APPENDIX B

SELECTION OF APPROPRIATE WHPA-Q1 DRAWDOWN CONTOUR

Observed Seasonal Aquifer Water Level Fluctuations

The municipal drinking water wells in the cities of Kitchener and Waterloo are primarily screened within the overburden aquifers of the Waterloo Moraine and underlying sediments. The municipal production wells in Cambridge, in contrast, are typically completed as open hole wells in the underlying carbonate bedrock aquifers. As such, water level fluctuations in the two areas were examined to ensure an appropriate WHPA-Q1 drawdown threshold will be applied in each area.

Seasonal water level fluctuations were estimated through review of long-term hydrographs for wells completed near the municipal wells and those located away from the urban area to examine ambient water level fluctuations that are not impacted by the cycling on and off of municipal wells.

Few monitoring wells in the Region are located far from the municipal pumping centres to show the seasonal water level variability (i.e., groundwater elevations collected at a monthly or bi-weekly basis). The majority of the monitoring wells within the Region are located within the urban centres and the groundwater elevations are impacted to some degree by nearby pumping wells.

Cambridge Area

Within the Cambridge area, monitoring well OW8-95 near the Elgin Street Well Field was interpreted to show natural variability in the groundwater flow system without being impacted by municipal or non-municipal pumping. Chart 1 is a hydrograph showing groundwater elevations over time from within OW8-95, and approximately 1.5 m of seasonal water level fluctuation within the overburden system.

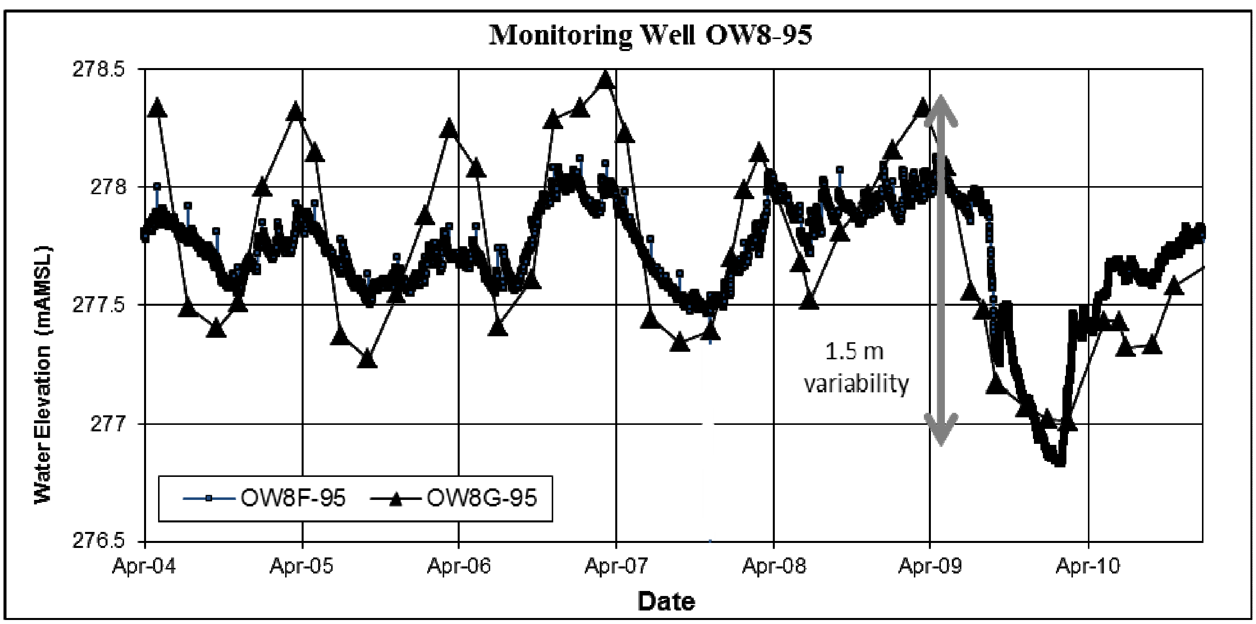

Chart 1: Seasonal water level fluctuations in-well OW8-95 in the Cambridge area

Monitoring Well OW104-90 is located in the southern portion of Cambridge outside the zone of influence of the Middleton Street well field; this monitoring well shows a seasonal fluctuation of approximately 2 m (Chart 2).

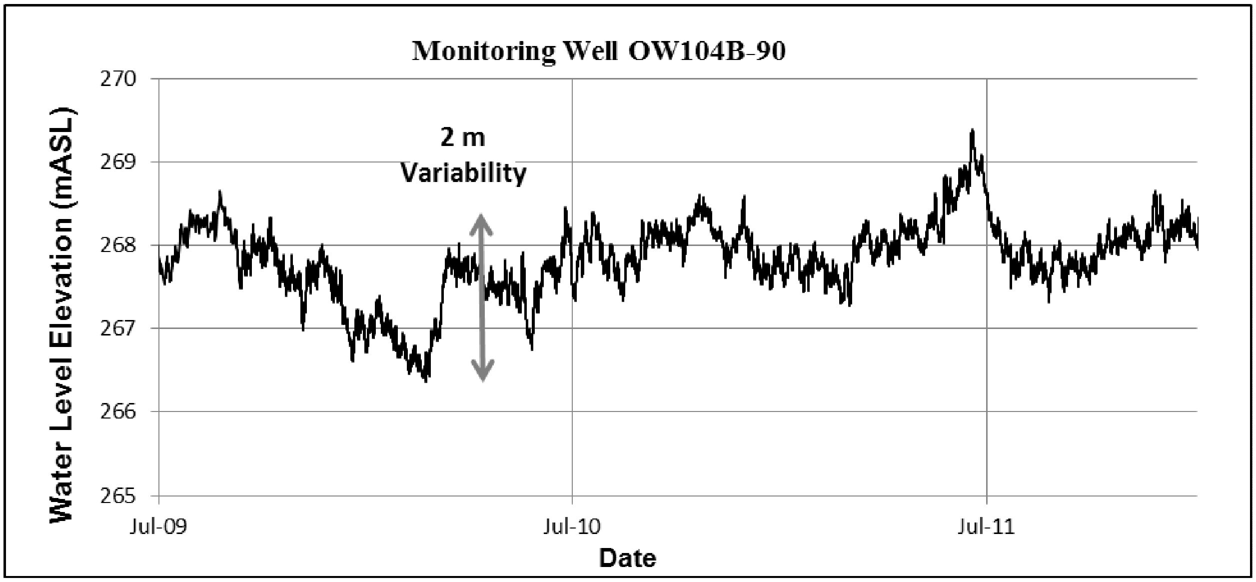

Chart 2: Seasonal water level fluctuations in-well OW104B-90 in the Cambridge area

Kitchener-Waterloo Area

Within the Kitchener area, monitoring well PK8A-96 shows over 1.5 m of seasonal fluctuation (Chart 3) within a deep overburden aquifer unit (AFD1).

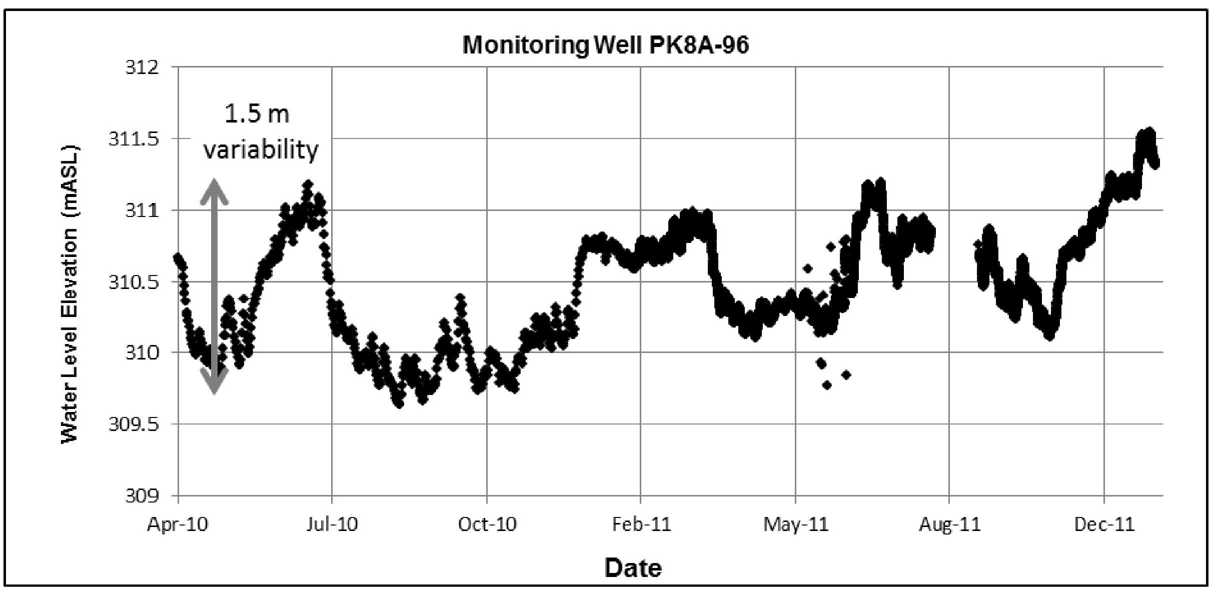

Chart 3: Seasonal water level fluctuation in Well PK8-96 in the Kitchener area

Summary

Given the seasonal variability present in the few monitoring wells located outside the municipal well field areas, a contour interval of 2 m was selected for use in the delineation of the WHPA-Q1 area for the Region of Waterloo in the Regional Model, and the Cambridge Area using the Cambridge Model. This threshold is consistent with the drawdown contour used in the nearby City of Guelph Tier Three Assessment. As noted above, the difference between the model-predicted heads for the two aforementioned simulations were determined and the results were contoured.

Appendix C

Uncertainty Analysis Conducted for the Regional and Cambridge Models

Appendix C: Uncertainty Analysis Performed on the Regional and Cambridge Models

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1 INTRODUCTION

Numerical models are generalizations of the physical world. The input parameters applied in numerical models are estimated based on our best understanding of the groundwater flow system; however, there is innate uncertainty in the assumptions made in building and calibrating a groundwater flow model. Uncertainty exists in the subsurface structure (e.g., continuity of till units), the parameter values applied to represent material properties (e.g., hydraulic conductivity values) and the model boundary conditions (e.g., recharge and surface water discharge features). The aim of this portion of the Tier Three Assessment and this document is to acknowledge and quantify the impact of these sources of uncertainty.

When calibrating a groundwater flow model, the values of the model input parameters are updated until the model-predicted groundwater level elevations are a reasonable match to observed values. It is important to recognize that the observed values contain uncertainty in reference elevations, seasonal water level variability, and varying time periods of the measurements, which contribute to the non-uniqueness of a model and the input parameter values. As a result, many combinations of parameter values can produce a good fit to the observed data. Model predictions depend upon parameter values and therefore, understanding parameter uncertainty can help evaluate the certainty (or uncertainty) in the model predictions.

Numeric uncertainty can be assessed by making small perturbations to parameter values and evaluating the fit to the observed data. Exploring these minor changes provides insight into parameter-specific numeric uncertainty. However, to examine the uncertainty in the overall flow system, alternative conceptual models with various parameter value combinations can be created to provide more insight into the uncertainty in the groundwater flow system and the potential impact on model predictions.

In this assessment, a series of alternative conceptual models (herein termed realizations) were created with the aid of the software program PEST (Watermark Numerical Computing 2012). Each alternative model was considered statistically calibrated to a level that was as good as, or better than, the original base case model presented in the Region of Waterloo Tier Three Assessment Model Calibration and Water Budget Report (Matrix and SSPA 2012).

Three realizations were developed for each of the Regional and Cambridge Models to assess the uncertainty in the model parameters, and how that uncertainty may impact the Risk Assessment and the assignment of the Risk Level. Each of the three alternative realizations were defined to test key uncertainties that were noted prior to, or during, the model calibration process. For example, during the calibration of the Strange Street Well Field, the hydraulic conductivity of the upper bedrock was found to play a role in the predicted groundwater level elevations within the production aquifer. As such, an uncertainty realization was created to test the conceptual understanding that the bedrock flow system beneath the Waterloo Moraine consists of low hydraulic conductivity units. Similarly, during the calibration of the Cambridge Model (and review of vertical groundwater level elevation data across the Guelph Formation), it was noted that the Guelph Formation can behave as an aquifer, an aquitard or both depending on the area within Cambridge. Consequently, an uncertainty realization was conducted to test the impact of additional vertical stratification and variable hydraulic conductivity values within the Guelph Formation. The key aim of the uncertainty assessment was to test the modelling assumptions that would have the greatest potential impact on the Risk Assessment results.

2 UNCERTAINTY ANALYSIS APPROACH AND METHODOLGY

2.1 PEST Setup

The software program Parameter ESTimation (PEST) was used to help develop three alternative conceptual models for each of the Regional Model and the Cambridge Model. PEST is an optimization process that estimates the value of selected model parameters to minimize the discrepancy between simulated and observed conditions. PEST estimates parameter values based on input values and parameters that are assigned by the user. PEST is used to help determine the optimum parameter values that results in the best overall fit between simulated and observed conditions within the context of each conceptual model. The optimized results are referred to as alternative realizations, as different sets of parameter values maintain a calibrated condition. The instructions provided to PEST consist of two main parts: a defined set of observations and their relative weights (termed the objective function) which PEST aims to minimize (Section 2.1.1), and secondly, a list of parameters that can be varied by PEST and their corresponding constraints (Section 2.1.2).

2.1.1 Observations

The objective function is a single value that summarizes the model fit to all observations. Mathematically, the objective function is defined as the sum of weighted, squared residuals. Residuals are the difference between the model simulated and the observed (or field measured) value. The weighting of an observation informs PEST of the relative worth or value of each point. For example, a groundwater level elevation collected in 2008 is of greater value when calibrating to existing 2008 conditions than a water level collected in the same area in 1990, and thus would be given a greater weight than the 1990 observation. Those with a higher weight have a greater influence when determining an optimized set of parameter values. For each observation, the residual is calculated, squared and then the weight is applied. The sum of weight squared residuals provides one value that represents the discrepancy between the observed and simulated observations, and is referred to as the "objective function".

In this assessment, four types of observation data contribute to the objective function including: groundwater level elevation measurements, groundwater level elevation differences across an aquitard (i.e. vertical groundwater level elevation differences), time-varying trends in groundwater level elevations, and baseflow estimates. Each of these data types capture different aspects of the groundwater flow system, which strengthens the process used to estimate the parameter values.

Groundwater level elevation measurements taken at one point in time represent the elevation in the aquifer at that time. In general these measurements have good spatial coverage horizontally and vertically throughout the subsurface across the study area. Groundwater level elevation differences across aquitards provide insight into the hydraulic conductivity of a discrete aquitard and these measurements help constrain the amount of leakage that is simulated across the aquitard. Time-varying trends in groundwater level elevations collected in groundwater monitoring wells capture the response of the system to typical municipal operating conditions. Though this type of data is the most informative for estimating parameter values, it has limited spatial coverage. Baseflow estimates provide insight into local, intermediate and regional flow systems, the interactions between groundwater and surface water systems, and provide a check on the specification of recharge values applied.

2.1.2 Parameters

The selection of adjustable parameters and their constraints guides PEST to determine the parameter values that can be varied and the magnitude of the change, in an effort to minimize the objective function. Parameters can be adjusted independent of other parameters, “tied” to other parameters (i.e. adjusted simultaneously while preserving their ratio), or “fixed” (i.e. the value is held constant during the optimization process). In the context of a groundwater flow model, parameters defining the distributions of recharge and hydraulic conductivity values have the greatest influence on the simulated groundwater level elevations and discharge values.

A detailed hydrogeological characterization of the urban well field area within the cities of Kitchener, Waterloo, and Cambridge was conducted and used to develop the base case models that are outlined in the Model Calibration and Water Budget Report (Matrix and SSPA 2012). Outside this area, greater uncertainty exists regarding the model structure and hydrogeologic characterization as regional scale (i.e. OGS defined) model layers were applied. The parameters in this area were fixed as the values estimated using PEST are interpreted to be far removed from the urban well field areas, and updating these values is unlikely to impact the predictions around the municipal well fields of interest in the Tier Three Assessment.

Each parameter was constrained in PEST with a user-defined upper and lower bound, which were selected to be consistent with the parameter conceptualization. Wide bounds were chosen to give the optimization process the freedom to produce solutions that may be different from the base case model, but consistent with the observation dataset. Only parameters most relevant to each alternative conceptualization were selected to be adjustable in PEST. Additional details regarding the selection of parameters and how they were constrained are described in the following sections.

2.1.2.1 Recharge

Variables that influence recharge include climate, surficial geology, vegetation and land use cover. Due to the variability of these factors across urban and rural landscapes, recharge has a high degree of spatial and temporal variability. The Guelph All Weather Sequential Runoff (GAWSER) surface water model was calibrated to long-term continuous stream flow data and the spatial distribution of recharge was an output of the model. Given the spatial and temporal variability of the factors impacting recharge, the recharge estimates applied to the Cambridge and Regional models had a degree of uncertainty. As such, recharge parameters were included in the optimization process.

Bounds applied to recharge parameters were wider for lower recharge rates and narrower for higher recharge rates. For example, a given parcel of land with recharge estimate of 10 mm/year may be a factor of 5 or 10 times higher (i.e. 50 or 100 mm/yr) considering the variability in near surface hydraulic conductivity values, land use cover, etc. However, a parcel of land with a recharge estimate of 300 mm/yr may have an uncertainty range that is 1.5 times higher or lower, and result in a feasible range of 200 to 400 mm/yr.

2.1.2.2 Hydraulic Conductivity Values

Hydraulic conductivity zones and values control the flow of groundwater through the subsurface. The distribution of higher and lower conductivity units can be inferred based on the interpreted depositional environment from lithologic descriptions in borehole logs and aquifer tests results. Interpreted aquifer test (e.g., pumping test) results provide an estimate of hydraulic conductivity values; however, a level of uncertainty exists within the interpretation of the field data. Literature values can be applied to units based on understanding of the depositional environments and/or lithologic units reported in borehole logs; however, borehole data represent point locations and hydraulic conductivity zones often span larger areas. Calibrating a groundwater flow model can also provide insight on the potential range of hydraulic conductivity values by matching predicted and observed groundwater level elevation values. While these data sources provide insight into potential hydraulic conductivity values, uncertainty in the hydraulic conductivity values exists, particularly in the absence of long-term pumping test data that stress the groundwater flow system on a broad-scale. For this reason, hydraulic conductivity parameters were allowed to vary by orders of magnitude during the optimization process.

The hydraulic conductivity values for the zones representing the surficial geology layers (model layers 1 and 2) were fixed. These parameters control the rate at which recharge reaches the underlying units, and given the close relationship between recharge and hydraulic conductivity values, allowing both to be estimable would result in a very large number of parameter sets that produce the same calibration, which may have hampered the optimization process. In addition, the alternative realizations aimed to improve the understanding of the aquifer systems, and therefore, adjustable parameters focused on the production aquifers and intervening till units.

Regional Model

The zones representing aquitards ATB1, ATB2, ATB3, ATC/AFC1/ATC2 and ATE1 (on model layers 3, 5, 8, 10 and 12, respectively) were estimable parameters in the urban well field areas of the Regional Model. These units were conceptualized to have a vertical hydraulic conductivity typically in the range of 1x10-8 to 1x10-9 m/s, and the default upper and lower bounds for the horizontal hydraulic conductivity were 5x10-7 and 1x10-10 m/s, respectively. Vertical anisotropy was fixed and set to one-tenth of the horizontal hydraulic conductivity to account for bedding within the units. Zones that represent windows in aquitards or areas of increased leakage had higher upper bounds (i.e. 5x10-5 m/s or a maximum of 6x10-4 m/s). These bounds were wide but consistent with the conceptualization and allowed PEST the freedom to explore alternative parameter values that maintained a calibrated condition.

The parameter zones representing aquifers AFB1, AFB2, AFB3 and AFD1 (on model layers 4, 6/7, 9 and 11, respectively) were estimable parameters within the urban well field areas of the Regional Model. These units had a typical horizontal hydraulic conductivity that range from 5x10-4 to 5x10-6 m/s, with the most productive areas reaching as high as 5x10-3 m/s. The resultant values from the realizations are discussed at length in the subsections of Section 3 (Regional Model Uncertainty Realizations) and Section 4 (Cambridge Model Uncertainty Realizations).

