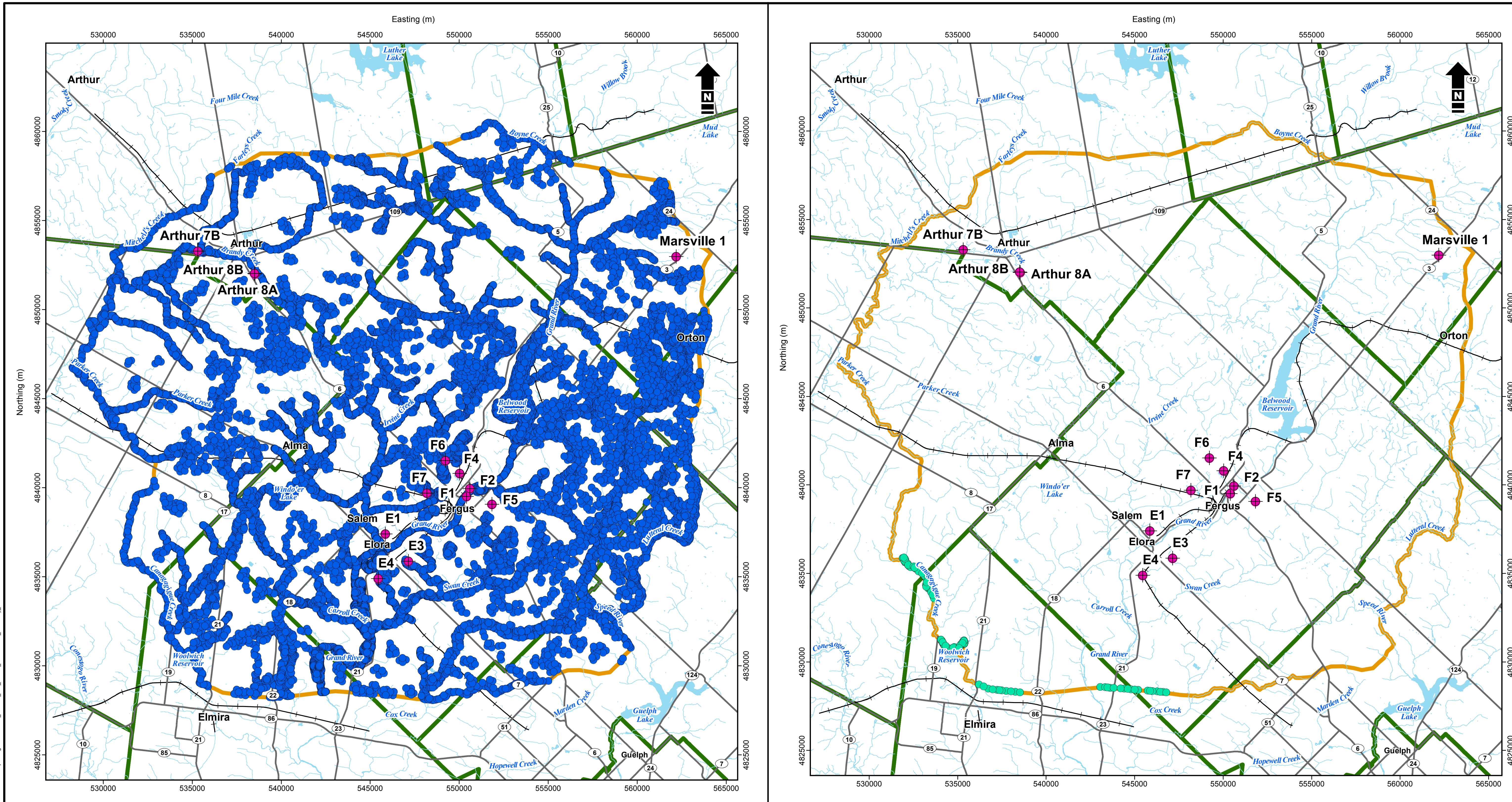
06 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 3



Study Area
Municipal Boundary
Water Body
Watercourse
Highway
Railroad Trail
Municipal Well
Stream, Lake or Wetland (Constant Head Boundary Condition)
Cross-boundary Groundwater Flow (Lateral Constant Head Boundary Condition)

1:210,000

metres

2,100 0 2,100 4,200

NAD 1983 UTM Zone 17N

I:\GrandRiverCA\23876\FiguresandTables\T32017\Report\ModelDevelopmentandCalibrationReport\Figure-4-Ground_Surface_and_Lateral_Overburden_Boundary_Conditions.mxd

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Ground Surface and Lateral Overburden Boundary Conditions

Date:	Project:	Technical:	Reviewer:	Drawn:
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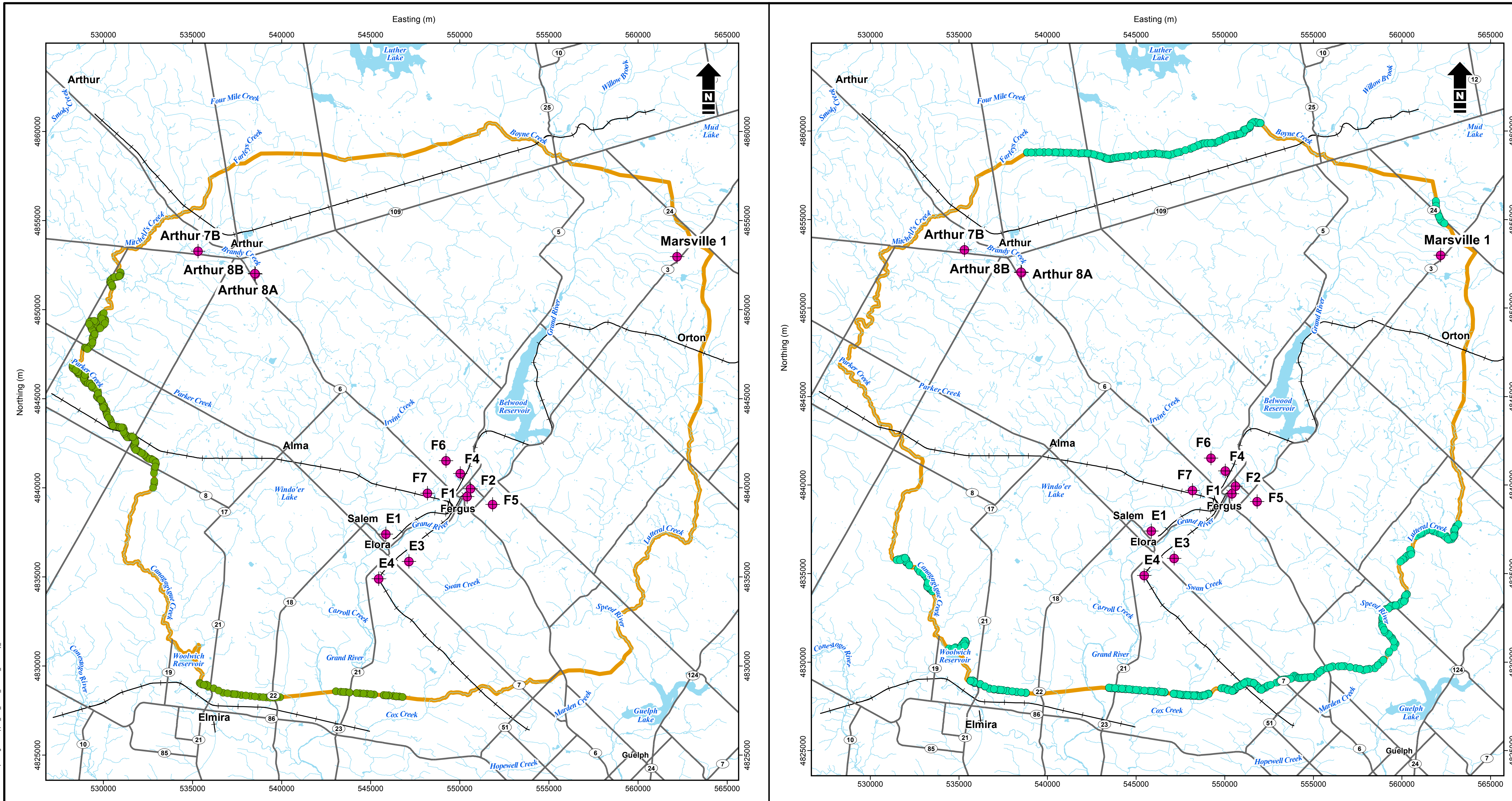
Figure
4



Study Area
Municipal Boundary
Water Body
Watercourse
Highway
Railroad Trail
Municipal Well
Upper Bedrock Boundary Condition
Lower Bedrock Boundary Condition

1:210,000
metres
2,100 0 2,100 4,200
NAD 1983 UTM Zone 17N

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Upper and Lower Bedrock Boundary Conditions

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Figure 5

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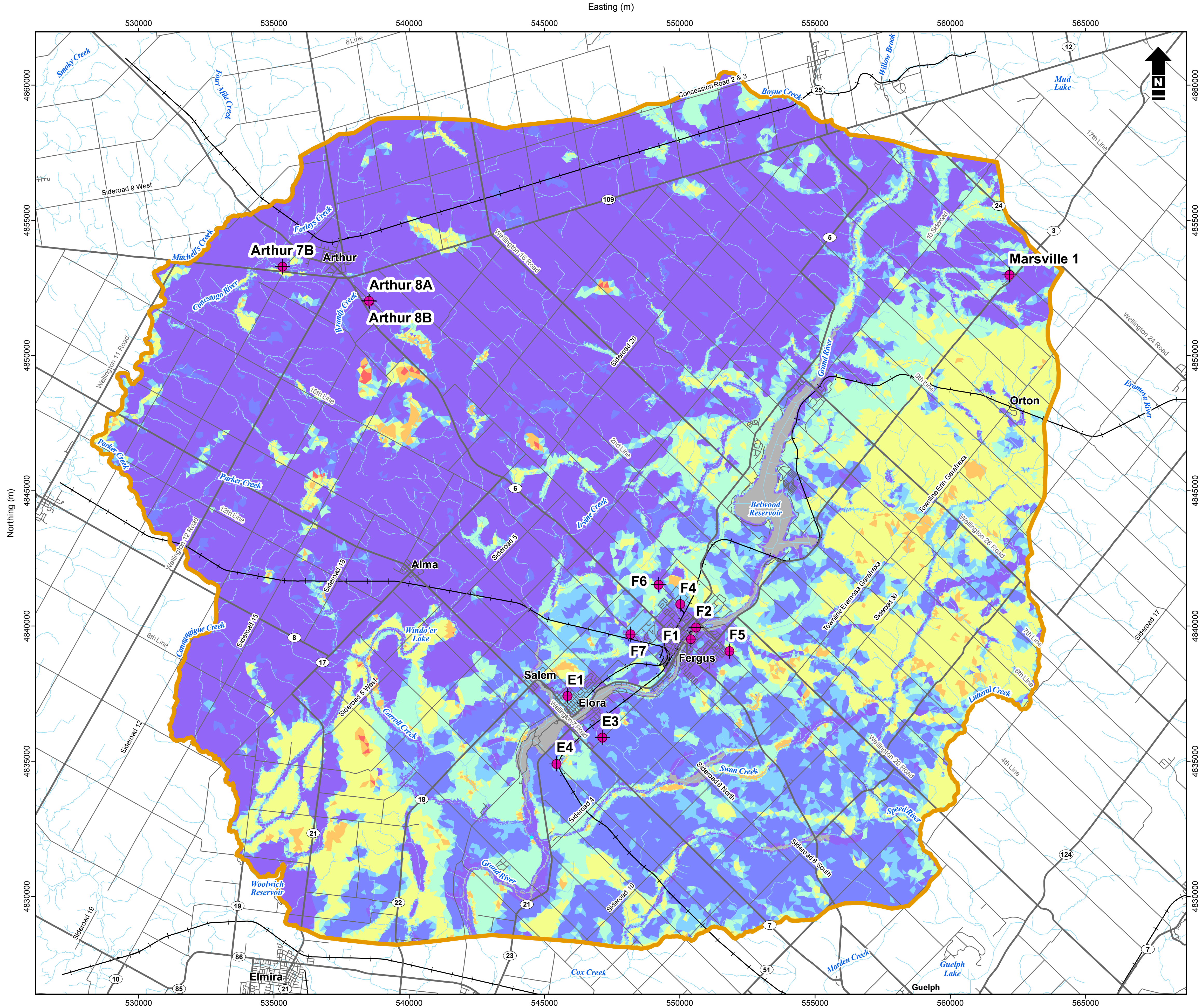

Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Groundwater Recharge Distribution (mm/yr)

- 0
- 0 < ... <= 75
- 75 <...<= 125
- 125 < ...<= 200
- 200 < ... <= 300
- 300 < ... <= 400
- 400 < ... <= 500
- > 500

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000

1,400 0 1,400 2,800 m

NAD 1983 UTM Zone 17N

Grand River Conservation Authority

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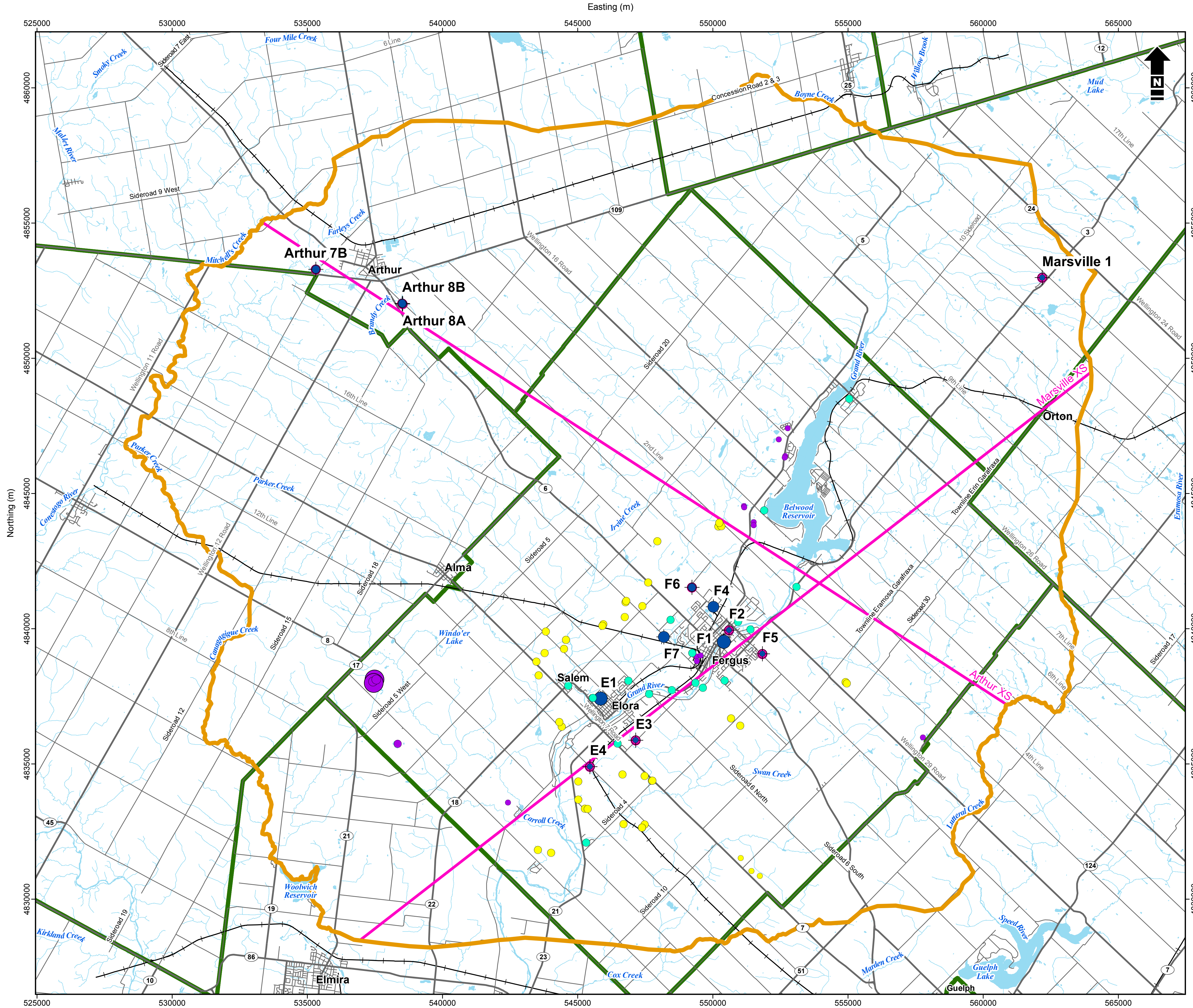
Recharge Distribution

Date:	Project:	Technical:	Reviewer:	Drawn:
15 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 6



Study Area
Municipal Boundary
Wetland
Water Body
Watercourse
Highway
Road
Railroad Trail
Cross Section Location
Municipal Well

Type
- Municipal PTTW
- Non-Permitted Agriculture
- Non-Municipal PTTW
- Well Representing a Cluster of Domestic Wells

Average Annual Consumptive Rate (m^3/day)
- < 250
- 250 - 500
- 500 - 750
- 750 - 1000
- 1000 - 1250
- 1250 - 1500
- 1500 - 1750
- > 1750

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

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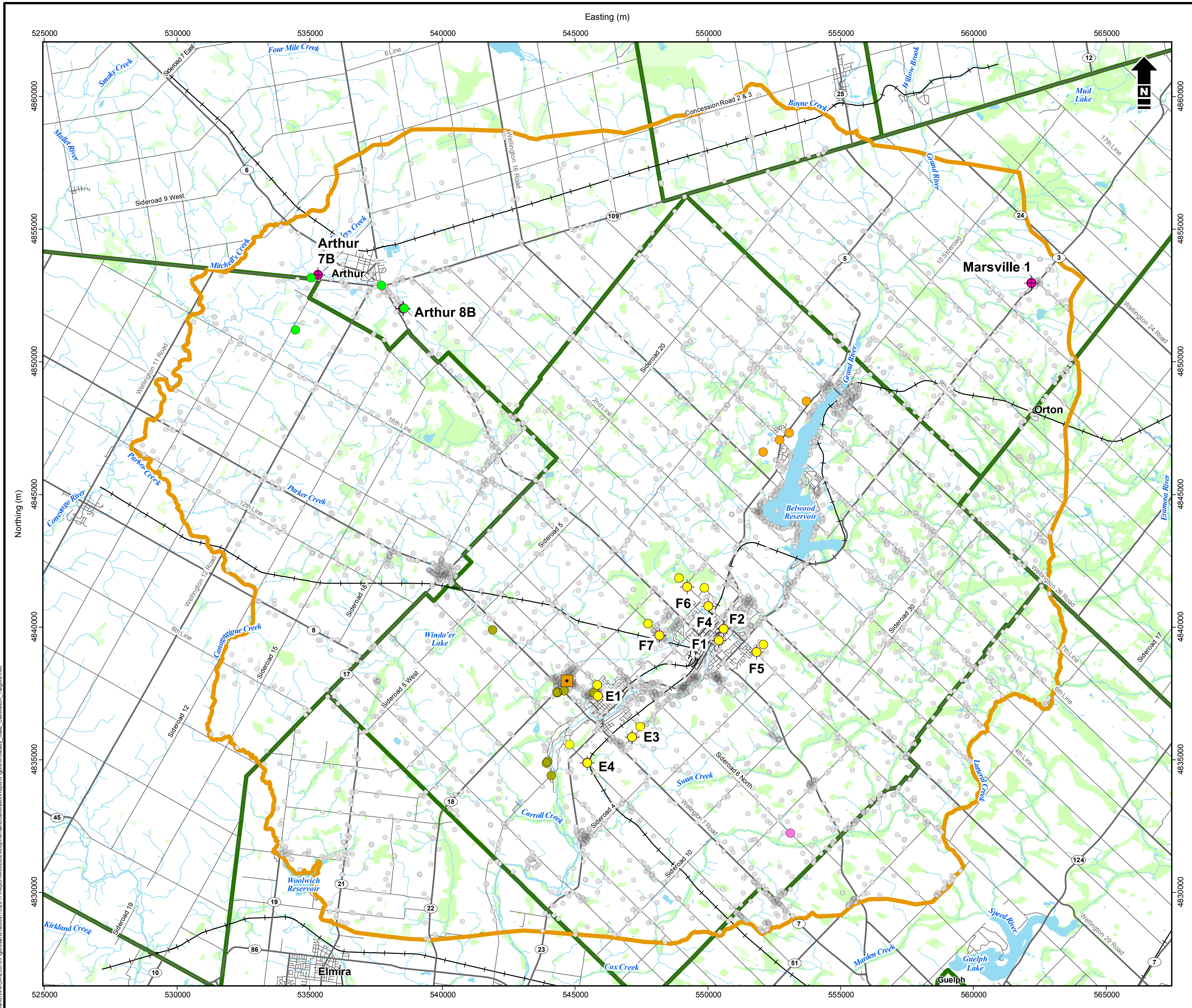
Municipal and Non-Municipal Demands

Date:	Project:	Technical:	Reviewer:	Drawn:
02 May 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 7

I:\GrandRiverCA\23876\FiguresandTables\T3\2017\ReportModelDevelopmentandCalibrationReport\Figure-7-Municipal_and_Non-Municipal_Demands.mxd



Study Area
Municipal Boundary
Wetland
Water Body
Watercourse
Highway
Road
Railroad Trail
Municipal Well
Baseflow Gauge
Higher Quality Monitoring Well – GRCA
Higher Quality Monitoring Well – Centre Wellington
Higher Quality Monitoring Well – Nestle Provided Well Data
Higher Quality Monitoring Well – Highland Pines
Higher Quality Monitoring Well – Arthur
Lower Quality WWIS Well

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministry of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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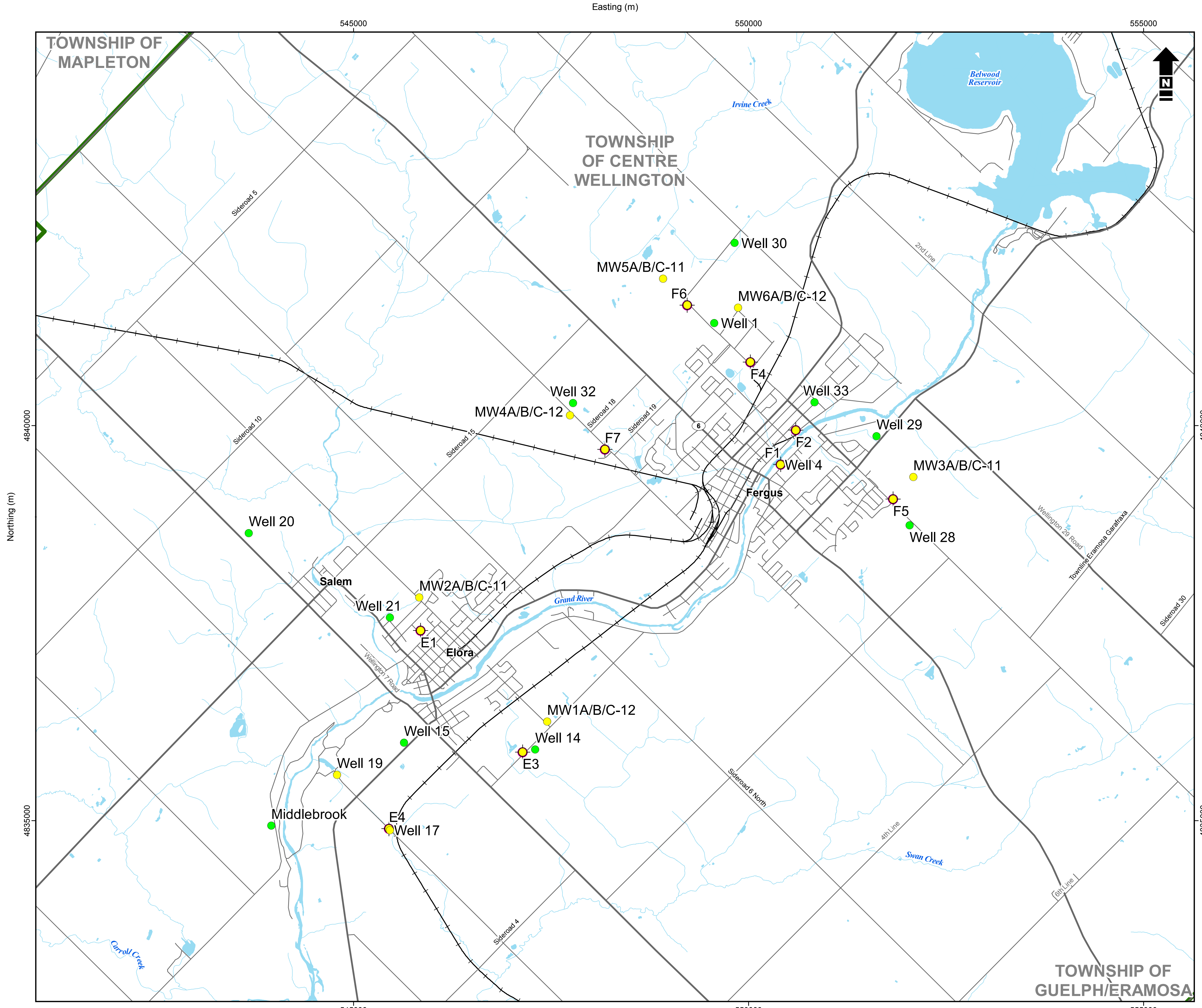
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration Targets

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 8



Study Area
Municipal Boundary
Water Body
Watercourse
Highway
Road
Railroad Trail
Municipal Well
Monitoring Well - Centre Wellington
Monitoring Well - Other

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:50,000 m
500 0 500 1,000
NAD 1983 UTM Zone 17N

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Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration Targets

Date:	Project:	Technical:	Reviewer:	Drawn:
14 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

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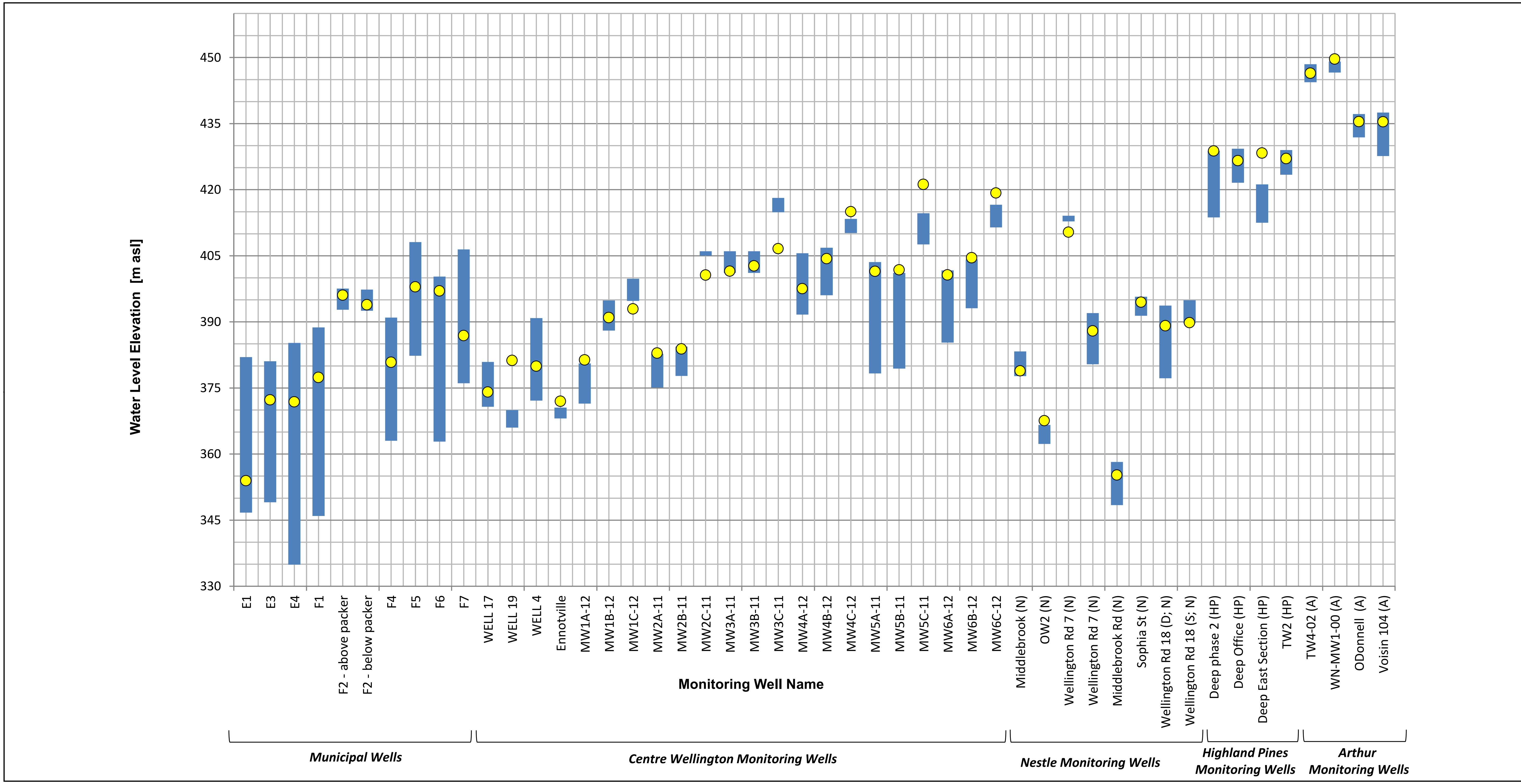
Figure 9



Observed Water Level Elevation Range

Simulated Water Level Elevation

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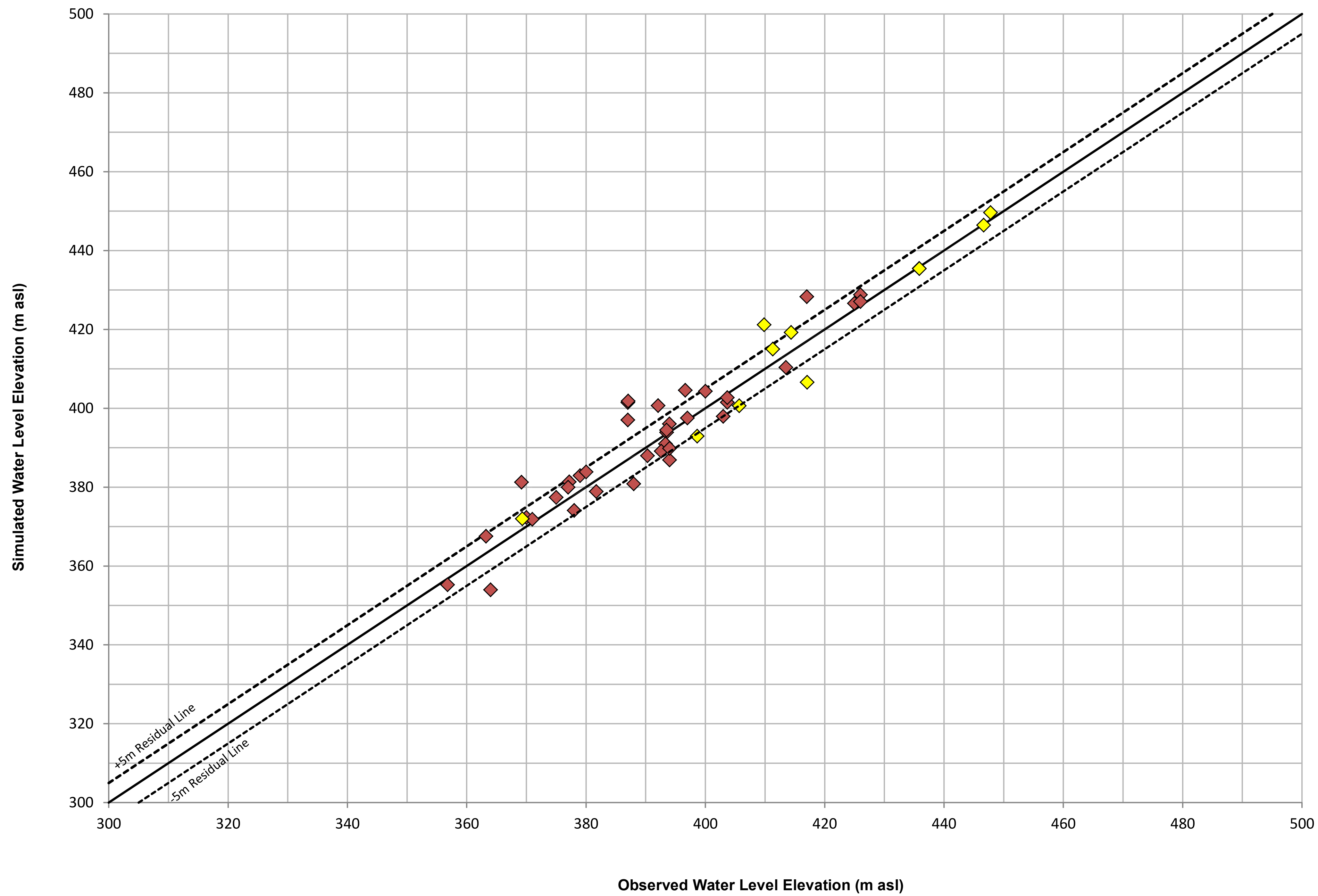
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Higher Quality Wells