Cambridge Model

The goal of developing alternative realizations in this area was to better understand the bedrock groundwater flow system, as all the municipal production wells for the City of Cambridge (with the exception of the Shades Mill Well Field) draw their water from bedrock aquifers. As such, the adjustable parameters focused on the bedrock aquifers and intervening aquitards and to a lesser extent on the overburden materials.

The lower and upper bound hydraulic conductivity values were specified as an order of magnitude higher and lower than the conductivity values applied in the base case Cambridge Model. Both horizontal and vertical hydraulic conductivity values were adjustable during the optimization process to provide the flexibility to alter those parameters to minimize the objective function.

2.2 Approach to the Evaluation of Uncertainty Analysis Results

The results of each optimization were examined in two ways: first, the fit to observed data was assessed to ensure the results maintained a calibrated condition; and second, the estimated parameter values were examined to ensure they were consistent with the conceptual model. The approach used to evaluate these aspects of the optimization is discussed in the following sections.

2.2.1 Fit to Observed Data

The optimization aims to minimize the difference between simulated and observed values for steady-state groundwater level elevation targets, time-varying groundwater level elevation targets and steady baseflow targets in the (weighted) least squared sense, by varying parameter values within the defined boundaries. To be consistent with the base case model calibration, the same metrics were applied to quantify the global (regional-scale) and well field (local-scale) fit.

Statistical metrics used to assess the fit of the calibration included mean residual (MR), mean absolute residual (MAR), root mean squared residual (RMS), and normalized root mean squared residual (NRMS). The mean residual is the arithmetic average of residuals (Note: Residual is the difference between simulated and observed values). A low mean residual indicates a balance between over and under predicted water level elevations and the ideal value is zero. The mean absolute residual is an indicator of the overall magnitude of the differences between simulated and observed values. This metric differs from the mean residual as it does not allow for over and under predicted groundwater level elevations to negate each other. The root mean squared residual is a measure of the central tendency of the absolute mean residual. The normalized root mean squared residual normalizes the root mean squared residual to the range in observed water level elevations to provide context to the variation of the absolute mean.

The calibration for each realization was also assessed visually using scatter plots and plan view maps. On the scatter plot, measured groundwater level elevations are plotted on the x-axis and the simulated groundwater level elevations are plotted on the y-axis with the aim of having all data points lay along the one-to-one line. Clustering above or below this line indicates a simulated bias to over- or under-predicting measured groundwater level elevations, respectively. On the plan view map, residuals are plotted spatially to identify spatial trends. Ideally, the over- or under-prediction of model predicted groundwater level elevations should be randomly distributed across the area.

2.2.2 Estimated Parameters

Estimated model parameters for both recharge and hydraulic conductivity were reviewed to ensure they were reasonable and consistent with the objective in the context of each realization. Optimized parameter values were checked with respect to their initial value (i.e. base case model value) and their parameter bounds.

3 REGIONAL MODEL UNCERTAINTY REALIZATIONS

For the uncertainty assessment, three alternative conceptual models were developed for the Regional and Cambridge Models to explore uncertainty in the conceptualization presented in the Water Budget Report (Matrix and SSPA 2012). The three alternative realizations were created using an inverse modelling approach whereby parameter values were estimated with the aim of reducing the difference between simulated and observed values. Each alternative realization contained a different set of parameter values (i.e. hydraulic conductivity values) that together produced a model that was statistically as well calibrated (or better calibrated) to field observations than the base case model (see Matrix and SSPA 2012). The uncertainty analyses for the Regional Model focused on the urban areas of

Kitchener-Waterloo as well as the Fountain Street Well Field area to the east, the Conestogo Plains Well Field area to the north, and the New Dundee Well Field area, located southwest of Kitchener (Figure 1).

3.1 Realization 1 – Optimization to Transient Observations

Realization 1 was an alternative numeric model consistent with the base case model. The realization aimed to maintain a good fit to the steady-state observation dataset and simulate time-varying trends in groundwater level elevations representative of typical operating conditions (aggregating to a bi-monthly period) between 2003 and 2011. The base case model, in contrast, was calibrated to individual pumping tests or shut down conditions at each well field. The calibration in Realization 1 to long-term, time-varying groundwater level elevations provided greater spatial coverage, particularly in the areas between well fields, and is referred to as the “Optimization to Transient Observations” realization.

3.1.1 Set-Up and Observation Data Set

The modeller instructs PEST on which recharge and hydraulic conductivity values to adjust to best match two conditions: 1) observed (steady-state) groundwater level elevations and baseflow conditions under average annual 2003 production conditions; and 2) time-varying groundwater level elevations (averaged over two-month intervals) at long-term monitoring locations during the 2003 to 2011 time frame.

To accomplish this, PEST was used to evaluate the steady-state model under average 2003 municipal production conditions, and the simulated groundwater level elevation outputs from this model were then applied as the initial condition for a transient model which simulated representative municipal production conditions from 2003 to 2011. For the transient model, the production rates at municipal wells were averaged on a bi-monthly period. For both models, the values applied to the individual recharge zones were spatially variable and estimable parameters in PEST.

The goal of the PEST optimization was to minimize the objective function. In this case, the objective function was comprised of a few different types of data (e.g., groundwater level elevations, groundwater fluxes) as well as groups of data (e.g., high quality targets, low quality targets). As noted previously, the objective function is the sum of weighted squared differences for the various observations. The weight applied to each observation conveys its relative worth, whereby observations with a larger weight have a greater contribution to the objective function and a greater influence in estimating the parameter values.

3.1.1.1 Steady-State Groundwater Level Elevations

The steady-state groundwater level elevation targets used were a subset of those described in the Model Calibration and Water Budget Report (Matrix and SSPA 2012). Observations outside of the urban well field area were assigned a weight of zero, which meant they did not contribute to the objective function, whereas those lying inside the urban well field area were assigned a weight relative to their quality ranking (see Matrix and SSPA 2012 for details on well rankings). Medium quality observations at the Greenbrook and Strange Street well fields were assigned a weight of zero, as the groundwater levels for these observations corresponded to production conditions that were considerably different from those in 2003 (the optimization period; see Appendix H of Matrix and SSPA 2012 for details). These observations were not retained as they would have added ‘noise’ to the optimization process and led to unreasonable parameter values.

The weighting scheme applied is outlined in Table 1 with the well quality, and the number of observations within each group. It was desirable to have the highest quality observations contribute the most to the objective function so they had the greatest influence when estimating parameter values. The high and medium quality observations contributed 51% and 32%, respectively to the initial objective function for this observation group (Table 1).

Table 1: Weighting Scheme for Observations of Steady Groundwater Level Elevation – Regional Model

Quality	Weight	Count	Phi Contribution	Rationale
High	2.00	97	51%	Most reflective calibration conditions but relatively few observations.
Medium	1.00	330	32%	Typically reflective calibration conditions with relatively large number observations.
Medium-Low	1.00	118	12%	Moderately reflective calibration conditions with relatively few observations.
Low	0.25	517	5%	Somewhat reflective calibration conditions with relatively large number of observations.

The spatial distribution of observations is shown on Figure 2. In general, high to medium quality observations lie closer to the municipal wells, whereas lower quality observations tended to fill in the areas between well fields and in the surrounding areas.

3.1.1.2 Time-Varying Trends in Groundwater Level Elevations

Including time-varying groundwater level elevations in the objective function ensured that the hydraulic responses of the aquifer systems under typical operating conditions were included in the optimization and were available to inform the parameter values.

The time-varying groundwater level elevation data included long-term monitoring data from the Region’s groundwater monitoring network. The activity of the Aquifer Storage and Recovery (ASR) system at the Mannheim Well Field was not represented in this simulation, and observations relating to the ASR system were not included.

Quality checks were performed to identify data gaps and issues of data integrity. Attempts were made to retain as much data as possible by reconciling data integrity issues with available groundwater monitoring data (Burnside, 2011), well field characterization reports or water level data stored within the Region’s WRAS+ database. Data with errors that could not be resolved were excluded from the objective function.

To be consistent with the simulated municipal pumping, the groundwater level elevations at individual wells between 2003 and 2011 were averaged at bi-monthly intervals, resulting in one observation (of groundwater level elevation) for every 2-month period. This was done to reduce the length of the transient calibration period, yet capture the short- and long-term trends in groundwater levels throughout the 8-year period. Time-varying groundwater level elevation data were translated to trends of the variations in elevations, so the optimized parameter values could capture the responses of the system (i.e. changes in groundwater levels over time) while not compensating for an offset in groundwater level elevations caused by imperfect initial conditions.

Quality checks were performed to ensure the data were not skewed by transducer readings or inconsistent monitoring intervals, for example. Trends in the groundwater level elevations were also compared to well field production to omit any potentially unreliable data points.

A total of 448 monitoring locations with 8,932 data points were used as observation points for PEST. Each data point was assigned a default weight of 1. Monitoring locations with a longer period of record were given a proportionately larger weight than those with shorter records and were more informative for optimizing parameter values, which was consistent with the aim of this realization. As there were more than twice as many monitoring locations at the Greenbrook Well Field than any other well field, its data points were assigned a weight of 0.5 so they did not disproportionately contribute to the objective function.

The locations of the time-varying data are shown on Figure 3 with the size of the dot indicating the relative weight. Larger dots had a greater contribution to the objective function and smaller dots had a lesser contribution.

3.1.1.3 Baseflow

Baseflow targets for stream assessment reaches (Figure 4) were presented as estimated ranges of values (see Matrix and SSPA 2012 for details). Target values of one-third the magnitude from the high to the low estimates were applied, as the base case model simulated baseflows nearer the low end of the estimated ranges. The minimum and maximum estimated and target baseflows for each assessment reach are summarized in Table 2. The weight applied to baseflow targets ($2x10^{-3}$) accounted for the difference in units between groundwater level elevation and stream flow measurements.

Table 2: Assessment Reaches Included in Optimization – Regional Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Target
Alder Creek headwaters	Spot measurement range	10	60	27
Alder Creek at Mannheim West	Spot measurement range	14	50	26
Alder Creek at New Dundee	90% exceedance and mean annual baseflow	10	100	40
Clair Creek near Well W10	90% exceedance and mean annual baseflow	10	90	37
Laurel/Beaver Headwaters	Spot measurement range and mean annual baseflow	30	160	73
Laurel Creek at William Street	90% exceedance	40	330	137
Waterloo North	90% exceedance and mean annual baseflow	30	240	100
Airport Creek	Spot measurement range	50	60	53

Hopewell Creek	Spot measurement range	92	163	116
Idlewood Creek	Spot measurement range	10	20	13
Freeport Creek	Spot measurement range	10	70	30
Schneider Creek	90% exceedance and mean annual baseflow	10	130	50
Shoemaker Creek	90% exceedance and mean annual baseflow	10	130	50
Strasburg Creek	Spot measurement range	70	80	73

3.1.2 Set Up – Parameters

Parameter values were constrained in PEST during the optimization process by identifying which parameters could be estimated in PEST, what their bounding values were, and any prior knowledge. Prior knowledge was the preferred values of the parameters within PEST. For example, hydraulic conductivity values interpreted from pumping test results can be applied as prior knowledge for hydraulic conductivity zones. This information acted as a constraint on parameter values (note: all parameters were constrained by lower and upper bound values). Prior knowledge guided the PEST solution toward the parameter's preferred values whenever possible. Parameters varied in this realization included the hydraulic conductivity and groundwater recharge values, as described in the following sections.

3.1.2.1 Recharge

The recharge distribution in the numeric model was derived by applying the GAWSER model-estimated recharge onto the finite element mesh. As a result, each element typically had a unique value. Zones were created so recharge multipliers could be applied to all elements that fell within a given zone. This approach had the advantage of preserving the relative differences between adjacent elements, as opposed to assigning a single value for all elements within the zone.

A two-part approach was undertaken to define recharge multiplier zones. First, the extents of the zones were created by dividing the model domain into broad areas of recharge adjustment, which generally followed rivers, as shown on Figure 5. Polygons were smallest in the urban well field area, larger in the area surrounding the urban well field area, and largest on the periphery of the model. The zones in the urban well field area were adjustable, those in the surrounding area were tied so they were adjusted in unison, and the zones on the periphery of the model were fixed. This provided the greatest flexibility in the area of interest, limited flexibility in the area surrounding the urban well fields, and no flexibility on the periphery of the model, where changes to parameter values were interpreted to have a lesser influence on the municipal wells.

Second, the spatial zones were subdivided by grouping the recharge rates into increments of 50 mm/year (see Table 3). This allowed rates of similar recharge to be varied together, helping to preserve the relative differences in applied recharge, thereby maintaining a greater degree of consistency between the recharge applied to represent various land use types. For each group a lower and upper multiplier was specified. The multiplier lower bound was smaller for relatively higher recharge rates and the multiplier upper bound was larger for relatively lower recharge rates, as discussed earlier. Using this approach 82, 49 and 126 recharge multiplier zone parameters were adjustable, tied and fixed, respectively.

Table 3: Recharge Range – Regional Model

Recharge Group	Recharge Range		PEST Recharge Range		Note
	Min	Max	Min	Max	
1	0	0	0	0	No recharge. These areas were not adjustable (e.g., represent discharge zone such as rivers).
2	0	50	0	200	Low recharge. Relatively higher uncertainty, particularly at upper end of range due ground disturbance, macro-pores, preferential pathways, etc.
3	50	100	47	250	
4	100	150	95	300	
5	150	200	142	300	
6	200	250	170	325	Moderate recharge. Relatively moderate uncertainty due to soil characterization and generalization of land use.
7	250	300	212	360	
8	300	350	255	420	
9	350	400	297	480	
10	400	450	300	495	High recharge. Relatively lower uncertainty, particularly at lower end of range due to stratification of finer grained materials, for example.
11	450	500	337	550	
12	500	>500	375		These areas are already very high (e.g., gravel pits at 1,000 mm/year and should not be further adjusted).

3.1.2.2 Hydraulic Conductivity

The hydraulic conductivity zones and values were a product of the well field characterization and calibration process. In this realization, only the horizontal hydraulic conductivity parameter values were estimable, whereas the vertical anisotropy ratio was held constant. The hydraulic conductivity parameters selected to be adjustable in this realization are summarized in Table 4.

Table 4: Adjustable Hydraulic Conductivity Parameters for Realization 1 – Regional Model

Aquifer/ Aquitard	Number of Adjustable Parameters	Explanation of Selected Parameter Zones
ATB1	4	Zones near Erb Street Well Field where perched water tables are present.
AFB1	67	Zones in production aquifers (e.g., New Dundee Well Field) or the manual calibration determined the zones had a greater sensitivity relative to other parameter zones in the urban well field areas.
ATB2	66	Zones that overlie AFB2 production aquifers, or where leakage may contribute water to a deeper production aquifer, or where parameter zones had a greater sensitivity relative to other parameters in the urban well field areas.
AFB2	133	Zones in production aquifers, zones where leakage may contribute water to a deeper production aquifer, or parameter zones that had a greater sensitivity relative to other parameters in the urban well field areas. Note: AFB2 is simulated with 2 layers; lower layer zones were adjustable and upper layer zones were tied to underlying parameters.
ATB3	62	Zones covered entire urban well field area west of the Grand River, and parameter zones that had a greater sensitivity relative to other parameters in the urban well field areas
AFB3	28	Zones included the William St. Well Field production aquifer, where parameter zones had a

Aquifer/ Aquitard	Number of Adjustable Parameters	Explanation of Selected Parameter Zones
		greater sensitivity relative to other parameters in the urban well field areas.
ATC1, AFC1, ATC2	67	Zones that overlie production aquifers, or where leakage may contribute water to a deeper production aquifer, or where parameter zones had a greater sensitivity relative to other parameters in the urban well field areas.
AFD1	80	Zones in production aquifers or parameter zones that had a greater sensitivity relative to other parameters in the urban well field areas.
ATE1	14	Zones where municipal well fields may have a connection to bedrock water (i.e. Waterloo North, Greenbrook and Parkway Well Fields).
AFF1, ATG1	28	Zones where municipal well fields may have a connection to bedrock water (i.e. Waterloo North, Greenbrook and Parkway Well Fields), or parameter zones that had a greater sensitivity relative to other parameters in the urban well field areas.

3.1.2.3 Storage

The storage parameters were fixed in this realization. Storage parameters are important when matching hydraulic responses to short-term changes in production, such as a pumping test. However, simulating long-term effects of continuous production over 8 years meant hydraulic conductivity values would dominate the responses of the system to fluctuations in production, and assigning the storage parameters to be fixed helped keep the computational requirements manageable.

3.1.3 Realization 1 – Quantitative Results

The calibration to observed data was assessed in the same manner as the base case model so the results were comparable. The simulation results were evaluated at the scale of the urban well field area, and at the well field scale. The steady-state groundwater level elevations, time-varying trends in groundwater level elevations and baseflow estimates are discussed in the following sections.

3.1.3.1 Steady-State Groundwater Level elevations

Good agreement was achieved between the observed and model-simulated average groundwater level elevations, with the simulated groundwater level elevations being predicted slightly higher than the observed values (see scatter plot of simulated versus observed groundwater level elevations; Figure 6). All quality groupings had absolute mean residuals of 4 m or less and medium- and high-quality data had absolute mean residuals of 3 m or less, indicating a strong match to observed conditions. The root mean squared residuals were between 3 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups were within 4% to 6%, indicating a good match. As a guideline, a normalized root mean squared residual of less than 10% was considered acceptable (Anderson and Woessner 1992). A summary of the calibration statistics, grouped by observation quality and aggregated across the urban well field area, is presented in

Table 5.

Table 5: Urban Well Field Area Scale Calibration Statistics for Realization 1 – Regional Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	104	-1.36	2.62	3.52	3.27
Medium	422	-0.15	2.64	3.62	3.05
Medium-Low	127	-1.34	3.08	4.02	3.56
Low	703	-0.13	4.00	5.67	5.16
All	1,356	-0.37	3.38	4.82	3.67

Spatially, across the urban well field area, the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 7). Clusters of localized trends included a tendency to over-predict observed groundwater level elevations at the Erb Street Landfill and the William Street, Mannheim West, Pompeii/Forwell and Woolner well fields. Reviewing the well field scale statistical fit at these well fields (Table 6) indicated that the simulated groundwater level elevations were only slightly over-predicted relative to observed elevations. The poor fit to medium-quality data at the Strange Street and Greenbrook well fields was expected, as discussed in the following section.