Date: 27 Mar 2019	Project: 23876	Technical: J. Melchin	Reviewer: D. Van Vliet	Drawn: C. Curry

Figure 10



- +/-5m Residual Line
- High Quality Overburden Target
- High Quality Bedrock Target

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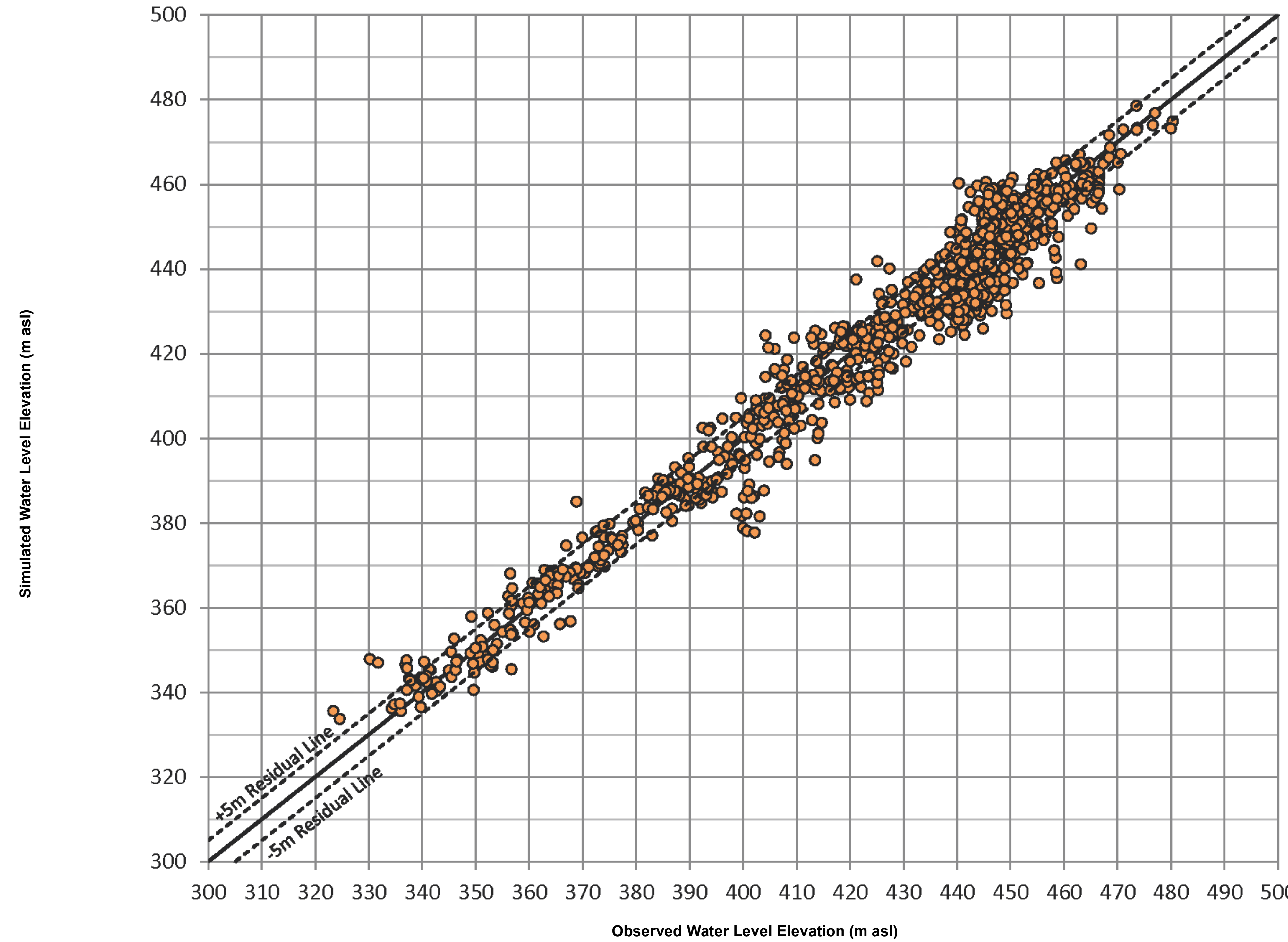
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Higher Quality Wells - Scatter Plot

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure **11a**



+/-5m Residual Line

Lower Quality Overburden Target

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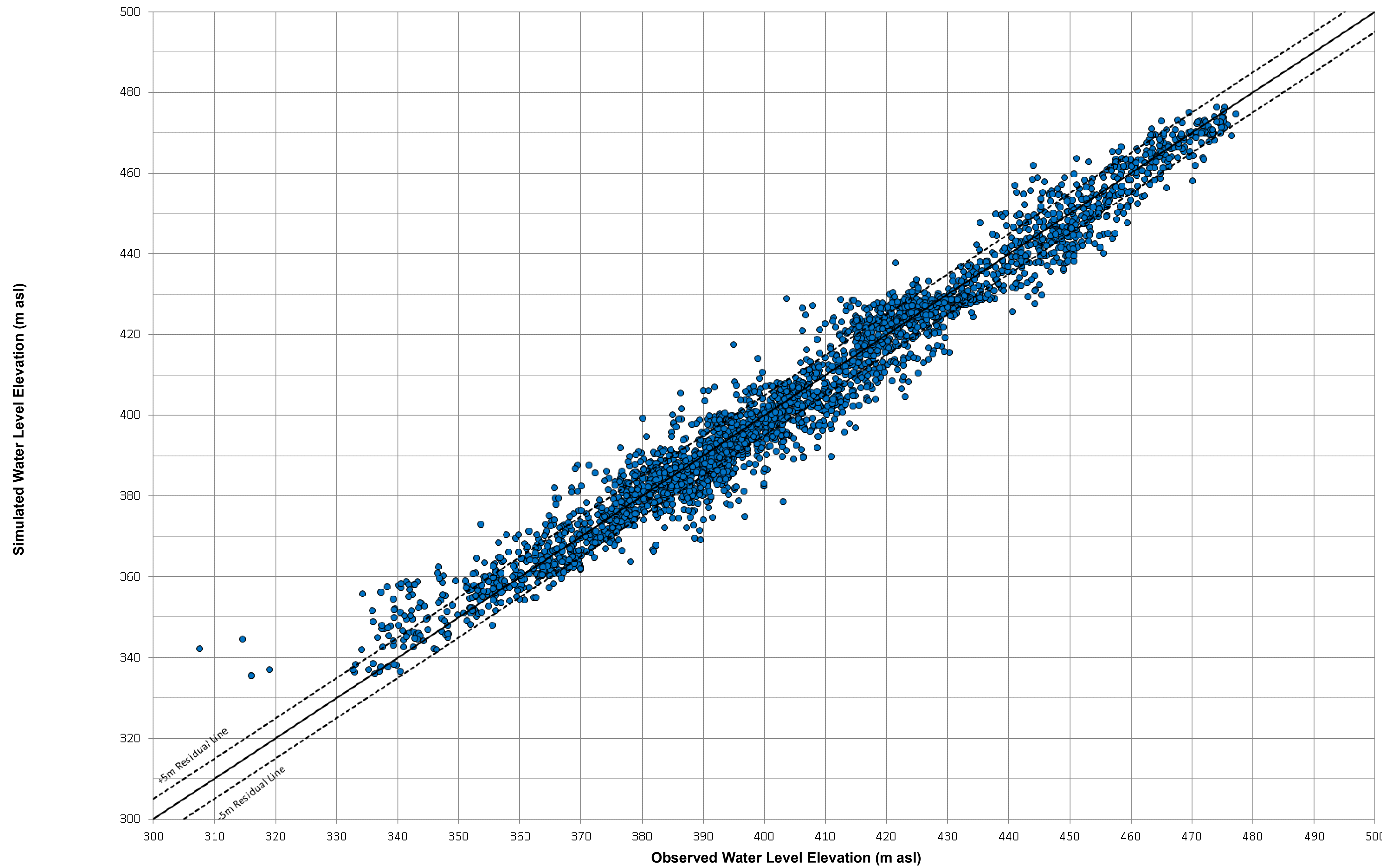
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Lower Overburden Quality Wells - Scatter Plot

Date: 27 Mar 2019	Project: 23876	Technical: J. Melchin	Reviewer: D. Van Vliet	Drawn: C. Curry

Figure 11b

I:\GrandRiverCA\23876\FiguresandTables\T3\2017\Report\ModelDevelopmentandCalibrationReport\Figure-11b-Steady-State_Calibration_to_Lower_Quality_Overburden_Wells-Scatter_Plot.mxd



+/-5m Residual Line
Lower Quality Bedrock Target

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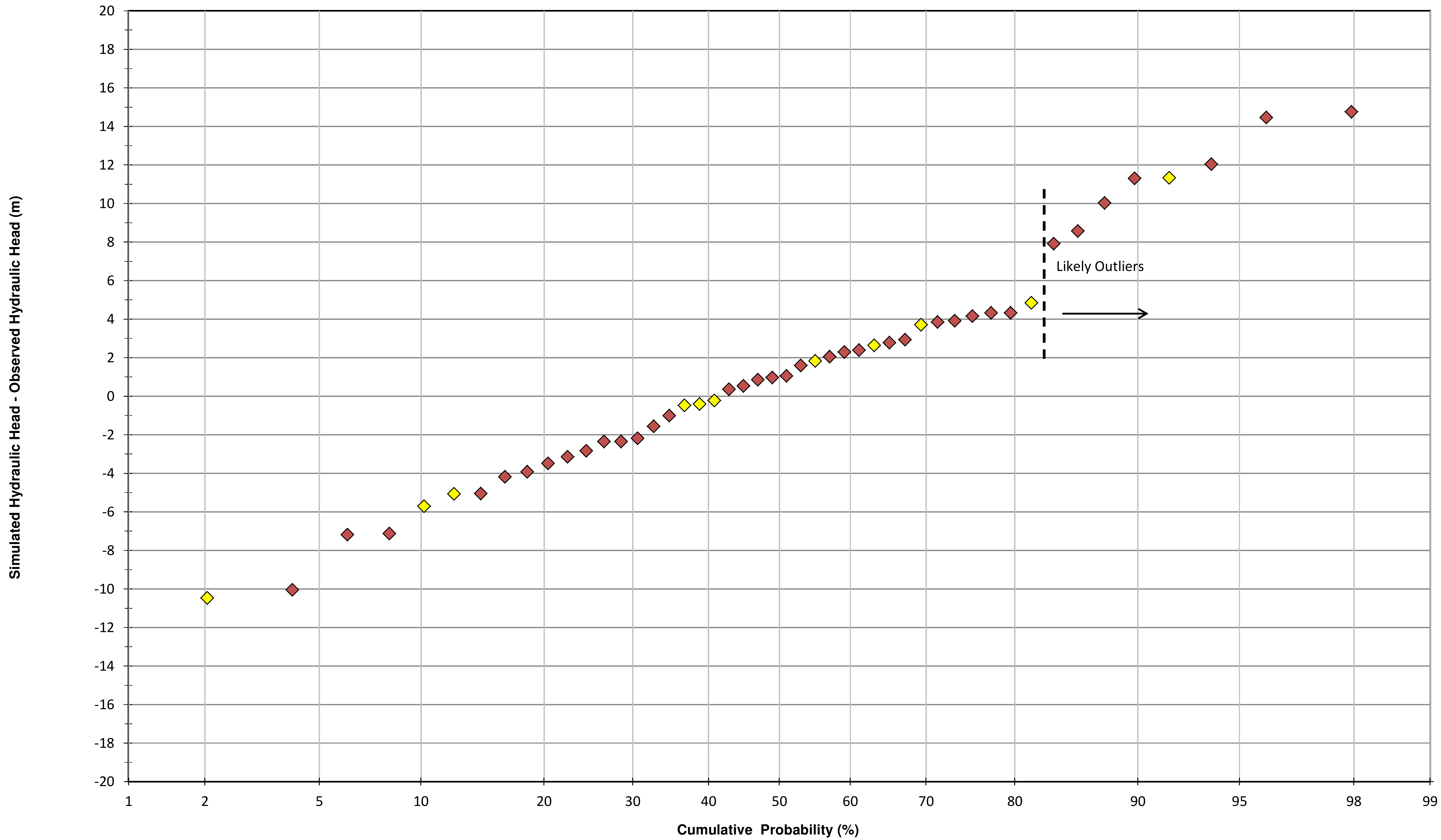
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Lower Quality Bedrock Wells - Scatter Plot

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure
11c



- - +/-5m Residual Line
◇ High Quality Overburden Target
◆ High Quality Bedrock Target

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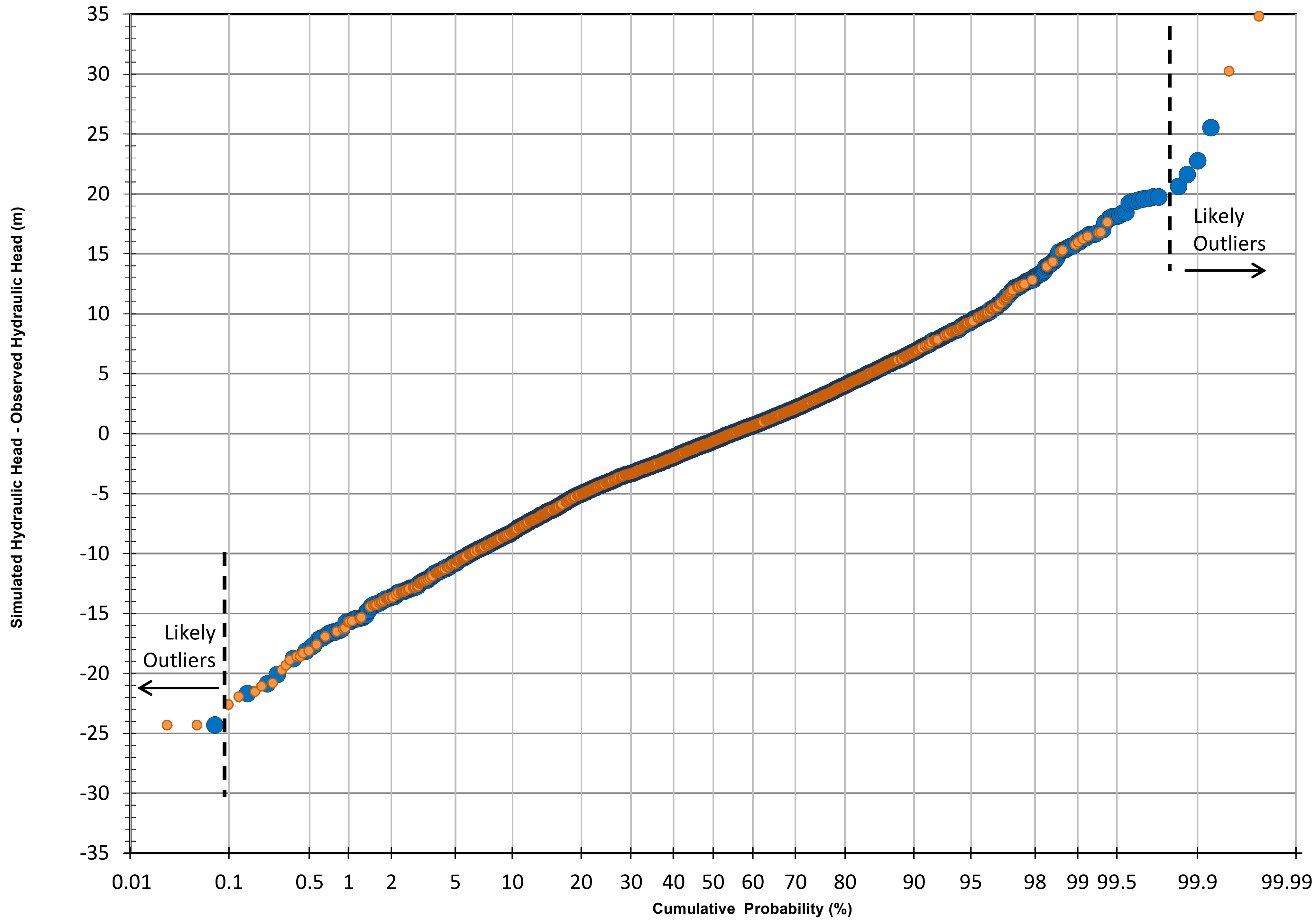
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Higher Quality Wells - Cumulative Probability Plot

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 11d



- Lower Quality Overburden Target
- Lower Quality Bedrock Target

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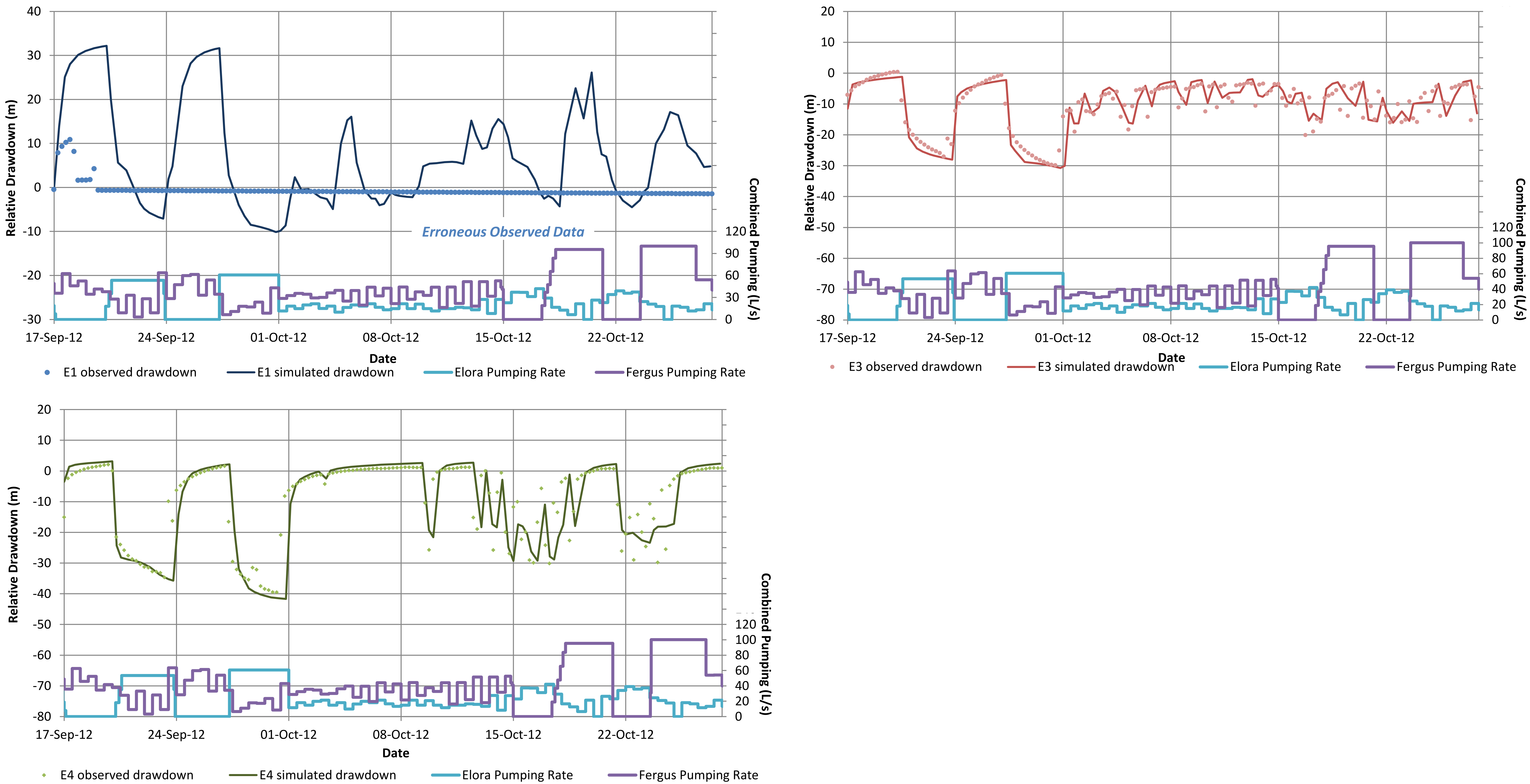
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Steady-State Calibration to Lower Quality Wells - Cumulative Probability Plot

Date:	Project:	Technical:	Reviewer:	Drawn:
01 Apr 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 11e

I:\GrandRiverCA\23876\FiguresandTables\T3\2017\Report\ModelDevelopmentandCalibrationReport\Figure-11e-Steady-State_Calibration_to_Lower_Quality_Wells-Cumulative_Probability_Plot.mxd



Higher Quality Pumping Wells
- Elora – E1
- Elora – E3
- Elora – E4

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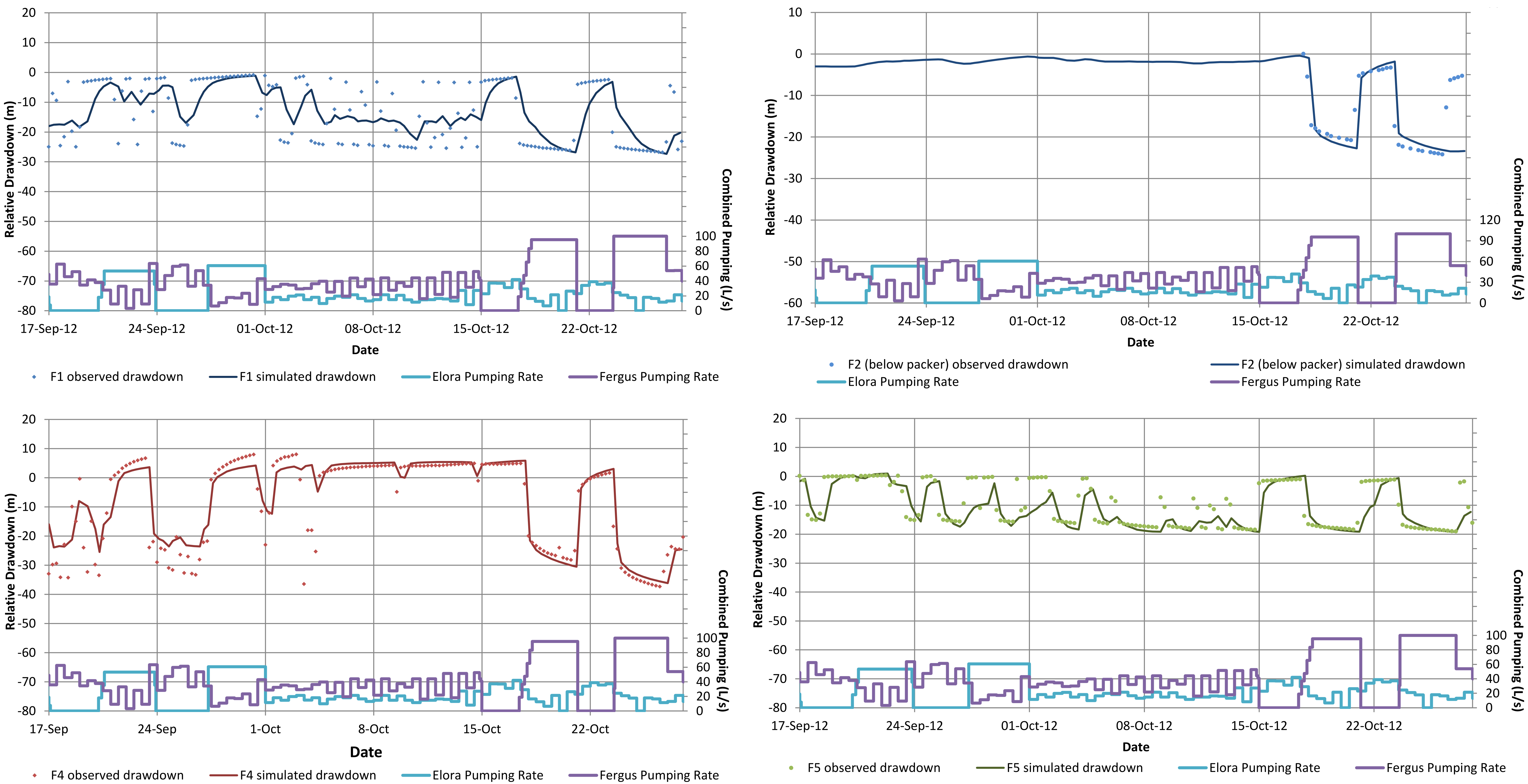
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration:
Higher Quality Pumping Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure 12a



Higher Quality Pumping Wells
- Fergus – F1
- Fergus – F2 (below packer)
- Fergus – F4
- Fergus – F5

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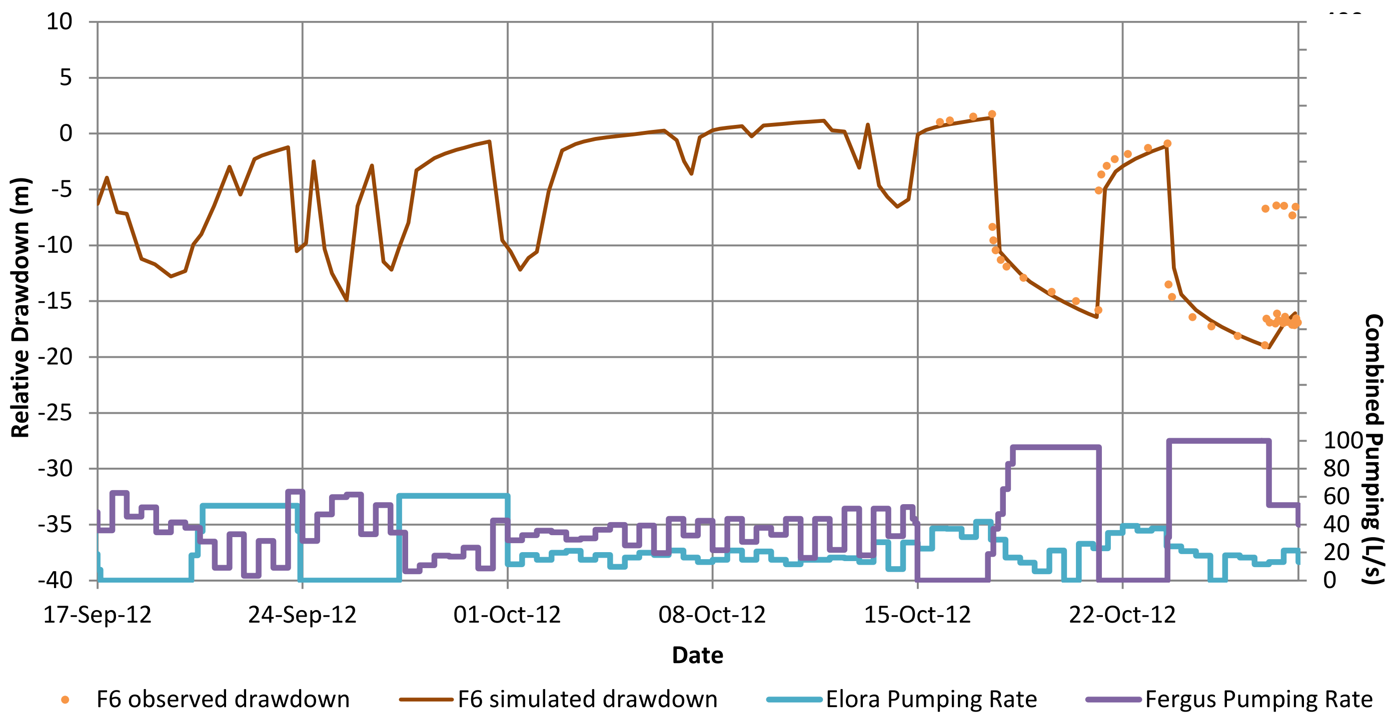
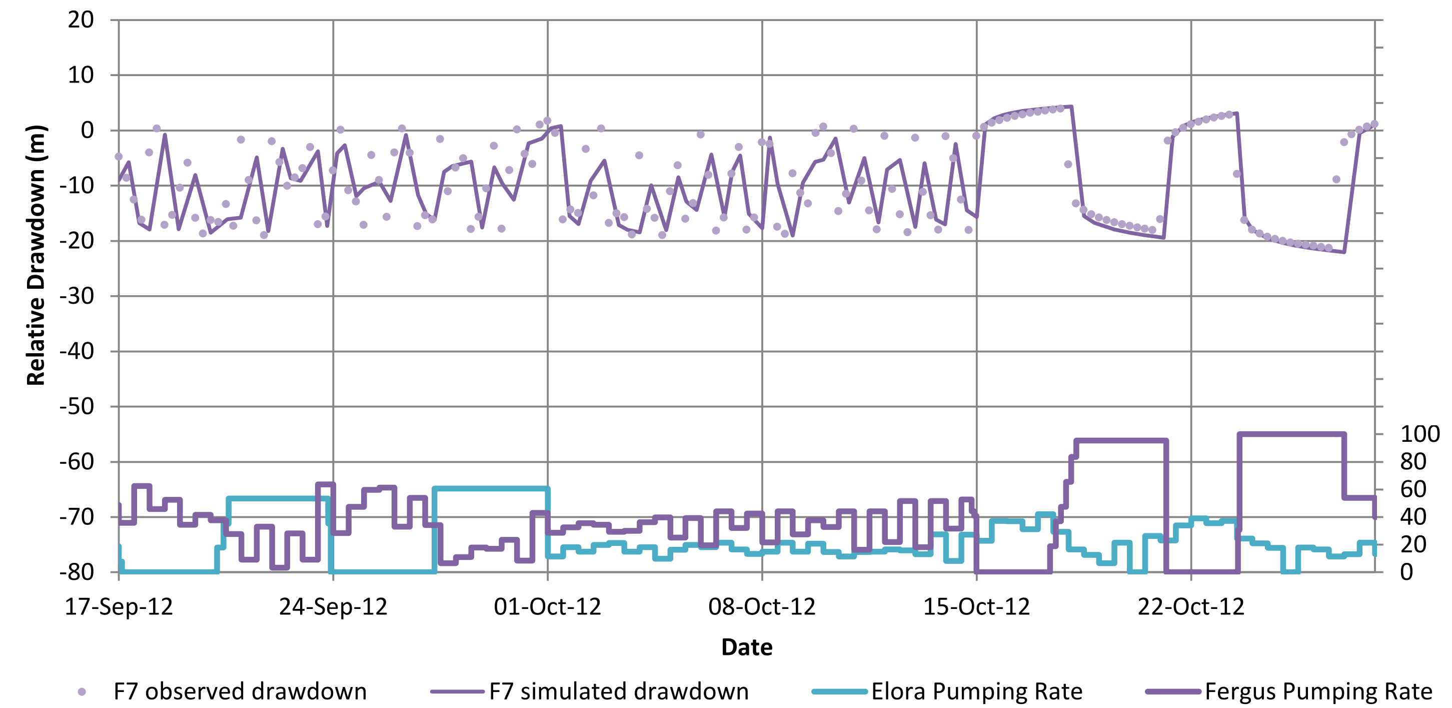
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration:
Higher Quality Pumping Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure 12b





Higher Quality Pumping Wells

- Fergus – F6
- Fergus – F7

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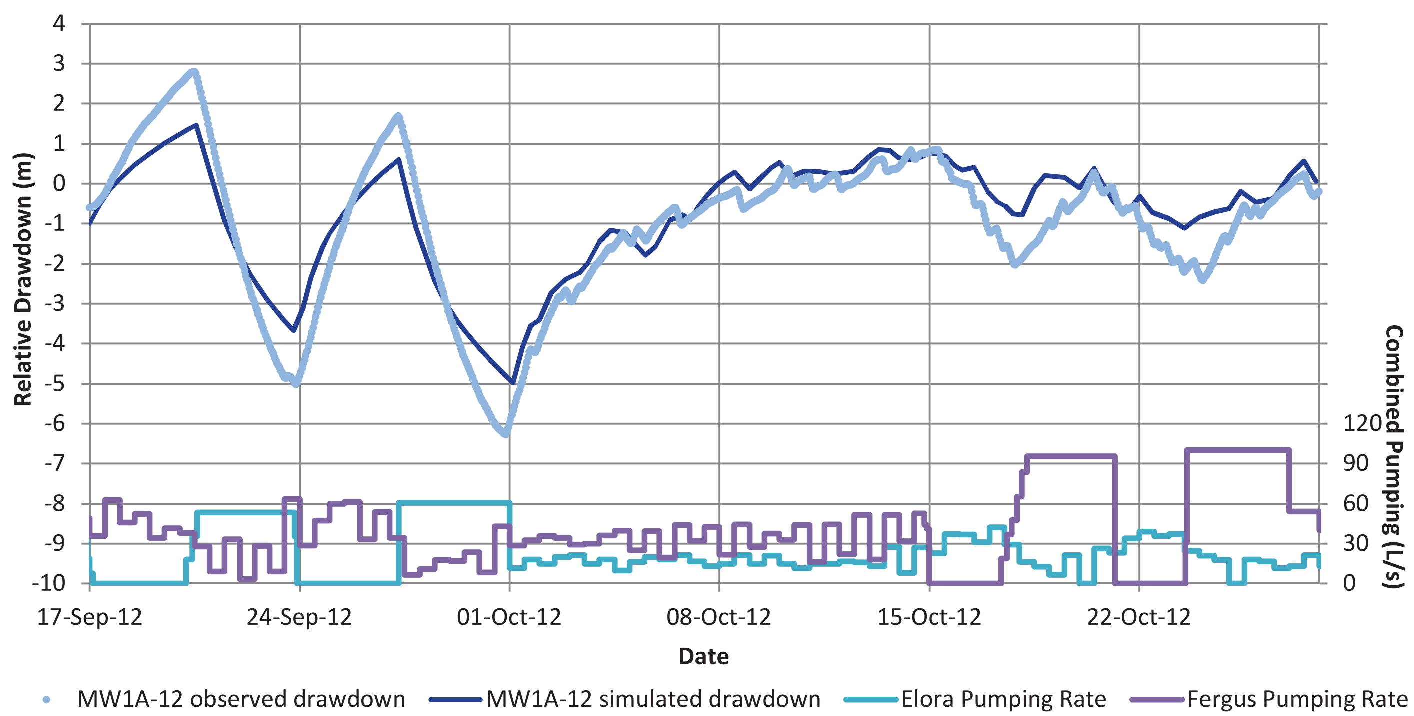
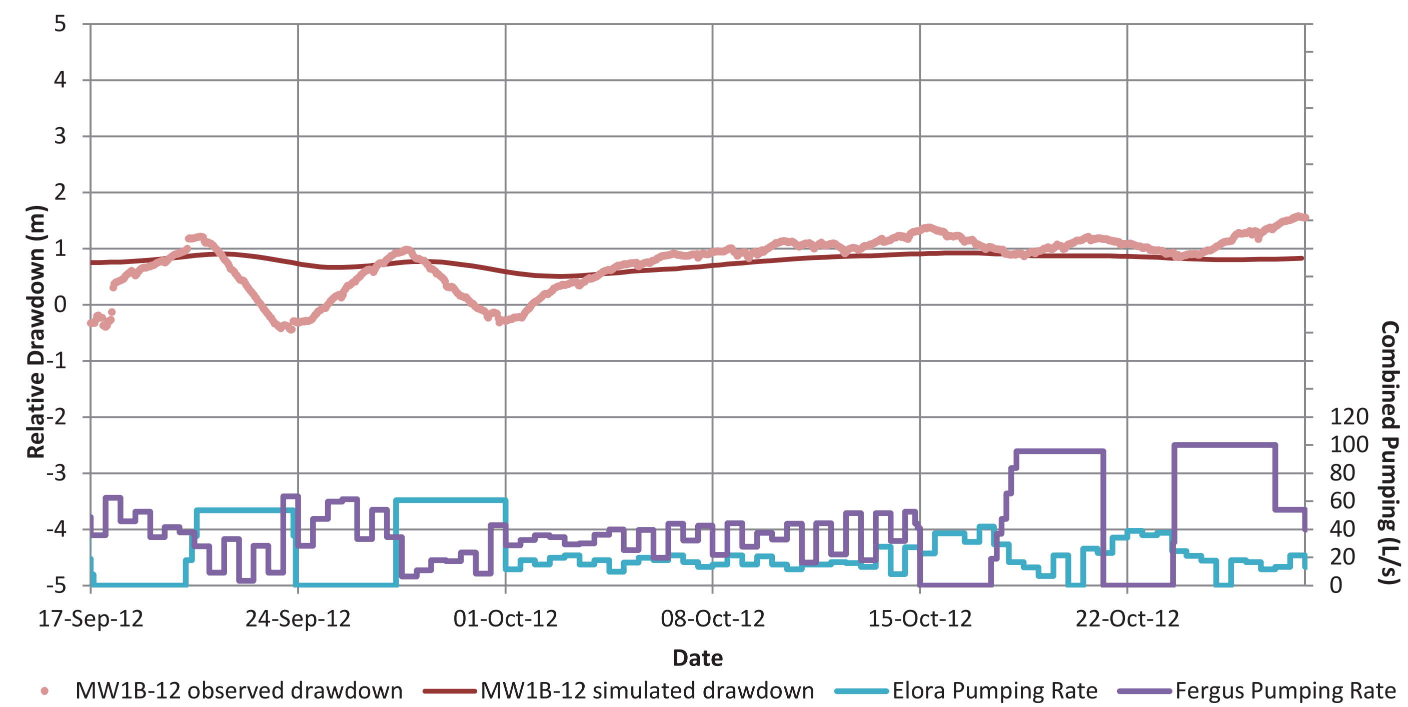
Centre Wellington Tier Three Model Development and Calibration Report

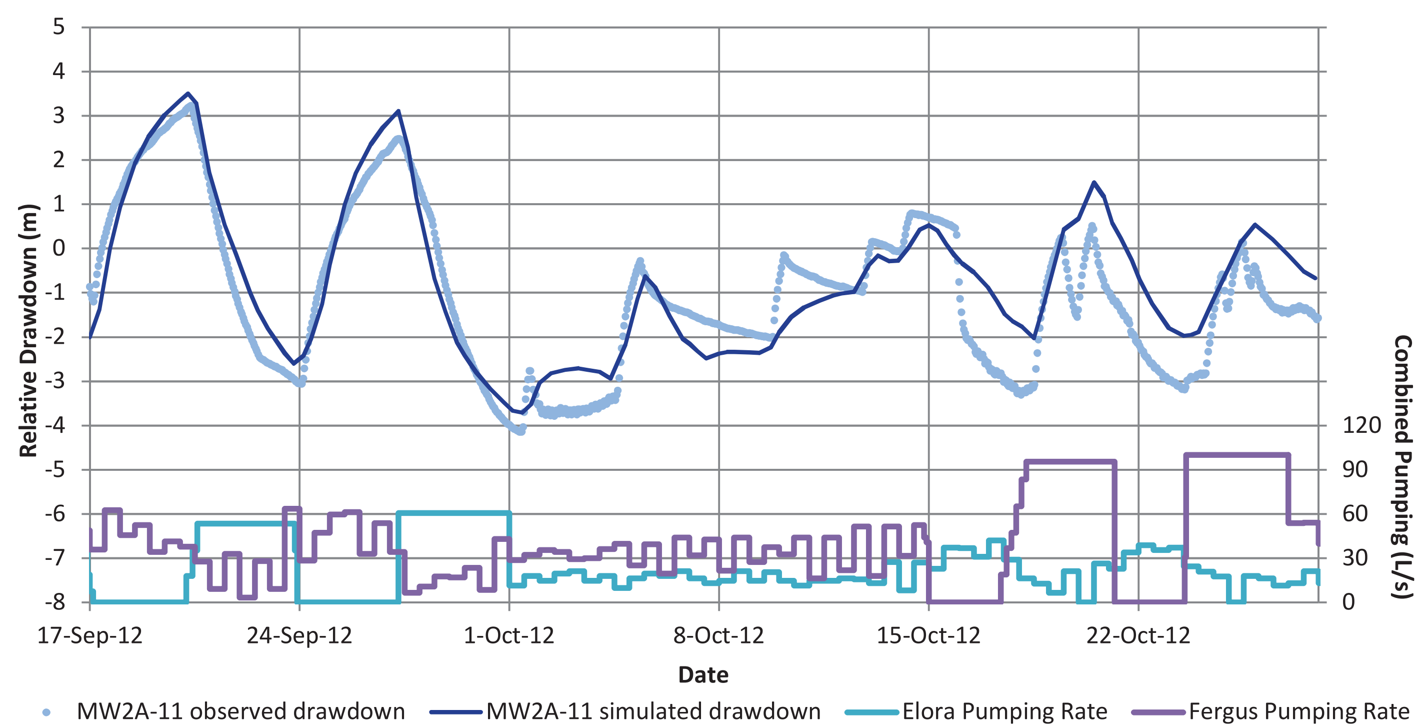
Transient Calibration:
Higher Quality Pumping Wells

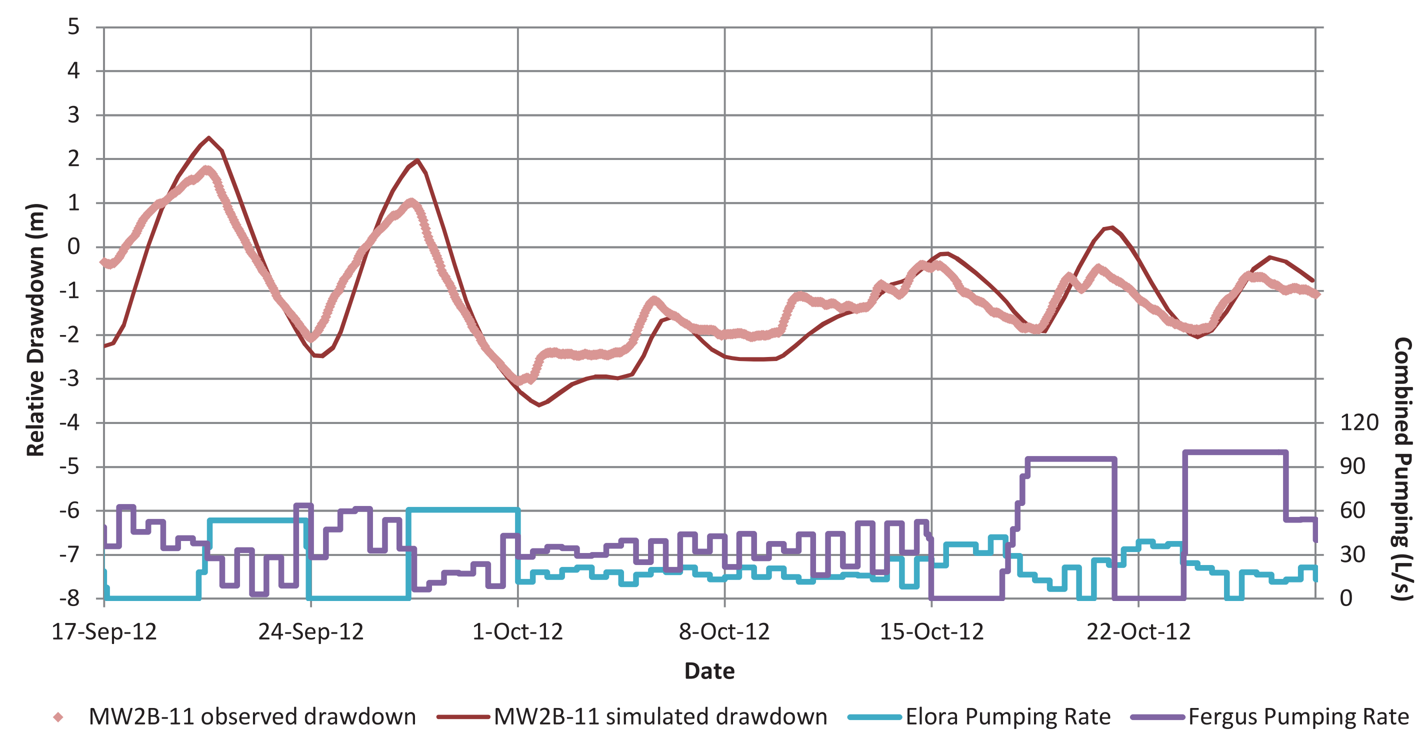
Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure 12c









Higher Quality Bedrock Wells
- MW1A-12 and MW1B-12
- MW2A-11 and MW2B-11

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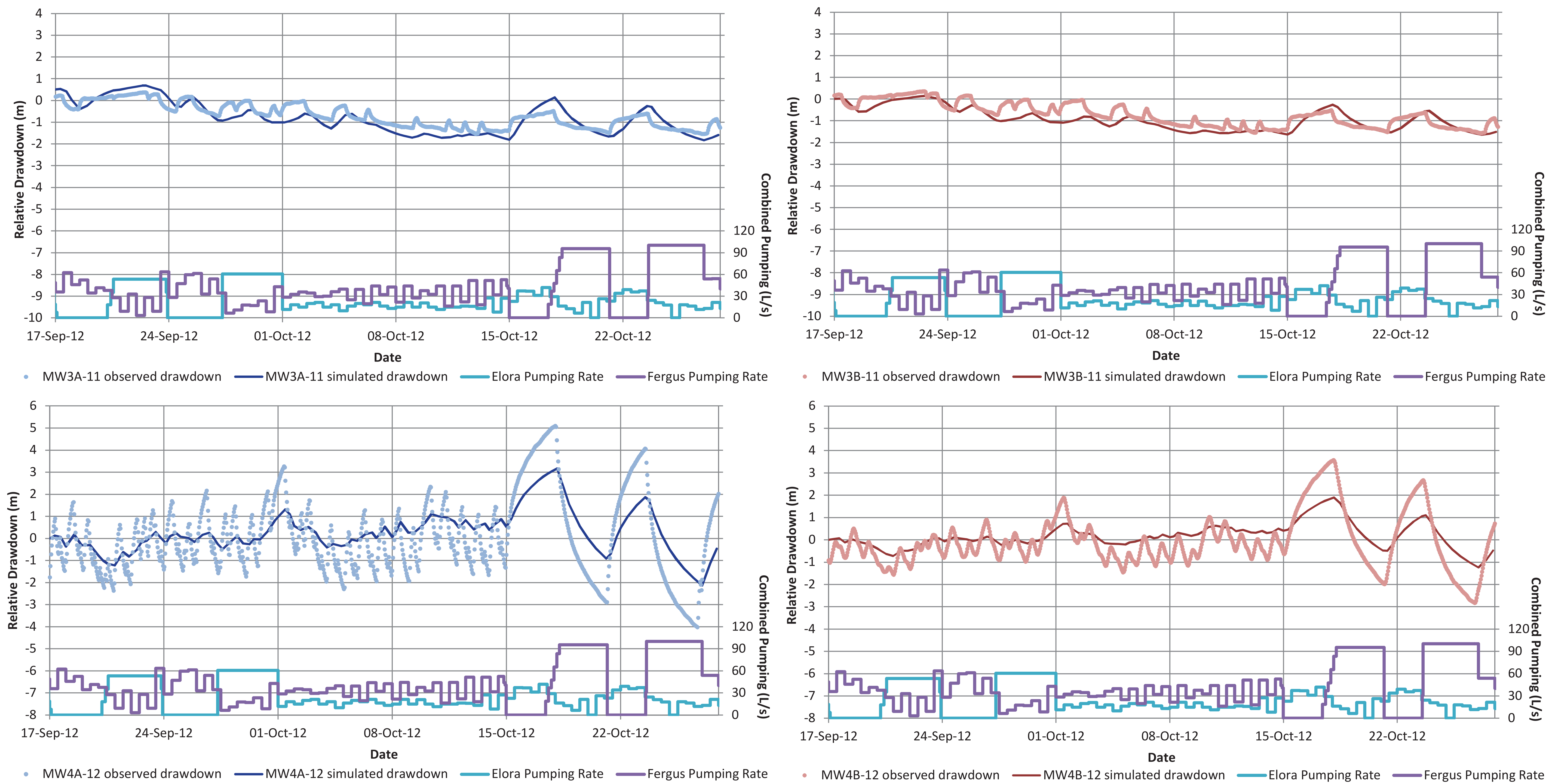
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration:
Higher Quality Bedrock Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure
13a



Higher Quality Bedrock Wells
- MW3A-11 and MW3B-11
- MW4A-12 and MW4B-12

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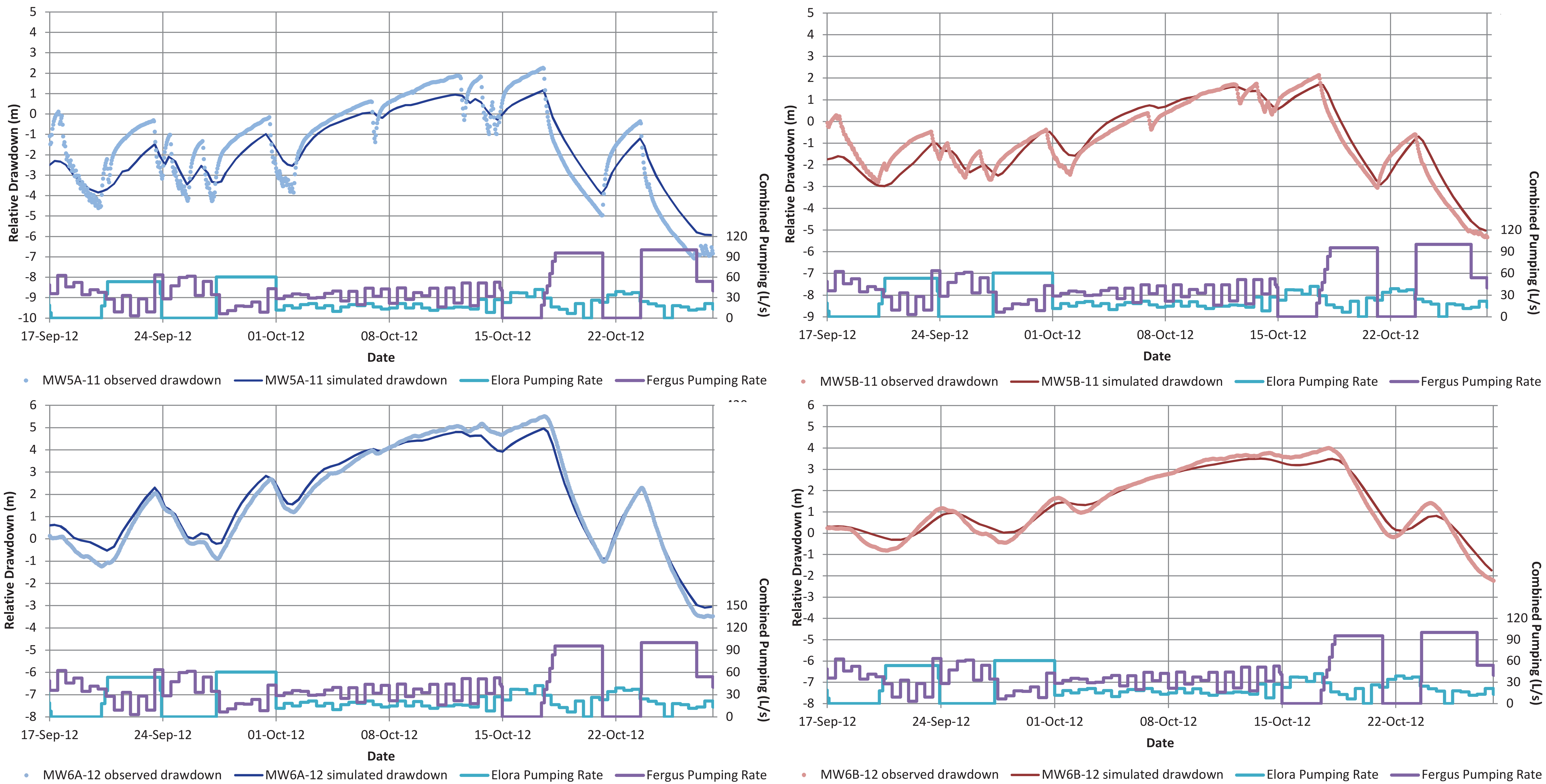
Transient Calibration:
Higher Quality Bedrock Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure 13b



Higher Quality Bedrock Wells
- MW5A-11 and MW5B-11
- MW6A-12 and MW6B-12

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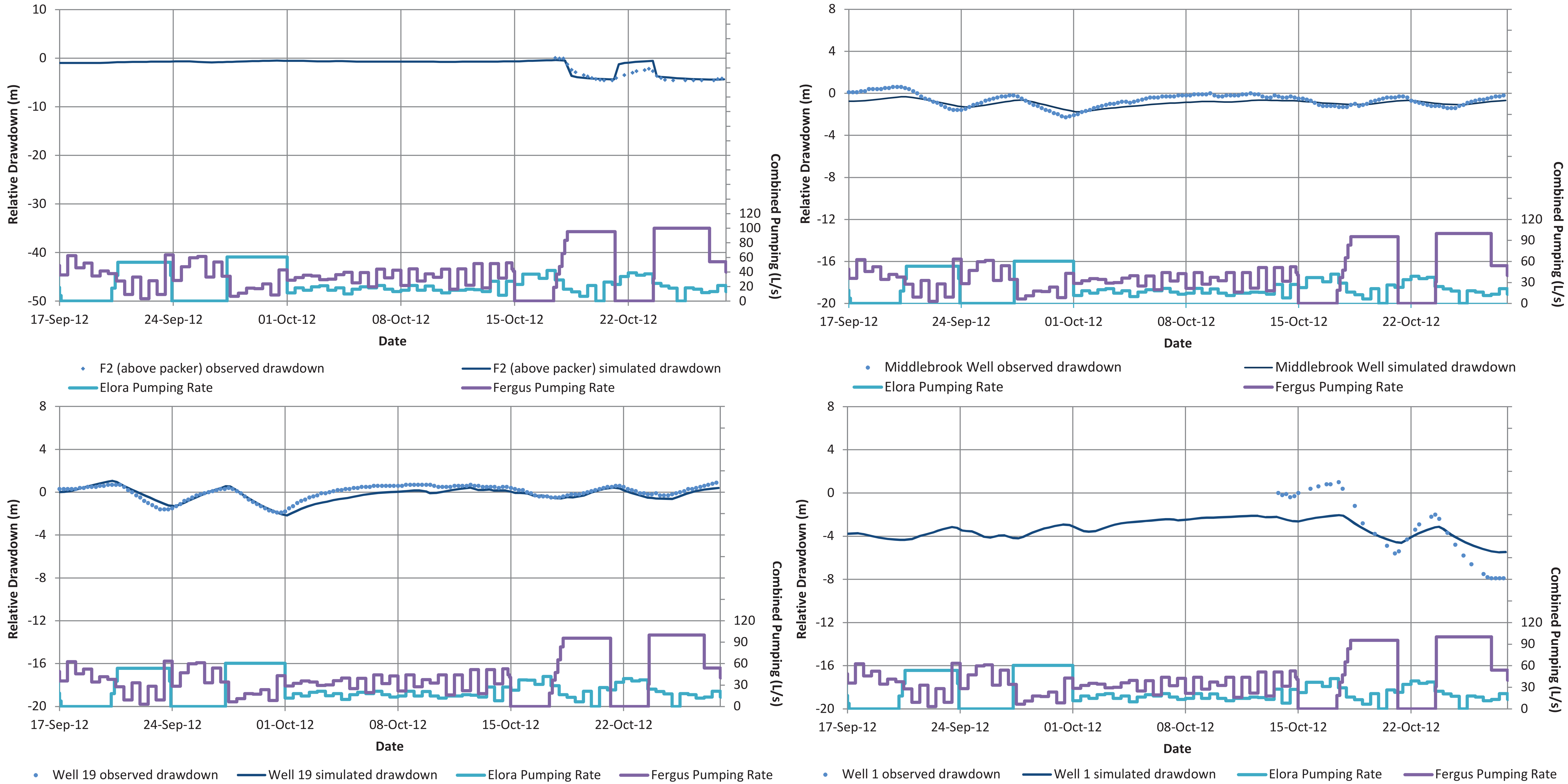
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration:
Higher Quality Bedrock Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure 13c



Higher Quality Bedrock Wells
- Fergus – F2 (above packer)
- Middlebook Well
- Well 19
- Well 1

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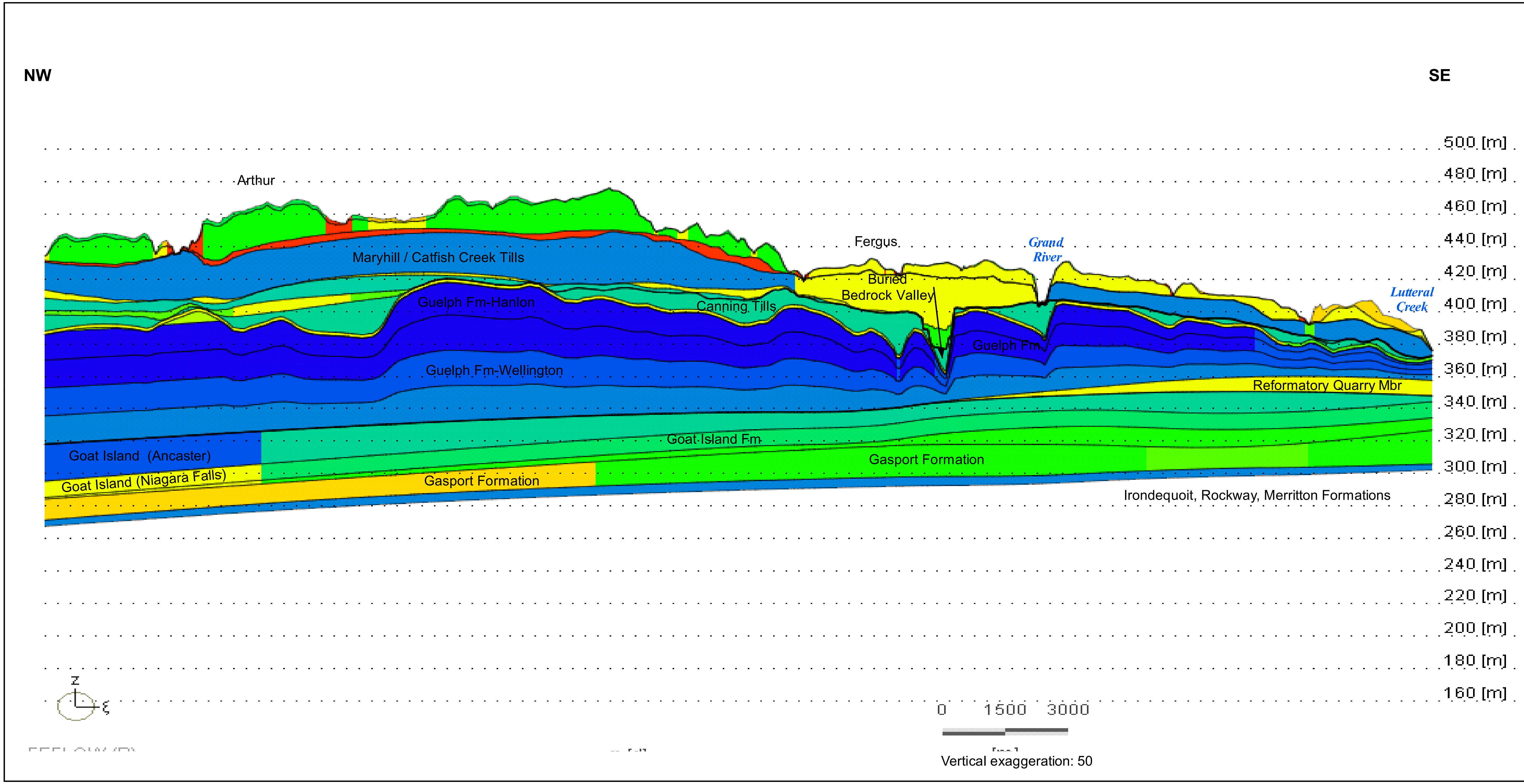
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration:
Higher Quality Bedrock Wells

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure
13d



Conductivity (m/s)

- 1.0e-4 <= ... <= 1.0e-3
- 1.0e-5 <= ... <= 1.0e-4
- 1.0e-6 <= ... <= 1.0e-5
- 1.0e-7 <= ... <= 1.0e-6
- 1.0e-8 <= ... <= 1.0e-7
- 1.0e-9 <= ... <= 1.0e-8
- <= 1.0e-9