Table 6: Well Field Scale Calibration Statistics for Realization 1 – Regional Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Waterloo North	High	1	1.46	1.46	
Waterloo North	Medium	13	-0.84	1.23	1.70
Waterloo North	Medium-Low	1	2.65	2.65	
Waterloo North	Low	8	-2.04	3.07	3.89
Waterloo North	All	23	-1.01	1.94	2.70
William Street	High	3	0.79	2.06	2.61
William Street	Medium	24	-1.79	2.18	2.40
William Street	Low	6	-2.29	2.65	3.51
William Street	All	33	-1.65	2.25	2.66
Erb Street	High	2	0.31	0.31	0.33
Erb Street	Medium	20	-0.03	1.33	2.01
Erb Street	Medium-Low	6	-1.08	1.45	2.10
Erb Street	Low	7	1.13	1.86	2.23
Erb Street	All	35	0.04	1.40	2.02
Strange Street	High	3	0.56	1.70	2.12
Strange Street	Medium	7	4.95	4.95	5.62
Strange Street	Medium-Low	13	0.93	2.71	3.56
Strange Street	Low	16	0.36	4.37	5.47
Strange Street	All	39	1.39	3.72	4.75
Greenbrook	High	6	1.51	1.79	2.26
Greenbrook	Medium	63	7.15	7.22	7.60
Greenbrook	Medium-Low	15	1.60	3.11	3.82

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Greenbrook	Low	9	1.74	1.74	1.89
Greenbrook	All	93	5.37	5.68	6.49
Mannheim East	High	4	-0.35	0.82	0.97
Mannheim East	Medium	4	3.46	3.46	3.46
Mannheim East	Medium-Low	2	-2.19	4.09	4.64
Mannheim East	Low	8	2.23	4.09	5.69
Mannheim East	All	18	1.44	3.22	4.43
Mannheim Peaking	Medium	8	3.63	3.63	3.71
Mannheim Peaking	Medium-Low	1	3.28	3.28	
Mannheim Peaking	Low	6	9.63	9.63	16.20
Mannheim Peaking	All	15	6.01	6.01	10.63
Mannheim West	High	7	-1.18	1.18	1.40
Mannheim West	Medium	8	-0.74	1.12	1.44
Mannheim West	Medium-Low	5	0.16	1.21	1.62
Mannheim West	Low	10	-0.19	3.44	4.67
Mannheim West	All	30	-0.51	1.92	2.95
Parkway	High	5	-0.43	1.81	2.21
Parkway	Medium-Low	1	0.95	0.95	
Parkway	Low	4	6.22	6.22	6.60
Parkway	All	10	2.37	3.49	4.47
Strasburg	High	2	1.97	1.97	2.22
Strasburg	Medium	1	-4.43	4.43	
Strasburg	Medium-Low	7	-4.67	5.94	6.09
Strasburg	Low	1	-1.12	1.12	
Strasburg	All	11	-3.12	4.64	5.13
Lancaster	Medium	9	-1.50	3.13	3.68
Lancaster	Low	4	-1.89	3.49	3.53
Lancaster	All	13	-1.62	3.24	3.63
Pompeii / Forwell	High	8	-1.71	1.71	1.81
Pompeii / Forwell	Medium	6	-0.84	0.84	0.85
Pompeii / Forwell	Medium-Low	23	-3.76	3.76	4.31
Pompeii / Forwell	Low	21	-2.73	2.91	3.37
Pompeii / Forwell	All	58	-2.80	2.87	3.46
Woolner	High	1	-0.66	0.66	0.00
Woolner	Medium	15	-1.02	1.09	1.29
Woolner	Medium-Low	9	-2.05	2.05	2.30
Woolner	Low	30	2.65	3.78	5.13
Woolner	All	55	0.82	2.70	3.96
Fountain Street	High	1	1.88	1.88	
Fountain Street	Medium	5	1.21	1.21	1.24
Fountain Street	Low	6	-1.09	2.37	2.61
Fountain Street	All	12	0.11	1.85	2.08
Conestogo	High	2	0.05	0.08	0.09

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Conestogo	Medium	7	2.87	4.28	5.30
Conestogo	Low	13	-2.20	2.97	3.85
Conestogo	All	22	-0.38	3.12	4.20
New Dundee	High	2	-0.93	0.93	0.95
New Dundee	Medium	8	-0.05	1.45	1.75
New Dundee	Low	15	-0.59	2.65	3.07
New Dundee	All	25	-0.45	2.13	2.59
St. Agatha	High	3	-3.63	3.83	5.07
St. Agatha	Medium	3	-2.11	2.11	2.61
St. Agatha	Medium-Low	2	3.33	3.33	3.67
St. Agatha	Low	18	2.50	4.82	6.61
St. Agatha	All	26	1.32	4.28	5.92

At the well field scale, the residuals indicated a good fit to the data. For the high and medium quality observations, most well fields typically had absolute mean residuals less than 3 m. The medium-low and low-quality observations, whose groundwater levels were not necessarily commensurate with 2003 production rates, had greater variability of the absolute mean residuals, with values typically less than 4 m. At the scale of the entire urban well field area, and at the individual well field scales, the fit to observed data was typically as good as, or better than, the base case model and maintained calibrated conditions.

3.1.3.2 Time-Varying Trends in Groundwater Level Elevations

The simulated groundwater level elevations reproduced the observed trends in time-varying groundwater level elevations. A sample hydrograph comparing observed and simulated groundwater level elevation trends is presented for each well field. Sample hydrographs of simulated versus observed groundwater level elevations at the Waterloo well fields is presented for observation wells MWWN1-02 (Figure 8), OW5A-87 (Figure 9), and OW7-57B (Figure 10) corresponding to the Waterloo North, William Street and Erb Street well fields, respectively.

Hydrographs of simulated versus observed groundwater level elevations at the City of Kitchener well fields are presented for observation wells OW 1-82 (Figure 11), GB1ABC-96 (Figure 12), PK1-95 (Figure 13), PK5-96 (Figure 14) and OW8-61 (Figure 15) corresponding to wells located in the Strange Street, Greenbrook, Parkway, Strasburg, and Mannheim well fields, respectively.

A sample hydrograph of simulated versus observed groundwater level elevations at OW12-78 of the Woolner well field is shown on Figure 16. Sample hydrographs of simulated versus observed groundwater level elevations at the rural well fields are presented for observation wells C5 (Figure 17), OW1-03 (Figure 18) and MW2-93 (Figure 19) corresponding to the Conestogo, New Dundee and St. Agatha well fields, respectively. The groundwater level elevation scale on the left hand side of the hydrographs varies between the graphs; Figure 18 illustrates the observed elevation in the New Dundee observation well varied by less than 0.7 m on an average annual basis. This difference was interpreted to be due to seasonal changes in recharge rather than due to the influence of municipal pumping.

3.1.3.3 Baseflow

The predicted groundwater discharge values showed a good fit to the estimated ranges in observed baseflow conditions. These are summarized for the stream assessment reaches in the urban well field area in Table 7. In this realization, the model under-predicted the minimum estimates of baseflow for the following stream assessment reaches: Airport Creek, Freeport Creek and Strasburg Creek. The maximum estimate of baseflow was over-predicted at Hopewell Creek. Idlewood Creek was simulated as a losing condition, which was contrary to the observation data which suggested the creek was gaining 10 to 20 L/s. The simulated baseflow conditions for all other stream reaches were within their respective estimated ranges. For all reaches the results were equivalent to, or better than, the base case model and maintained calibrated conditions.

Table 7: Simulated Baseflow for Realization 1 – Regional Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Alder Creek Headwaters	Spot measurement range	10	60	45
Alder Creek at Mannheim West	Spot measurement range	14	50	47
Alder Creek at New Dundee	90% exceedance and mean annual baseflow	10	100	16
Clair Creek at W10	90% exceedance and mean annual baseflow	10	90	36
Laurel/Beaver Headwaters	Spot measurement range and mean annual baseflow	30	160	120
Laurel Creek at William Street	90% exceedance	40	330	46
Waterloo North	90% exceedance and mean annual baseflow	30	240	54
Airport Creek	Spot measurement range	50	60	34
Hopewell Creek	Spot measurement range	92	163	311
Idlewood Creek	Spot measurement range	10	20	-24
Freeport Creek	Spot measurement range	10	70	5
Schneider Creek	90% exceedance and mean annual baseflow	10	130	26
Shoemaker Creek	90% exceedance and mean annual baseflow	10	130	38
Strasburg Creek	Spot measurement range	70	80	64

3.1.4 Realization 1 – Qualitative Results (Estimated Parameters)

3.1.4.1 Recharge

The optimized recharge distribution showed an overall trend of increased recharge in the urban areas and decreased recharge in the rural, surrounding areas, relative to the base case model. The recharge rate was most notably increased in areas of low recharge, where there was greater uncertainty in the estimated recharge values. Over the footprint of the Region of Waterloo (Region) the average recharge rates for the base case model and this realization were 178 and 177 mm/year, respectively. This indicated that the volume of water in this Realization was consistent with the base case model, but it had a different spatial distribution. For comparison, the spatial distributions of recharge for the base case and optimized model are presented on Figure 20.

3.1.4.2 Hydraulic Conductivity

Considering the urban well field area as a whole, the optimized hydraulic conductivity zone values exhibited greater contrast between the aquifers and aquitards, whereby the aquifer values were increased and the aquitard values were decreased, relative to the base case values. The hydraulic conductivity zone values applied in this realization are discussed below relative to the base case values.

The greatest increase in hydraulic conductivity zone values was applied to the shallow bedrock, where values were increased by a factor of 2. The optimized value for this parameter reached its upper bound of $1x10^{-6}$ m/s, which suggested the value may have increased further to improve the fit to the observed dataset if a larger upper bound value had been specified. This upper bound value was chosen to be consistent with the base case conceptual model. The greatest decrease in hydraulic conductivity was applied to aquitard ATB3, which on average decreased from $4.7x10^{-9}$ m/s in the base case model to $3.8x10^{-9}$ m/s in the optimized model. With the exception of the shallow bedrock and ATB3, the average adjustments across the hydrogeologic units were +/-15% of the base case value. The average hydraulic conductivity value adjustments on a hydrogeologic unit basis are summarized in Table 8.

Table 8: Optimized Hydraulic Conductivity Values Aggregated by Hydrogeologic Unit for Realization 1 – Regional Model

Hydrogeologic Unit	Number of Parameters	Average Hydraulic Conductivity Value		
		Base Case (m/s)	Optimized (m/s)	Multiplier
ATB1	4	$3.50x10^{-09}$	$3.00x10^{-09}$	0.86
AFB1	67	$1.35x10^{-05}$	$1.43x10^{-05}$	1.06
ATB2	66	$2.27x10^{-09}$	$2.48x10^{-09}$	1.09
AFB2	133	$1.59x10^{-04}$	$1.73x10^{-04}$	1.09
ATB3	62	$4.68x10^{-09}$	$3.80x10^{-09}$	0.81
AFB3	28	$5.29x10^{-05}$	$5.32x10^{-05}$	1.01
ATC1/AFC1/AFC2	67	$4.16x10^{-08}$	$3.18x10^{-08}$	0.76
AFD1	80	$1.72x10^{-04}$	$1.82x10^{-04}$	1.06
ATE1	14	$8.22x10^{-07}$	$7.38x10^{-07}$	0.90
AFF1/ATG1	28	$1.80x10^{-05}$	$1.64x10^{-05}$	0.91
Shallow Bedrock	1	$5.00x10^{-07}$	$1.00x10^{-06}$	2.00

The hydraulic conductivity zone values for aquitard ATB1 were decreased at the Waterloo North and Erb Street well fields. The hydraulic conductivity values for aquifer AFB1 were generally decreased across the urban well field area, with local increases at the Erb Street, William Street, Parkway and Strasburg well fields. For both ATB1 and AFB1, the optimized hydraulic conductivity values closely resembled those of the base case model. Figure 21 illustrates the optimized hydraulic conductivity values for the individual parameter zones for ATB1 and AFB1. This figure aims to illustrate the magnitude and the direction that PEST changed the individual parameter zones. The shapes, sizes and locations of the zones varied across the unit; however, this figure, and the subsequent figures, aim to identify systematic increases or decreases in parameter values relative to the base case model.

Relative to the base case model, the hydraulic conductivity zone values for aquitard ATB2 were decreased, and those for aquifer AFB2 were increased, along the core of the Waterloo Moraine. The hydraulic conductivity values for AFB2 were also decreased at the Strange Street, Parkway and Strasburg well fields; but increased in the areas between the Mannheim and Strange Street well fields and between the Mannheim and Parkway well fields. For ATB2, the optimized hydraulic conductivity values closely resembled those of the base case model, whereas for AFB2 there was a greater variability in parameter adjustments relative to the base case model (Figure 22).

The hydraulic conductivity zone values for aquitard ATB3 were decreased over most of the urban well field area footprint. At the Waterloo North, Mannheim, Greenbrook and Lancaster well fields, the values were similar to those of the base case model. Immediately north of the Parkway Well Field, the hydraulic conductivity value was increased. This was interpreted to represent a mechanism that provided a pathway for source waters to reach the Parkway Well Field that was not well captured in the base case model. The hydraulic conductivity values for aquifer AFB3 were decreased at the Greenbrook Well Field, between the Greenbrook and Parkway well fields, and at the Strasburg Well Field. For ATB3, several hydraulic conductivity zone values were adjusted by half an order of magnitude or more with respect to the base case model, whereas those for AFB3 closely resembled those of the base case model (Figure 23).

The hydraulic conductivity zone values for aquitard ATC1/AFC1/ATC2 typically decreased, with the greatest changes occurring in the area of the Greenbrook, Parkway and Strasburg well fields. In these areas, the hydraulic conductivity values of these units in the base case model were greater to allow increased leakage to the underlying AFD1 production aquifer. As the recharge was increased in the urban area in this realization, the hydraulic conductivity values of this unit were decreased accordingly. Decreasing the hydraulic conductivity values restricted the hydraulic connections at depth to Shoemaker, Schneider and Strasburg creeks, which improved the baseflow calibration relative to the base case model. West of the Waterloo North Well Field and west of the Greenbrook Well Field, the optimized hydraulic conductivity values of the lower ATC1/AFC1/ATC2 units were higher than the base case model. This was interpreted to represent a mechanism that allowed additional upgradient groundwater to travel to these well fields. Although several hydraulic conductivity zone values were adjusted, the values typically remained within half an order of magnitude of the base case model (Figure 24).

The optimized hydraulic conductivity zone values for aquitard ATE1 were lower at the Waterloo North, Greenbrook and Parkway well fields relative to the base case model. This was interpreted to represent a mechanism that provided groundwater level support to the overburden system, as the optimized hydraulic conductivity values of the shallow bedrock were doubled. Similarly, the hydraulic conductivity values for aquifer/aquitard AFF1/ATG1 were decreased at the Parkway and Strasburg well fields, possibly to compensate for the increased hydraulic conductivity values of the shallow bedrock relative to the base case model. These parameter adjustments are summarized on Figure 25.

3.1.5 Realization 1 - Overall Impression and Understanding

Overall, the optimized recharge and hydraulic conductivity parameter values were consistent with the conceptual model of the base case model and showed a good fit to average groundwater level elevations, average baseflow estimates and time-varying trends in groundwater level elevations. This realization was characterized as a fine tuning of the base case model, whereby parameter values were adjusted to better reflect the long-term hydraulic responses of the system under typical operating conditions at, and in between, the urban well fields. The simulation results were a good match to the observation data and maintained calibrated conditions at both regional and local scales. Therefore, the simulation result was acceptable as an uncertainty realization in the Risk Assessment Report.

3.2 Realization 2 – Aquitard Leakage

Realization 2 was an alternative numeric model whereby the regional till units were allowed to be as leaky as possible (i.e. high hydraulic conductivity values) and the other parameters (i.e. aquifers) were adjusted using PEST within a set limit to produce a calibrated model. This tested the assumption that the regional tills presented in the Model Calibration and Water Budget Report (Matrix and SSPA 2012) effectively form confining barriers to the underlying groundwater aquifers. This realization attempted to determine the upper bounds of the hydraulic conductivity values of the aquitard units on a regional scale, and is referred to as the “Leaky Aquitards” realization.

3.2.1 Set-Up and Observation Data Set

For this realization, PEST was used to determine how leaky the regional aquitards (ATB2, ATB3, ATC1/AFC1/AFC2, and ATE1) could be while maintaining a fit to the observed data under average annual 2003 production conditions. Increasing the hydraulic conductivity zone values of the aquitards meant the recharge rates and aquifer hydraulic conductivity zone values needed to be adjusted to maintain a fit between model-predicted and observed conditions. To ensure the conceptual behaviour of the aquitards was properly represented (i.e. provide an appropriate barrier to flow) the differences in groundwater level elevations across the various aquitards were introduced as calibration targets.

To meet the objectives of this realization, PEST was used to find the highest hydraulic conductivity values for regional tills that were still consistent with the observation data. To accomplish this, PEST was run in “regularization mode”, which allowed information to be specified for the adjustable parameters (to help further constrain the values). Using this feature facilitated use of the PEST optimization to satisfy two different objective functions; the measurement objective function and the regularization objective function.

The measurement objective function (referred to previously as the objective function), quantifies the differences between model-simulated and observed values, and the goal of any PEST optimization is to minimize the differences between field measured and model-simulated values. The regularization objective function seeks to minimize the differences between the user-specified prior knowledge values and the simulated hydraulic conductivity values. In this realization, the upper bounds were specified based on prior knowledge of the hydraulic conductivity values of the regional till units, to encourage the optimization to increase their values. The prior knowledge for the aquifers was specified in accordance with the base case calibrated values. The modeller guides PEST toward the specified prior knowledge values whenever feasible (i.e. so the model remains calibrated).

During the optimization process, PEST was used to help manage both the measurement and regularization objective functions. In this uncertainty case, PEST was used to find a solution that had the highest hydraulic conductivity values for the regional tills (i.e. minimize the regularization objective function) but that was consistent with the observation data (i.e. minimize the measurement objective function). In creating this realization, the hydraulic conductivity of the regional tills was increased as much as possible, and in turn, PEST adjusted the aquifer hydraulic conductivity values and recharge parameters to maintain calibrated conditions.

The groundwater level elevation differences across the various aquitard units in the model were used as calibration targets, alongside the long-term groundwater level elevation data and baseflow discharge estimates, in the same format as Realization 1.

3.2.1.1 Groundwater Level Elevation Differences Across Aquitards

To supplement the groundwater level elevations and baseflow estimates, groundwater level elevation differences (i.e. groundwater level elevations collected above and below aquitard units) were introduced as additional observations to optimize the hydraulic conductivity values of the aquifers and aquitards. Measurements of groundwater level elevation differences were derived from multi-level monitoring wells and monitoring wells located near one another (i.e. <500 m), both of which were part of the calibration dataset applied in the base case model (see Appendix C of the Water Budget and Model Calibration Report, Matrix and SSPA 2012). Multi-level monitoring wells predominantly exist at urban well fields, within deep overburden production aquifers such as William Street, Greenbrook, Parkway and Strasburg. Variable weights were applied to the monitoring wells to account for the quality of the wells (and measurements) and to ensure clustered wells did not bias the overall objective function. A total of 104 wells were used as observations in this realization and their spatial locations are shown on Figure 26.

3.2.2 Set Up - Parameters

In this realization, PEST was used to help optimize groundwater recharge values and treated in the same manner as Realization 1. Adjustable hydraulic conductivity values are discussed in the underlying section.

3.2.2.1 Hydraulic Conductivity

As this realization was run in steady-state, more parameters could be adjusted as compared to the number of parameters that were adjustable in Realization 1 (Transient Long-Term realization).

Table 9 outlines the number of parameters that were allowed to be varied in PEST in this realization.

Table 9: Adjustable Hydraulic Conductivity Parameters for Realization 2 – Regional Model

Aquifer/ Aquitard	Number of Adjustable Parameters	Notes
ATB1	84	Initial hydraulic conductivity values based on base case values. Prior knowledge reflects the upper bound of conceptual understanding.
AFB1	67	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
ATB2	129	Initial hydraulic conductivity values based on base case values. Prior knowledge reflects the upper bound of conceptual understanding.
AFB2	133	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model
ATB3	86	Initial hydraulic conductivity values based on base case values. Prior knowledge reflects the upper bound of conceptual understanding.
AFB3	28	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
ATC1, AFC1, ATC2	122	Initial hydraulic conductivity values based on base case values. Prior knowledge reflects the upper bound of conceptual understanding.
AFD1	80	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
ATE1	77	Initial hydraulic conductivity values based on base case values. Prior knowledge reflects the upper bound of conceptual understanding.
AFF1, ATG1	0	All parameters were fixed at the calibrated (base case) model value.
Shallow Bedrock	0	All parameters were fixed at the calibrated (base case) model value.

3.2.3 Realization 2 – Quantitative Results

The simulation results were evaluated at the regional (considered the urban well field area as a whole) and local (well field) scale. The results with respect to groundwater level elevations, groundwater level elevation differences across aquitards, and baseflow estimates are discussed in the following sections.

3.2.3.1 Steady-State Groundwater Level elevations

Generally, the optimized model for this realization produced calibrated conditions with a slight bias to under-predicting simulated groundwater level elevations relative to observed values (see scatter plot on Figure 27). All quality groupings had mean absolute residuals of 4 m or less, except the low-quality grouping, with a mean absolute residual of 4.3 m. The root mean squared residuals were between 4 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups in the regional model were within 4% to 6%, indicating a good match. As a guideline, a normalized root mean squared residual of less than 10% was considered acceptable. Table 10 presents a summary of the calibration statistics, grouped by observation quality, aggregated across the urban well field area.

Table 10: Urban Well Field Area Calibration Statistics for Realization 2 – Regional Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	104	-0.40	3.31	4.92	4.58
Medium	422	1.52	3.70	5.07	4.28
Medium-Low	127	-0.57	3.72	4.60	4.08
Low	703	-0.01	4.30	5.96	5.43
All	1,356	0.37	3.99	5.50	4.19

Spatially, across the urban well field area, the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 28). Groundwater level elevations were simulated to be slightly over-predicted relative to observed elevations at the William Street, Pompeii/Forwell and Woolner well fields. The poor fit to medium quality data at the Strange Street and Greenbrook well fields was expected and is discussed in greater detail below.