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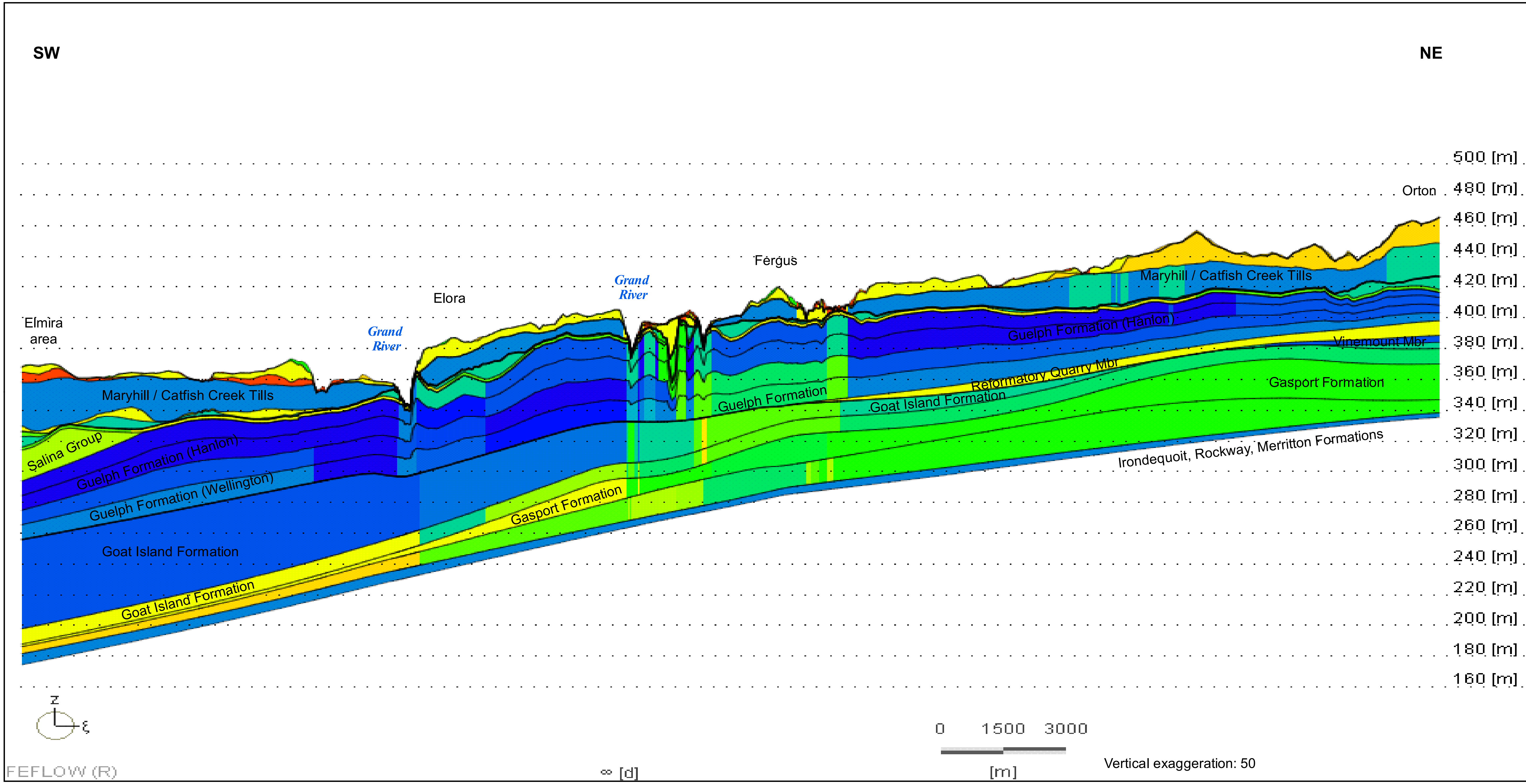
Centre Wellington Tier Three Model Development and Calibration Report

Model Cross-Section (Northwest-Southeast)

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 14



Conductivity (m/s)

- 1.0e-4 <= ... <= 1.0e-3
- 1.0e-5 <= ... <= 1.0e-4
- 1.0e-6 <= ... <= 1.0e-5
- 1.0e-7 <= ... <= 1.0e-6
- 1.0e-8 <= ... <= 1.0e-7
- 1.0e-9 <= ... <= 1.0e-8
- <= 1.0e-9

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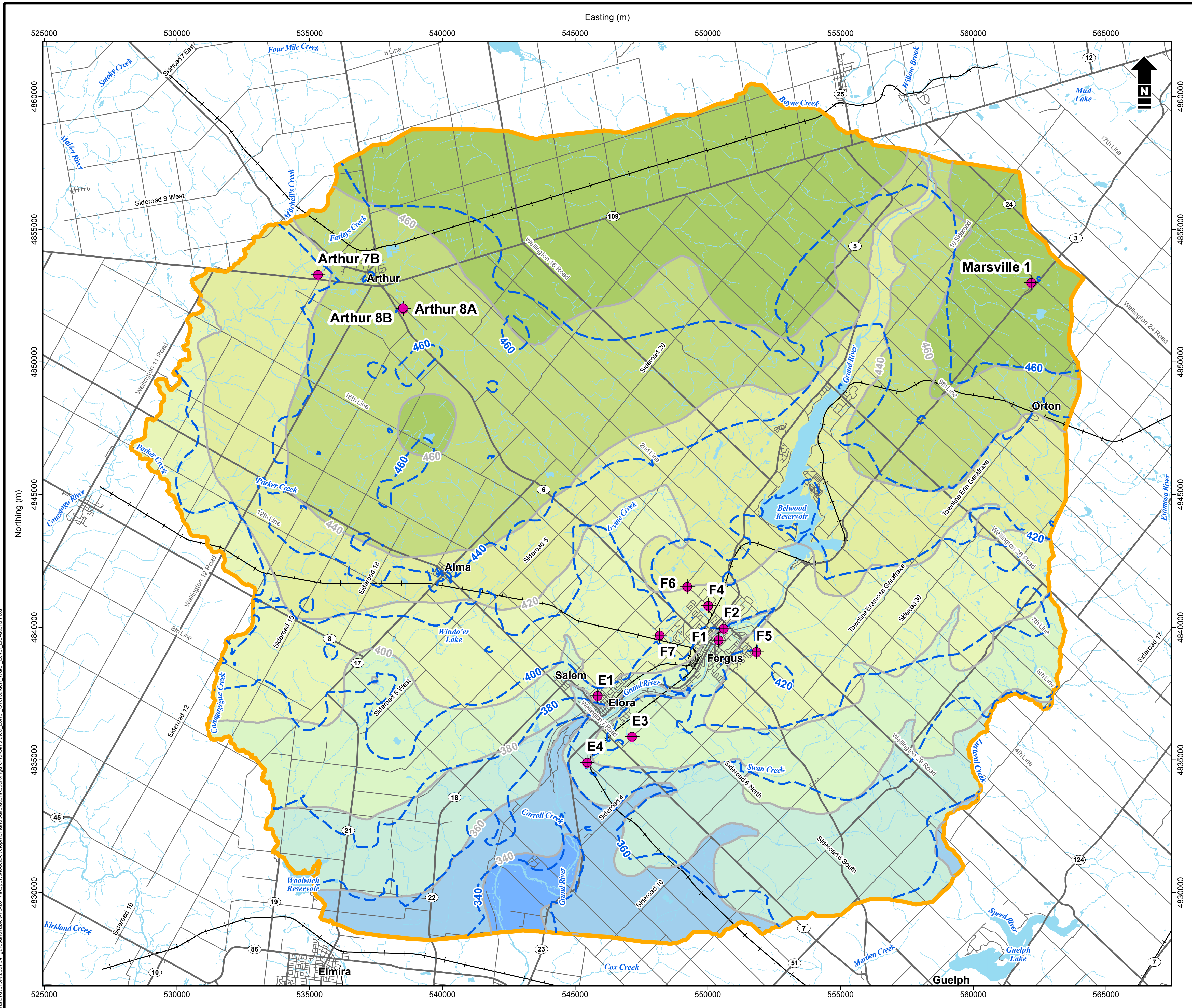
Centre Wellington Tier Three Model Development and Calibration Report

Model Cross-Section (Southwest-Northeast)

Date:	Project:	Technical:	Reviewer:	Drawn:
27 Mar 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 15



Study Area
Water Body
Watercourse
Highway
Road
Railroad Trail
Simulated Water Level Elevation (m asl); 20 m Contour Interval
Observed Water Level Elevation (m asl); 20 m Contour Interval
Municipal Well within the Study Area

Simulated Lower Overburden Water Level Elevation (m asl)

- < 340
- 340 - 360
- 360 - 380
- 380 - 400
- 400 - 420
- 420 - 440
- 440 - 460
- > 460

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000

1,400 0 1,400 2,800 m

NAD 1983 UTM Zone 17N

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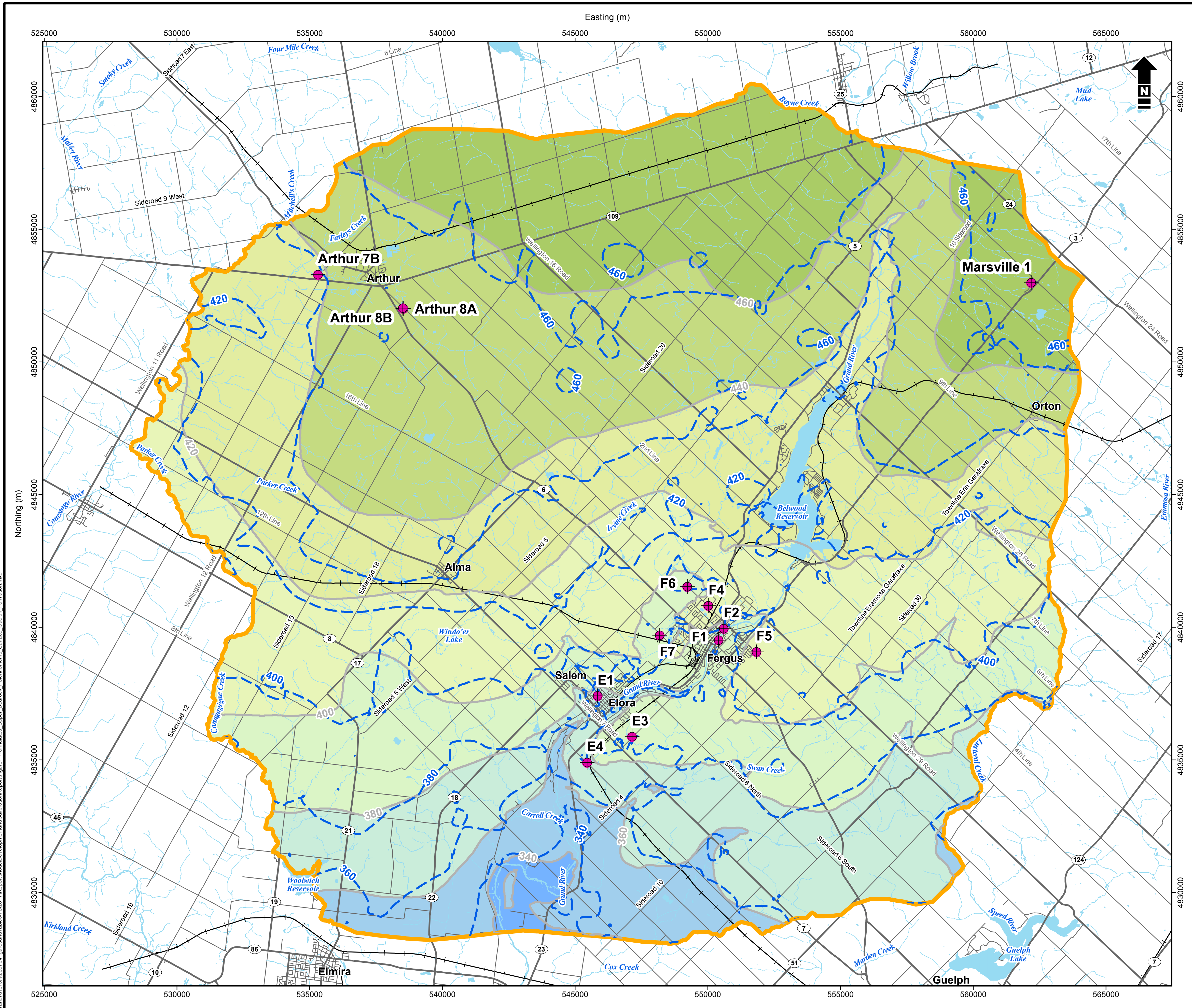
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Simulated Lower Overburden Water Level Elevations

Date:	Project:	Technical:	Reviewer:	Drawn:
15 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 16



Study Area
Water Body
Watercourse
Highway
Road
Railroad Trail
Observed Water Level Elevation (m asl); 20 m Contour Interval
Simulated Water Level Elevation (m asl); 20 m Contour Interval
Municipal Well within the Study Area

Simulated Upper Bedrock Potentiometric Surface (m asl)

- < 340
- 340 - 360
- 360 - 380
- 380 - 400
- 400 - 420
- 420 - 440
- 440 - 460
- > 460

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministry of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

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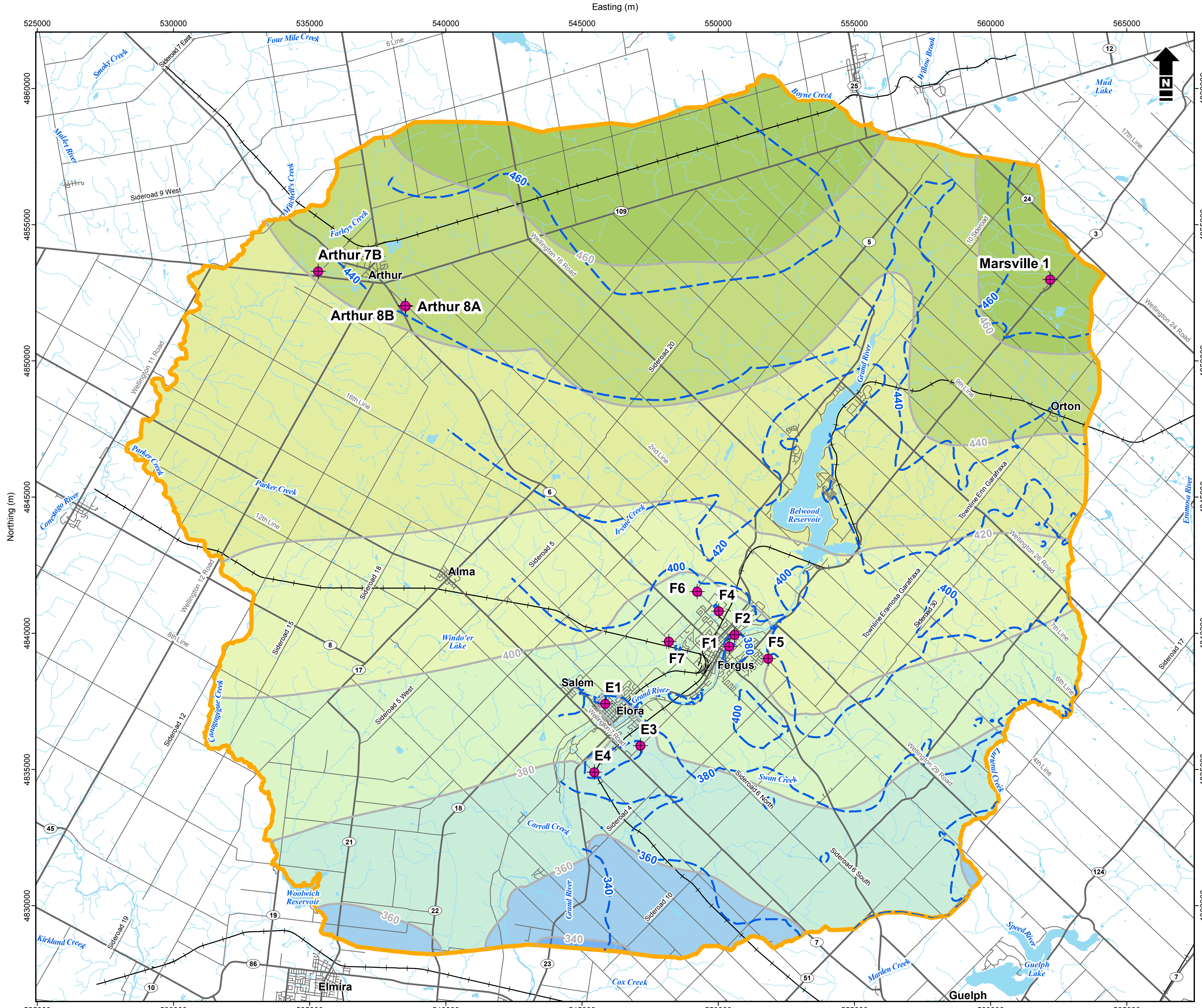
Simulated Upper Bedrock Potentiometric Surface (Guelph Formation)

Date:	Project:	Technical:	Reviewer:	Drawn:
15 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 17



Study Area
Water Body
Watercourse
Highway
Road
Railroad Trail
Observed Water Level Elevation (m asl); 20 m Contour Interval
Simulated Water Level Elevation (m asl); 20 m Contour Interval
Municipal Well within the Study Area

Simulated Lower Bedrock Potentiometric Surface (m asl)

- < 340
- 340 - 360
- 360 - 380
- 380 - 400
- 400 - 420
- 420 - 440
- 440 - 460
- > 460

1:145,000

NAD 1983 UTM Zone 17N

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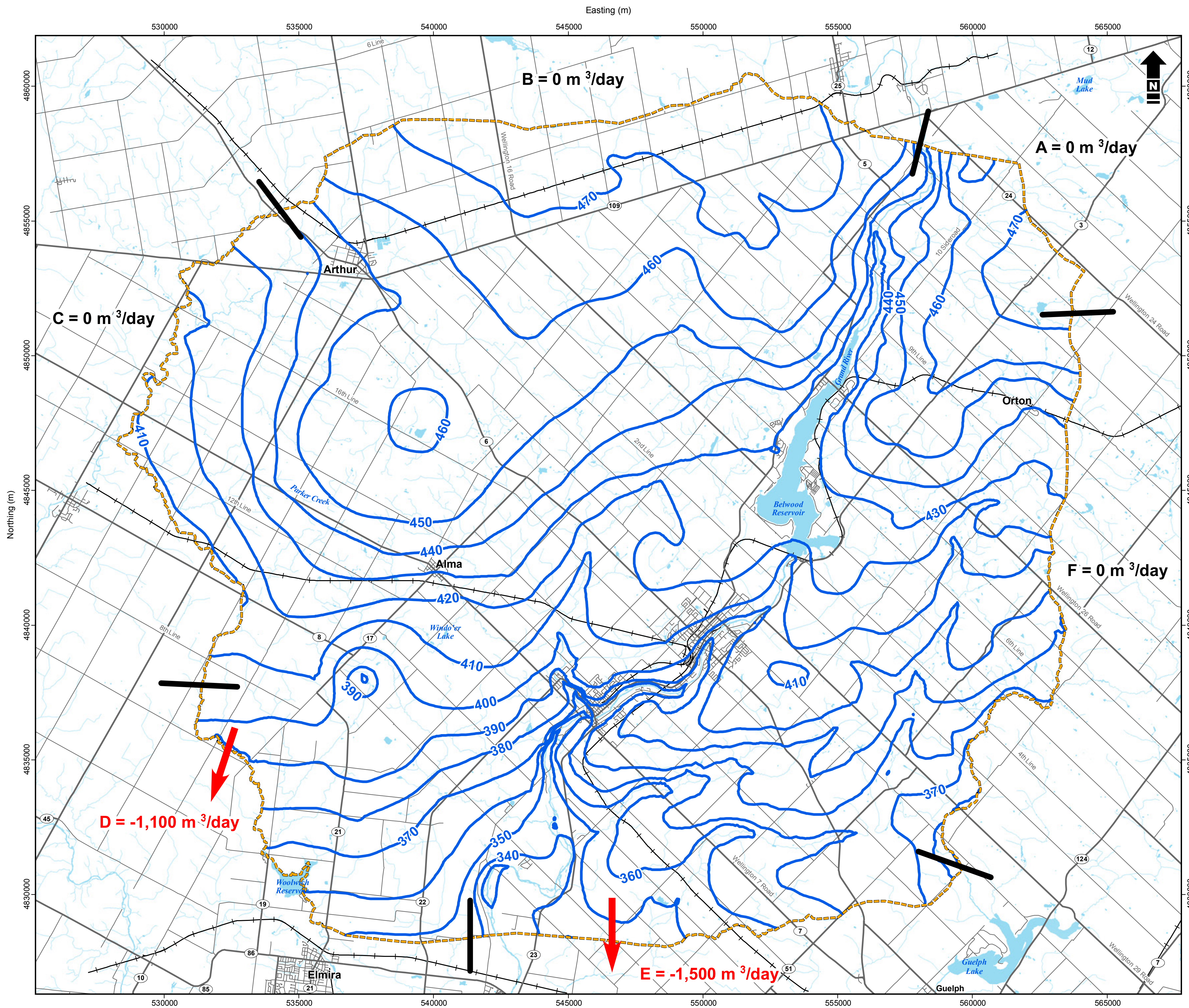
Simulated Lower Bedrock Potentiometric Surface (Goat Island and Gasport Formations)

Date:	Project:	Technical:	Reviewer:	Drawn:
15 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure 18



Model Domain
Water Body
Watercourse
Highway
Road
Railroad Trail
Boundary Division
Overburden Simulated Head Contour
450 Groundwater Elevation (masl)

1:145,000

1,400 0 1,400 2,800 m

NAD 1983 UTM Zone 17N

Reference: Data obtained from GeoBase® used under license. Contains information licensed under the Open Government Licence – Ontario.

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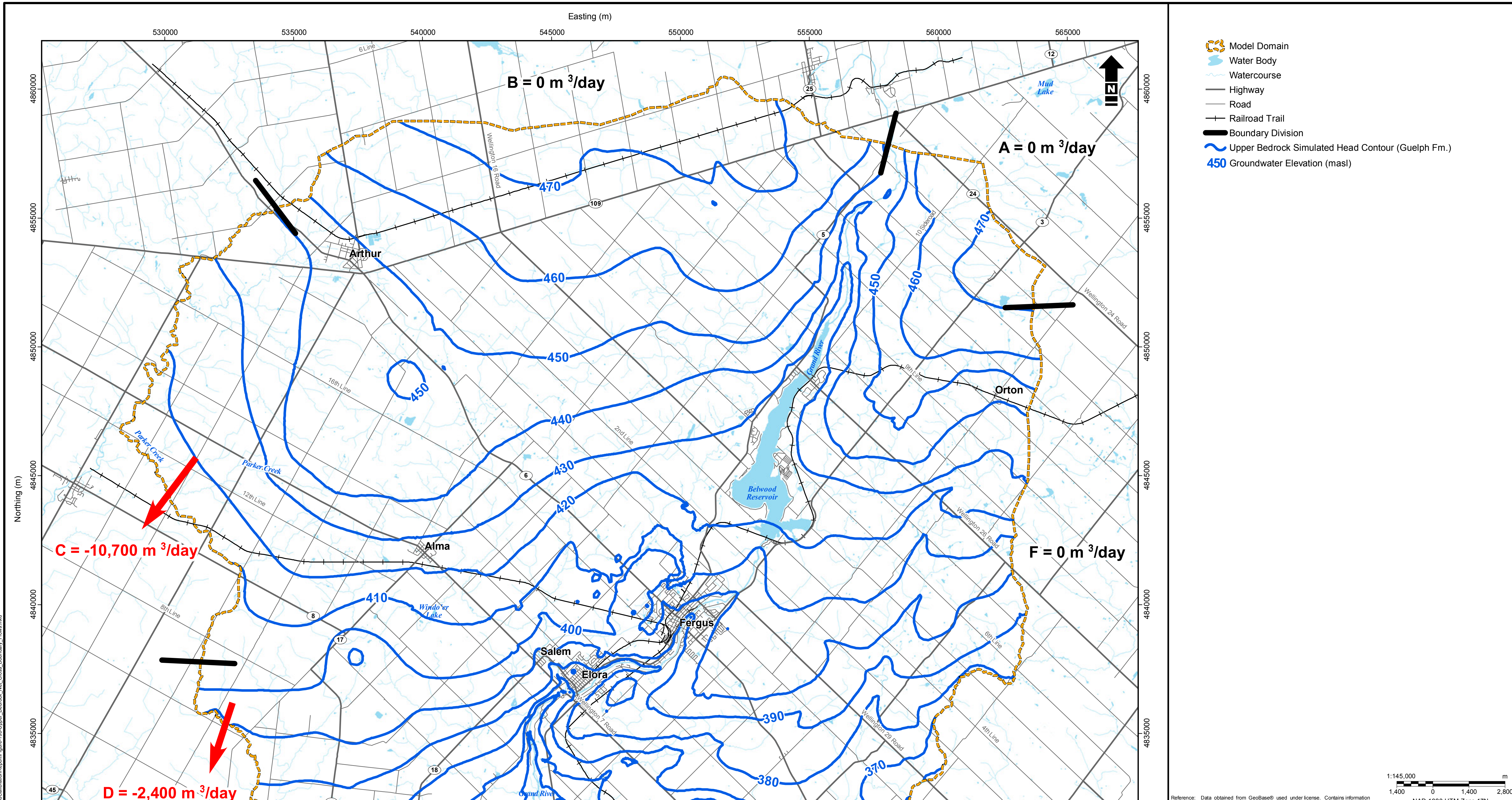
Overburden Net Cross-Boundary Flows

Date:	Project:	Technical:	Reviewer:	Drawn:
01 Apr 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 19a



Reference: Data obtained from GeoBase® used under license. Contains information licensed under the Open Government Licence – Ontario.

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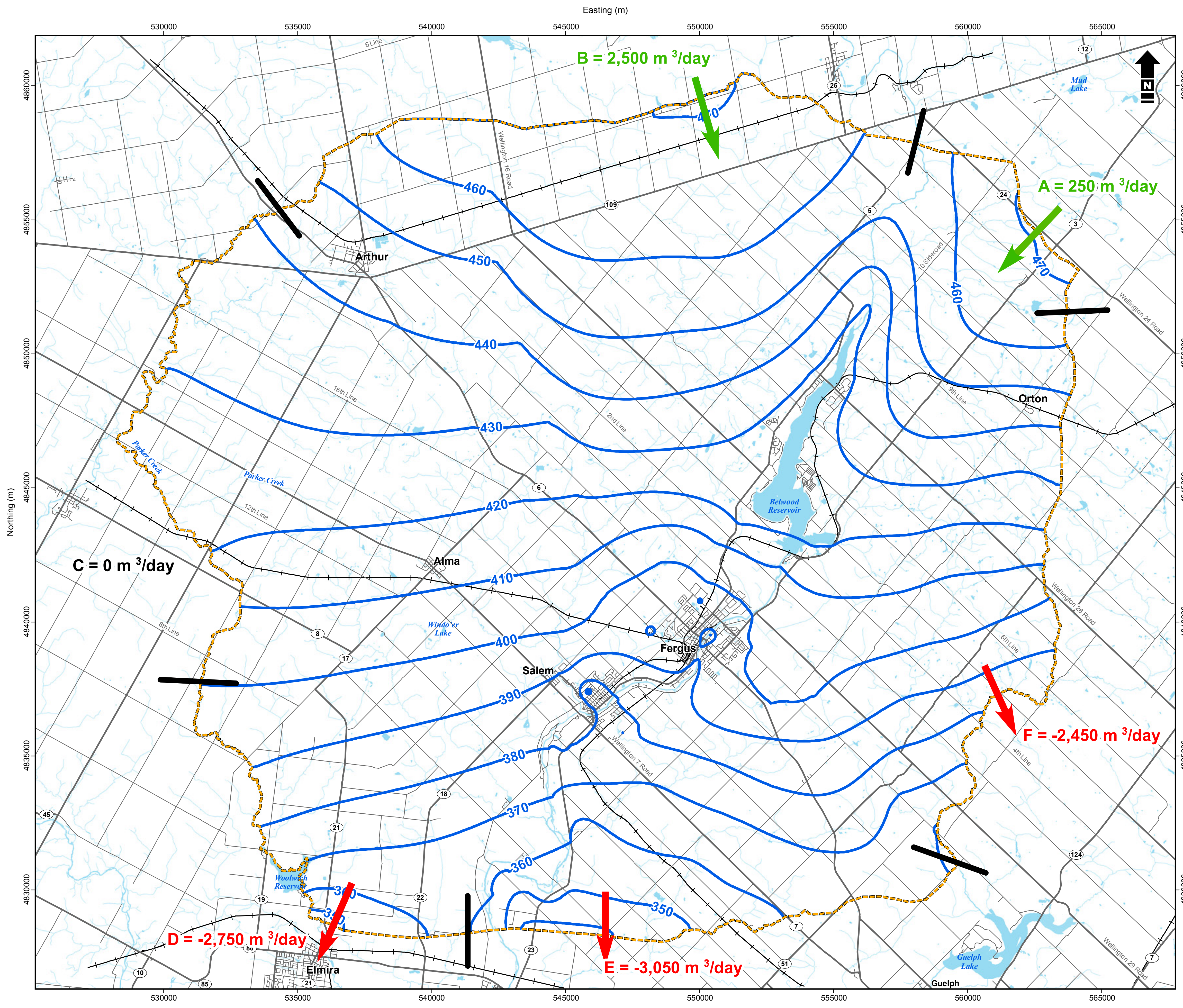
Upper Bedrock Net Cross-Boundary Flows

Date:	Project:	Technical:	Reviewer:	Drawn:
01 Apr 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 19b



Model Domain
Water Body
Watercourse
Highway
Road
Railroad Trail
Boundary Division
Lower Bedrock Simulated Head Contour (Goat Island Fm.)
450 Groundwater Elevation (masl)

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

Reference: Data obtained from GeoBase® used under license. Contains information licensed under the Open Government Licence – Ontario.