At the well field scale, the residuals indicated a good fit to the data. For the high and medium quality observations, most well fields typically had mean absolute residuals less than 3 m. The medium-low and low-quality observations, whose groundwater level elevations were not necessarily commensurate with 2003 production rates, had a greater variability of the mean absolute residuals with values typically less than 4 m. Statistics for all well fields are reported in Table 11.

Table 11: Well Field Scale Calibration Statistics for Realization 2 – Regional Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Waterloo North	High	1	2.44	2.44	
Waterloo North	Medium	13	-0.39	0.82	1.21
Waterloo North	Medium-Low	1	3.13	3.13	
Waterloo North	Low	8	-1.94	3.00	3.71
Waterloo North	All	23	-0.65	1.75	2.51
William Street	High	3	2.66	3.08	3.69
William Street	Medium	24	-0.76	1.59	1.85
William Street	Low	6	-0.96	2.48	3.24
William Street	All	33	-0.48	1.89	2.37
Erb Street	High	2	3.58	3.58	3.58
Erb Street	Medium	20	0.58	2.05	2.70
Erb Street	Medium-Low	6	-3.16	3.38	3.91
Erb Street	Low	7	-0.15	2.88	3.20
Erb Street	All	35	-0.04	2.53	3.09
Strange Street	High	3	1.60	2.52	2.87
Strange Street	Medium	7	7.48	7.48	8.12
Strange Street	Medium-Low	13	2.18	3.40	4.39
Strange Street	Low	16	1.88	4.79	5.62

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Strange Street	All	39	2.96	4.63	5.64
Greenbrook	High	6	2.89	2.89	3.48
Greenbrook	Medium	63	8.52	8.55	8.94
Greenbrook	Medium-Low	15	2.64	4.00	4.62
Greenbrook	Low	9	3.38	3.38	3.49
Greenbrook	All	93	6.71	6.95	7.72
Mannheim East	High	4	2.08	2.08	2.30
Mannheim East	Medium	4	5.67	5.67	5.68
Mannheim East	Medium-Low	2	-0.14	3.83	3.83
Mannheim East	Low	8	4.56	5.29	6.73
Mannheim East	All	18	3.74	4.50	5.49
Mannheim Peaking	Medium	8	6.00	6.00	6.09
Mannheim Peaking	Medium-Low	1	5.31	5.31	
Mannheim Peaking	Low	6	11.45	11.45	17.34
Mannheim Peaking	All	15	8.13	8.13	11.91
Mannheim West	High	7	0.46	0.84	0.89
Mannheim West	Medium	8	-0.10	1.92	2.08
Mannheim West	Medium-Low	5	1.23	1.54	2.24
Mannheim West	Low	10	-0.10	3.41	5.23
Mannheim West	All	30	0.25	2.10	3.36
Parkway	High	5	0.94	2.72	3.94
Parkway	Medium-Low	1	0.27	0.27	
Parkway	Low	4	10.26	10.26	11.09
Parkway	All	10	4.60	5.49	7.55
Strasburg	High	2	1.09	1.09	1.31
Strasburg	Medium	1	-3.12	3.12	
Strasburg	Medium-Low	7	-4.65	6.39	6.68
Strasburg	Low	1	0.66	0.66	
Strasburg	All	11	-2.98	4.60	5.45
Lancaster	Medium	9	-2.47	4.39	4.98
Lancaster	Low	4	-4.63	4.63	5.35
Lancaster	All	13	-3.14	4.46	5.10
Pompeii / Forwell	High	8	-1.56	1.56	1.67
Pompeii / Forwell	Medium	6	-0.77	0.77	0.78
Pompeii / Forwell	Medium-Low	23	-3.73	3.73	4.32
Pompeii / Forwell	Low	21	-2.53	2.66	3.13
Pompeii / Forwell	All	58	-2.69	2.74	3.38
Woolner	High	1	-0.77	0.77	
Woolner	Medium	15	-1.39	1.39	1.63
Woolner	Medium-Low	9	-2.39	2.39	2.61
Woolner	Low	30	1.65	3.47	4.62
Woolner	All	55	0.12	2.68	3.67
Fountain Street	High	1	0.03	0.03	

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Fountain Street	Medium	5	0.04	1.59	1.83
Fountain Street	Low	6	-4.02	4.69	4.96
Fountain Street	All	12	-1.99	3.01	3.70
Conestogo	High	2	-0.38	0.38	0.38
Conestogo	Medium	7	4.12	5.02	6.50
Conestogo	Low	13	-0.99	2.52	3.12
Conestogo	All	22	0.69	3.12	4.38
New Dundee	High	2	-0.60	0.60	
New Dundee	Medium	8	0.12	1.68	2.01
New Dundee	Low	15	-0.57	2.91	3.31
New Dundee	All	25	-0.35	2.33	2.81
St. Agatha	High	3	-7.09	7.09	9.24
St. Agatha	Medium	3	-3.15	3.15	3.18
St. Agatha	Medium-Low	2	0.90	4.12	4.22
St. Agatha	Low	18	-0.22	3.95	6.69
St. Agatha	All	26	-1.27	4.23	6.59

At urban well field area and well field scales, the fit to observed data was typically equivalent to, or better than, the base case model and maintained a calibrated condition.

3.2.3.2 Groundwater Level Elevation Differences Across Aquitards

The simulation results indicated this realization did a good job of representing groundwater level elevations recorded in aquifers above and below aquitards. For multi-level observations, the mean absolute residuals in these wells were less than 5.5 m (and less than 3 m at the Greenbrook Well Field). However, the fit on a local scale at the urban well fields was generally worse than the statistical calibration achieved in the base case model (i.e. mean absolute residuals were greater by 0.5 to 1.0 m).

Simulated groundwater level elevation differences across aquitards for nearby monitoring wells also showed a good fit to observed data. For the high-and medium-quality observations, the absolute mean residuals were less than 3 m, which was worse than the base case model by less than 0.5 m. For the medium-low and low-quality observations, the mean absolute residuals were just over 5 m, which was worse than the base case model by less than 1 m.

Overall the fit was slightly worse than of the base case model but still in good agreement with observed values. This slightly worse fit was expected given that the contrast between the hydraulic conductivity values of the aquifers and aquitards was reduced in this realization.

3.2.3.3 Baseflow

Results for this realization showed a good fit to the estimated ranges in observed baseflow conditions for all stream reaches. The simulated results are summarized in Table 12 and were as good as, or better than, the base case model. Under this realization, the minimum estimates of baseflow were under-predicted at Laurel Creek, Airport Creek, Freeport Creek, Schneider Creek and Strasburg Creek and the maximum estimates of baseflow were over-predicted at Laurel/Beaver Headwaters and Hopewell Creek. The simulated conditions for all other stream reaches were within the estimated ranges.

Table 12: Simulated Baseflow for Realization 2 – Regional Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Alder Creek Headwaters	Spot measurement range	10	60	35
Alder Creek at Mannheim West	Spot measurement range	14	50	30
Alder Creek at New Dundee	90% exceedance and mean annual baseflow	10	100	16
Clair Creek at W10	90% exceedance and mean annual baseflow	10	90	30
Laurel/Beaver Headwaters	Spot measurement range and mean annual baseflow	30	160	174
Laurel Creek at William Street	90% exceedance	40	330	28
Waterloo North	90% exceedance and mean annual baseflow	30	240	52
Airport Creek	Spot measurement range	50	60	6
Hopewell Creek	Spot measurement range	92	163	348
Freeport Creek	Spot measurement range	10	70	0
Schneider Creek	90% exceedance and mean annual baseflow	10	130	4
Shoemaker Creek	90% exceedance and mean annual baseflow	10	130	11
Strasburg Creek	Spot measurement range	70	80	42

3.2.4 Realization 2 – Qualitative Results (Estimated Parameters)

3.2.4.1 Recharge

The optimized recharge distribution showed an overall trend of increased recharge in the urban areas and decreased recharge in the rural, surrounding areas, relative to the base case model. The recharge rates were most notably increased in areas of low recharge, consistent with lower recharge rates having a relatively greater uncertainty in estimated values. Over the footprint of the Region, the average recharge rate for the base case model was 178 mm/year and for the optimized model, 171 mm/year. The volume of water was relatively consistent between this optimized realization and the base case model, but the spatial distribution was different. For comparison, the spatial distributions of recharge for the base case model and the optimized Realization 2 model are presented on Figure 29.

3.2.4.2 Hydraulic Conductivity

The optimized hydraulic conductivity zone values were consistent with the objective of this realization and were different from the base case model. In this optimization, the hydraulic conductivity values of the aquitards were increased and PEST was used to help decrease the hydraulic conductivity values of the aquifer units to maintain calibrated conditions. Overall, the contrast between the aquifer and aquitard units was decreased.

On average, the hydraulic conductivity values of the aquitard units increased by factors ranging from 1.4 to 3.1, whereas the hydraulic conductivity values of the aquifer units decreased by factors ranging from

0.5 to just under 1.0, relative to the values applied in the base case model. The greatest average increases in hydraulic conductivity values were applied to aquitard ATB3, which on average increased by a factor of 3.1 (Table 13). Correspondingly, the greatest decreases in hydraulic conductivity values were applied to overlying aquifer AFB3, which on average decreased by a factor of 0.5 (Table 13).

Table 13: Optimized Hydraulic Conductivity Values by Hydrogeologic Unit for Realization 2 – Regional Model

Hydrogeologic Unit	Number of Parameters	Average Hydraulic Conductivity		
		Base Case (m/s)	Optimized (m/s)	Multiplier
ATB1	84	9.10E-09	1.56E-08	1.72
AFB1	67	1.35E-05	9.99E-06	0.74
ATB2	129	3.99E-09	7.06E-09	1.77
AFB2	133	1.59E-04	7.66E-05	0.48
ATB3	86	3.88E-09	1.19E-08	3.06
AFB3	28	5.29E-05	5.07E-05	0.96
ATC1/AFC1/AFC2	122	1.84E-08	2.37E-08	1.29
AFD1	80	1.72E-04	1.21E-04	0.71
ATE1	77	1.78E-08	4.65E-08	2.62

For aquitard ATB1, hydraulic conductivity zone values on average increased (relative to the base case model) by a factor of 1.72, but most values increased by less than half an order of magnitude. The greatest increases occurred at the Waterloo North, Erb Street, William Street, Lancaster and Woolner well fields. Few hydraulic conductivity zone values decreased compared to the base case model, yet all decreases were less than half an order of magnitude. For aquifer AFB1, hydraulic conductivity values decreased by a factor of 0.74 relative to the values applied in the base case model (Table 13). The changes in hydraulic conductivity zone values relative to the base case model for ATB1 and AFB1 are summarized on Figure 30.

Relative to the base case model, hydraulic conductivity zone values in aquitard ATB2 increased by a factor of 1.77 on average. The majority of hydraulic conductivity values for ATB2 increased, by half an order of magnitude or more, with the greatest increases at the Erb Street and St. Agatha well fields, where some zones increased by more than an order of magnitude. The greatest decreases occurred north of the Erb Street Well Field, at the Strange Street and Lancaster well fields and west of the Parkway Well Field. On average, for aquifer AFB2 the optimized values for hydraulic conductivity zones were decreased by a factor of 0.48 relative to base case values. Localized increases to hydraulic conductivity zone values were simulated at the Erb Street, William Street, and Strange Street well fields, whereas the greatest decreases occurred near the Mannheim West, Parkway, and Strasburg well fields. The changes to the hydraulic conductivity zone values with respect to the base case model for ATB2 and AFB2 are summarized on Figure 31.

Relative to the base case model, hydraulic conductivity zone values in aquitard ATB3 increased by a factor of 3.06 on average, with the majority of values increasing by half an order of magnitude or more. The greatest increases occurred at the St. Agatha and Mannheim well fields. On average, the optimized hydraulic conductivity zone values for aquifer AFB3 decreased slightly by a factor of 0.96 relative to base case values. Individual hydraulic conductivity values changed by less than 10%, suggesting this unit was represented in this realization in a similar manner to the base case model. The changes to hydraulic conductivity zone values with respect to the base case model for ATB3 and AFB3 are summarized on Figure 32.

For aquitard ATC1/AFC1/ATC2, hydraulic conductivity zone values on average increased by a factor of 1.41 relative to the base case model, with the greatest increases at the Waterloo North, St. Agatha and Mannheim well fields. Hydraulic conductivity values increased between the Greenbrook, Pompeii/Forwell and Woolner well fields. Decreased hydraulic conductivity values occurred at the Greenbrook Well Field, north of the Mannheim and Lancaster well fields, and west, south and east of the Strasburg Well Field. On average, the optimized hydraulic conductivity zone values for aquifer AFD1 were decreased by a factor of 0.71 relative to base case values. The greatest decreases to hydraulic conductivity values occurred between the Greenbrook and Woolner well fields and between the Parkway and Fountain Street well fields. The changes to hydraulic conductivity zone values with respect to the base case model for ATC1/AFC1/ATC2 and AFD1 are summarized on Figure 33.

For aquitard ATE1, hydraulic conductivity zone values on average increased by a factor of 2.62. The increases to hydraulic conductivity values were more-or-less uniformly distributed across the urban well field area, with the greatest increases occurring at the Mannheim well fields and southeast of the Strasburg Well Field. Hydraulic conductivity values also increased within the Conestogo Well Field but decreased in the area surrounding it. The changes to hydraulic conductivity zone values with respect to the base case model for ATE1 are summarized on Figure 34.

3.2.5 Realization 2 - Overall Impression and Understanding

The optimized recharge and hydraulic conductivity parameter values were consistent with the design of Realization 2, which aimed to estimate how leaky the regional tills could be while maintaining a reasonable fit to field observations. The hydraulic conductivity zone values for all till units increased relative to the base case model, but predominantly remained within the range of conceptual understanding for their material types (e.g., finer grained tills). Correspondingly, the hydraulic conductivity zone values for the aquifers decreased to maintain groundwater levels. With increases in leakage for the till units, the volume of recharge required to maintain calibrated conditions decreased but was still in good agreement with the base case model. This simulation result was a good match to the observation data and maintained calibrated conditions regionally and locally. The simulation was considered acceptable to be included as an uncertainty realization.

3.3 Realization 3 - Bedrock Transmissivity

Realization 3 was an alternative numeric model whereby the Salina Formation bedrock was simulated as having a higher hydraulic conductivity relative to the base case model, while adjusting other parameters within reason to maintain a calibrated model. The base case model assumed flow through the Salina Formation was relatively minor and the bedrock, in general, should be represented in the model with low hydraulic conductivity values. This assumption was based on the bedrock groundwater chemistry which has elevated concentrations of sulphides and iron, suggesting the bedrock material has a long residence time that allows bedrock minerals to dissolve into the groundwater flow system. Some permits to take water within the urban areas were noted to pump large volumes of water from the bedrock, and as such, isolated or regional zones/units of higher hydraulic conductivity values may exist within the Salina Formation. This alternative realization is referred to as the “Bedrock Uncertainty” realization.

3.3.1 Set Up and Observation Data Set

In this realization, PEST was used to help determine how recharge and overburden hydraulic conductivity parameter values could be changed to match field conditions by increasing the hydraulic conductivity zone values representing the Salina Formation beneath the Region. This realization simulated an increased hydraulic connection between the deep overburden system and underlying bedrock, and allowed wells completed in deep overburden units to potentially source more water from the bedrock aquifers, rather than the overburden.

The set of observations outlined in Realization 2 (i.e. groundwater level elevations, groundwater level elevation differences in aquifers above and below aquitards, and baseflow estimates) were applied.

3.3.2 Set Up - Parameters

Parameters varied in this realization included hydraulic conductivity and groundwater recharge. The variability of groundwater recharge was the same as outlined in Realization 1.

3.3.2.1 Hydraulic Conductivity

As this realization was run in steady-state, more parameters could be adjusted in this scenario as compared to the number of parameters that were adjustable in Realization 1 (Transient Long-Term realization). Table 14 outlines the number of parameters that were allowed to vary in this realization.

Table 14: Adjustable Hydraulic Conductivity Parameters for Realization 3

Aquifer/ Aquitard	Number of Adjustable Parameters	Notes
ATB1	4	Initial hydraulic conductivity value coincide with base case calibrated model values
AFB1	67	Initial hydraulic conductivity value coincide with base case calibrated model values
ATB2	66	Initial hydraulic conductivity value coincide with base case calibrated model values
AFB2	133	Initial hydraulic conductivity value coincide with base case calibrated model values

Aquifer/ Aquitard	Number of Adjustable Parameters	Notes
ATB3	62	Initial hydraulic conductivity value coincide with base case calibrated model values
AFB3	28	Initial hydraulic conductivity value coincide with base case calibrated model values
ATC1, AFC1, ATC2	67	Initial hydraulic conductivity value coincide with base case calibrated model values
AFD1	80	Initial hydraulic conductivity value coincide with base case calibrated model values
ATE1	74	Initial hydraulic conductivity value coincide with base case calibrated model values
AFF1, ATG1	68	Initial hydraulic conductivity value coincide with base case calibrated model values
Shallow Bedrock	1	Initial hydraulic conductivity value of 5x10-5 m/s; shallow bedrock refers to top two bedrock layers (thickness of 5 m) and is conceptualized as being more fractured relative to deep bedrock.
Deep bedrock	1	Combined thickness of approximately 15 m; initial hydraulic conductivity value of 1x10-6 m/s.

3.3.3 Realization 3 – Quantitative Results

The simulation results were evaluated at the scale of the urban well field area as a whole, as well as at the well field scale. The results with respect to groundwater level elevations, groundwater level elevation differences across aquitards, and baseflow estimates are discussed in the following sections.

3.3.3.1 Steady-State Groundwater Level Elevations

Generally, the optimized model for this realization produced a good fit to the observation data, with a slight bias to under-predicting simulated groundwater level elevations relative to observed values (see scatter plot on Figure 35). The high, medium and medium-low quality groupings had mean absolute residuals of less than 3 m and the low quality grouping had absolute mean residuals of less than 4 m. The root mean squared residuals were between 2 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups in the regional model were within 2% to 5%, indicating a good match. As a guideline, a normalized root mean squared residual of less than 10% was considered acceptable. Table 15 presents a summary of the calibration statistics, grouped by observation quality, aggregated across the urban well field area.

Table 15: Urban Well Field Area Calibration Statistics for Realization 3 – Regional Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	104	-0.46	1.56	2.18	2.03
Medium	422	1.06	2.73	3.73	3.15
Medium-Low	127	-0.80	2.70	3.62	3.20
Low	703	0.19	3.86	5.50	5.00
All	1,356	0.32	3.22	4.65	3.54

Spatially, across the urban well field area, the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 36). Localized trends included groundwater level elevations that were simulated to be slightly over-predicted relative to observed elevations at the William Street, Pompeii/Forwell and Woolner well fields. As outlined in Table 16, the discrepancy at these well fields was minor. The poor fit to medium-quality data at the Strange Street and Greenbrook well fields was expected and is discussed in the following sections.

Table 16: Well Field Scale Calibration Statistics for Realization 3 – Regional Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Waterloo North	High	1	1.48	1.48	
Waterloo North	Medium	13	-0.64	1.24	1.69
Waterloo North	Medium-Low	1	2.03	2.03	
Waterloo North	Low	8	-1.74	2.57	3.19
Waterloo North	All	23	-0.81	1.75	2.33
William Street	High	3	-0.04	2.33	2.58
William Street	Medium	24	-2.36	2.74	3.11
William Street	Low	6	-2.90	2.90	4.04
William Street	All	33	-2.25	2.73	3.26
Erb Street	High	2	1.22	1.22	1.23
Erb Street	Medium	20	1.05	1.69	2.10
Erb Street	Medium-Low	6	0.95	1.27	1.50
Erb Street	Low	7	2.08	2.32	2.91
Erb Street	All	35	1.25	1.72	2.16
Strange Street	High	3	1.01	1.21	1.58
Strange Street	Medium	7	3.93	3.93	4.73
Strange Street	Medium-Low	13	-0.14	2.35	3.28
Strange Street	Low	16	-0.13	4.22	5.30
Strange Street	All	39	0.68	3.31	4.40
Greenbrook	High	6	0.07	1.11	1.37
Greenbrook	Medium	63	5.90	6.02	6.43
Greenbrook	Medium-Low	15	-0.49	2.17	3.33
Greenbrook	Low	9	-0.09	0.71	0.81
Greenbrook	All	93	3.91	4.57	5.47
Mannheim East	High	4	-0.58	0.63	0.86
Mannheim East	Medium	4	2.79	2.79	2.79
Mannheim East	Medium-Low	2	-2.17	4.10	4.64
Mannheim East	Low	8	1.97	4.14	5.83
Mannheim East	All	18	1.12	3.05	4.40
Mannheim Peaking	Medium	8	2.87	2.87	2.95
Mannheim Peaking	Medium-Low	1	2.76	2.76	
Mannheim Peaking	Low	6	9.05	9.05	15.88
Mannheim Peaking	All	15	5.33	5.33	10.29
Mannheim West	High	7	-0.76	0.80	1.10
Mannheim West	Medium	8	-0.34	1.21	1.40

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Mannheim West	Medium-Low	5	0.13	1.12	1.47
Mannheim West	Low	10	0.32	3.54	4.72
Mannheim West	All	30	-0.14	1.88	2.93
Parkway	High	5	-0.78	1.53	1.59
Parkway	Medium-Low	1	0.22	0.22	
Parkway	Low	4	2.36	2.36	2.89
Parkway	All	10	0.57	1.73	2.15
Strasburg	High	2	2.29	2.29	2.46
Strasburg	Medium	1	-1.50	1.50	
Strasburg	Medium-Low	7	-3.78	4.40	4.69
Strasburg	Low	1	-3.26	3.26	
Strasburg	All	11	-2.42	3.65	4.04
Lancaster	Medium	9	-2.12	3.36	3.99
Lancaster	Low	4	-3.78	3.78	4.35
Lancaster	All	13	-2.63	3.49	4.10
Pompeii / Forwell	High	8	-1.54	1.54	1.63
Pompeii / Forwell	Medium	6	-0.68	0.68	0.74
Pompeii / Forwell	Medium-Low	23	-3.51	3.51	4.07
Pompeii / Forwell	Low	21	-2.37	2.65	3.08
Pompeii / Forwell	All	58	-2.53	2.63	3.23
Woolner	High	1	-0.59	0.59	
Woolner	Medium	15	-0.90	0.99	1.18
Woolner	Medium-Low	9	-1.95	1.95	2.21
Woolner	Low	30	2.82	3.83	5.27
Woolner	All	55	0.96	2.69	4.04
Fountain Street	High	1	0.72	0.72	
Fountain Street	Medium	5	1.25	1.59	2.16
Fountain Street	Low	6	-2.49	3.39	3.51
Fountain Street	All	12	-0.67	2.42	2.85
Conestogo	High	2	-1.53	1.53	1.72
Conestogo	Medium	7	2.03	3.98	4.78
Conestogo	Low	13	-3.38	3.89	4.66
Conestogo	All	22	-1.49	3.70	4.51
New Dundee	High	2	-1.21	1.21	1.26
New Dundee	Medium	8	-0.17	1.77	2.14
New Dundee	Low	15	-0.36	2.73	3.08
New Dundee	All	25	-0.37	2.31	2.70
St. Agatha	High	3	-1.65	2.39	2.95
St. Agatha	Medium	3	-3.01	3.01	3.05
St. Agatha	Medium-Low	2	2.42	2.42	2.93
St. Agatha	Low	18	-0.36	2.65	5.38
St. Agatha	All	26	-0.60	2.64	4.77

At the well field scale the residuals indicated a good fit to the data. For the high- and medium-quality observations, most well fields typically had absolute mean residuals less than 3 m. The medium-low and low-quality observations, whose groundwater levels were collected when the pumping rates were not commensurate with 2003 rates, had greater variability of the absolute mean residuals, with values typically less than 4 m. Statistics for all well fields are reported in Table 16. At the urban well field area and well field scales, the fit to observed data was typically as good as, or better than, the base case model and maintained calibrated conditions.

3.3.3.2 Groundwater Level Elevation Differences Across Aquitards

Groundwater level elevations from multi-level observations had absolute mean residuals less than 3 m, indicating a very good fit to observed values, and an improved fit relative to the base case model. Simulated groundwater level elevation differences across aquitards for monitoring wells located close the municipal wells also showed a good fit to observed data. For the high and medium-quality observations, the mean absolute residuals were less than 3 m, which was slightly worse (0.5 m) than the base case model. For the medium-low and low-quality observations, the absolute mean residuals were just over 5 m, which was worse than the base case model by less than 1 m. Overall the fit was in good agreement with observed values and improved relative to the base case model.

3.3.3.3 Baseflow

The results showed a good fit to the estimated ranges in observed baseflow conditions (Table 17). The minimum estimates of baseflow at Airport and Freeport creeks were under-predicted in this realization, and the maximum estimate of baseflow was over-predicted at Hopewell Creek. The simulated conditions for all other stream reaches were within the estimated ranges. An improved fit (relative to the base case model and Realizations 1 and 2) was achieved at Schneider and Shoemaker creeks. This was attributed to the fact that under this realization, the production wells at the Greenbrook and Parkway well fields received an increased contribution of water from bedrock, rather than the urban surface water features. For all reaches, the results were as good as, or better than, the base case model, and maintained calibrated conditions.

Table 17: Simulated Baseflow for Realization 3 – Regional Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Alder Creek Headwaters	Spot measurement range	10	60	57
Alder Creek at Mannheim West	Spot measurement range	14	50	51
Alder Creek at New Dundee	90% exceedance and mean annual baseflow	10	100	17
Clair Creek at W10	90% exceedance and mean annual baseflow	10	90	33
Laurel/Beaver Headwaters	Spot measurement range and mean annual baseflow	30	160	101
Laurel Creek at William Street	90% exceedance	40	330	46
Waterloo North	90% exceedance and mean annual baseflow	30	240	51
Airport Creek	Spot measurement range	50	60	12
Hopewell Creek	Spot measurement range	92	163	291

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Idlewood Creek	Spot measurement range	10	20	-12
Freeport Creek	Spot measurement range	10	70	4
Schneider Creek	90% exceedance and mean annual baseflow	10	130	35
Shoemaker Creek	90% exceedance and mean annual baseflow	10	130	37
Strasburg Creek	Spot measurement range	70	80	72

3.3.4 Realization 3 – Qualitative Results (Estimated Parameters)

3.3.4.1 Recharge

The optimized recharge distribution showed an overall trend of increased recharge in the urban areas and decreased recharge in the rural, surrounding areas, relative to the base case model. The recharge rates increased the most in zones of low recharge where there was the greatest uncertainty. Over the Region's footprint, the average recharge rates for the base case model and the optimized model were 178 and 181 mm/year, respectively. The volume of water was consistent between the two models, but the spatial distribution differed. The greatest increase in recharge occurred between the Mannheim and Greenbrook well fields, and north of Waterloo North, William Street and Lancaster well fields. The greatest decreases in recharge occurred around the Pompeii/Forwell and Woolner well fields. For comparison, the spatial distributions of recharge for the base case model and optimized model are presented on Figure 37.

3.3.4.2 Hydraulic Conductivity

The optimized hydraulic conductivity zone values were consistent with the objective of this realization. The hydraulic conductivity values of the shallow and deep bedrock were increased, the hydraulic conductivity values for the shallow overburden units increased (i.e. AFB2 and overlying layers), and those of most of the deep overburden units decreased. The average adjustment to hydraulic conductivity values on a hydrogeologic unit basis is summarized in Table 18. The change in hydraulic conductivity zone values, relative to the values applied in the calibrated base case model, is discussed below.

Table 18: Optimized Hydraulic Conductivity Values Aggregated by Hydrogeologic Unit for Realization 3 – Regional Model

Hydrogeologic Unit	Number of Parameters	Average Hydraulic Conductivity		
		Base Case (m/s)	Optimized (m/s)	Multiplier
ATB1	4	3.50E-09	7.25E-09	2.07
AFB1	67	1.35E-05	1.61E-05	1.19
ATB2	66	2.27E-09	2.74E-09	1.21
AFB2	133	1.59E-04	1.71E-04	1.08
ATB3	62	4.68E-09	3.72E-09	0.79
AFB3	28	5.29E-05	5.02E-05	0.95
ATC1/AFC1/AFC2	67	4.16E-08	2.52E-08	0.61

Hydrogeologic Unit	Number of Parameters	Average Hydraulic Conductivity		
		Base Case (m/s)	Optimized (m/s)	Multiplier
AFD1	80	1.72E-04	1.46E-04	0.85
ATE1	74	1.81E-08	1.55E-08	0.86
AFF1/ATG1	68	3.72E-05	4.28E-05	1.15
Shallow Bedrock	1	5.00E-07	6.46E-05	129.20
Deep Bedrock	1	1.00E-08	6.76E-07	67.20

For aquitard ATB1, the values for the four adjustable hydraulic conductivity zones on average increased by a factor of 2.07. One hydraulic conductivity zone located west of the Erb Street Well Field increased by over one order of magnitude, and was interpreted to represent a mechanism to allow more recharge to reach the underlying aquifer (AFB1). The optimized values for the remaining zones were similar to the values applied in the base case model. For aquifer AFB1, hydraulic conductivity zone values on average increased by a factor of 1.19, with the majority being within half an order of magnitude of the base case model. Hydraulic conductivity values decreased the most (relative to the base case model) in the areas north of the Waterloo North and Erb Street well fields, as well as south of the Mannheim and Strasburg well fields. The greatest increases occurred at the Erb Street, William Street, New Dundee and Parkway well fields. The changes in hydraulic conductivity zone values relative to the base case model for ATB1 and AFB1 are summarized on Figure 38.

For aquitard ATB2, hydraulic conductivity zone values on average increased by a factor of 1.21, with the majority being within half an order of magnitude of base case model values. The greatest decreases occurred between the Strange Street and St. Agatha well fields and on the periphery of the Mannheim West Well Field, which was interpreted to represent a mechanism to provide water level support to the shallow groundwater flow system. The greatest increases occurred near the Greenbrook, Parkway and Strasburg well fields to allow greater localized leakage to the deep overburden system. For aquifer AFB2, hydraulic conductivity zone values on average increased by a factor of 1.08 with respect to the base case model. The majority of these hydraulic conductivity values were similar to the base case model values. The greatest decreases in hydraulic conductivity values (relative to the base case model) occurred at the Strange Street, Mannheim, Greenbrook, Parkway and Strasburg well fields, likely to provide support to groundwater level elevations in the shallow system and to allow greater discharge to surface water features such as Schneider and Shoemaker creeks. The greatest increases occurred between the Mannheim and Strange Street well fields, and the Mannheim and Strasburg well fields. The hydraulic conductivity values in these areas may have increased to allow greater leakage from surface to the deeper overburden system. The changes in hydraulic conductivity zone values relative to the base case model for ATB2 and AFB2 are summarized on Figure 39.

For aquitard ATB3, the optimized hydraulic conductivity zone values were on average 0.71 of the base case model values. The greatest decreases occurred north of the Erb Street Well Field, west of the Mannheim well fields as well as in the Greenbrook, Parkway and Strasburg well field areas. For aquifer

AFB3, the optimized hydraulic conductivity zone values were on average 0.95 of the base case model values and as such, were very similar to those applied in the base case model. The changes in hydraulic conductivity zone values relative to the base case model for ATB3 and AFB3 are summarized on Figure 40.

For aquitard ATC1/AFC1/ATC2, the optimized hydraulic conductivity zone values were on average 0.61 of the base case model values, with the majority being within half an order of magnitude of the base case model. The greatest differences to the hydraulic conductivity values for this unit occurred near the River Wells well fields along the Grand River. Zones west of the Grand River were reduced in hydraulic conductivity whereas those beneath the Grand River were increased. For aquifer AFD1, the optimized hydraulic conductivity zone values were on average 0.85 of the base case model values, with the majority being within half an order of magnitude of the base case values. At the Greenbrook Well Field, zones along the outer periphery decreased in hydraulic conductivity whereas those central to the well field typically increased. In this realization, the municipal production wells in the deep overburden aquifer system were able to receive an increased contribution of source water from bedrock relative to the base case model. As such, zones in the production aquifer did not need to be as transmissive as in the base case model, due to decreases in production volume sourced from lateral flow toward the well field. In a similar fashion, the hydraulic conductivity values of the production aquifers at Parkway and Strasburg well fields were also decreased relative to their base case model values. The changes in hydraulic conductivity zone values relative to the base case model are summarized on Figure 41.

For aquitard ATE1, the optimized hydraulic conductivity zone values were on average 0.86 of the base case model values. Spatially, the decrease in hydraulic conductivity values coincided with the zone representing the Salina Formation that was adjustable for this realization. The greatest decreases occurred in the zones surrounding the Greenbrook Well Field. Typically, parameter values increased in this unit west of the Lancaster, Parkway and Strasburg well fields. For aquifer AFF1/ATG1, hydraulic conductivity zone values increased on average by a factor of 1.15, with the majority being within half an order of magnitude of the base case model. The changes in hydraulic conductivity zone values relative to the base case model for ATE1 and AFF1/ATG1 are summarized on Figure 42.

3.3.5 Realization 3 - Overall Impression and Understanding

Overall, the optimized recharge and hydraulic conductivity parameter values were consistent with the conceptualization of Realization 3, which was to estimate how transmissive the Salina Formation could be while maintaining a fit to field observations. The hydraulic conductivity values of the overburden units were adjusted to compensate for the increases in transmissivity of the Salina Formation. With respect to the values applied in the base case model, the overall trend was toward increases in hydraulic conductivity values for the shallow overburden units and decreases for the deep overburden units. This realization showed a marked improvement of simulated baseflows at Shoemaker and Schneider creeks relative to the base case model, as well as Realizations 1 and 2. This was interpreted to be the result of the Greenbrook and Parkway well fields being able to draw a greater contribution of their source water from bedrock, as opposed to nearby surface water features. This allowed for local, shallow groundwater to discharge as baseflow to these surface water features.

This simulation result was a good match to the observation data and maintained calibrated conditions both globally and locally. Therefore, the simulation result was acceptable to be included as an uncertainty realization in the Risk Assessment Report.

3.4 Summary and Conclusions

The base case model was developed based on detailed characterization studies and an exhaustive calibration effort. The base case model parameters had a degree of uncertainty that originated from gaps in the conceptual understanding, and/or data gaps. Testing the impact of this parameter uncertainty, and the potential impact of this uncertainty on model predictions, was the aim of the uncertainty assessment and the development of the three alternative conceptual models. Within the context of each conceptual model, a numeric model was calibrated to field observations using the software program PEST, and the three alternative conceptual models were referred to as realizations.

Three realizations were defined. Realization 1 built on the conceptualization of the base case model and adjusted parameter values to better reflect the responses of the groundwater flow systems under typical, long-term operating conditions. This realization represented a fine-tuning of base case model parameter values, and generally resulted in increased contrasts of hydraulic conductivity values between aquifers and aquitards. Realization 2 estimated how leaky the regional aquitards that protect the underlying aquifers could be, and this realization resulted in reduced contrasts of hydraulic conductivity values between aquifers and aquitards, and markedly different parameterization of the numeric model. Realization 3 evaluated how overburden parameter values may differ if the Salina Formation was simulated with an increased transmissivity relative to the base case model, which assumed this unit had relatively low hydraulic conductivity values. Relative to the base case, this realization resulted in higher and lower hydraulic conductivity values in the shallow and deep overburden systems, respectively. This realization showed a marked improvement of simulated baseflow at Shoemaker and Schneider creeks relative to the base case model, as well as Realizations 1 and 2. This was interpreted to be the result of the Greenbrook and Parkway well fields being able to draw a greater contribution of their source water from bedrock, as opposed to nearby surface water features. This allowed for local, shallow groundwater to discharge as baseflow to these surface water features.

For each realization, the parameter values were consistent with the conceptualization and statistically, the individual realizations were able to maintain a level of calibration that was comparable to, or better than, the base case model. Given this, each realization was considered acceptable to be included as an uncertainty realization to evaluate the Risk Assessment scenarios.

4 CAMBRIDGE MODEL UNCERTAINTY REALIZATIONS

For the uncertainty assessment, three alternative conceptual models were developed for the Regional and Cambridge Models to explore uncertainty in the conceptualization presented in the Water Budget Report (Matrix and SSPA 2012). The three alternative realizations were created using an inverse modelling approach whereby parameter values were estimated with the aim of reducing the differences between simulated and observed values. Each alternative realization contained a different set of parameter values (i.e. hydraulic conductivity values) that together produced a model that was statistically as well calibrated (or better calibrated) to field observations than the base case model (see Matrix and SSPA 2012). The uncertainty analysis for the Cambridge Model focused on the urban area of Cambridge and the conceptual understanding of the bedrock groundwater flow systems (Figure 43).

4.1 Realization 1 - Optimization to Transient Observations

Realization 1 in the Cambridge Model was the same as Uncertainty Realization 1 in the Regional Model (Section 3.1). The realization was consistent with the conceptual model, maintained a good fit to the steady-state observation dataset and simulated time-varying trends in groundwater level elevations representative of typical operating conditions (aggregated to a bimonthly period) between 2003 and 2011. The water budget model described in the companion report (Matrix and SSPA 2012) was calibrated to individual short or long-term pumping or shut down tests at each well field. However, Realization 1 involved a calibration to the long-term, time-varying records of groundwater level elevations with greater spatial coverage, particularly in the areas between well fields. This alternative realization is referred to in this report as the "Optimization to Long-Term Transient Observations" realization.

Similar to the development of Realization 2 for the Regional Model, Realization 2 in the Cambridge Model was designed to examine the impacts of modifying the hydraulic conductivity values of the regional bedrock aquitard units to the upper range of our conceptual understanding. The hydraulic conductivity values of the bedrock aquitards were guided to their upper limits of their conceptual understanding within the PEST software program, while at the same time adjusting the hydraulic conductivity values of the other input parameters (i.e. the aquifers) to produce a model that was statistically calibrated to the steady-state groundwater level elevations in the model. This realization was completed to test the assumption the aquitard units, such as the Vinemount Member of the Eramosa Formation, have low hydraulic conductivity values that support the groundwater level elevations in the overlying aquifers, and act as confining units to the underlying aquifers. This realization aimed to examine the impact of the variability in the hydraulic conductivity values of the aquitard units, and this alternative realization is referred to in this document as the "Leaky Aquitards" realization.

Realization 3 simulated additional layers within the Guelph Formation to allow for vertical variability within the formation. The conceptual model presented in the Model Calibration and Water Budget Report (Matrix and SSPA 2012) simulated the Guelph Formation as one hydrogeologic unit; however, through the manual calibration it was concluded that additional vertical discretization may be desirable within the formation. This realization was completed to test the assumption that additional characterization within the Guelph Formation would aid the model calibration process within the Cambridge Well Field areas.

4.1.1 Setup and Observation Data Set

The modeller instructs PEST on which recharge and hydraulic conductivity values to adjust to best match two conditions: 1) observed (steady) groundwater level elevation and baseflow conditions under average annual 2003 production conditions; and 2) time-varying groundwater level elevations (averaged over two-month intervals) at long-term monitoring locations during the 2003 to 2011 timeframe. To accomplish this, the steady-state model under average 2003 municipal production conditions was evaluated using PEST, and then the simulated groundwater level elevation outputs from this model were then applied as the initial condition for a transient model which simulated representative municipal production conditions from 2003 to 2011. For the transient model, the production rates at municipal wells were averaged on a bi-monthly period. For both models, the values applied to the individual recharge zones were spatially variable and estimable parameters for PEST.

The observation data for this realization was setup in the same manner as Realization 1 for the Regional Model. The observations applied to evaluate this realization consisted of high and low quality steady groundwater level elevation targets, time-varying groundwater level elevation targets, and steady baseflow targets.

4.1.1.1 Steady-State Groundwater Level Elevations

The steady-state groundwater level elevation targets used were a subset of those described in the Water Budget and Model Calibration Report (Matrix and SSPA 2012). More rigorous checks on the low-quality observation data derived from MOE well records were conducted prior to the PEST analysis; the aim of this check was to remove observations that were inconsistent with the bulk of the observations in the immediate surroundings.