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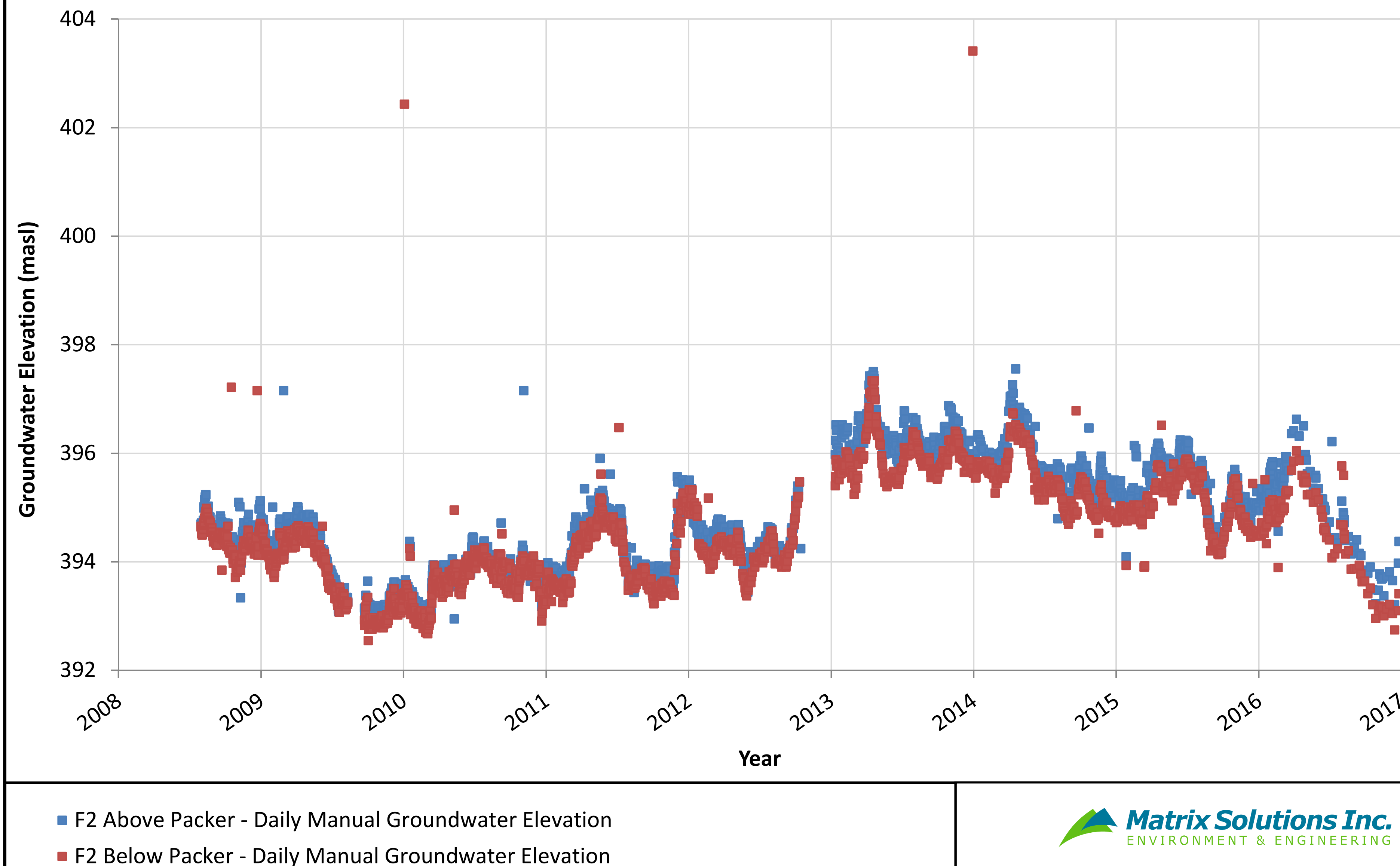
Lower Bedrock Net Cross-Boundary Flows

Date:	Project:	Technical:	Reviewer:	Drawn:
01 Apr 2019	23876	J. Melchin	D. Van Vliet	C. Curry

Figure 19c

I:\GrandRiverCA\23876\FiguresandTables\T3\2017\ReportModelDevelopmentandCalibrationReport\Figure-19c-Lower_Bedrock_Net_Cross_Boundary_Flows.mxd

APPENDIX A
Additional Groundwater Level Monitoring Hydrographs



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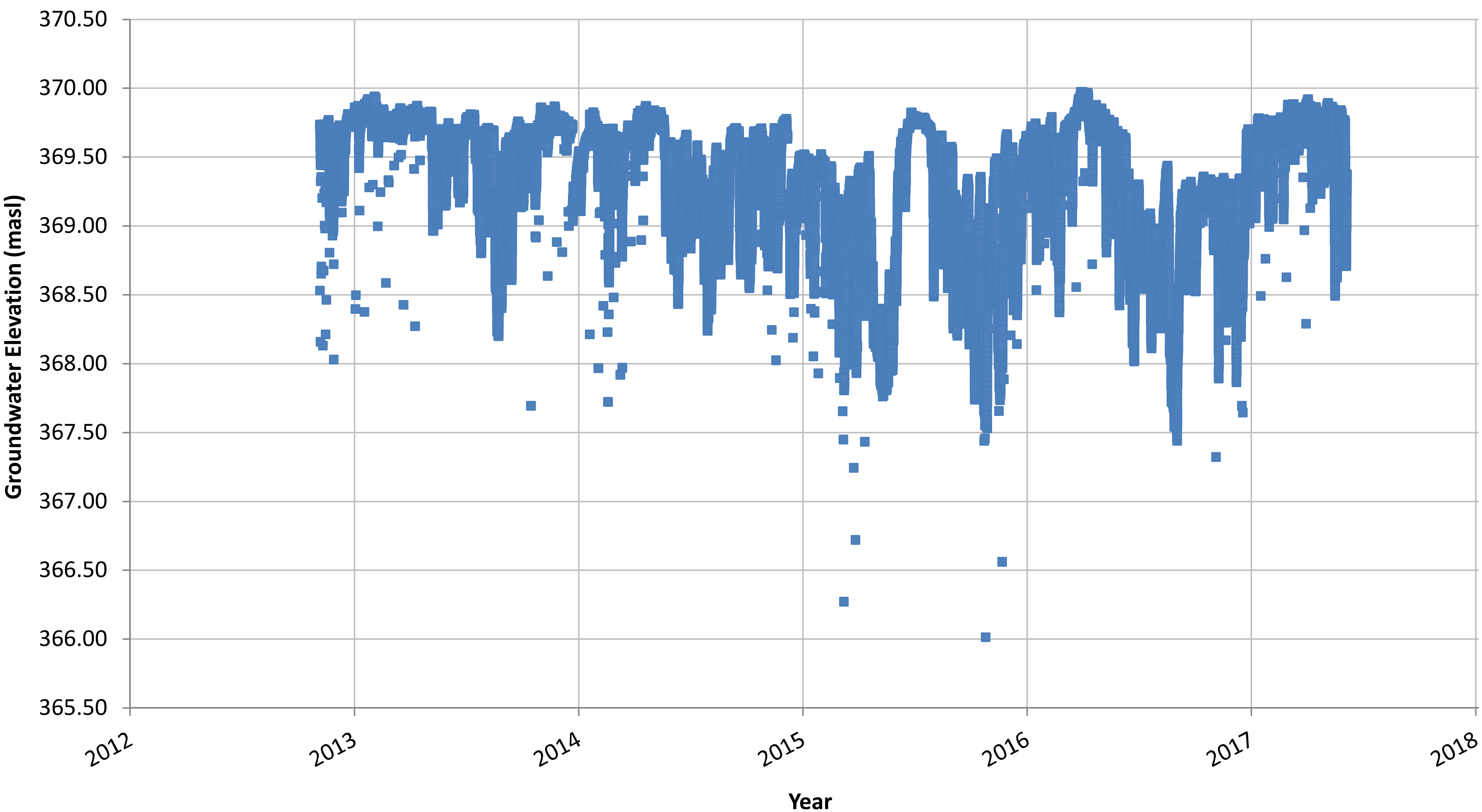
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Municipal Well F2 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A1



Groundwater Elevation

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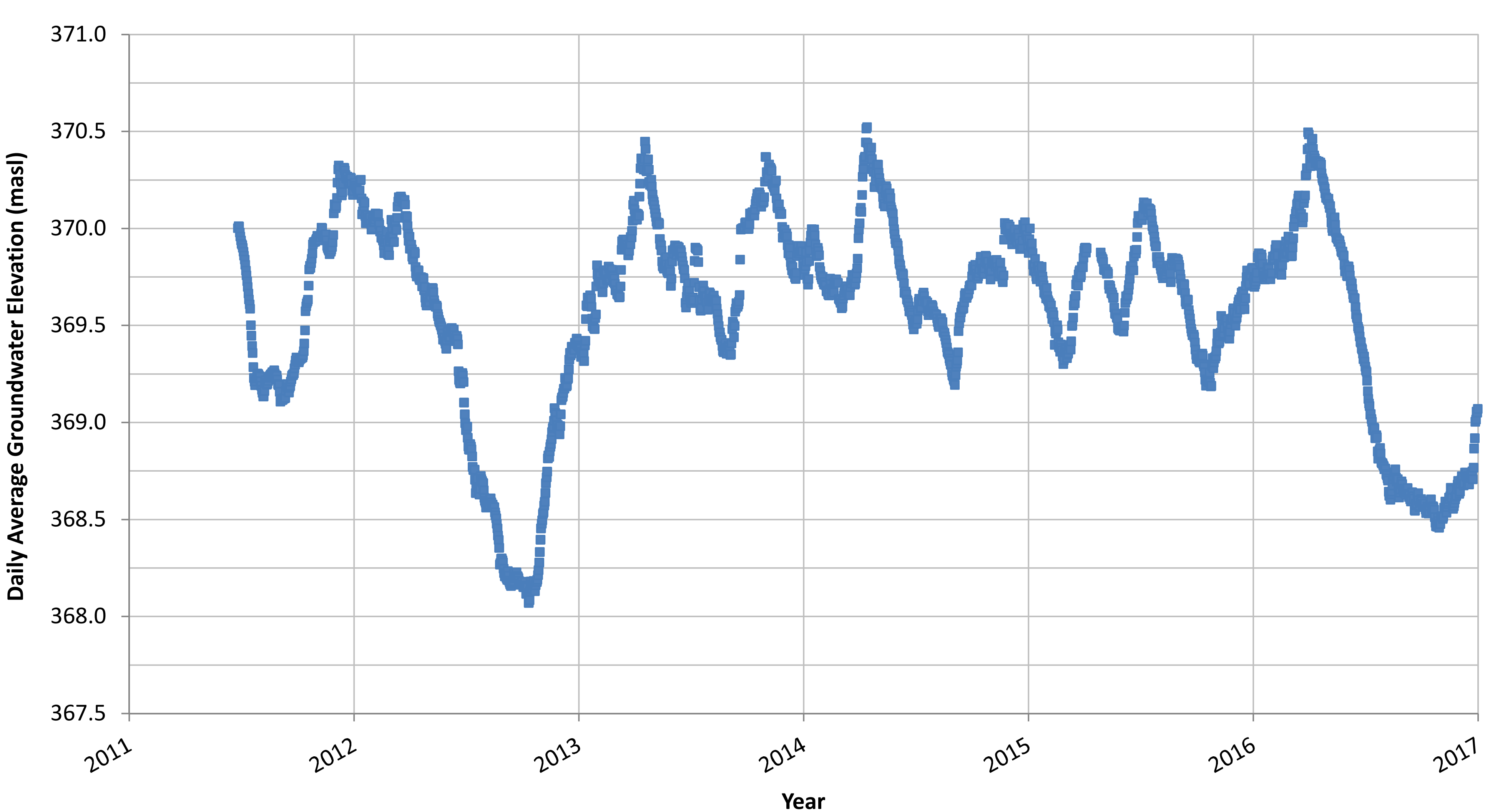
Well 19 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure A2



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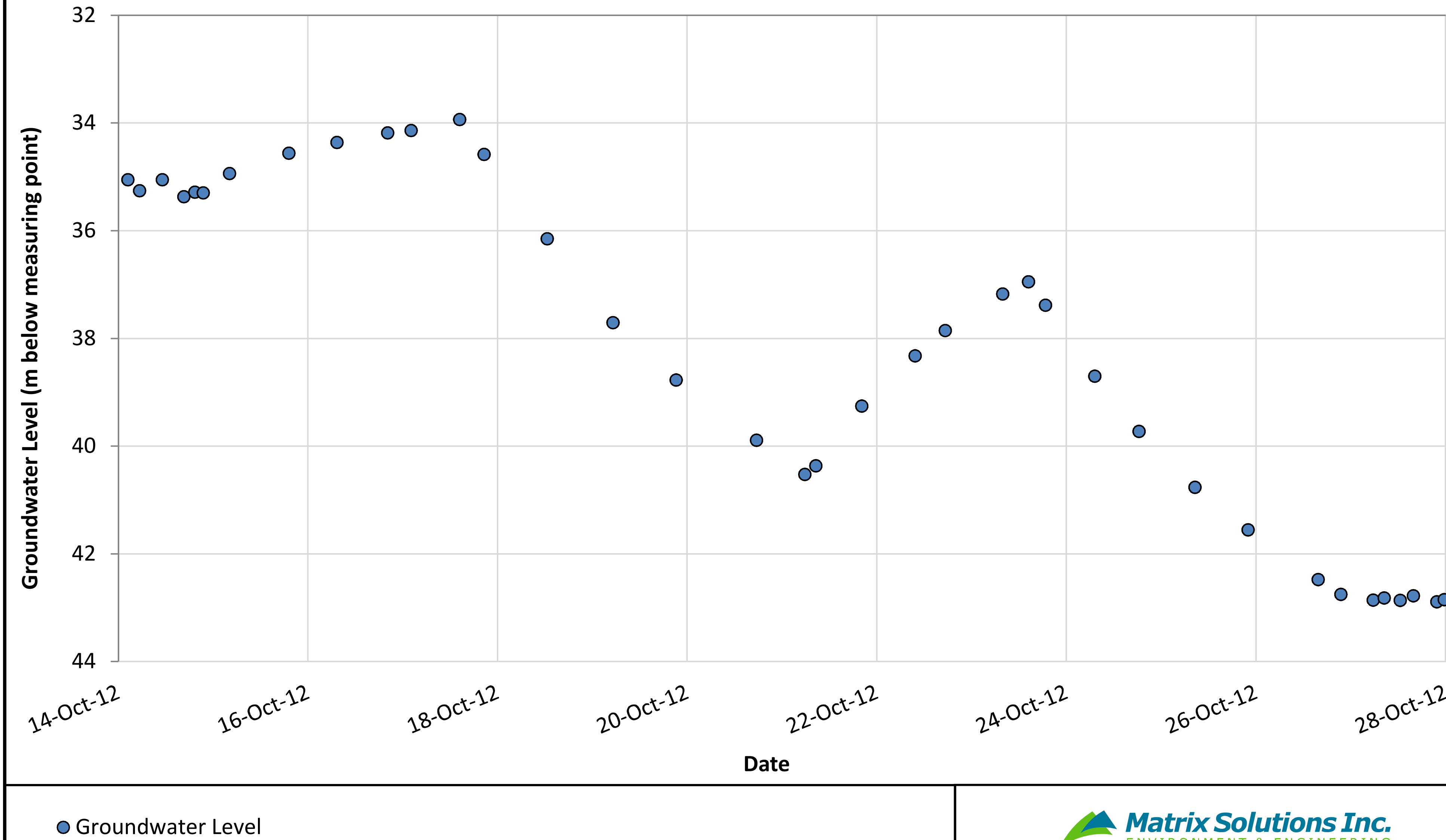
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Ennotville Well – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure A3



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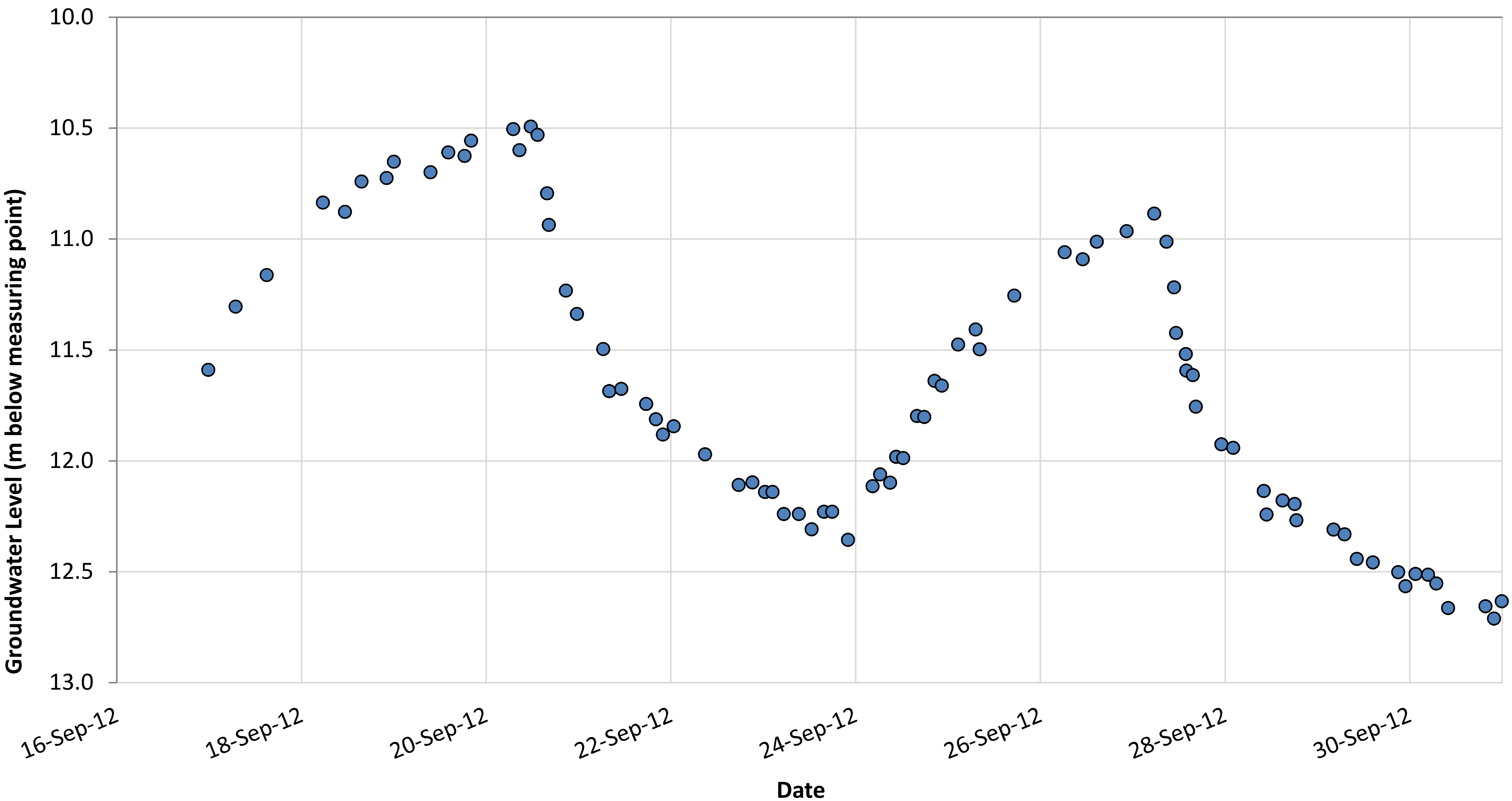
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 1 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A4



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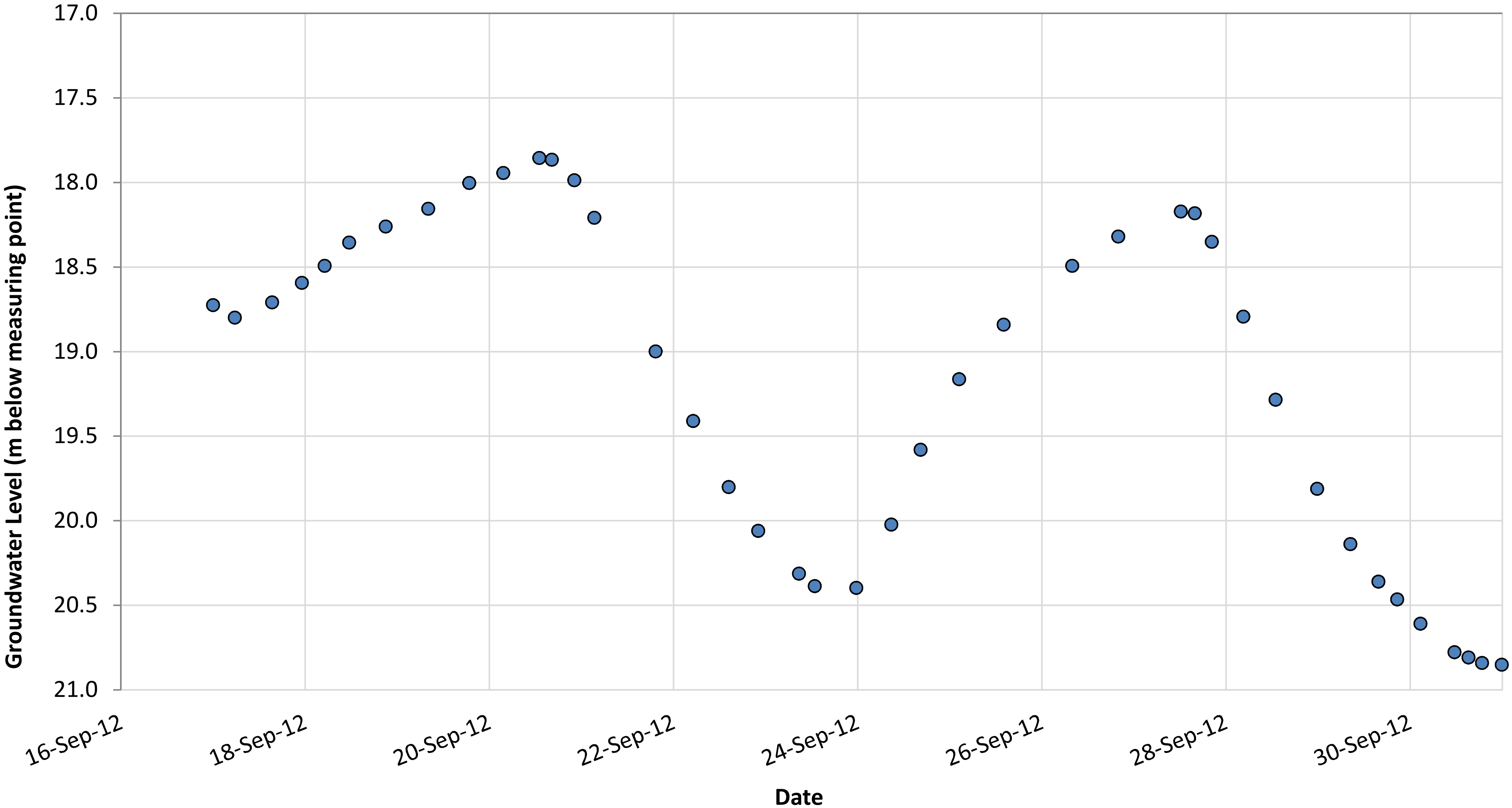
Centre Wellington Tier Three Model Development and Calibration Report

Well 14 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A5



● Groundwater Level

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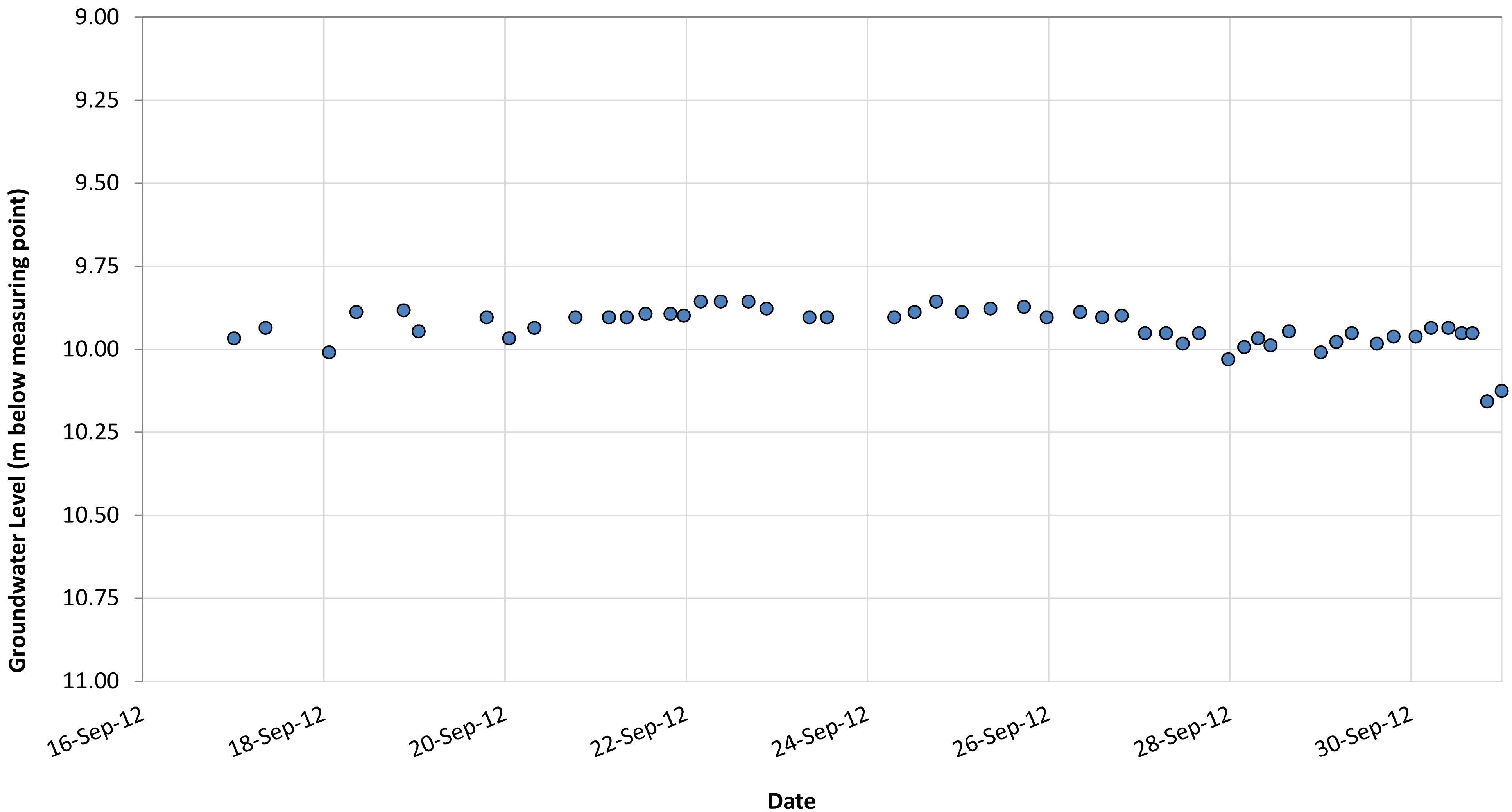
Centre Wellington Tier Three Model Development and Calibration Report

Well 15 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A6



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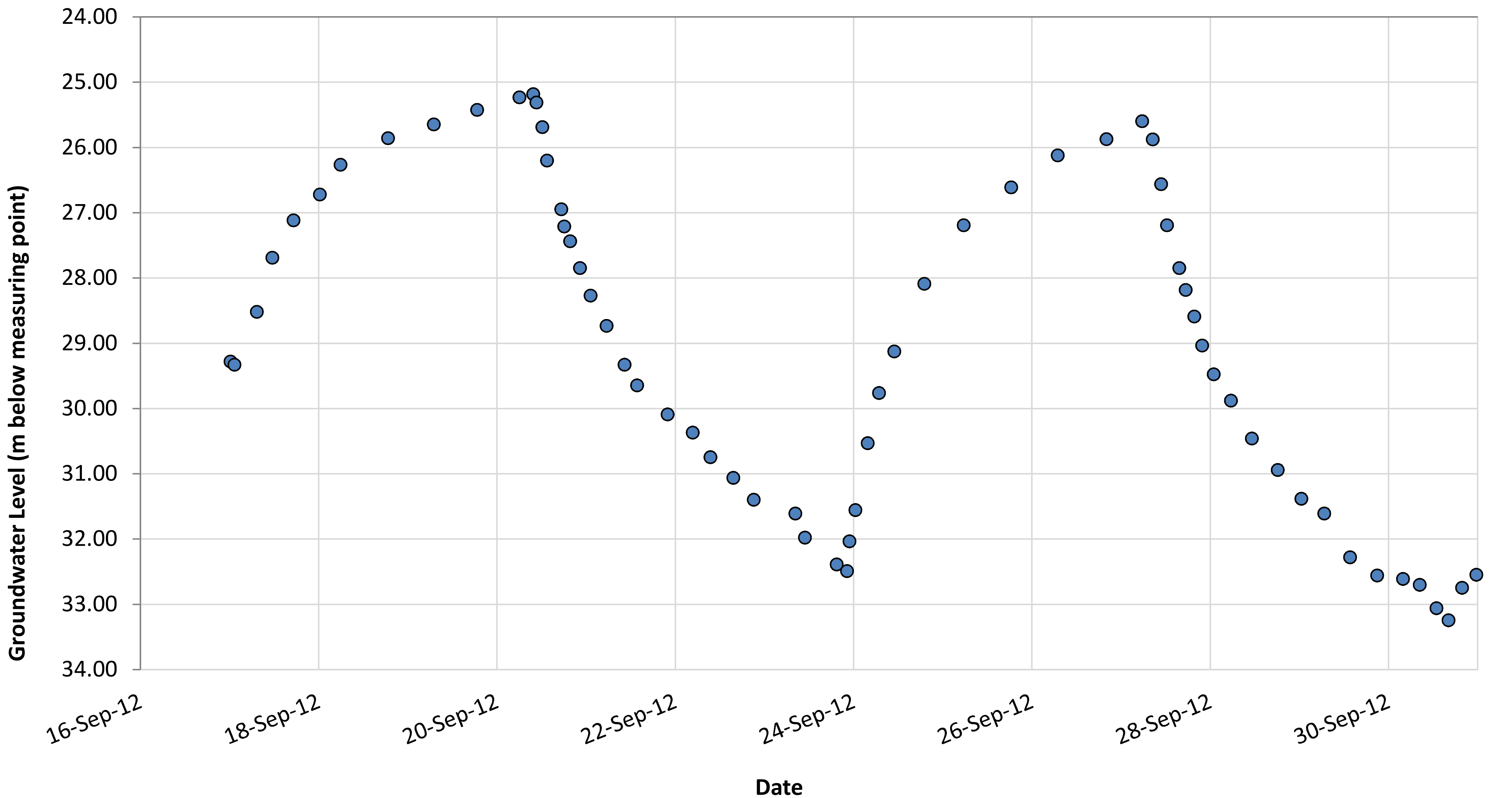
Centre Wellington Tier Three Model Development and Calibration Report

Well 20 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A7



● Groundwater Level

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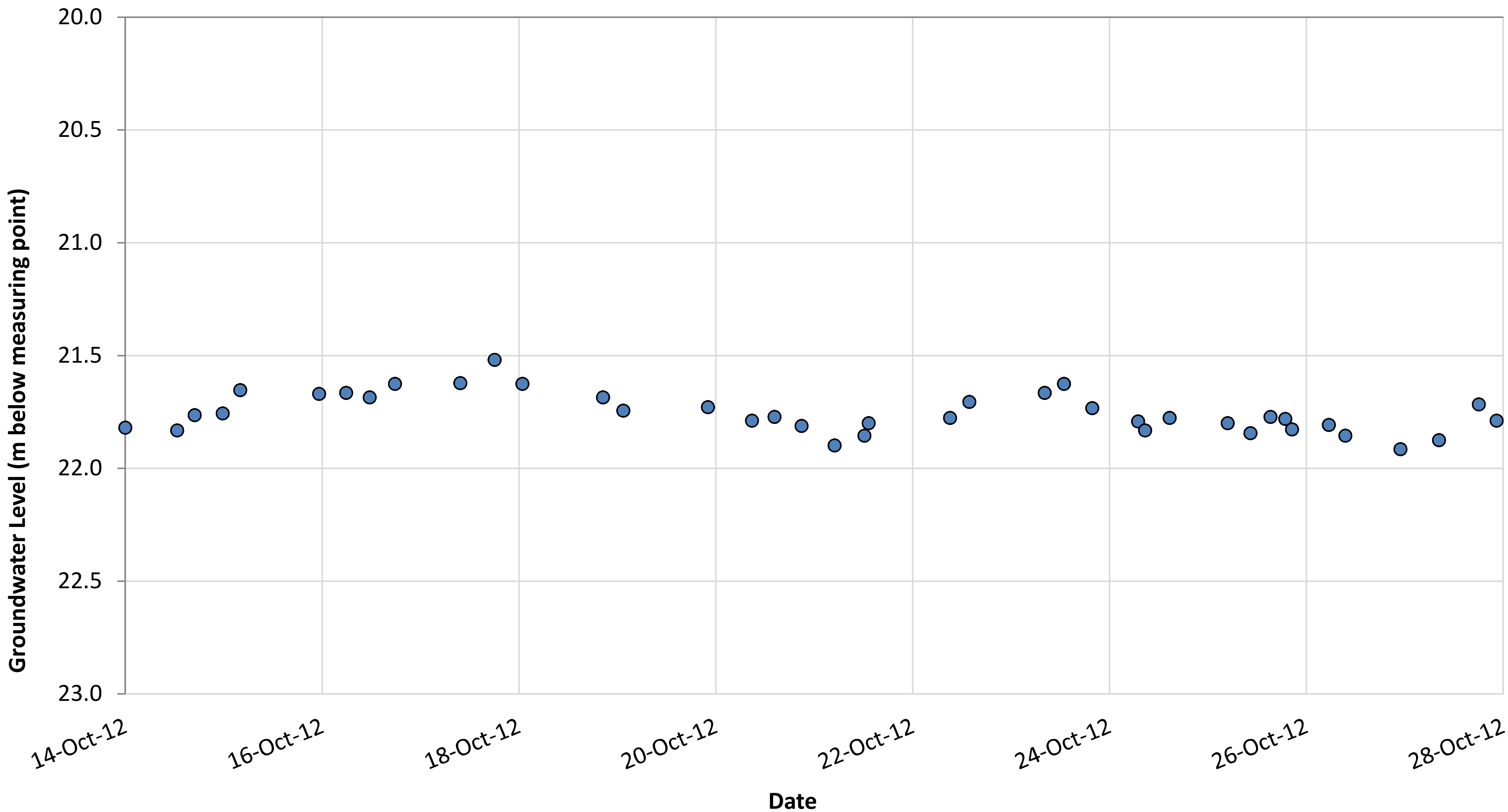
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 21 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure A8



Matrix Solutions Inc.
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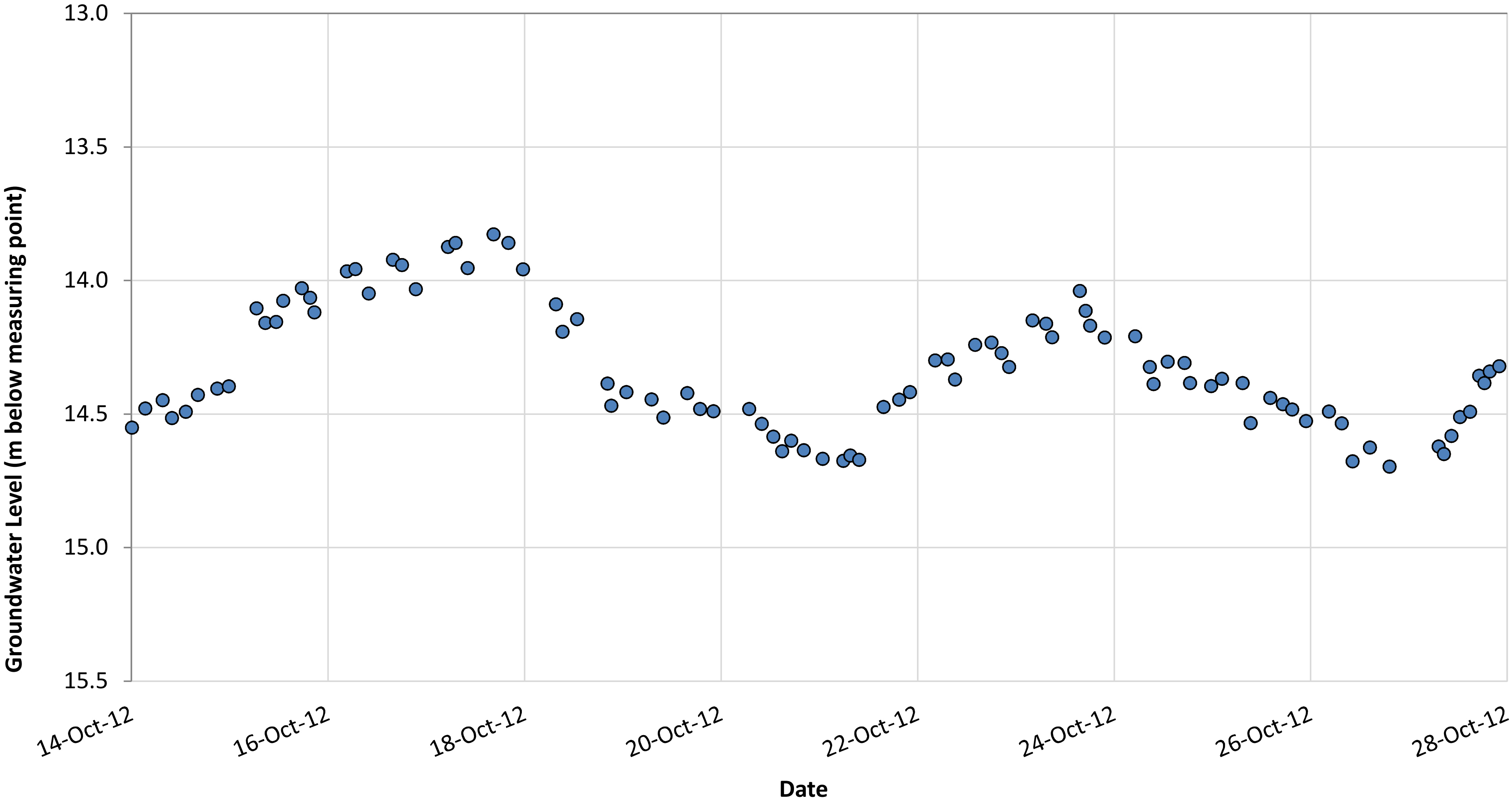
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 28 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A9



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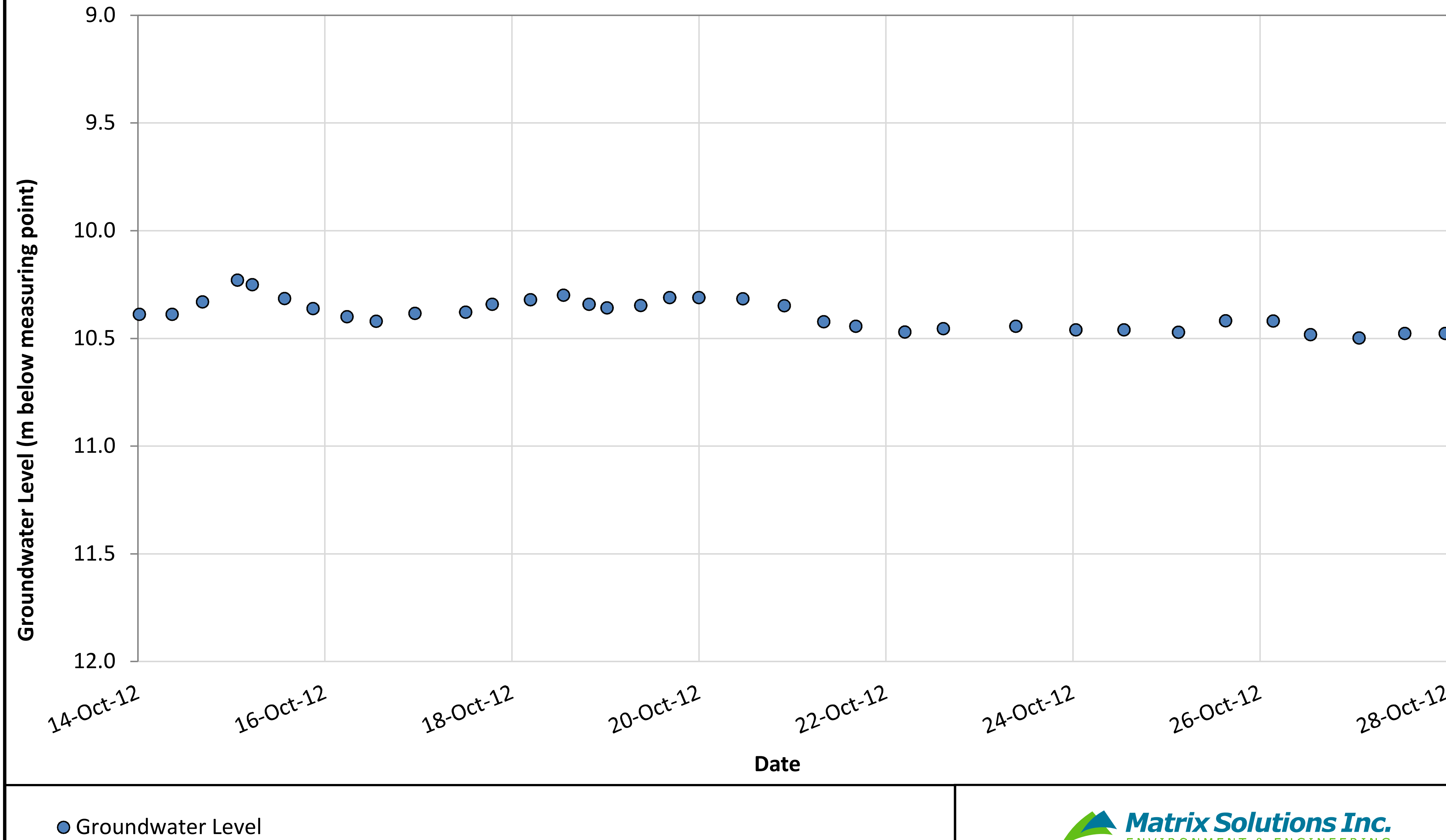
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 29 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A10



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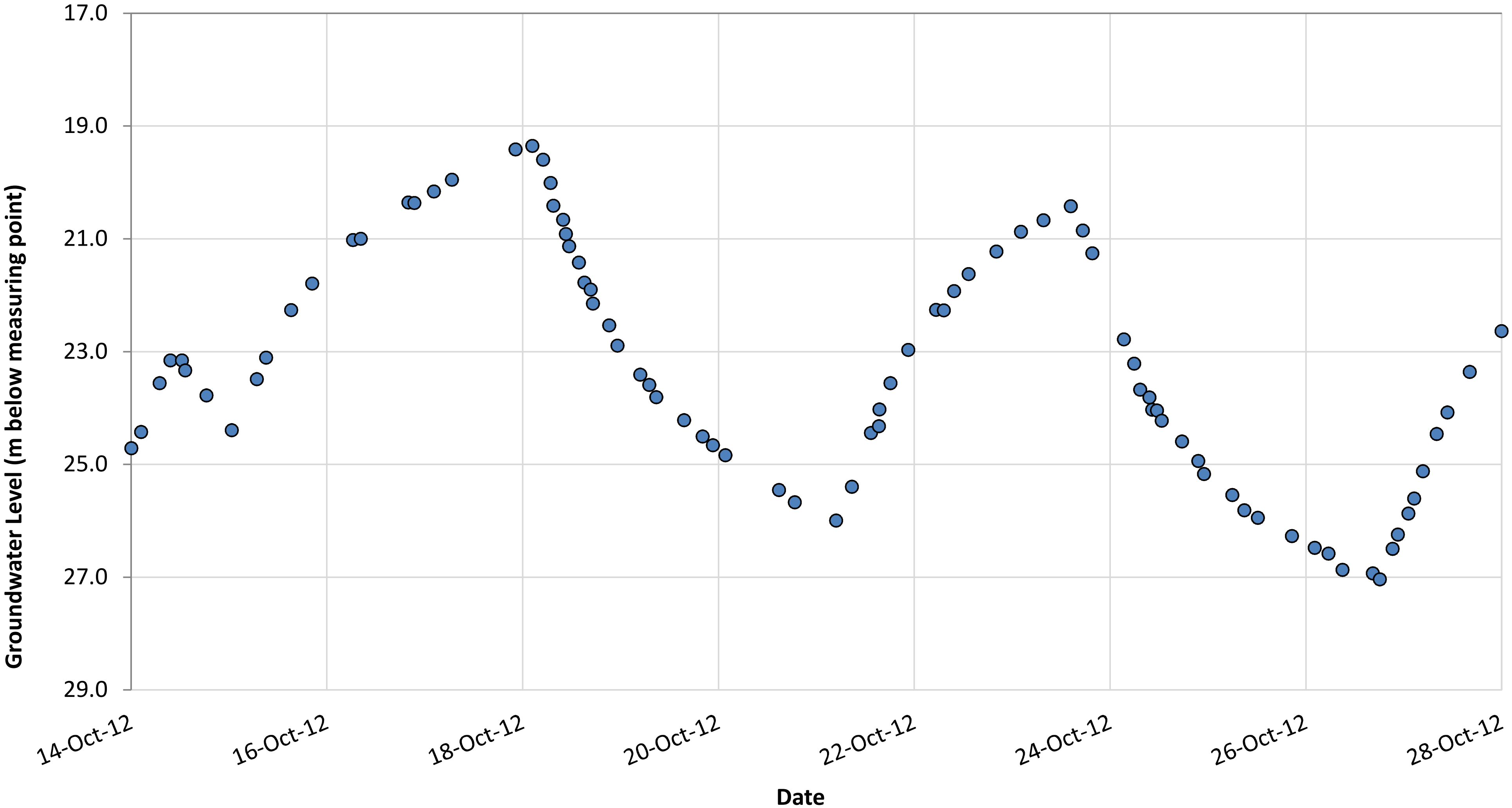
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 30 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A11



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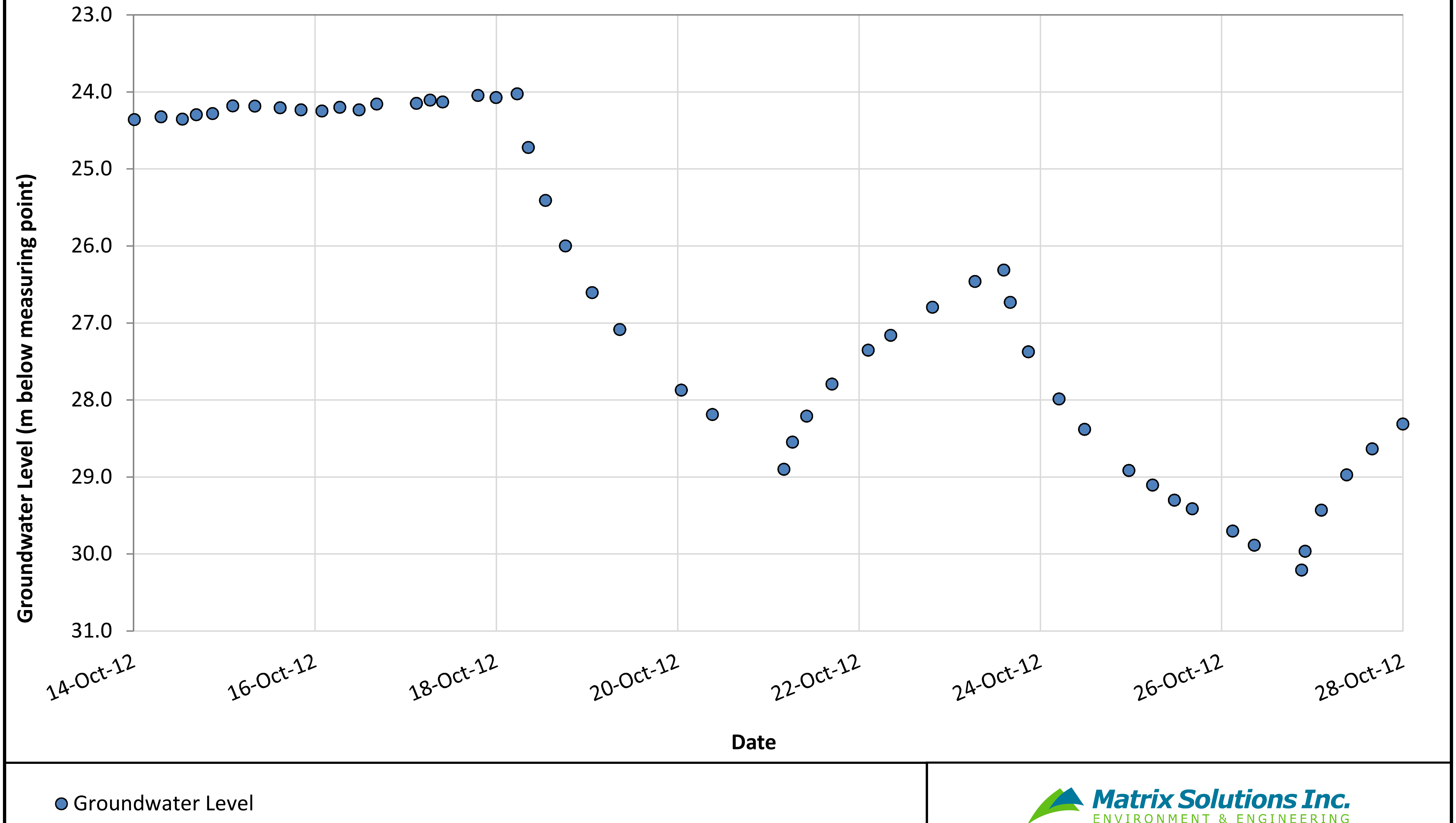
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 32 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A12



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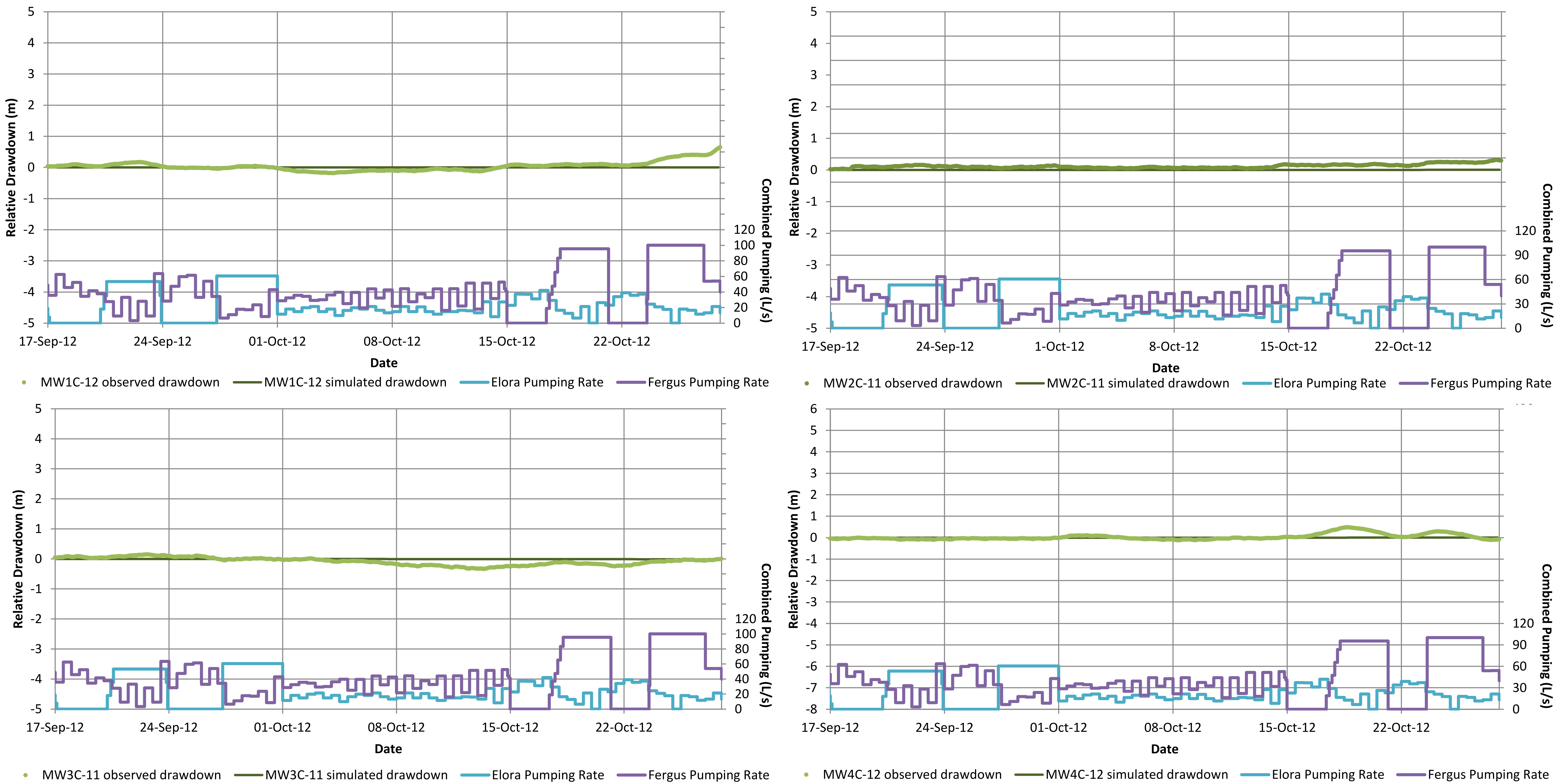
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Well 33 – Water Levels

Date:	Project:	Technical:	Reviewer:	Drawn:
4 Mar 2019	23876	J. Melchin	D. Van Vliet	J. Melchin

Figure
A13

APPENDIX B
Transient Calibration Results; Well Hydrographs



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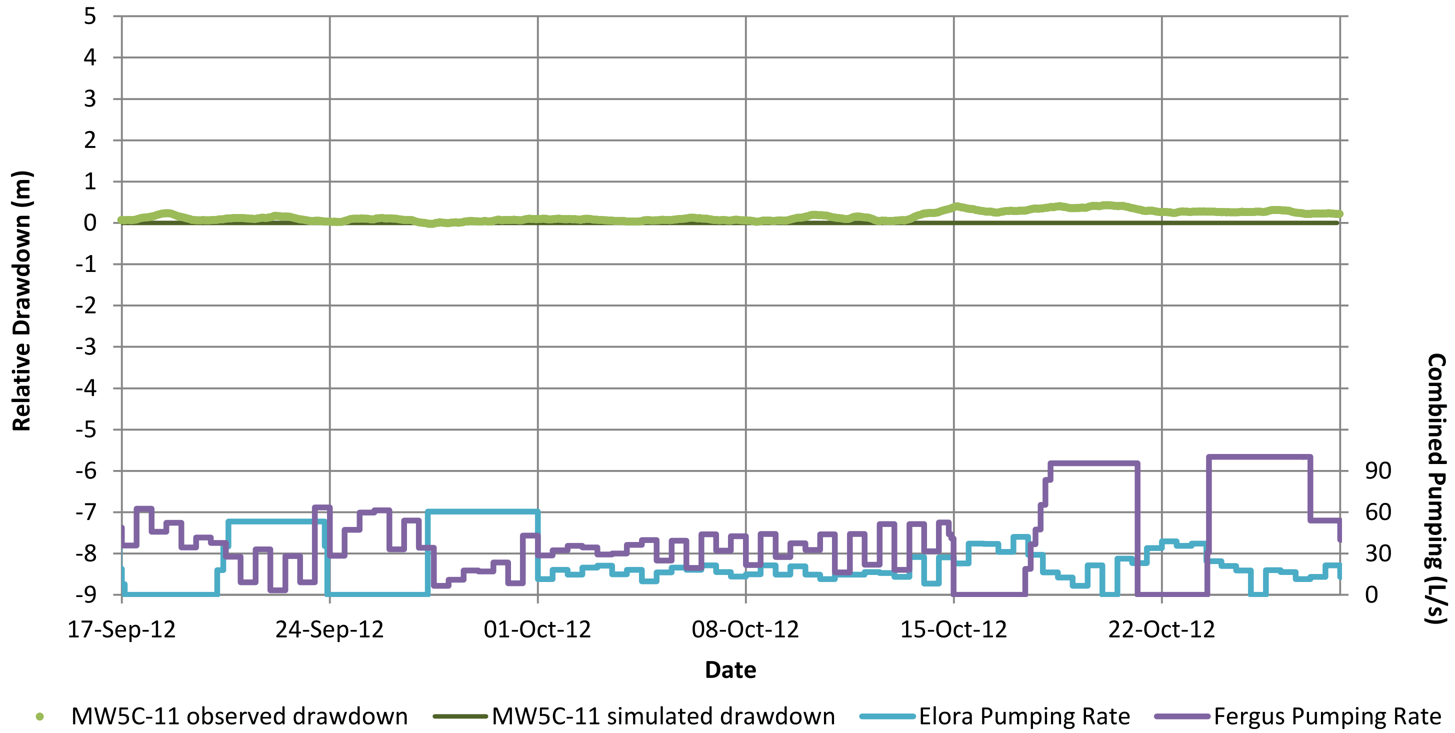
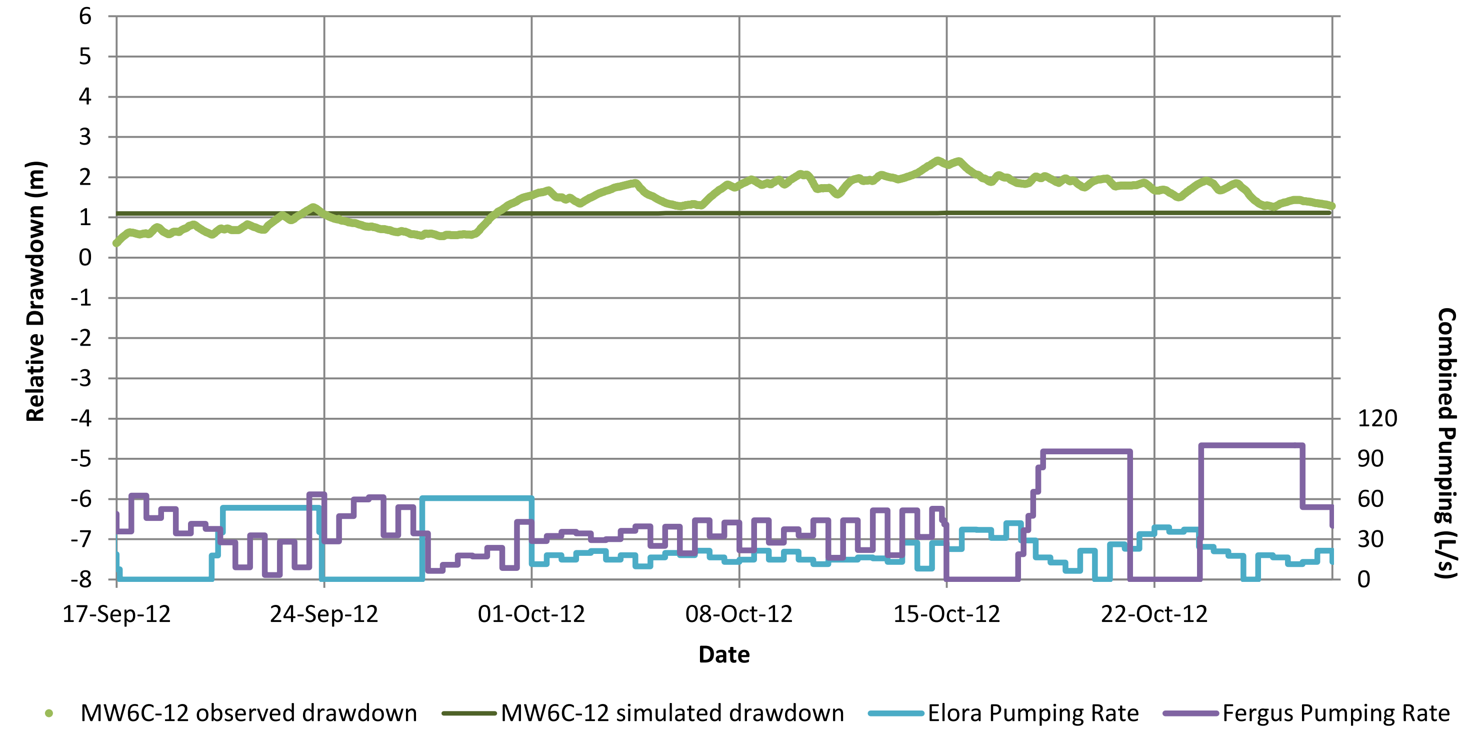
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

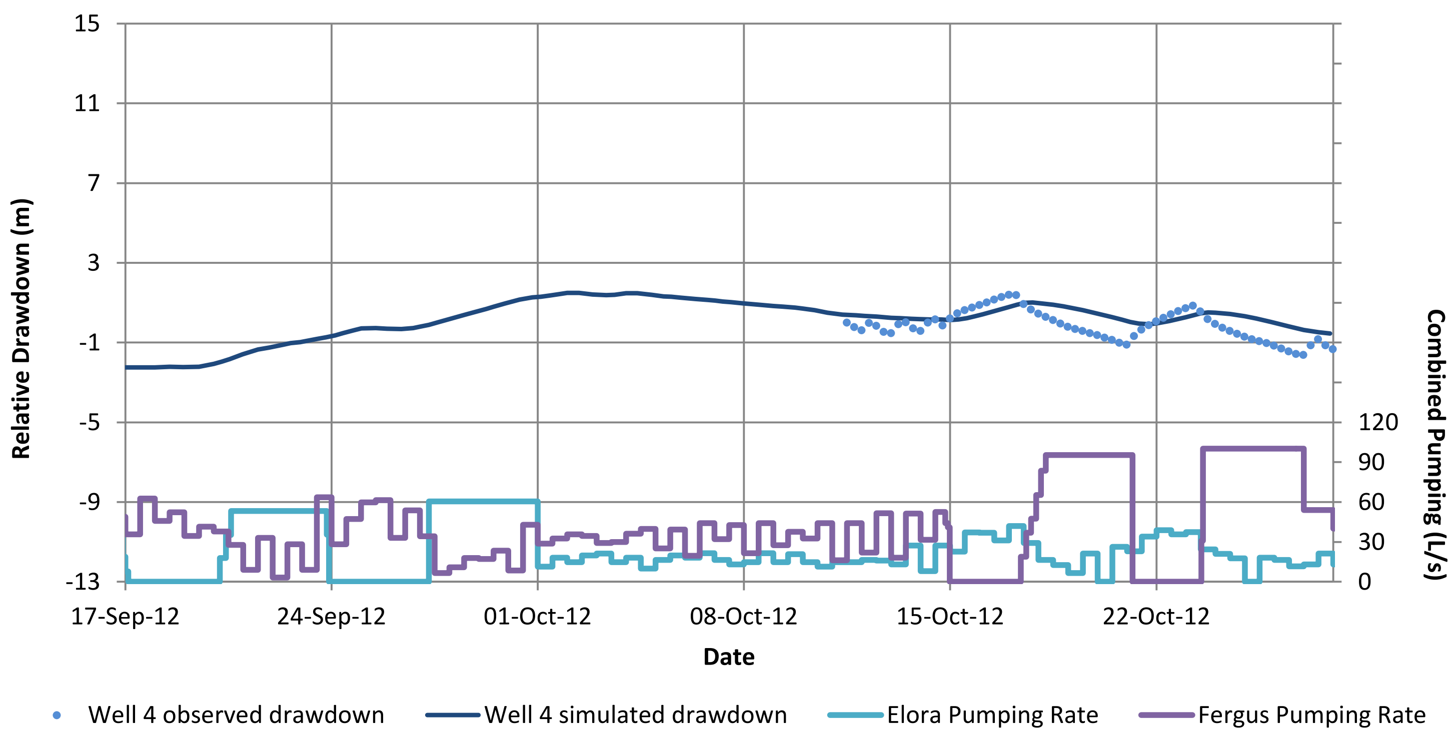
Transient Calibration Hydrographs

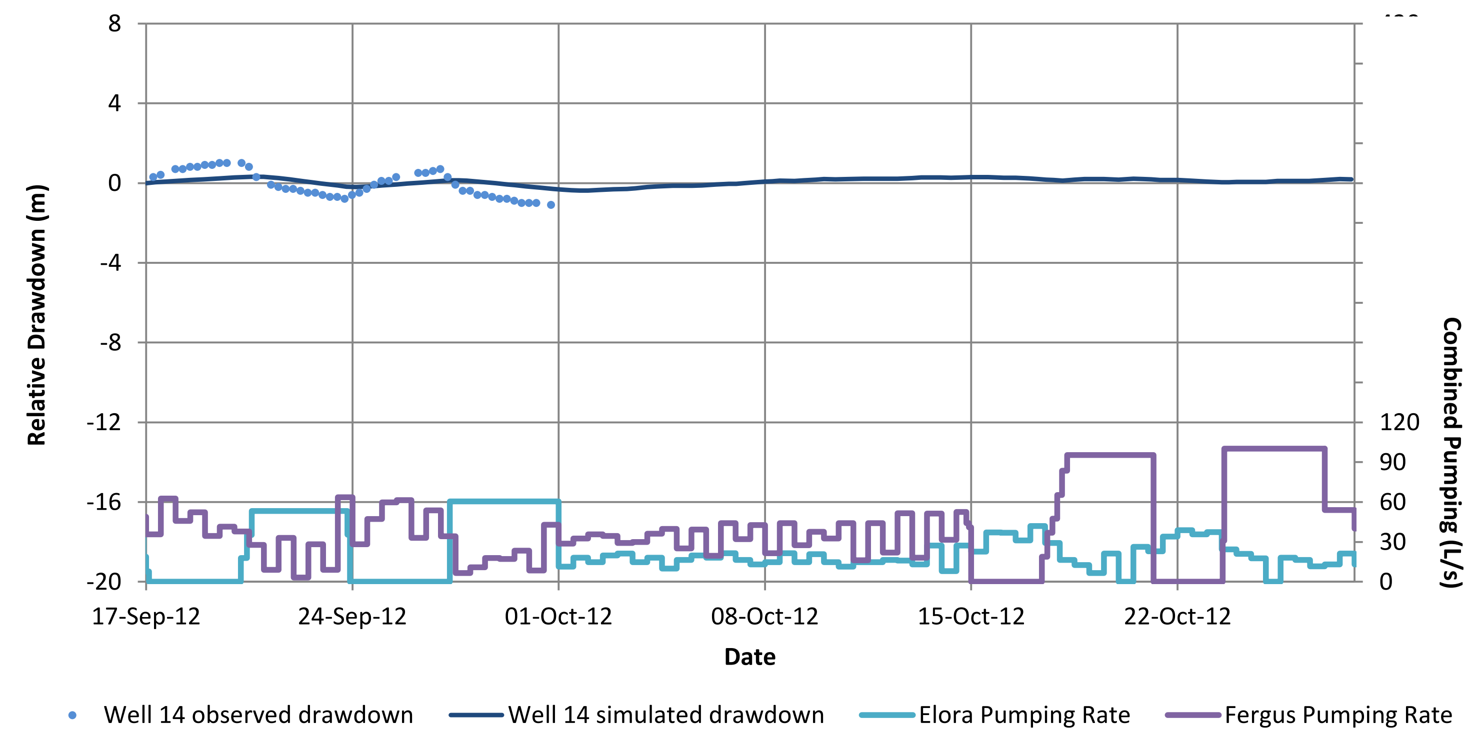
Date: 28 March 2019	Project: 23876	Submitter: J. Melchin	Reviewer: D. Van Vliet