The weighting scheme applied, shown in Table 19, was reflective of quality as well as the number of observations within each quality group. It was desirable to have the highest quality observations contribute the most to the objective function, so that they had the greatest influence on estimating parameter values. The high- and low-quality observations contributed about 71% and 29% of the initial objective function for this observation group, respectively.

Table 19: Weighting Scheme for Observations of Steady Groundwater Level Elevation – Cambridge Model

Quality	Weight	Count	Phi Contribution	Rationale
High	1.0	205	71%	High quality water level measurement from the long-term municipal monitoring wells and the measurement during the IUS study

Quality	Weight	Count	Phi Contribution	Rationale
Low	0.2	1337	29%	'Static' groundwater level elevations (primarily MOE water well records). The data quality were mixed, and provided a broad spatial coverage across the area.

The spatial distribution of these observations is shown on Figure 43. The high-quality observations and long-term monitoring data were typically located near the municipal well fields, whereas low- quality observations were commonly associated with MOE water well records and tended to fill in the areas between well fields.

4.1.1.2 Time-Varying Trends in Groundwater Level Elevations

The inclusion of time-varying groundwater level elevations in the objective function ensured that this information influenced parameter values that were estimated by the optimization process. Long-term, time-varying groundwater level elevations captured the hydraulic responses of the aquifer system under typical operating conditions and should inform parameter values.

The time-varying groundwater level elevation data was sourced from the WRAS database. Only data within the urban well field area was included in the objective function. Quality checks were performed to identify data gaps and issues of data integrity. Attempts were made to retain as much data as possible by reconciling data integrity issues with available groundwater monitoring data (Burnside, 2011), well field characterization reports or water level data stored within WRAS+. Data with any errors that could not be resolved were removed from the objective function.

To be consistent with the simulated municipal pumping, the groundwater level elevations at individual wells between 2003 and 2011 were averaged at bi-monthly intervals, resulting in one observation (of groundwater level elevation) for every 2 month period. The time-varying elevation data were translated to trends of the variations in groundwater level elevations, to optimize parameter values and capture the responses of the system, while not compensating for an offset in groundwater level elevations caused by imperfect initial conditions.

Quality checks were performed to ensure the data were not skewed by transducer readings or inconsistent monitoring intervals, for example. Trends in groundwater level elevations were also compared to well field production rates to omit any suspicious data points. This process resulted in a total of 198 monitoring locations with 6,213 data points to use as observations in PEST. Each data point was assigned a default weight of 0.3 to balance the contribution of time-varying data to the objective function. Monitoring locations with a longer period of record had a proportionately larger weight than those with shorter records and were more informative for optimizing parameter values, which was consistent with the aim of this realization.

The locations of these time-varying data are shown on Figure 44. The size of dot indicates the relative weight. The larger dots have a large contribution to the objective function owing to the amount of data present in the processed hydrograph.

4.1.1.3 Baseflow

Baseflow targets for the stream assessment reaches were presented as an estimated range of values (see Matrix and SSPA, 2012 for details). These ranges were collapsed to single values for each stream reach for use in PEST because the PEST software program requires a single value, rather than a range of values, to calculate the objective function. The single target values for the stream reaches were chosen to be one-third of the range between the low and high estimated baseflow values, as it would be more conservative to calibrate the model to lower baseflow values. The minimum estimated, maximum estimated and target baseflows for each stream assessment reach are summarized in Table 20. The weight applied to baseflow targets ($3x10^{-3}$) accounts for the difference in units between groundwater level elevation and flow measurements, and on the whole, the baseflow values have a total weight of 7% of the initial objective function (with the remainder being attributed to the groundwater level elevations). Assessment reaches are shown on Figure 45.

Table 20: Assessment Reaches Included in Optimization– Cambridge Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Target
Aberfoyle	Spot measurement range	198	255	217
Cedar Creek Headwaters	90% exceedance and mean annual baseflow	5	14	8
Ellis Creek below Chilligo Creek	90% exceedance and mean annual baseflow	27	101	52
Irish Creek	Spot measurement range and mean annual baseflow	62	107	77
Mill Creek	90% exceedance	589	733	637

4.1.2 Set Up - Parameters

Several options were available to constrain how parameter values behaved during the optimization process. These included which parameters were allowed to be adjusted in PEST, what their bounding values were, and any prior knowledge (i.e. the parameter's preferred value). Parameters varied in this realization included the hydraulic conductivity and groundwater recharge values, as described in the following sections.

4.1.2.1 Recharge

The recharge distribution in the numeric model was derived from aggregating the GAWSER model estimated recharge to the finite element mesh. As a result, each element typically had a unique recharge value. Zones were created so recharge multipliers could be applied to all elements that fell within a given zone. This approach had the advantage of preserving the relative differences between adjacent elements, as opposed to assigning a single value for all elements within the zone.

The approach taken in the Regional Model (see Section 3.2.1.2) was also applied in the Cambridge Model. The broad areas of recharge adjustment are presented on Figure 46, which were subdivided based on the texture of surficial materials. Within the Cambridge Model, the number of recharge zones (parameters) that were adjustable, tied and fixed in the model were 20, 111 and 12, respectively.

4.1.2.2 Hydraulic Conductivity

The spatial extents and values of the hydraulic conductivity zones were a product of the characterization and calibration process. In this realization, the horizontal and vertical hydraulic conductivity values were adjustable in PEST for each adjustable zone. Table 21 outlines the number of parameters that were allowed to be varied by PEST in this realization.

Table 21: Adjustable Hydraulic Conductivity Parameters in Realization 1 – Cambridge Model

Unit	Hydraulic Conductivity Parameter	Number of Adjustable Parameters	Notes
Overburden	Horizontal	11	Initial hydraulic conductivity values reflect base case calibrated model.
Overburden	Vertical	11	Initial anisotropy ratio values reflect base case calibrated model.
Contact Zone	Horizontal	10	Initial hydraulic conductivity values reflect base case calibrated model.
Contact Zone	Vertical	10	Initial anisotropy ratio values reflect base case calibrated model.
Bedrock	Horizontal	77	Initial hydraulic conductivity values reflect base case calibrated model.
Bedrock	Vertical	77	Initial anisotropy ratio values reflect base case calibrated model.

In total, 22 parameters (11 hydraulic conductivity zones) in the overburden model layers were adjustable. They were chosen as the results of the PEST sensitivity analysis suggested that adjusting the value of these parameters impacted the model calibration or they corresponded to municipally significant (e.g., aquifer at Wells G7 and G8) or major overburden aquifers (i.e. Grand River Outwash, Pre-Catfish Creek Outwash, weathered bedrock and Upper Waterloo Moraine), or major overburden aquitards (i.e. Maryhill, Catfish Creek and Port Stanley Tills). The two hydraulic conductivity zones located along Mill Creek were also made adjustable to account for the importance of interactions between groundwater and surface water along this feature.

Twenty parameters (10 hydraulic conductivity zones) were adjustable in PEST for the layer that represented the hydrostratigraphic unit present at the interface between the overburden and bedrock unit, which includes coarse-grained sands and gravels, and the upper portion of fractured bedrock (i.e. Contact Zone Aquifer). This model layer represented the main water producing unit for several municipal production wells including wells G5 and P10.

Layers 9 through 14 sequentially represented the bedrock formations of the Cambridge area. In total, 154 parameters (77 hydraulic conductivity zones) were specified as adjustable parameters. The adjustable parameters varied on a layer by layer basis but were assigned as follows: 24 in the Guelph Formation, 34 in the Reformatory Quarry Member of Eramosa Formation, 24 in the Vinemount Member, 24 in the Goat Island Formation, and 26 in the Upper Gasport, 22 in the Middle Gasport Formation. For each layer the adjustable parameters covered the majority of the Cambridge Model area, as the majority of the municipal production wells in Cambridge are completed as open borehole wells that intersect three or more bedrock units. All parameters representing the Lower Gasport were fixed as there was no production simulated to be drawn from this unit.

4.1.2.3 Storage

In this realization the storage parameters were fixed. Storage parameters have increased importance when matching hydraulic responses to short-term changes in production, such as a pumping test. In this case, the long-term effects of continuous production over 8 years were simulated. As such, the effects of changes in storage were averaged over time. Assigning fixed storage parameters focussed the adjustments to those parameters that had a significant impact on the changing groundwater levels in the urban well field areas.

4.1.3 Realization 1 – Quantitative Results

The fit to observed data was assessed in the same manner as the base case model, so the results were comparable. The simulation results were evaluated at the scale of the urban well field area, and at the well field scale. The steady-state groundwater level elevations, time-varying trends in groundwater level elevations and baseflow estimates are discussed in the following sections.

4.1.3.1 Steady-State Groundwater Level Elevations

Generally, the model slightly over-predicted simulated groundwater level elevations, relative to observed values, as reflected in the mean residual statistics being less than zero. A scatter plot of simulated versus observed groundwater level elevations is presented on Figure 47, showing a very good fit. Nearly all of the high- and low-quality data were simulated within 5 m of the observed groundwater level elevations. All the data points are scattered around the line of perfect fit with no obvious bias. There was considerably more scatter for the low-quality targets, which was expected. The high and low-quality data had absolute mean residuals of 2.31 m and 4.33 m, respectively. The root mean squared residuals were between 3 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups were within 5% to 6%, indicating a good match. As a rule, a normalized root mean squared residual of less than 10% was considered acceptable. The low-quality group had the worst statistical fit, which was expected given their inherent increased variability in observed (static) groundwater levels and broader spatial coverage. A summary of the calibration statistics, grouped by observation quality and aggregated across the urban area of Cambridge, is presented in Table 22.

Table 22: Urban Area of Cambridge Scale Calibration Statistics for Realization 1– Cambridge Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	205	0.83	2.31	3.99	5.07
Low	1421	-0.24	4.33	5.86	5.86
All	1626	-0.10	4.07	5.58	5.58

Spatially, across the urban area of Cambridge the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 48). There were clusters that indicated localized trends. These included a tendency to under-predict observed groundwater level elevations, particularly at the Pinebush and Clemens Mill well fields. Observed groundwater level elevations tended to be slightly over-predicted toward the northeast, outside of the urban areas. The well field scale statistical fit (Table 23) indicated that while the observed groundwater level elevations were slightly under-predicted, the simulation results were a good fit. At the well field scale, the residuals indicated a good fit to the high quality data around the well fields, with nearly all having mean absolute residual less than 3 m.

Table 23: Well Field Scale Calibration Statistics for Realization 1 – Cambridge Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Hespeler	High	10	1.89	2.88	3.74
Pinebush	High	36	1.75	2.13	2.42
Clemens Mill	High	34	0.78	2.24	2.93
Shade's Mills	High	35	-0.27	1.86	2.60
Elgin Street	High	6	-0.41	1.28	2.12
Middleton Street and Willard	High	37	0.85	3.43	4.20
Blair Road	High	5	0.30	2.29	2.92
Dunbar Road	High	6	-0.04	1.63	1.78

At the Cambridge urban area and well field scales, the fit to observed data was typically as good as, or better than, the base case and maintained calibrated conditions.

4.1.3.2 Time-Varying Trends in Groundwater Level Elevations

In general, the transient model captured the general trends of groundwater level elevation fluctuations with time at most of the target locations. However, at some locations the model tended to underestimate the amplitude of the fluctuations. Sample hydrographs comparing observed and simulated groundwater level elevation trends are presented for each well field. For example, a hydrograph of simulated versus observed groundwater level elevations at the Hespeler Well Field (Well OW2-95A; Figure 49) shows the simulated results generally matched the trend in groundwater level elevation fluctuations, but under-predicted the drawdown during the first half of the simulation. The hydrostratigraphic model in this area was not well known, so some of the mismatch at the well field may be due to issues with the deeper overburden characterization in the Hespeler Well Field area.

Sample hydrographs of simulated versus observed groundwater level elevations are presented for observation wells CM-OW1A-92 and OW3-95D (Figures 50 and 51, respectively) for the Pinebush Well Field, and OW6-94C (Figure 52) for the Clemens Mill Well Field. The hydrograph for the Pinebush Well Field matched the broad trends in groundwater level elevation fluctuations but was unable to resolve the short-term changes to observed drawdown. The hydrograph for the Clemens Mill Well Field showed a good match for the first half of the simulation, but was unable to resolve the changes to drawdown for the second half of the simulation.

Sample hydrographs of simulated versus observed groundwater level elevations are presented for observation wells OW6ABCD-95 (Figure 53) and OW5B-95 (Figure 54) corresponding to the Dunbar Road and Blair Road well fields, respectively. The hydrographs for both well fields show that the transient model captured the average groundwater level elevation trends, but was unable to capture the observed short-term fluctuations. This suggested that hydraulic conductivity distributions and storage parameters at those wells may be more refined than the current model represents.

Sample hydrographs of simulated versus observed groundwater level elevations are presented for observation wells SM3-93 (Figure 55) and OW8C-95 (Figure 56) in the Shades Mill and Elgin Street well fields, respectively. The hydrographs for both well fields showed a good match to trends in groundwater level elevation fluctuations; however, the magnitude of responses was under-estimated.

Sample hydrographs of simulated versus observed groundwater level elevations are presented for observations wells MI-OW2A-92 (Figure 57) and OW1A-87 (Figure 58) in the Middleton and Willard well fields, respectively. The hydrographs for both showed a good match to trends in groundwater level elevation fluctuations. The hydrogeological conditions around the Middleton Street and Willard well fields are complex, and the continuous water level monitoring data in the area showed that groundwater level elevations over a large area responded almost immediately to municipal pumping, with a similar magnitude of water level changes. The available manual water level measurements were not frequent enough to capture the detailed water level fluctuations with changes in pumping. Depending on when the observations were taken during the day, and pumping fluctuations, groundwater level elevations could be significantly different.

4.1.3.3 Baseflow

The simulation result showed a good fit to the estimated ranges in observed baseflow conditions. These are summarized for the stream assessment reaches in the urban area of Cambridge in Table 24. Aberfoyle, Ellis Creek below Chilligo Creek and Mill Creek were all simulated within the respective estimated ranges. For the Cedar Creek Headwaters reach, this realization slightly over-predicted the maximum estimate of baseflow, whereas for Irish Creek, the model under-predicted the minimum estimate of baseflow by a factor of two. With the exception of Irish Creek, the simulated results were as good as, or better than, the base case model and maintained calibrated conditions.

Table 24: Simulated Baseflow for Realization 1– Cambridge Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Aberfoyle	Spot measurement range	198	255	222
Cedar Creek Headwaters	90% exceedance and mean annual baseflow	5	14	18
Ellis Creek below Chilligo Creek	90% exceedance and mean annual baseflow	27	101	66

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Irish Creek	Spot measurement range and mean annual baseflow	62	107	36
Mill Creek	90% exceedance	589	733	591

4.1.4 Qualitative Results (Estimated Parameters)

4.1.4.1 Recharge

The optimized recharge distribution showed an overall trend of decreased recharge in the urban areas of Cambridge and increased recharge in the surrounding areas, relative to the base case model. The recharge rate decreased on the high recharge areas west of the Blair Road and Middleton Street well fields. Over the Cambridge Model footprint, the average recharge rates for the base case model and this realization were 209 and 231 mm/year, respectively; an increase in recharge volume of approximately 10%. The spatial distributions of recharge for the base case and optimized models are presented on Figure 59.

4.1.4.2 Hydraulic Conductivity

Considering the urban well field areas of Cambridge as a whole, the optimized hydraulic conductivity zone values were slightly adjusted with respect to the base case modelled values. In the overburden, the average hydraulic conductivity values increased. In the bedrock, the hydraulic conductivity values of the low conductivity units increased, and for the high conductivity units decreased, relative to the base case model values. The calibrated base case model and optimized hydraulic conductivity values through the use of PEST were compared for overburden and bedrock units in Figures 60 and 61, respectively. The average adjustments made to the hydraulic conductivity values on a hydrogeologic unit basis are summarized in Table 25.

Table 25: Optimized Hydraulic Conductivity Values Aggregated by Hydrogeologic Unit for Realization 1 – Cambridge Model

Hydrogeologic Unit	Parameter	Number of Parameters	Average Hydraulic Conductivity		
			Base Case (m/s)	Optimized (m/s)	Multiplier
Conductance	Horizontal Hydraulic Conductivity	5	7.52E-06	1.29E-05	1.72
	Vertical Hydraulic Conductivity	5	7.52E-07	1.79E-06	2.38
Grand River Outwash and Port Stanley Till	Horizontal Hydraulic Conductivity	5	7.00E-05	5.30E-05	0.76
	Vertical Hydraulic Conductivity	5	7.00E-06	8.82E-06	1.26
Pre-Catfish Creek Outwash	Horizontal Hydraulic Conductivity	1	1.85E-04	3.72E-04	2.01
	Vertical Hydraulic Conductivity	1	1.85E-05	3.94E-05	2.13
Contact Zone	Horizontal Hydraulic Conductivity	10	2.57E-04	2.02E-04	0.79
	Vertical Hydraulic Conductivity	10	7.14E-06	7.45E-06	1.04
Guelph Formation	Horizontal Hydraulic Conductivity	12	9.73E-06	8.86E-06	0.91
	Vertical Hydraulic Conductivity	12	2.77E-07	1.77E-07	0.64
Reformatory Quarry	Horizontal Hydraulic Conductivity	17	7.21E-05	1.14E-04	1.58

Hydrogeologic Unit	Parameter	Number of Parameters	Average Hydraulic Conductivity		
			Base Case (m/s)	Optimized (m/s)	Multiplier
	Vertical Hydraulic Conductivity	17	6.86E-06	1.39E-05	2.02
Vinemount Member	Horizontal Hydraulic Conductivity	12	4.40E-06	4.74E-06	1.08
	Vertical Hydraulic Conductivity	12	1.45E-07	1.30E-07	0.89
Goat Island	Horizontal Hydraulic Conductivity	12	1.22E-05	1.27E-05	1.04
	Vertical Hydraulic Conductivity	12	9.13E-07	9.24E-07	1.01
Upper Gasport	Horizontal Hydraulic Conductivity	13	1.59E-05	1.14E-05	0.72
	Vertical Hydraulic Conductivity	13	2.70E-06	2.19E-06	0.81
Middle Gasport	Horizontal Hydraulic Conductivity	11	2.52E-05	2.41E-05	0.96
	Vertical Hydraulic Conductivity	11	3.02E-06	2.70E-06	0.89

Among the adjustable horizontal hydraulic conductivity zone values in the overburden model layers, the horizontal and vertical hydraulic conductivity values for zones located along the middle and lower reaches of Mill Creek were increased. This change was consistent with recent spot flow measurements from the GRCA, which suggested the middle reach of Mill Creek was losing water to the groundwater system and the lower reach of Mill Creek was gaining. This information was not available during the model calibration, so the calibrated base case model may underestimate the groundwater and surface water interaction along this portion of the reach. However, it is recommended that continuous flow measurements be collected to confirm the gaining/losing conditions along that portion of the creek.

The hydraulic conductivity zone values representing the Grand River Outwash, Pre-Catfish Creek Outwash and weathered bedrock were increased (relative to the base case model) to help sustain municipal pumping from wells that draw from the interface between the overburden and bedrock (i.e. Contact Zone Aquifer). The hydraulic conductivity of the small zone of Grand River Outwash at Wells G7 and G8, of the Shades Mill Well Field, was decreased to a value similar to the optimized hydraulic conductivity value of the rest of the Grand River Outwash material.

The horizontal and vertical hydraulic conductivity values for some small areas of Upper Waterloo Moraine sediments were reduced within the urban well field areas of Cambridge to help resolve large groundwater level elevation differences between overburden units. A large portion of the Upper Waterloo Moraine sediments in the southwestern area of the model domain was also increased slightly relative to the base case model.

Both horizontal and vertical hydraulic conductivity values of the Port Stanley Till were increased slightly during the optimization, and the horizontal hydraulic conductivity of the Maryhill Till was also increased, but the vertical hydraulic conductivity decreased slightly.

Changes to the hydraulic conductivity zone values of the Contact Zone Aquifer during the PEST optimization were generally small. Zones located in the Pinebush, Clemens Mill and Shades Mill (near Wells G7 and G8) areas were reduced by approximately half of the base case values.

Within the Guelph Formation, the value of the hydraulic conductivity zone that lies along the western portion of the model domain was increased by approximately 3.5 times relative to its base case value. The zone along the northern portion of the model domain immediately north of the Pinebush and Clemens Mill area decreased, and a similar decrease was observed south of the Clemens Mill area including the southern part of the central portion of the model domain. Hydraulic testing data were not available to constrain the hydraulic conductivity values of the Guelph Formation in these areas, so PEST adjusted the values to match the observed targets.

The hydraulic conductivity zone values of the zones surrounding Wells P6, G9 and G15 were increased during the optimization to sustain the municipal pumping and to maintain the groundwater level elevations in nearby monitoring wells. Vertical and hydraulic conductivity values for zones surrounding the municipal pumping wells at Blair Rd., Middleton Street and Clemens Mill were decreased in the optimization. In these well fields, the Guelph Formation is not the main water production unit, so decreases in vertical hydraulic conductivity values may have been required to match the vertical groundwater level elevation differences in these areas.

The changes in hydraulic conductivity zone values representing the Reformatory Quarry over most of the model domain were relatively small (i.e. less than 50% of the initial values). The largest change in the Reformatory Quarry Member was in the zone that covers the northeastern portion of the model domain, and in this area both the horizontal and vertical hydraulic conductivity values were increased by nearly two orders of magnitudes. Sparse hydraulic testing data and lack of high quality borehole data were available in this zone to constrain the unit thickness or hydraulic conductivity. In this area, the Reformatory Quarry is less than 10 m thick, and the overlying Guelph Formation is generally absent, so the unit lies in direct contact with the overburden. The sensitivity analysis suggested that baseflows in Mill Creek were sensitive to the hydraulic conductivity values applied in this zone. Additional adjustments were made around several of the municipal pumping wells to help sustain pumping and to achieve a calibrated fit at the high (and low) quality observation wells. The hydraulic conductivity of the small zone around Well P6 increased by a factor of 3, as the Reformatory Quarry is the main water producing unit at this well.

The changes in the Vinemount Member of the Eramosa Formation were generally small. The hydraulic conductivity of the zone that covers the northeastern portion of the model domain was increased by a factor of 3 relative to the initial base case model values. The Vinemount Member in this area ranges from 5 to 10 m in thickness, and little information was available to constrain the hydraulic conductivity values for this area. A narrow zone that connects the Middleton Street and Willard well fields was increased, and this is supported by available hydraulic testing and groundwater level elevation data that suggested there is a good connection between the two well fields. The hydraulic conductivity of a small zone near Well G9 was increased, suggesting the Vinemount Member may be eroded or more permeable at this location.

The horizontal hydraulic conductivity values of three zones in the Goat Island Formation were increased significantly during the optimization, whereas the remaining zones experienced little change. The three zones where the conductivity values were increased lie in the middle portion of the model domain outside of the Hespeler, Pinebush and Clemens Mill well fields. Hydraulic testing data was unavailable in these areas to constrain the hydraulic conductivity range for the Goat Island Formation.

In the western part of the model in the Upper Gasport Formation, the hydraulic conductivity of this zone was reduced by approximately one order of magnitude relative to the base case model value. Review of the specific capacity values derived from the MOE water well records suggested that the hydraulic conductivity of this zone is generally low. The hydraulic conductivity value of the zone surrounding Well G18 was also reduced by about one order of magnitude. Review of borehole test and inspection records showed that the vast majority of flow into the well enters the well approximately 75-80 m below the top of casing (Lotowater 2010) at a depth above the top of the Gasport Formation.

The hydraulic conductivity zone values for the Upper Gasport zones surrounding the Middleton Street Well Field increased by 50 to 100% relative to the base case model values. The higher hydraulic conductivity values were required to sustain the municipal pumping at the Middleton Street Well Field. A hydraulic conductivity zone (in the Upper Gasport), lying between the Middleton Street and Clemens Mill well fields, experienced a reduction in hydraulic conductivity of approximately 75% from the initial value, and this was interpreted to be an area of less permeable rock between the two well fields.

The hydraulic conductivity zone values of the Middle Gasport Formation were adjusted to a large degree in a few areas. The largest change occurred in a high permeable tongue-shaped zone that extends from the City of Guelph to the area north of Puslinch Lake. The hydraulic conductivity of this zone increased by about 260% from its base case model value, and the optimized value was consistent with the findings of the City of Guelph Tier Three Assessment study (AquaResource, 2010). The hydraulic conductivity of the zone that extends from the permeable tongue-shaped zone toward municipal Well G16 to the south, was increased by about 65% relative to its base case value.

The hydraulic conductivity of the large zone that covers the western part of the model domain was decreased by about 80% from its base case model value, a change that was similar to that in the same area in the Upper Gasport Formation. In the eastern part of the model domain, the hydraulic conductivity values were increased by about 130% from their initial values during the optimization. In this area, there was little information available to constrain the hydraulic conductivity values.

4.1.5 Realization 1 - Overall Impression and Understanding

Overall, the optimized recharge and hydraulic conductivity parameter values were consistent with the conceptual model of the base case model and yielded an improved fit to steady-state groundwater level elevation targets, baseflow estimates and time-varying trends in groundwater level elevations. This realization represented a fine-tuning of the base case model, whereby parameter values were adjusted to reflect long-term hydraulic responses of the groundwater flow systems under typical operating conditions at, and in between, well fields. The simulation results produced a good match to the observation data and maintained calibrated conditions both globally and locally. Therefore, the simulation result was considered acceptable for use as an uncertainty realization in the Risk Assessment Report.

4.2 Cambridge Model - Realization 2; Aquitard Leakage

4.2.1 Set Up and Observation Data Set

This section describes the setup of the optimization for Realization 2. For this realization, PEST was setup to determine how leaky the bedrock aquitards could be while still maintaining a fit to the observed data under average annual 2003 municipal pumping conditions. This realization primarily targeted the Vinemount Member, and other (weak) aquitard units, including portions of the Reformatory Quarry Member, and the Goat Island Formation. Increasing the hydraulic conductivity zone values of the aquitards meant the recharge rates and aquifer hydraulic conductivity zone values needed to be adjusted to maintain a fit between model-predicted and observed conditions. To ensure the conceptual behaviour of the aquitards was properly represented (i.e. provided an appropriate barrier to flow) the differences in groundwater level elevations across the various aquitards were introduced as calibration targets.

As was described for Realization 1 of the Regional Model, PEST was run in regularization mode to allow for the inclusion of prior knowledge, which provided additional constraints to inform the optimization process. In the context of this realization, the upper bound values were specified for bedrock aquitard hydraulic conductivity zones. For all other zones, the hydraulic conductivity values of the base case model were applied, as they included the knowledge put forth in the characterization (e.g., aquifer test values) as well as the insight gained during the calibration process.

The groundwater level elevation differences across the various aquitard units in the model were used as calibration targets, alongside the long-term groundwater level elevation data and baseflow discharge estimates in the same format as Realization 1 for the Regional Model.

4.2.1.1 Groundwater Level Elevation Differences Across Aquitards

To supplement the groundwater level elevations and baseflow estimates, groundwater level elevation differences (i.e. groundwater level elevations measured above and below aquitard units) were introduced as additional observations to help optimize the hydraulic conductivity zone values of the aquifers and aquitards using PEST. Measurements of groundwater level elevation differences were derived from multi-level monitoring wells and monitoring wells located near one another (i.e. <500 m), both of which were part of the calibration dataset applied in the base case model (see Appendix C of the Water Budget and Model Calibration Report, Matrix and SSPA 2012). This dataset, shown on Figure 62, consisted of groundwater level elevation differences across the Guelph Formation and the Vinemount Formation, with 24 and 26 pairs of observations used in the optimization, respectively. Variable weights were applied to the monitoring wells to account for the quality of the wells (and measurements) and to ensure clustered wells did not bias the overall objective function.

4.2.2 Set up - Parameters

In this realization, hydraulic conductivity zone values and groundwater recharge values were optimized by the model and treated in the same manner as Realization 1. The hydraulic conductivity zones that were allowed to be adjustable in PEST are discussed in the following section.

4.2.2.1 Hydraulic Conductivity

As this realization was run in steady-state, more parameters could be adjusted in PEST in this scenario, relative to those that were adjustable in Realization 1 (Transient Long-Term realization). Table 26 outlines the number of parameters that were adjustable in PEST for this realization.

Table 26: Adjustable Hydraulic Conductivity Parameters in Realization 2 – Cambridge Model

Unit	Hydraulic Conductivity Parameter	Number of Adjustable Parameters	Notes
Overburden	Horizontal	27	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Overburden	Vertical	3	Initial vertical anisotropy ratios and prior knowledge reflects base case calibrated model.
Contact Zone	Horizontal	10	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Contact Zone	Vertical	10	Initial vertical anisotropy ratios and prior knowledge reflects base case calibrated model.
Bedrock	Horizontal	94	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Bedrock	Vertical	76	Initial vertical anisotropy ratios and prior knowledge reflects base case calibrated model for aquifer units. Initial vertical anisotropy ratios and prior knowledge reflects upper bound parameter value for aquitard units.

The adjustable parameters for this realization were selected using the following rationale: First, if the results of the sensitivity analysis determined that a parameter was sensitive to the calibration, the parameters of the zones were allowed to be adjustable in PEST. If the parameters were insensitive, they were fixed. Second, all zones lying outside the urban area of Cambridge were fixed as those were less likely to impact the overall groundwater flow systems within the urban well field areas. Lastly, zones in the northeastern portion of the model area that overlapped with the Guelph Tier Three Assessment model had fixed parameter values to maintain consistency with the Guelph groundwater flow model. Prior knowledge was also applied in PEST to help guide the optimization. In this realization, as the impacts associated with higher hydraulic conductivity aquitards were being tested, the vertical hydraulic conductivity values of zones with base case values less than 5×10^{-8} m/s, representing the Reformatory Quarry Member, Vinemount Member, and Goat Island Formation, had preferred values for the vertical hydraulic conductivity (i.e. the prior knowledge) set to their upper bounds. Similarly, the preferred values (prior knowledge) for the aquifers (conductivity value greater than $1x10^{-5}$ m/s) in the urban areas were set to be equal to the base case values. As such, these aquitard and aquifer values will be maintained in PEST close to the values applied, to maintain calibrated conditions. The values could be adjusted, but penalties would be imposed on the objective function if the values deviated from the preferred values (i.e. the prior knowledge).

The base case model values for aquifer hydraulic conductivity were appropriate choices for defining the prior knowledge as they represented the knowledge put forth in the characterization (e.g., aquifer test values) as well as the insight gained during the calibration process. They also served to balance the prior knowledge applied to the defined potential aquitards. As the aquitards became increasingly leaky through the optimization process, the hydraulic conductivity zone values of the aquifers were decreased to provide the necessary water level support to match observed groundwater level elevations. A weight of 0.01 was specified for each article of information pertaining to a parameter representing an aquifer unit. The weight applied to the aquitards was twice that of the aquifers, to emphasize the conceptualization of this realization (i.e. making the bedrock aquitards as leaky as possible) and was also partially based on experience. In this way, the regularization objective function relating to till units was optimized by increasing the hydraulic conductivity zone values of the bedrock aquitards toward their upper bounds, and decreasing the hydraulic conductivity zone values of the aquifer units away from their preferred values (i.e. the calibrated base case values).

With regard to the parameters that were allowed to vary during the PEST simulations, the horizontal hydraulic conductivity and anisotropy ratio (defined as the ratio of the horizontal hydraulic conductivity over the vertical hydraulic conductivity) of aquitards located near municipal wells were adjustable. If the zones were not located near municipal wells, only the horizontal hydraulic conductivity was adjustable, and the anisotropy ratio was fixed. Both the horizontal hydraulic conductivity and anisotropy ratio were adjustable for aquifer zones located near municipal wells. If the zones were far from the municipal wells, only the anisotropy ratio was adjusted.

In total, 131 horizontal hydraulic conductivity zone values and 89 anisotropy ratios were selected to be adjustable for this realization. When the anisotropy ratio was fixed for a zone, the vertical and horizontal hydraulic conductivity of the zone were varied during optimization. The lower and upper bound values for hydraulic conductivity zone values were increased to approximately one order of magnitude from the values used for Realization 1; this was done to allow more freedom to find a set of optimal parameters using PEST that fit the conceptual understanding for this realization.

4.2.3 Realization 2 – Quantitative Results

As was done with Realization 1, the simulation results were evaluated at the urban well field scale, considering the urban area of Cambridge as a whole, and at the local, well field scale. The results with respect to groundwater level elevations, groundwater level elevation differences across aquitards and baseflow estimates are discussed in the following sections.

4.2.3.1 *Steady-State Groundwater Level Elevations*

Generally, the model fit slightly over-predicted simulated groundwater level elevations relative to observed values, as reflected in the mean residual statistics being less than zero. A scatter plot of simulated versus observed groundwater level elevations is presented on Figure 63, showing a good fit. All high- and low- quality groupings had absolute mean residuals of less than 2 m and 4 m, respectively. The root mean squared residuals were between 2 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups were within 4% to 6%, indicating a good match. As a guideline, a normalized root mean squared residual of less than 10% was considered acceptable. The low-quality group had the worst statistical fit, which was expected given their inherent increased variability in observed groundwater level elevations. A summary of the calibration statistics, grouped by observation quality, aggregated across the urban area of Cambridge, is presented in Table 27.

Table 27: Urban Area of Cambridge Calibration Statistics for Realization 2 – Cambridge Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	205	0.34	1.90	2.77	4.72
Low	1421	-0.78	3.94	5.48	5.48
All	1626	-0.64	3.69	5.22	5.22

Spatially, across the urban area of Cambridge, the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 64). There were clusters that indicated localized trends, such as at the Middleton Street and Elgin Street well fields, which showed a tendency of under-predicting the observed groundwater level elevations (positive residuals). At the well field scale, the residuals indicated a good fit to the data, with nearly all having absolute mean residuals less than 2 m. In summary, the optimization of Realization 2 produced an improved fit to the observations, at both the regional and local well field scales, compared to the base case model (see well field scale statistics of model fit in Table 28).

Table 28: Well Field Scale Calibration Statistics for Realization 2 – Cambridge Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Hespeler	High	10	0.82	2.58	3.26
Pinebush	High	36	0.66	1.47	1.84
Clemens Mill	High	34	0.07	1.08	1.48
Shades Mill	High	35	-0.55	1.43	2.21
Elgin Street	High	6	-0.20	0.28	0.42
Middleton Street and Willard	High	37	1.86	4.10	5.01
Blair Road	High	5	0.35	2.13	3.05
Dunbar Road	High	6	0.25	1.45	1.66

4.2.3.2 Groundwater Level Elevation Differences Across Aquitards

The simulation results indicated this realization represented groundwater level elevation differences across aquitards well. For both groups of groundwater level elevation difference targets, the mean absolute residuals for the differences across the Guelph Formation and the Vinemount Member were approximately 1.3 and 1.4 m, respectively. These results were better than the representation of differences in the base case model, where the absolute mean residuals for the differences across the Guelph Formation and the Vinemount Member were approximately 2.6 and 2.7 m, respectively. The statistical fit to groundwater level elevation differences across aquitards is summarized in Table 29.

Table 29: Simulated Groundwater Level Elevation Differences Across Aquitards for Realization 2 – Cambridge Model

Observation Type	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Across the Guelph Formation	High	24	0.33	1.31	1.98
Across the Vinemount Member	High	26	0.10	1.41	1.81

4.2.3.3 Baseflow

The simulation result showed a good fit to the estimated ranges in observed baseflow conditions. These are summarized for the stream assessment reaches in the urban area of Cambridge in Table 30. For the Cedar Creek Headwaters reach, this realization slightly over-predicted the maximum estimate of baseflow, whereas all other stream reaches were simulated to be within their estimated ranges. The simulated results for all reaches in this realization were as good as, or better than, the base case model and maintained calibrated conditions.

Table 30: Simulated Baseflow for Realization 2 – Cambridge Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Aberfoyle	Spot measurement range	198	255	207
Cedar Creek Headwaters	90% exceedance and mean annual baseflow	5	14	17
Ellis Creek below Chilligo Creek	90% exceedance and mean annual baseflow	27	101	63
Irish Creek	Spot measurement range and mean annual baseflow	62	107	65
Mill Creek	90% exceedance	589	733	607

4.2.4 Realization 2 - Qualitative Results (Estimated Parameters)

4.2.4.1 Recharge

The optimized recharge distribution showed a similar distribution to that of the base case model along the urban core of Cambridge. To the southwest (near the Blair and Middleton Street well fields) and toward the northeast, recharge rates were elevated relative to the base case model.

Over the footprint of the Cambridge Model, the average recharge rates for the base case model and this realization were 209 and 239 mm/year, respectively. This indicated that the volume of water entering the system via recharge increased by 13%. The volume of recharge in this optimization was consistent with the base case model, but the spatial distribution was different. For comparison, the spatial distributions of recharge for the base case model and optimized model are presented on Figure 65.

4.2.4.2 Hydraulic Conductivity

The calibrated and optimized values of hydraulic conductivity of the model are overburden (and contact zone) and bedrock parameters on Figures 66 and 67, respectively. The average adjustments to hydraulic conductivity on a hydrogeologic unit basis are summarized in Table 31. Detailed discussions about some of the more significant changes in the hydraulic conductivity in each hydrogeologic unit are presented below.

Table 31: Optimized Hydraulic Conductivity Values by Hydrogeologic Unit for Realization 2 – Cambridge Model

Hydrogeologic Unit	Parameter	Number of Parameters	Avg Hydraulic Conductivity (m/s)		
			Base Case	Optimized	Multiplier
Conductance	Horizontal Hydraulic Conductivity	10	2.33E-05	4.99E-05	2.14
	Vertical Hydraulic Conductivity	0			
Grand River Outwash and Port Stanley Till	Horizontal Hydraulic Conductivity	4	3.31E-05	4.12E-05	1.24
	Vertical Hydraulic Conductivity	0			
Weathered Bedrock	Horizontal Hydraulic Conductivity	2	3.04E-04	4.65E-04	1.53
	Vertical Hydraulic Conductivity	1	5.00E-05	7.18E-05	1.44
Upper Waterloo Moraine Sediments	Horizontal Hydraulic Conductivity	2	1.22E-04	3.24E-05	0.27
	Vertical Hydraulic Conductivity	1	3.00E-5	2.04E-6	0.07
Maryhill Till, Gravel, Silt	Horizontal Hydraulic Conductivity	1	5.00E-07	2.46E-07	1.63
	Vertical Hydraulic Conductivity	0			
Pre-Catfish Creek Outwash Weathered Bedrock, Gravel, Silt	Horizontal Hydraulic Conductivity	1	1.72E-04	2.20E-04	1.28
	Vertical Hydraulic Conductivity	0			
Contact Zone	Horizontal Hydraulic Conductivity	10	2.68E-04	1.75E-04	0.65
	Vertical Hydraulic Conductivity	10	8.07E-06	5.25E-06	0.65
Guelph Formation	Horizontal Hydraulic Conductivity	14	9.06E-06	5.29E-06	0.58
	Vertical Hydraulic Conductivity	10	2.10E-07	8.66E-08	0.41
Reformatory Quarry	Horizontal Hydraulic Conductivity	20	4.19E-05	5.27E-05	1.26
	Vertical Hydraulic Conductivity	16	1.03E-05	9.92E-06	0.96
Vinemount Member	Horizontal Hydraulic Conductivity	10	6.35E-05	9.97E-06	1.57
	Vertical Hydraulic Conductivity	9	4.77E-07	5.71E-07	1.28
Goat Island	Horizontal Hydraulic Conductivity	15	7.84E-06	1.50E-05	1.91
	Vertical Hydraulic Conductivity	14	5.11E-07	7.56E-07	1.48
Upper Gasport	Horizontal Hydraulic Conductivity	15	1.15E-05	1.21E-05	1.06
	Vertical Hydraulic Conductivity	12	3.15E-06	3.74E-06	1.19

Hydrogeologic Unit	Parameter	Number of Parameters	Avg Hydraulic Conductivity (m/s)		
			Base Case	Optimized	Multiplier
Middle Gasport	Horizontal Hydraulic Conductivity	14	4.05E-05	3.11E-05	0.77
	Vertical Hydraulic Conductivity	10	7.17E-06	5.82E-06	0.81
Lower Gasport	Horizontal Hydraulic Conductivity	6	2.00E-06	1.62E-06	0.81
	Vertical Hydraulic Conductivity	5	2.00E-08	2.22E-08	1.11

For the overburden material, similar changes in hydraulic conductivity were observed in some zones as were observed during the optimization of Realization 1. The zones along the middle and lower reaches of Mill Creek showed similar increases as were observed during the optimization of Realization 1, for the same reasons listed in Section 4.1.4.2. The hydraulic conductivity of a broad zone representing the Wentworth Till at ground surface, in the eastern portion of the model domain, was increased by about six times its base case value. Modelling conducted in the neighbouring Tier Three Assessment in the City of Guelph suggested the hydraulic conductivity zone values of the Wentworth Till typically ranged from $1x10^{-4}$ to $1x10^{-5}$ m/s (AquaResource, 2010). The increase in hydraulic conductivity for the Wentworth Till was still within this range. For the Port Stanley Till and Maryhill Till that cover much of the City of Cambridge, the hydraulic conductivity zone values increased in a similar manner as the optimization result for Realization 1; however, the resulting hydraulic conductivity zone values of the Maryhill Till were higher than that of Realization 1.