Figure B1









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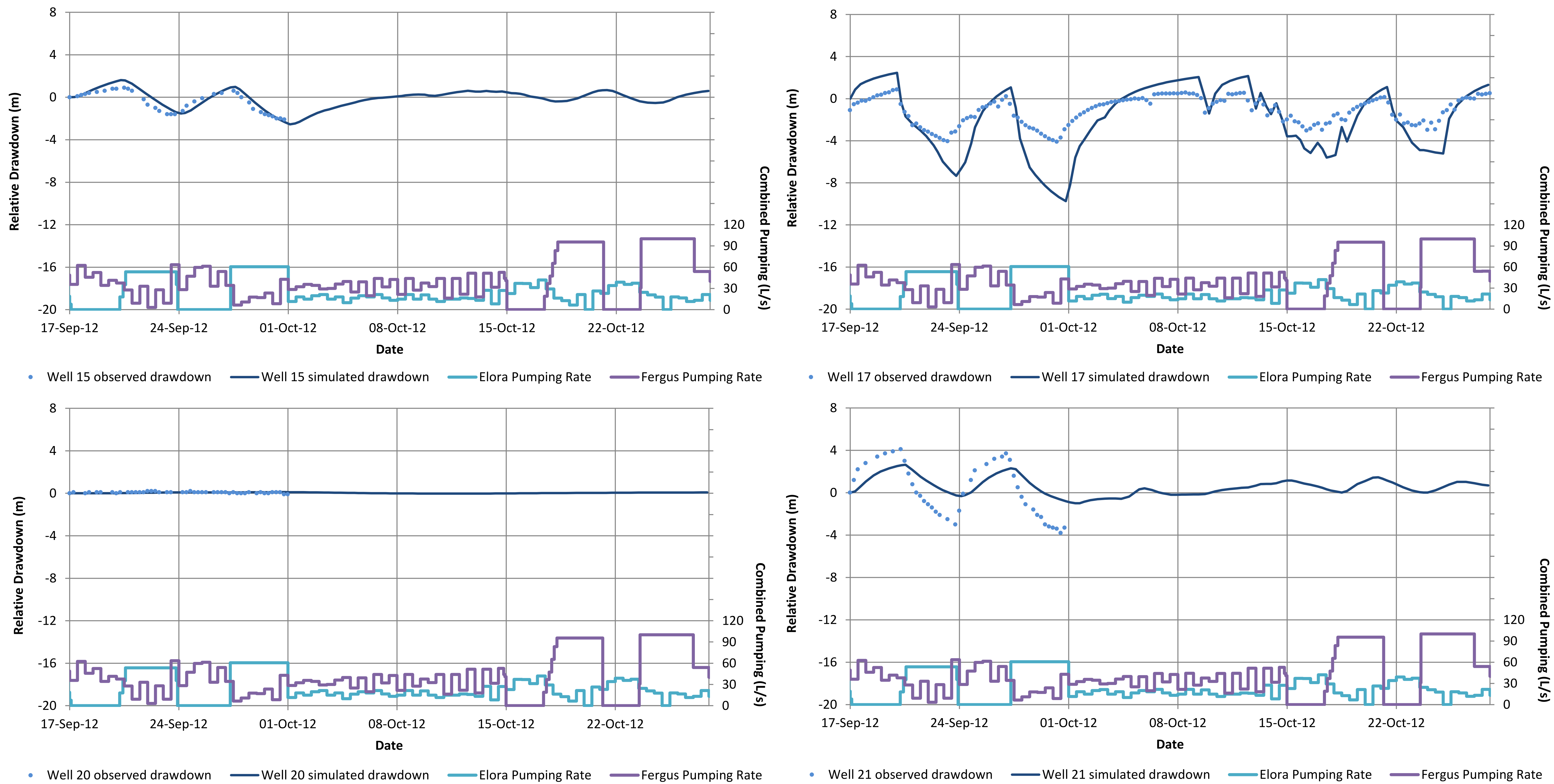
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration Hydrographs

Date: 28 March 2019 | Project: 23876 | Submitter: J. Melchin | Reviewer: D. Van Vliet

Figure B2



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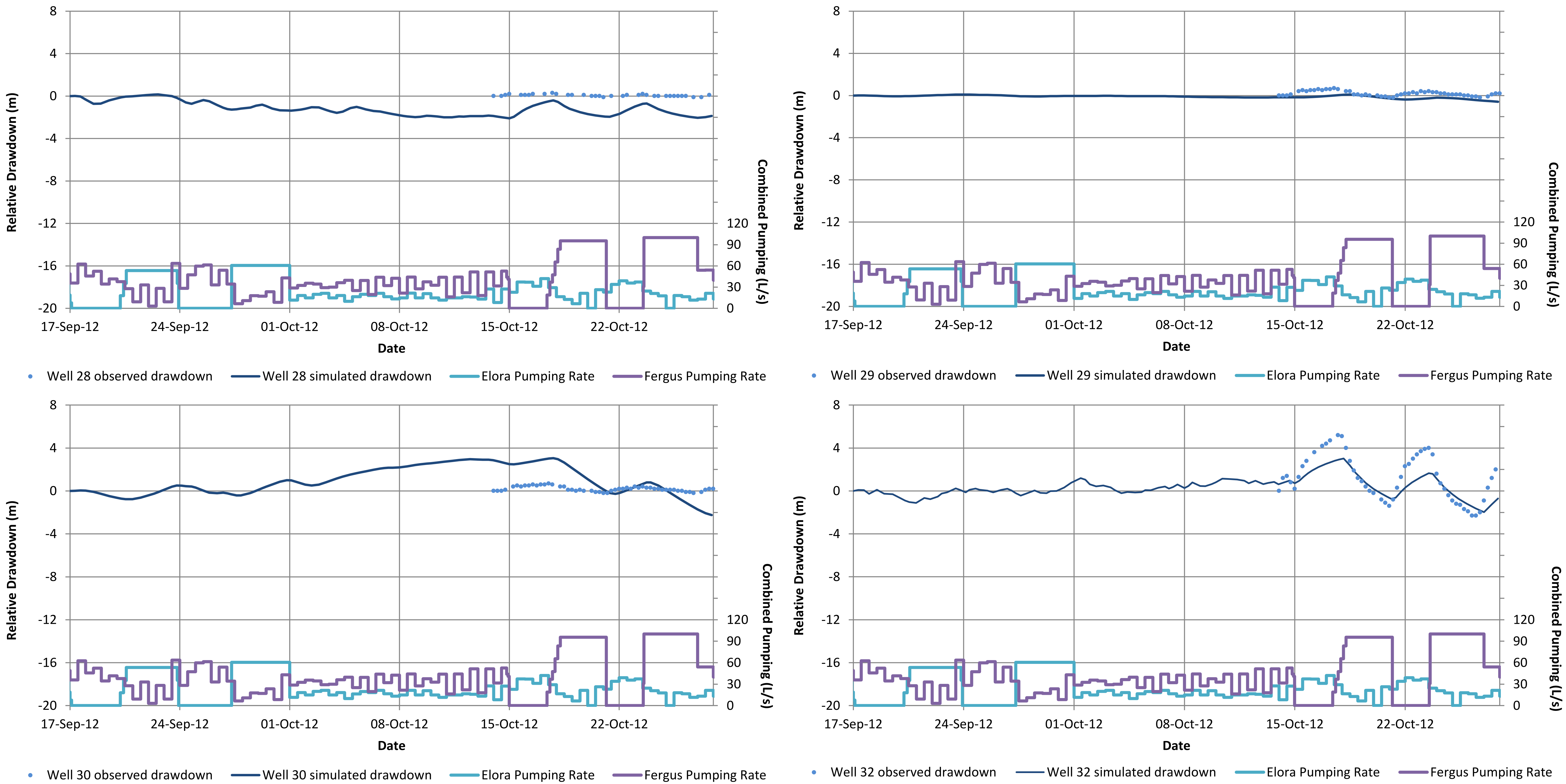
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration Hydrographs

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure B3



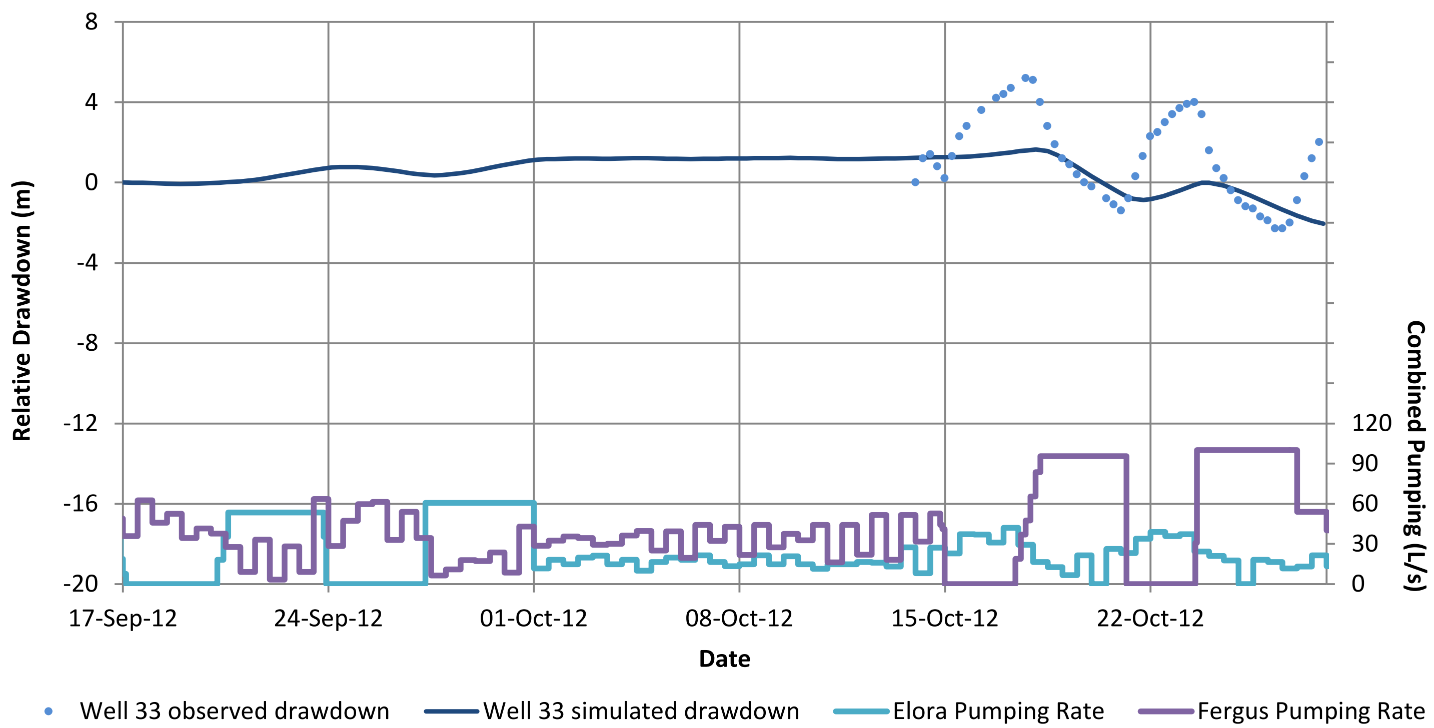
Matrix Solutions Inc.
ENVIRONMENT & ENGINEERING

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration Hydrographs

Date:	Project:	Submitter:	Reviewer:
28 March 2019	23876	J. Melchin	D. Van Vliet

Figure B4



Matrix Solutions Inc.
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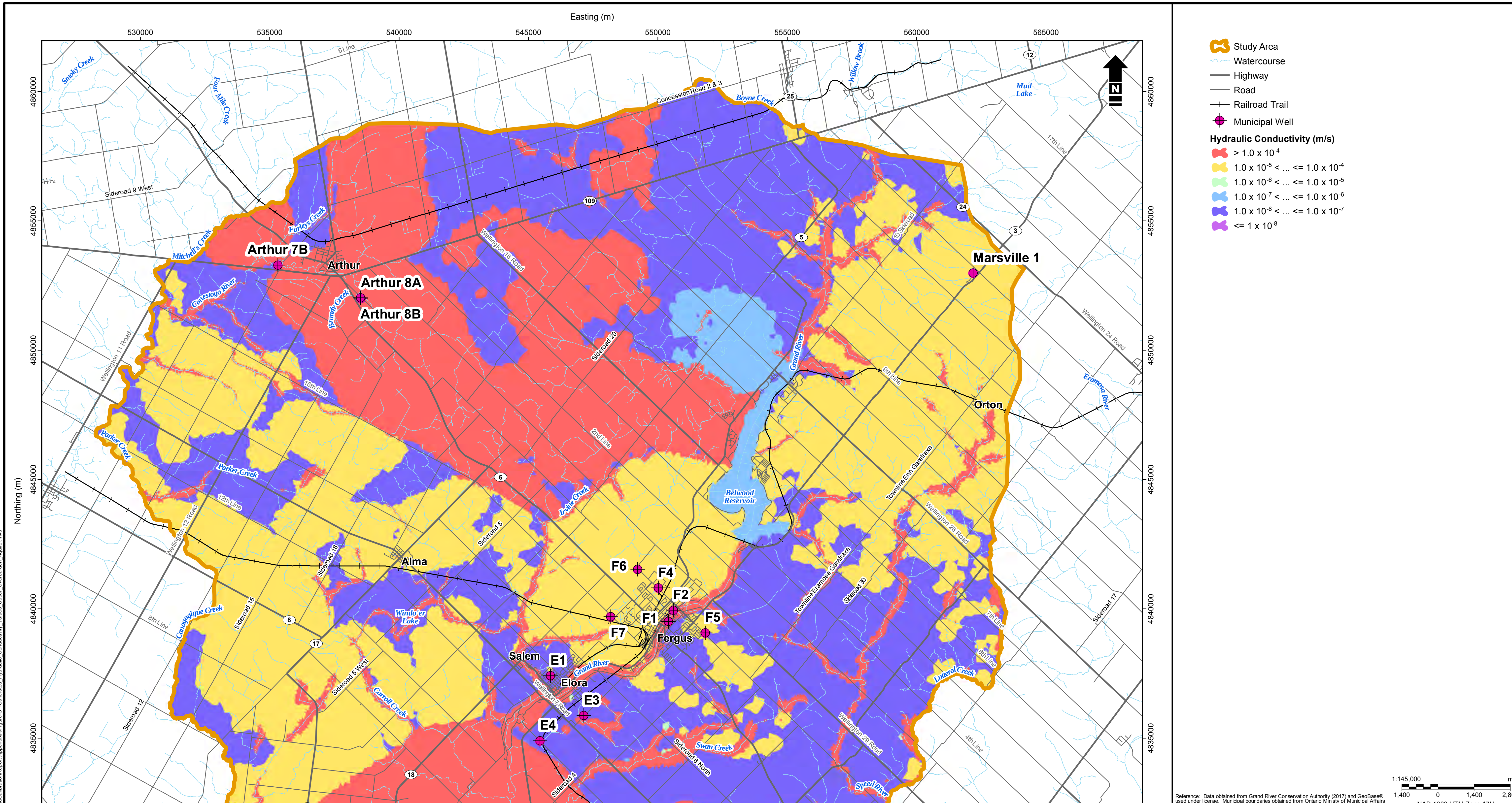
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Transient Calibration Hydrographs

Date: 28 March 2019	Project: 23876	Submitter: J. Melchin	Reviewer: D. Van Vliet

Figure B5

APPENDIX C
Hydraulic Conductivity Values Applied in the Groundwater Flow Model



Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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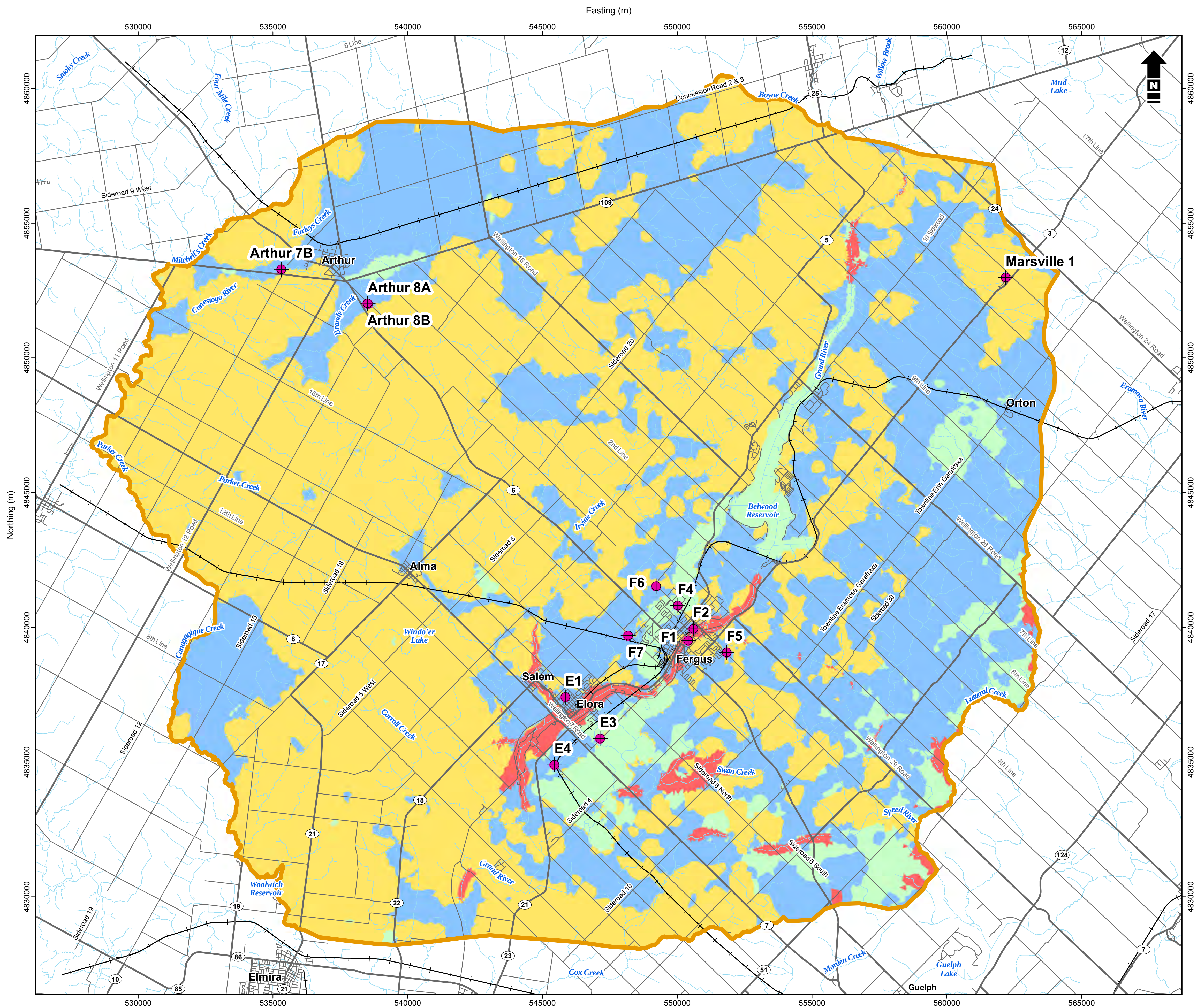
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Upper Overburden Aquifer

Date:	Project:	Technical:	Reviewer:	Drawn:
19 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure C1



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Conductivity (m/s)

- $> 1.0 \times 10^{-4}$
- $1.0 \times 10^{-5} < \ldots <= 1.0 \times 10^{-4}$
- $1.0 \times 10^{-6} < \ldots <= 1.0 \times 10^{-5}$
- $1.0 \times 10^{-7} < \ldots <= 1.0 \times 10^{-6}$
- $1.0 \times 10^{-8} < \ldots <= 1.0 \times 10^{-7}$
- $<= 1 \times 10^{-8}$

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

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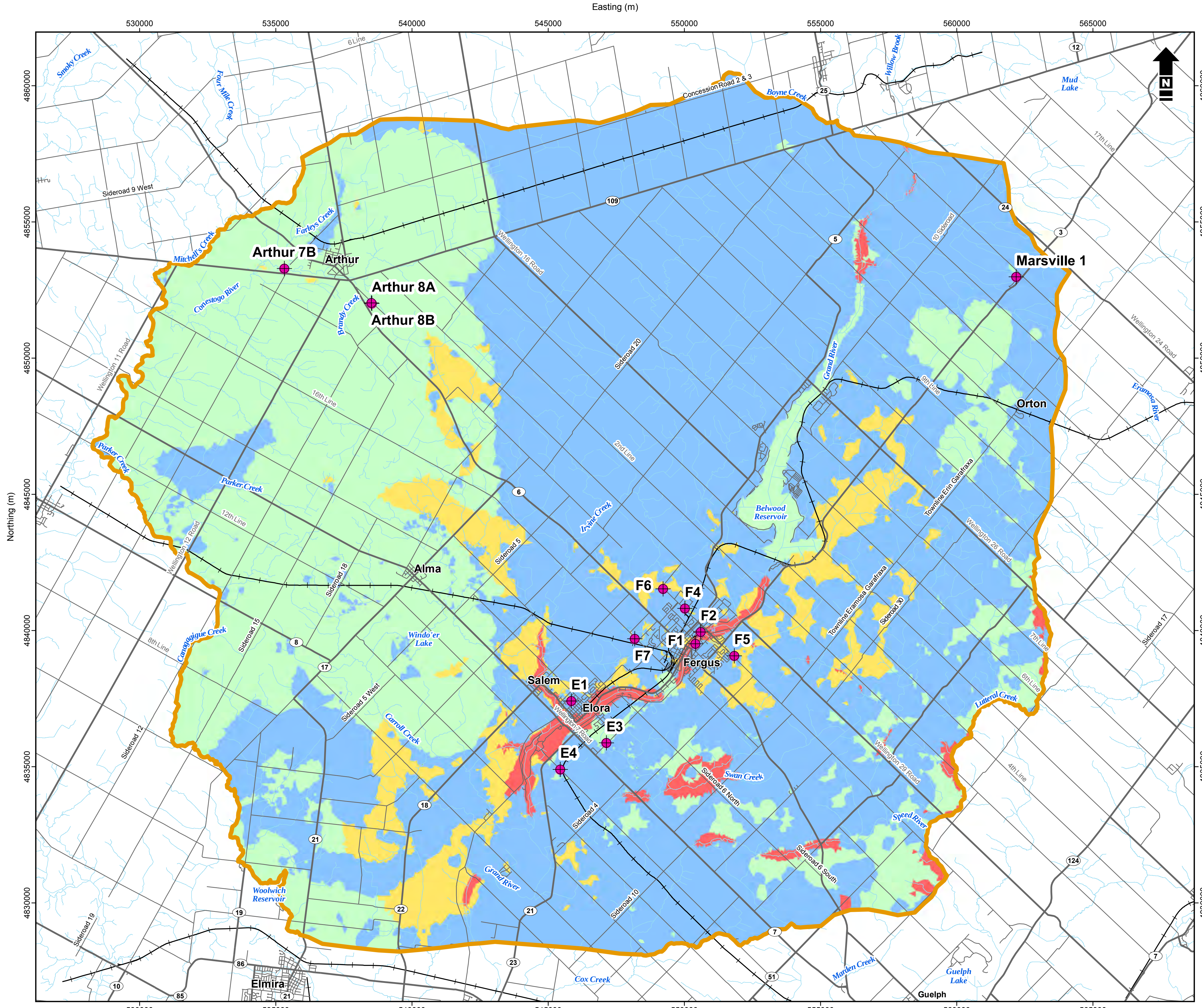
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Intermediate Overburden Aquifer

Date:	Project:	Technical:	Reviewer:	Drawn:
19 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure C2



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Conductivity (m/s)

- $> 1.0 \times 10^{-4}$
- $1.0 \times 10^{-5} < ... <= 1.0 \times 10^{-4}$
- $1.0 \times 10^{-6} < ... <= 1.0 \times 10^{-5}$
- $1.0 \times 10^{-7} < ... <= 1.0 \times 10^{-6}$
- $1.0 \times 10^{-8} < ... <= 1.0 \times 10^{-7}$
- $<= 1 \times 10^{-8}$

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:145,000

1,400 0 1,400 2,800 m

NAD 1983 UTM Zone 17N

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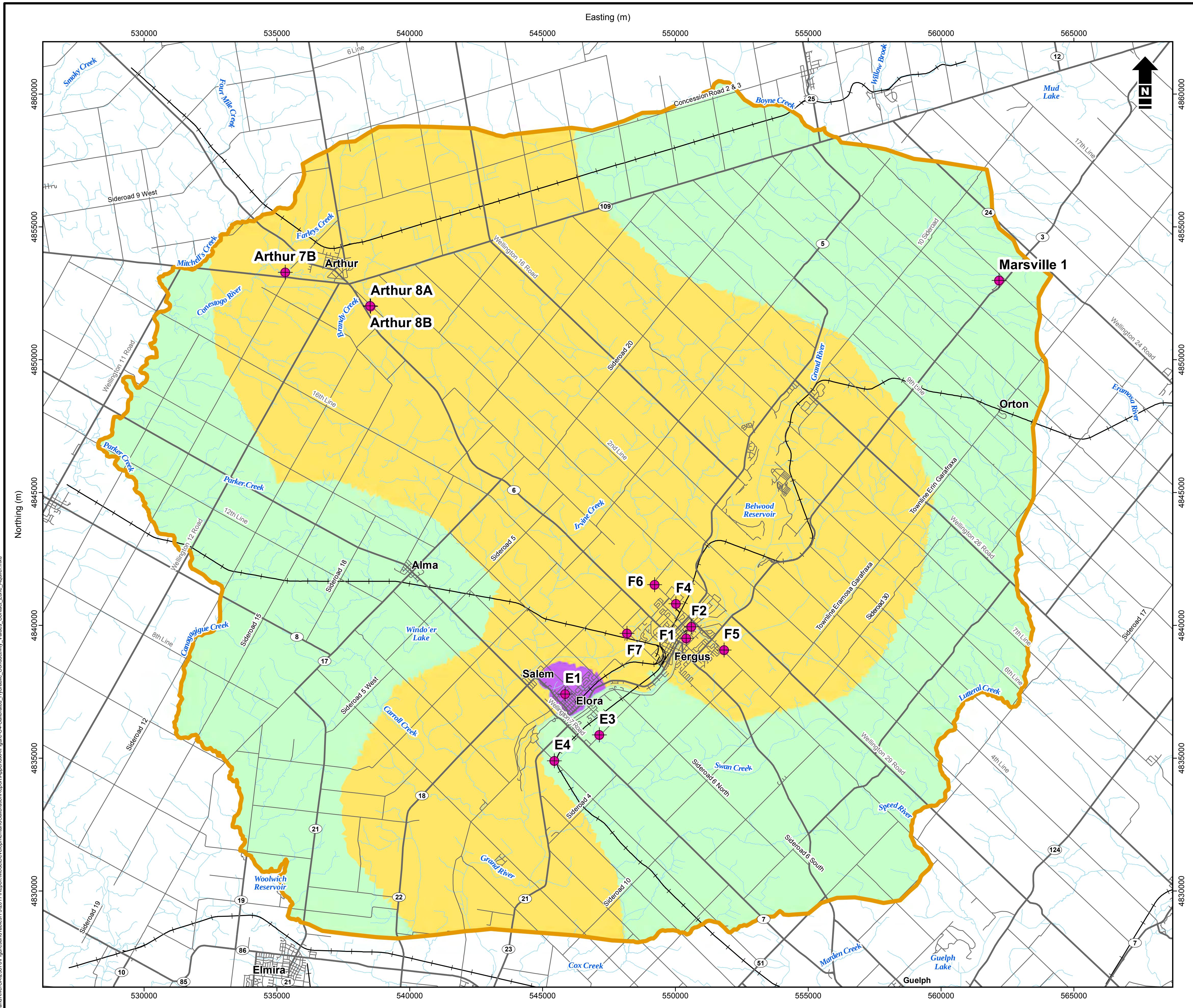
Grand River Conservation Authority

Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Lower Overburden Aquifer

Date:	Project:	Technical:	Reviewer:	Drawn:
02 May 2018	23876	J. Melchin	P. Meyer	C. Curry

Figure C3



Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Contact Zone Aquifer

Date:	Project:	Technical:	Reviewer:	Drawn:
19 Mar 2018	23876	J. Melchin	P. Meyer	C. Curry

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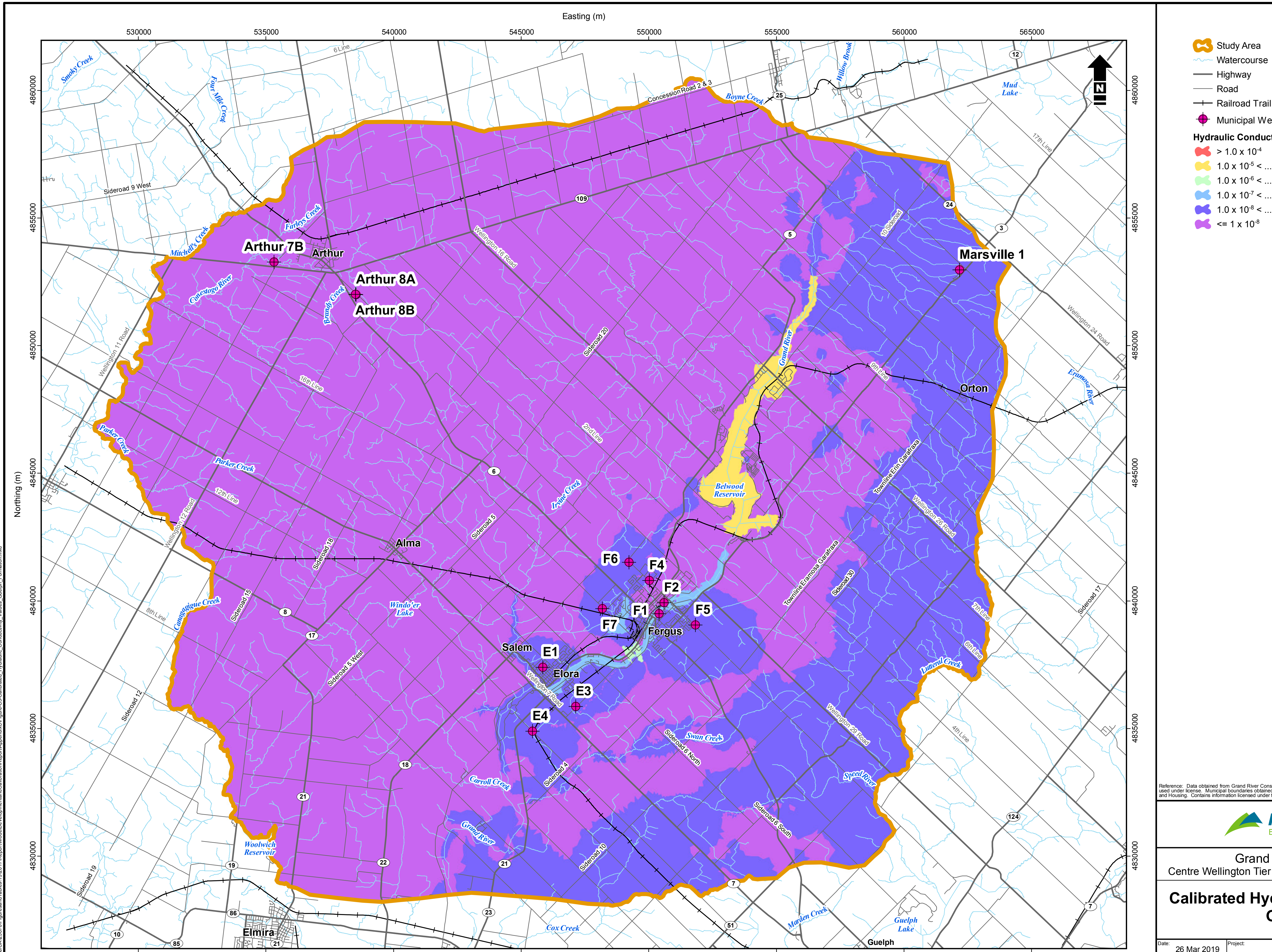
Figure C4



Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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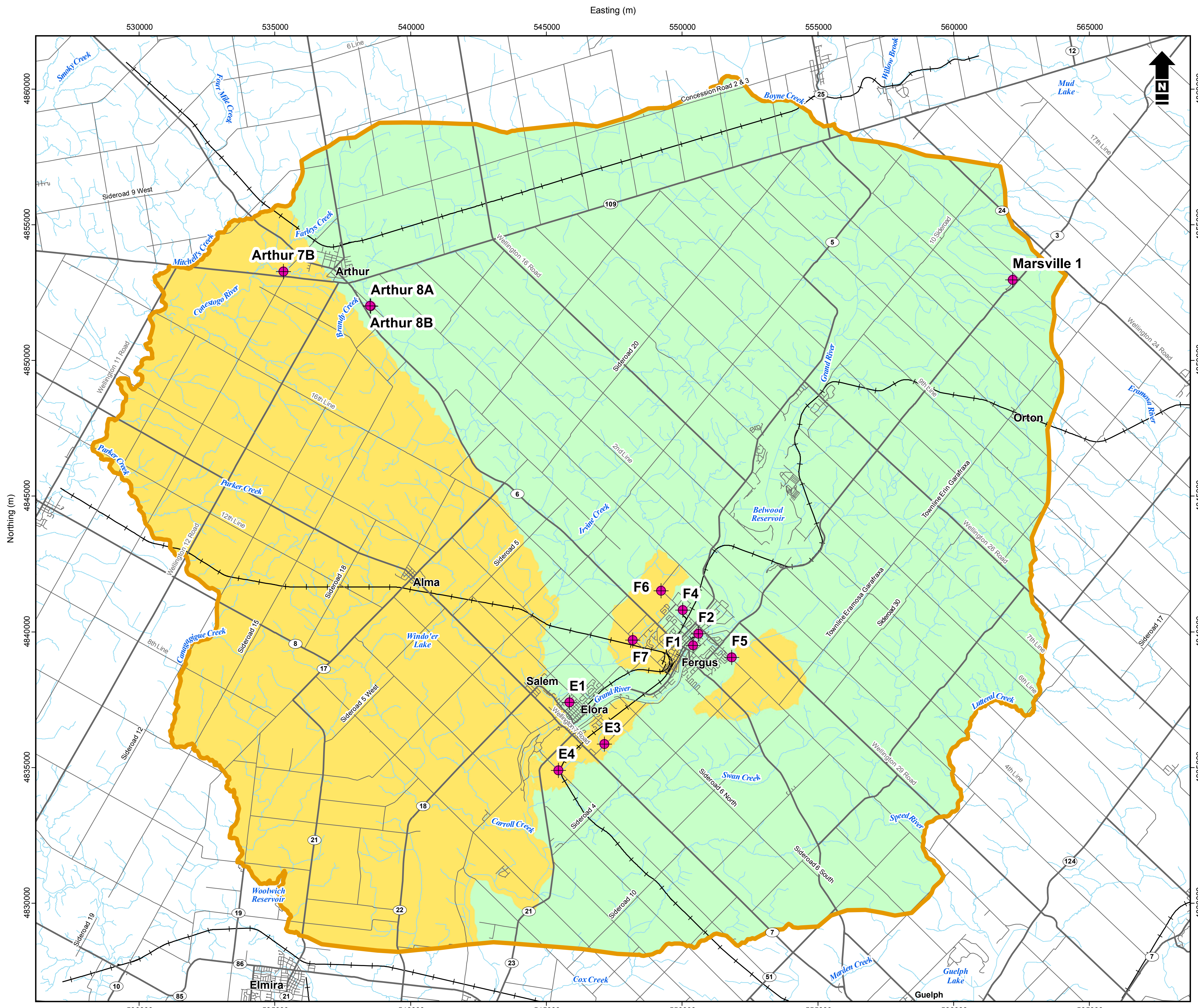
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Guelph Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
26 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure C5



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Conductivity (m/s)

- $> 1.0 \times 10^{-4}$
- $1.0 \times 10^{-5} < ... <= 1.0 \times 10^{-4}$
- $1.0 \times 10^{-6} < ... <= 1.0 \times 10^{-5}$
- $1.0 \times 10^{-7} < ... <= 1.0 \times 10^{-6}$
- $1.0 \times 10^{-8} < ... <= 1.0 \times 10^{-7}$
- $<= 1 \times 10^{-8}$

1:145,000
1,400 0 1,400 2,800 m
NAD 1983 UTM Zone 17N

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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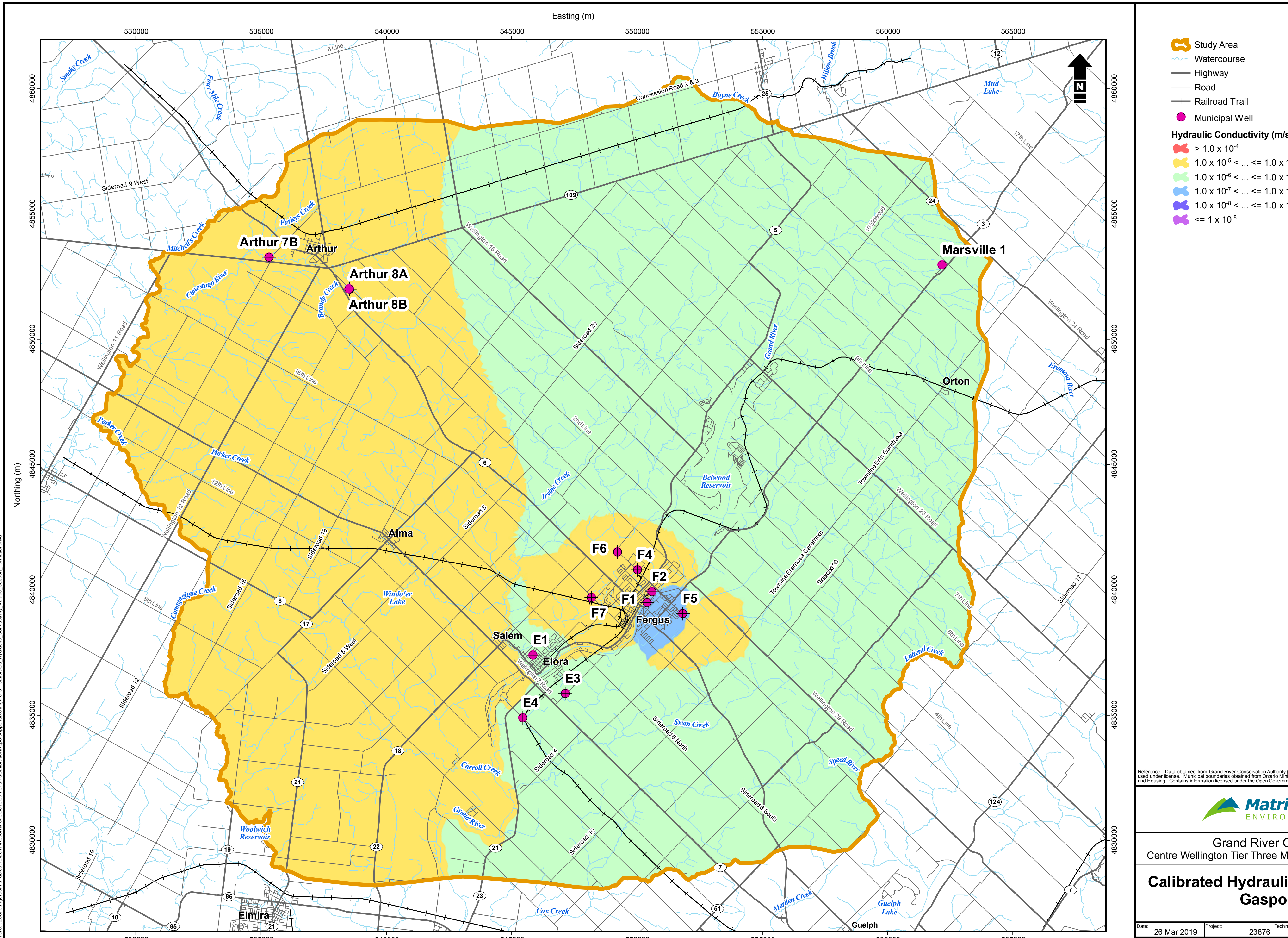
Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Goat Island Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
26 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure C6



Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

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Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Calibrated Hydraulic Conductivity Values – Gasport Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
26 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

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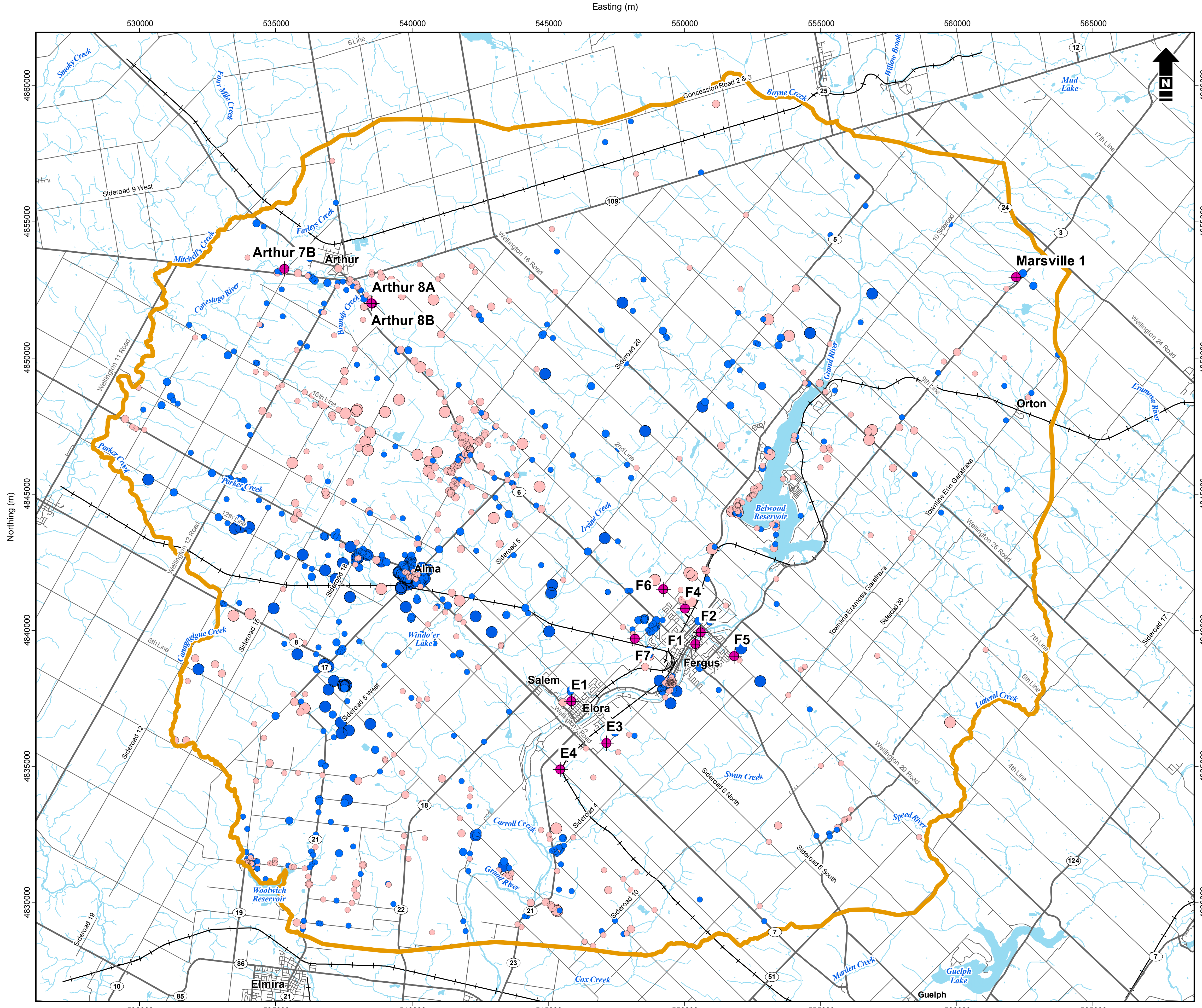
Figure C7

APPENDIX D
Steady-State Calibration Residual Plots



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Head Residual (Simulated - Observed) (m)

Simulated Value > 10m lower than Observed
Simulated Value 5 to 10m lower than Observed
Simulated Value 0 to 5m lower than Observed
Simulated Value 0 to 5m higher than Observed
Simulated Value 5 to 10m higher than Observed
Simulated Value > 10m higher than Observed

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

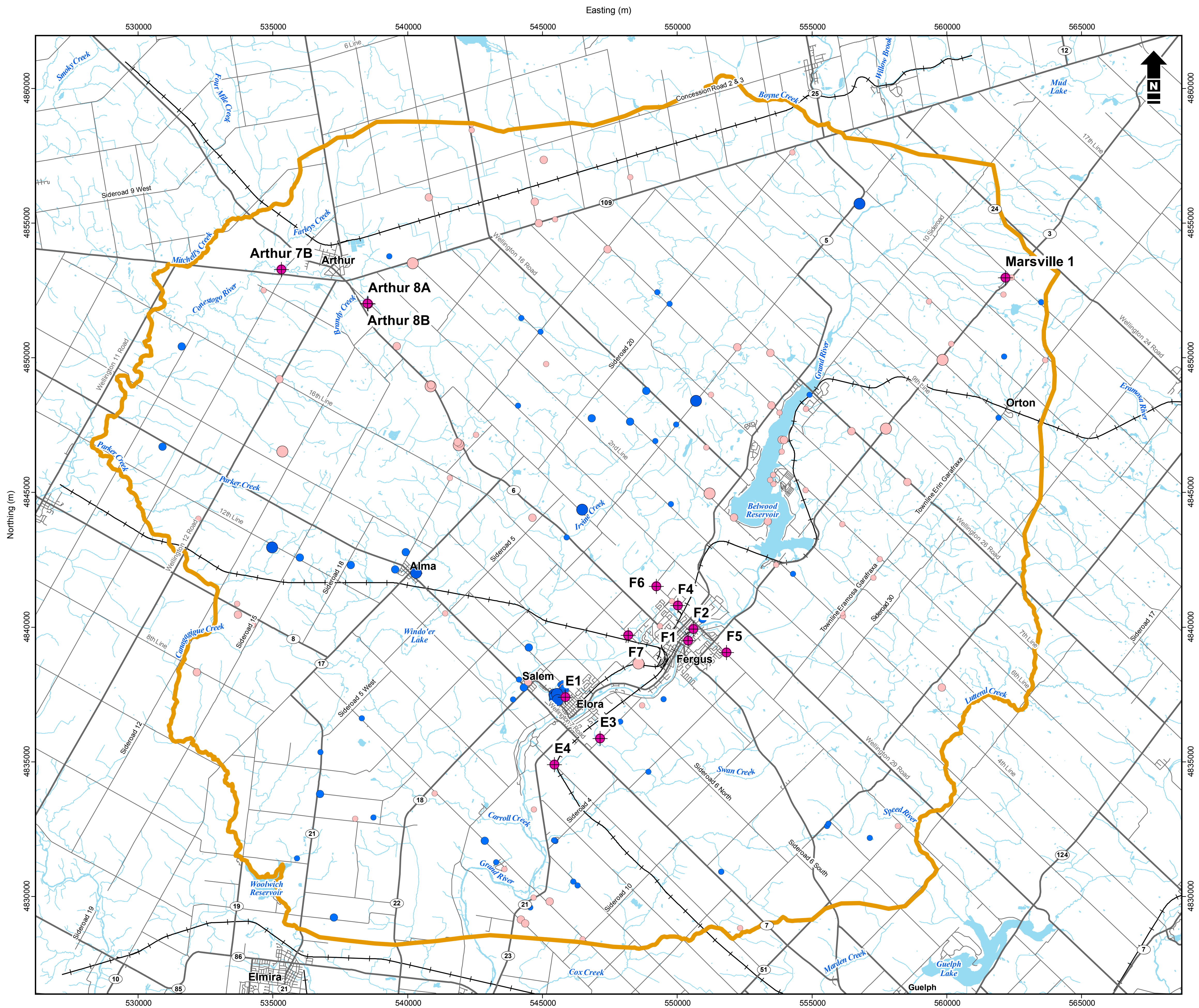
1:145,000 m
1,400 0 1,400 2,800
NAD 1983 UTM Zone 17N

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Spatial Residuals – Overburden

Date:	Project:	Technical:	Reviewer:	Drawn:
13 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure D1



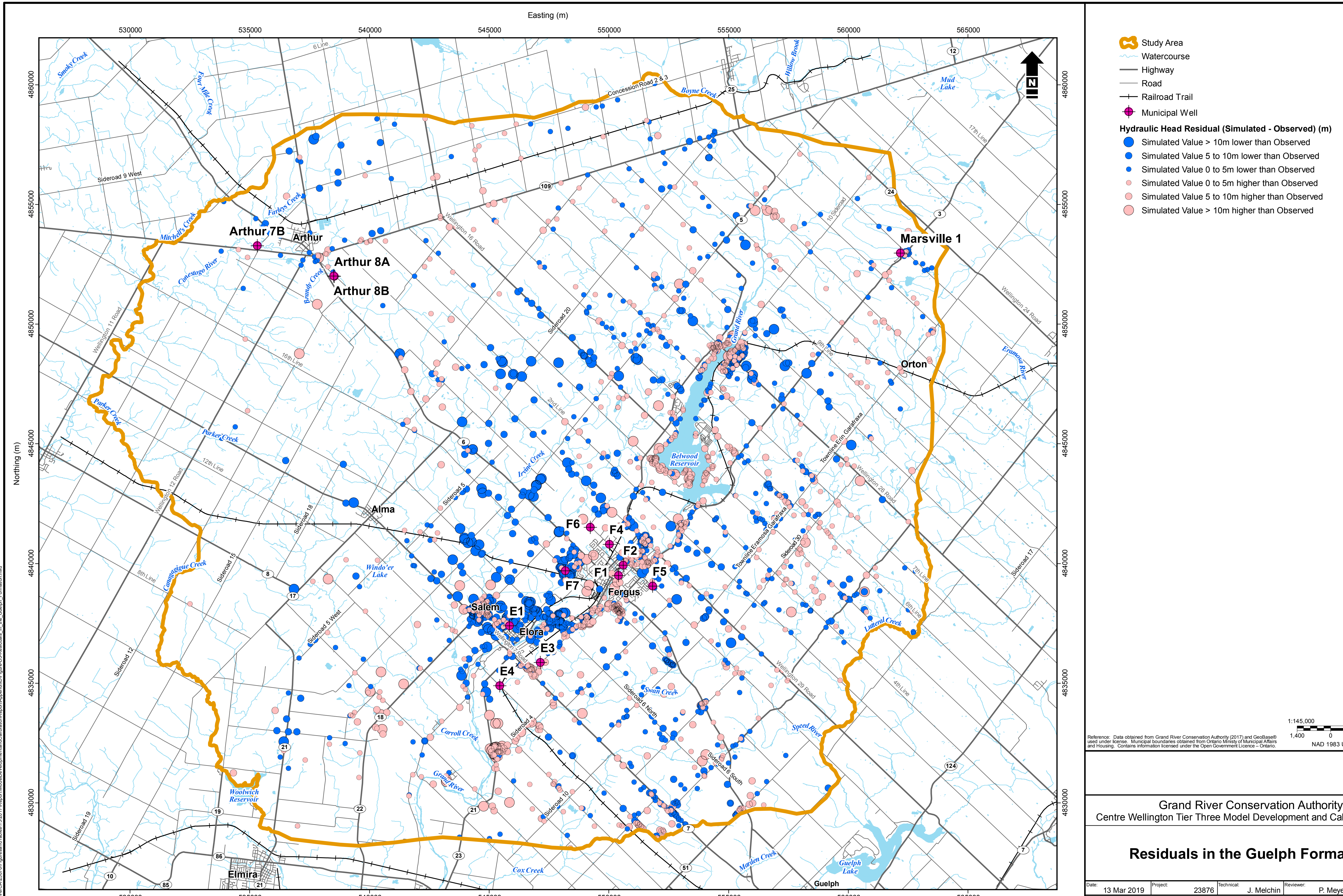
Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministry of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Residuals in the Contact Zone

Date:	Project:	Technical:	Reviewer:	Drawn:
13 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure D2



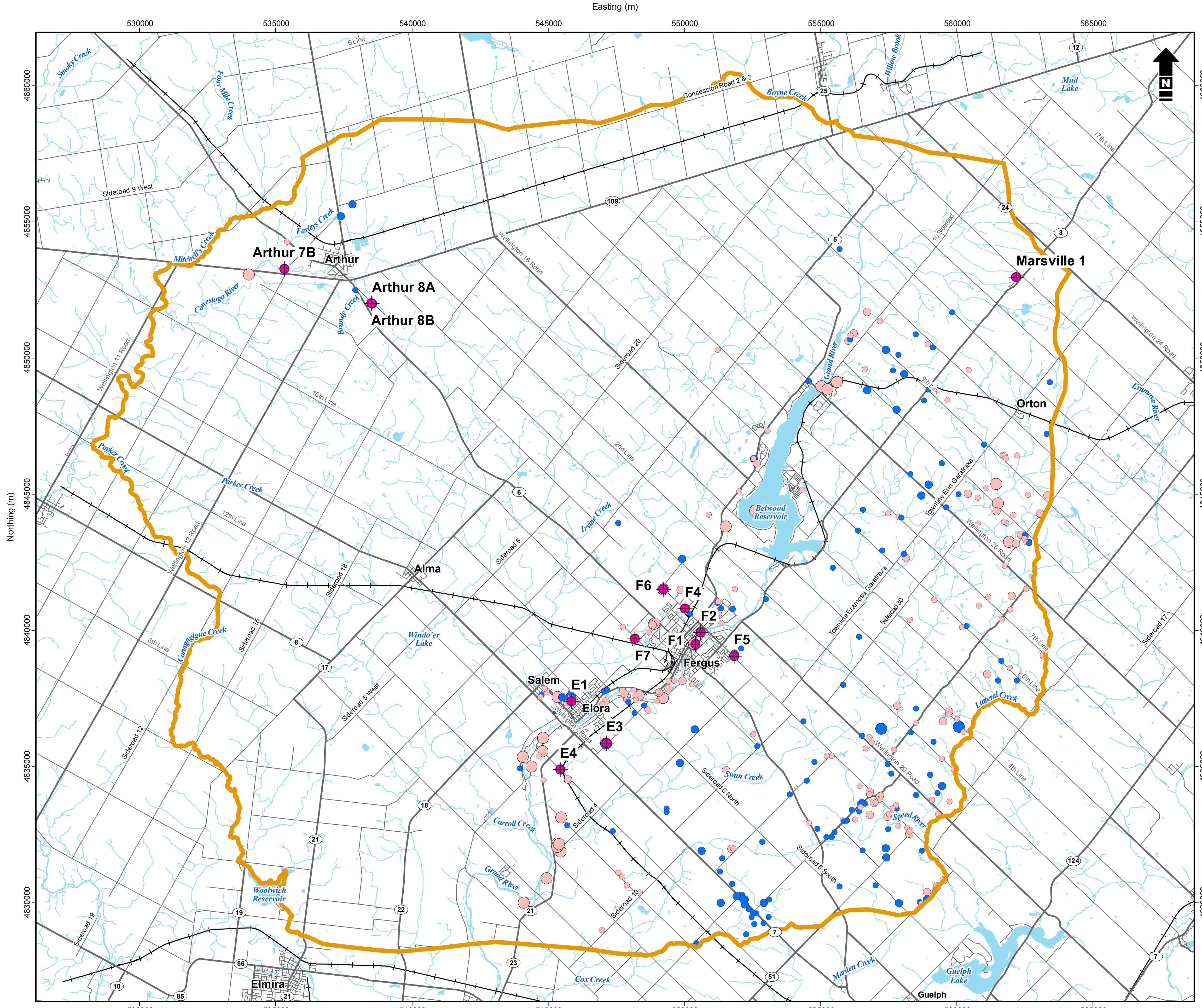
Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Residuals in the Guelph Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
13 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure D3



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Head Residual (Simulated - Observed) (m)

Simulated Value > 10m lower than Observed
Simulated Value 5 to 10m lower than Observed
Simulated Value 0 to 5m lower than Observed
Simulated Value 0 to 5m higher than Observed
Simulated Value 5 to 10m higher than Observed
Simulated Value > 10m higher than Observed

1:145,000 m
1,400 0 1,400 2,800
NAD 1983 UTM Zone 17N

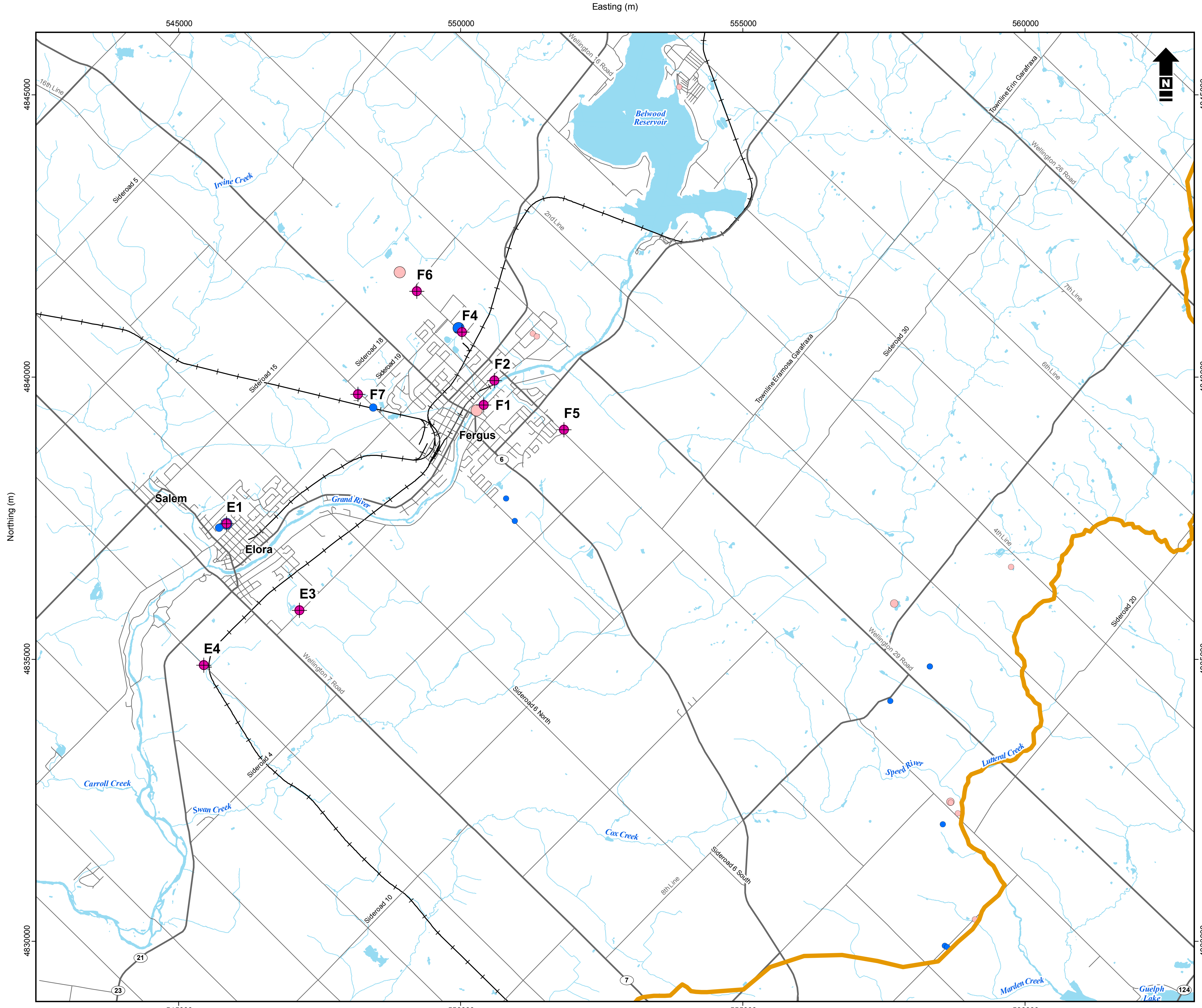
Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Residuals in the Goat Island Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
13 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure D4



Study Area
Watercourse
Highway
Road
Railroad Trail
Municipal Well

Hydraulic Head Residual (Simulated - Observed) (m)

- Simulated Value > 10m lower than Observed
- Simulated Value 5 to 10m lower than Observed
- Simulated Value 0 to 5m lower than Observed
- Simulated Value 0 to 5m higher than Observed
- Simulated Value 5 to 10m higher than Observed
- Simulated Value > 10m higher than Observed

Reference: Data obtained from Grand River Conservation Authority (2017) and GeoBase® used under license. Municipal boundaries obtained from Ontario Ministy of Municipal Affairs and Housing. Contains information licensed under the Open Government Licence – Ontario.

1:70,000 m
700 0 700 1,400
NAD 1983 UTM Zone 17N

Grand River Conservation Authority
Centre Wellington Tier Three Model Development and Calibration Report

Residuals in the Gasport Formation

Date:	Project:	Technical:	Reviewer:	Drawn:
13 Mar 2019	23876	J. Melchin	P. Meyer	C. Curry

Figure D5