The hydraulic conductivity zone values of the weathered bedrock were increased by about five times its base case value. This increase was much larger than the optimization result of Realization 1, and it was not clear why the hydraulic conductivity of this zone was increased mathematically in PEST to this extent.

The hydraulic conductivity zone values of the Upper Waterloo Moraine sediments that cover much of the City of Cambridge were lowered similar to the optimization result of Realization 1. Other zones that had relatively significant changes to their hydraulic conductivity values included those representing the Waterloo Moraine sediments and equivalents (model layers 4-7), which are situated in the northeastern portion of the model domain, where detailed overburden hydrostratigraphic information was not available. These zones are near the urban edge of the City of Cambridge or far upgradient toward the northeast. It was inferred that these zones were relatively insensitive to groundwater level elevations at the urban well fields, which was why the optimization was able to make relatively large changes to their hydraulic conductivity values.

The changes to hydraulic conductivity zone values with respect to the base case model for the overburden are summarized on Figure 66. None of the hydraulic conductivity zone values in overburden materials reached their upper or lower bounds during the optimization.

For the Contact Aquifer, there were significant changes in hydraulic conductivity values for zones located at the Pinebush, Clemens Mill, and Shades Mill well fields. The hydraulic conductivity values of these zones were increased similar to the optimization result of Realization 1. The hydraulic conductivity value of a small zone surrounding municipal pumping Well P10 was decreased. Well P10 extracts water from the Contact Aquifer and the upper part of the Guelph Formation. It was found that the hydraulic conductivity of the corresponding zone for the same area in the Guelph Formation was reduced about half from its base case value. The increase in hydraulic conductivity in the Contact Aquifer might be necessary to sustain the pumping of Well P10. None of the hydraulic conductivity values in the Contact Aquifer reached their upper or lower bounds during the optimization. The changes to hydraulic conductivity zone values with respect to the base case model for the overburden are summarized on Figure 67.

For the Guelph Formation, two narrow zones with a north-south orientation on the western flank of the model had notable adjustments for this realization. The hydraulic conductivity of the zone on the western periphery of the model was updated similar to the optimization result of Realization 1. The second zone, which lies immediately west of the Hespeler, Blair Rd., Dunbar Rd., Middleton and Willard well fields was increased about one order of magnitude. During the conceptualization, this zone was defined as a low transmissivity zone based on the specific capacity data derived from MOE water well records. The change in hydraulic conductivity for this zone during the optimization in Realization 1 was relatively small. It was not clear why a relatively high hydraulic conductivity value resulted in this zone. The hydraulic conductivity values of other adjustable zones were generally reduced in response to increases in hydraulic conductivity values of the underlying aquitard (i.e. Reformatory Quarry Member).

For the Reformatory Quarry Member of the Eramosa Formation, five zones were defined as aquitards. These five zones occupy most of the model domain, except for small localized areas around the Pinebush, Hespeler, Clemens Mill, Dunbar Road, Blair Road, and Middleton Street well fields. In general, relatively high vertical hydraulic conductivity values were applied for aquitards in the Reformatory Quarry Member (about 10 times larger than the base case value), which was consistent with the setup of this realization. Two exceptions were zones located in the northwestern and southwestern portions of the model domain. The optimized vertical hydraulic conductivity value of the northwestern zone was $1.7x10^{-8}$ m/s, which was similar to the base case value of $1x10^{-8}$ m/s. The optimized vertical hydraulic conductivity of the southwestern zone was $9x10^{-9}$ m/s, which was about 2 times greater than the base case value of $5x10^{-9}$ m/s.

In response to changes in the vertical hydraulic conductivity for the defined aquitards, the hydraulic conductivity values of the relatively permeable zones either remained similar to the base case, or were reduced during the optimization. Changes in hydraulic conductivity values at those relatively permeable zones were very similar between Realizations 1 and 2.

The Vinemount Member of the Eramosa is the major regional aquitard for the Cambridge area. It separates the shallow and deep bedrock aquifers. For Realization 2, fives zones were defined as aquitards and occupy most of the model domain, expect in the west where the Vinemount Member was known to be absent. There were also some small zones around the Middleton and Elgin Street well fields that were found to be relatively permeable. For all five zones, a higher vertical hydraulic conductivity value was maintained (10 times higher than the base case value) in all zones except two. One zone occupied the southeastern portion of the model domain, where little information was available to characterize and constrain the hydraulic conductivity values, and the thickness of the Vinemount Member was also poorly defined. The second zone was located east of the Pinebush and Clemens Mill well fields. The hydraulic conductivity of this zone was well defined through a transient calibration to a 28-day pumping test in Cambridge East. A large vertical hydraulic gradient was observed in this area, and as such, a low vertical hydraulic conductivity value was applied to simulate the vertical groundwater level elevation difference. Changes in hydraulic conductivity values at other zones in the Vinemount Member were relatively small.

The hydrogeological understanding of the Goat Island Formation was limited. Its characterization was variable and in some areas the unit acts as an aquitard whereas in other areas it acts as a production aquifer. Four zones in the Goat Island Formation were defined as aquitards and these four zones occupy the majority of the model domain, except in the vicinity of the municipal well fields, where small zones of higher hydraulic conductivity values were delineated. During the optimization of Realization 2, a vertical hydraulic conductivity that was 2 to 10 times greater than the base case value was maintained. Changes to hydraulic conductivity values at other zones were relatively small, with the exception of a few zones at Wells G5, P9 and P15 (of the Pinebush Well Field), and the area around the Clemens Mill Well Field. The hydraulic conductivity values of these zones were reduced to improve the model calibration.

The Gasport Formation for Realization 2 was exclusively simulated as a regional groundwater aquifer. For most zones of the Upper Gasport Formation, changes in hydraulic conductivity zone values were generally small, and showed similar patterns to the adjustments made in Realization 1 (although the magnitude of the changes were different). The zone representing the middle portion of the tongue-shaped high hydraulic conductivity feature, which extends from Guelph to Cambridge, was increased nearly 2 orders of magnitude. This increase was in response to the decrease in hydraulic conductivity in the overlying zone in the Goat Island Formation. Changes in hydraulic conductivity values in the Middle Gasport Formation, during the optimization of Realization 2, were similar with those observed during Realization 1, with the exception of the tongue-shaped high hydraulic conductivity zone noted above. In Realization 1, the hydraulic conductivity was increased; whereas in Realization 2, the hydraulic conductivity of this zone was decreased. This decrease was in response to the large increase in hydraulic conductivity in the overlying zone in the Upper Gasport Formation.

Six zones from the lower Gasport Formation within the urban area of Cambridge were adjustable and similar changes were observed as in the Upper and Middle Gasport Formations.

4.2.5 Realization 2 - Overall Impression and Understanding

Overall, the optimized recharge and hydraulic conductivity parameter values were consistent with the conceptualization of Realization 2, which was to estimate how leaky the regional aquitards could be while maintaining a good fit to field observations. The hydraulic conductivity zone values for most of the bedrock "aquitard" units were increased with respect to the base case model, but remained within the range of values characteristic of their material composition. Correspondingly, the hydraulic conductivity values for the aquifers within the same model layer, or in the neighboring model layer, were decreased to maintain groundwater levels. This simulation result was a good match to the observation data and maintained calibrated conditions both globally and locally. Therefore, the simulation was considered to be acceptable to be included as an uncertainty realization in the Risk Assessment Report.

4.3 Cambridge Model - Realization 3; Aquitard Leakage

4.3.1 Set Up and Observation Data Set

The aim of this realization was to create an alternative numeric model that provided increased refinement for the vertical representation of the Guelph Formation. The model layer representing the Guelph Formation in the base case model was subdivided from one layer to three layers. An underlying assumption of the base case model was that the Guelph Formation could be represented using a single model layer. Detailed examination of borehole data and water level monitoring data suggested the Guelph Formation has intervening layers of lower hydraulic conductivity that cause vertical gradients across this unit, which had implications for the interaction between the bedrock and overburden groundwater flow systems. This was particularly true in the vicinity of Dunbar Road, Blair Road, and Middleton Street well fields. The transient groundwater level monitoring data from multi-level monitoring points within the Guelph Formation at the Middleton Street Well Field showed different trends within the Guelph Formation, suggesting a vertical stratification in this area. Given this condition, the feasibility of vertical stratification of the Guelph Formation and how other parameters should vary to maintain the match to all observations was assessed using PEST.

As was described for Realization 2 of the Regional Model, PEST was run in regularization mode to allow for the inclusion of prior knowledge, which provided additional constraints to inform the optimization process. In the context of this realization, the prior knowledge of hydraulic conductivity zone values within the stratification of the Guelph Formation, were assigned based on detailed review of borehole lithology records, as well as groundwater level measurements that indicated vertical gradients within the formation. The prior knowledge for all other parameters was informed by the base case, as it embodied the knowledge put forth in the characterization (e.g., aquifer test values) as well as the insight gained during the calibration process.

To evaluate this realization, the set of observations employed to evaluate Realization 2 were applied. This consisted of groundwater level elevations, groundwater level elevation differences across aquitards, and baseflow estimates. For the groundwater level elevation differences set of data, an additional grouping was added, to represent groundwater level elevation differences within the Guelph Formation for this realization.

Thirteen groundwater level elevation differences within the Guelph Formation data, sourced from multi-level monitoring wells in the Pinebush, Clemens Mill, Dunbar Road, and Middleton Street well fields, were added to the groundwater level elevation differences data for the optimization. A weight of 3.5 was applied to this group, which was greater than the weight of 2.0 applied to groundwater level elevation differences across the Guelph Formation and Vinemount Member. This was done to ensure the setup of the optimization was consistent with the aim of this realization. This information was used to determine how to apply vertical stratification of hydraulic conductivity zone values within the Guelph Formation to best fit observed conditions. The spatial locations of the groundwater level elevation differences within the Guelph Formation are presented on Figure 68.

4.3.2 Set Up - Parameters

Parameters varied in this realization included hydraulic conductivity and groundwater recharge. The variability of groundwater recharge was treated in the same manner as Realization 1.

4.3.2.1 Hydraulic Conductivity

As this realization was run in steady-state, more parameters were selected to be adjustable compared to those that were adjustable in Realization 1 (Transient Long-Term realization).. Additional parameters of horizontal and vertical hydraulic conductivity were applied to the refined representation of the Guelph Formation. Table 32 outlines the number of parameters that were adjustable in PEST in this realization.

Table 32: Adjustable Hydraulic Conductivity Parameters in Realization 3 – Cambridge Model

Unit	Hydraulic Conductivity Parameter	Number of Adjustable Parameters	Notes
Overburden	Horizontal	27	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Overburden	Vertical	3	Initial vertical anisotropy values and prior knowledge reflects base case calibrated model.
Contact Zone	Horizontal	10	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Contact Zone	Vertical	10	Initial vertical anisotropy values and prior knowledge reflects base case calibrated model.
Guelph Formation	Horizontal	41	Initial hydraulic conductivity values and prior knowledge reflects interpreted heterogeneity based on lithology records.
Guelph Formation	Vertical	40	Initial vertical anisotropy values and prior knowledge reflects interpreted heterogeneity based on lithology records.
Other Bedrock	Horizontal	60	Initial hydraulic conductivity values and prior knowledge reflects base case calibrated model.
Other Bedrock	Vertical	52	Initial vertical anisotropy values and prior knowledge reflects base case calibrated model.

When selecting adjustable parameters for this realization, the same parameter zones were used for all three model layers representing the Guelph Formation. However, different parameter numbers were assigned for each zone to allow maximum flexibility in PEST. The following rules were also applied to select the zones that were adjustable in PEST. First, if the results of the sensitivity analysis identified that the parameters of the zone were sensitive, the parameters of the zones were allowed to be adjustable, but if not, they were fixed. If the zones were outside of the urban area of Cambridge and near the model boundary, the parameters of the zones were fixed. Second, zones located near the northeastern portion of the model area near Guelph were fixed to maintain consistency with the Guelph Tier Three Assessment model. Lastly, zones that contained at least one groundwater level elevation difference within the Guelph Formation had parameter values that were variable.

With respect to the starting parameter values, the calibrated hydraulic conductivity values of zones in all model layers were assigned their base case model values, including the Guelph Formation zones. When deciding how the horizontal and vertical hydraulic conductivity for a particular zone should be varied, zones defined as aquitards, that are located near municipal wells, had both the horizontal hydraulic conductivity and anisotropy ratio adjustable. Otherwise, only the horizontal hydraulic conductivity was adjusted, and the anisotropy ratio was fixed. Both horizontal hydraulic conductivity and anisotropy ratio were adjustable for aquifer zones located near municipal wells. Zones located further from the municipal wells had only the anisotropy ratio as the adjustable parameter.

Zones with at least one groundwater level elevation difference within the Guelph Formation had both the horizontal hydraulic conductivity and anisotropy ratios set as adjustable within PEST to allow maximum flexibility.

In total, 138 horizontal hydraulic conductivity zone values, and 105 anisotropy ratio parameters were adjustable in this realization. Although the anisotropy ratio was fixed for a particular zone, its vertical hydraulic conductivity was varied during optimization if the horizontal hydraulic conductivity of the zone was varied.

The calibrated hydraulic conductivity zone values in the base case Cambridge Model were used to define the prior knowledge of the parameters, as they represented the knowledge put forth in the characterization (e.g., aquifer test values) as well as the insight gained during the calibration process.

PEST was used to minimize the regularization objective function by applying stratification within the Guelph Formation. However, it could only honour the prior knowledge to the degree that the flow solution was consistent with the observation data (i.e. reduction to the measurement objective function). Consequently, the fit to observation data could be degraded at the expense of increasing the heterogeneity within the Guelph Formation.

4.3.3 Realization 3 - Qualitative Results (Estimated Parameters)

The simulation results were evaluated at the regional scale, considering the urban area of Cambridge as a whole, and at the local, well field scale. The results with respect to groundwater level elevations, groundwater level elevation differences across aquitards and baseflow estimates, are discussed in the following sections.

4.3.3.1 Steady-State Groundwater Level Elevations

Generally, the simulated groundwater level elevations were slightly under-predicted relative to observed values, as the mean residual statistics were greater than zero. A scatter plot of simulated versus observed groundwater level elevations is presented on Figure 69. All high- and low-quality groupings had absolute mean residuals of less than 2 m and 5 m, respectively. The root mean squared residuals were between 2 and 6 m for all quality groupings. The normalized root mean squared residuals for all quality groups were within 4% to 6%, indicating a good match. As a guideline, a normalized root mean squared residual of less than 10% was considered acceptable. The low-quality group had the worst statistical fit, which was expected given their inherent increased variability in observed groundwater level elevations. A summary of the calibration statistics, grouped by observation quality, aggregated across the urban area of Cambridge, is presented in Table 33.

Table 33: Urban Area of Cambridge Calibration Statistics for Realization 3 – Cambridge Model

Observation Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)	Normalized Root Mean Squared (%)
High	205	0.36	1.89	2.61	4.43
Low	1421	0.60	4.20	5.80	5.80
All	1626	0.47	3.91	5.50	5.50

Spatially, across the urban area of Cambridge the residuals showed a good balance of under- and over-predicting observed groundwater level elevations (Figure 70). Clusters in the data highlight localized trends such as at the eastern perimeter of the Pinebush and Clemens Mill well fields, as well as at the Branchton Meadows Well Field. At the well field scale, the residuals indicated a good fit to the data, with nearly all having absolute mean residuals less than 2 m. In summary, the optimization of Realization 3 showed an improved fit to the observations, in both regional and local well field scales, relative to the base case model. Well field scale statistics are presented in Table 34.

Table 34: Well Field Scale Calibration Statistics for Realization 3 – Cambridge Model

Well Field	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Hespeler	High	10	0.85	2.46	3.16
Pinebush	High	36	0.95	1.39	1.70
Clemens Mill	High	34	0.36	1.47	2.00
Shade’s Mills	High	35	-0.49	1.70	2.59
Elgin Street	High	6	-0.94	0.96	1.12
Middleton Street and Willard	High	37	1.06	3.34	4.15
Blair Road	High	5	0.12	2.11	2.81
Dunbar Road	High	6	0.76	1.55	1.77

4.3.3.2 Groundwater Level Elevation Differences Across Aquitards

The results indicated that the set of parameters produced in this realization were a marked improvement in simulating groundwater level elevation differences within the Guelph Formation, as well as across aquitards (Figure 71). The mean absolute residual for groundwater level elevation differences within the Guelph Formation was 0.92 m, whereas groundwater level elevation differences across the Guelph Formation and Vinemount Member were 1.56 m and 1.35 m, respectively. The statistical fit to groundwater level elevation differences are summarized in Table 35.

Table 35: Simulated Groundwater Level Elevation Differences Across Aquitards for Realization 3 – Cambridge Model

Observation Type	Quality	Count	Mean Residual (m)	Mean Absolute Residual (m)	Root Mean Squared Residual (m)
Within the Guelph Formation	High	13	0.01	0.92	1.14
Across the Guelph Formation	High	24	-0.02	1.56	2.24
Across the Vinemount Member	High	26	-0.29	1.35	1.81

4.3.3.3 Baseflow

The simulated and observed range in baseflow values for the stream assessment reaches in the urban area of Cambridge are summarized in Table 36. The simulated results for all stream reaches in this realization were within the estimated ranges and were as good as, or better than, the base case model and maintained calibrated conditions.

Table 36: Simulated Baseflow for Realization 2 – Cambridge Model

Assessment Reach	Type of Measurement	Baseflow (L/s)		
		Min	Max	Simulated
Aberfoyle	Spot measurement range	198	255	233
Cedar Creek Headwaters	90% exceedance and mean annual baseflow	5	14	12
Ellis Creek below Chilligo Creek	90% exceedance and mean annual baseflow	27	101	66
Irish Creek	Spot measurement range and mean annual baseflow	62	107	89
Mill Creek	90% exceedance	589	733	627

4.3.4 Realization 3 – Qualitative Results (Estimated Parameters)

4.3.4.1 Recharge

The optimized recharge distribution showed a similar distribution to that of the base case model along the urban core of Cambridge. To the southwest (near the Blair and Middleton Street well fields) and toward the northeast, recharge rates were elevated relative to the base case model.

Over the footprint of the Cambridge Model, the average recharge rates for the base case model and this realization were 209 and 241 mm/year, respectively. This indicated that the volume of water entering the system via recharge increased by 15%. The volume of recharge was considered to be consistent between this optimization and the base case model but its spatial distribution was different. Increased recharge was simulated west of the Grand River, at the Hespeler Well Field, as well as east of the Shades Mill, Clemens Mill, and Pinebush well fields. For comparison, the spatial distributions of recharge for the base case model and optimized model are presented on Figure 72.

4.3.4.2 Hydraulic Conductivity

The calibrated and optimized values of hydraulic conductivity zones of the model for overburden (and contact zone), Guelph Formation and other bedrock parameters are presented on Figures 73, 74 and 75, respectively. The average adjustments to hydraulic conductivity zone values on a hydrogeologic unit basis are summarized in Table 31. Detailed discussions about some of the more significant changes in hydraulic conductivity values in each hydrogeologic unit are presented below.

Table 37: Optimized Hydraulic Conductivity Values Aggregated by Hydrogeologic Unit for Realization 3 – Cambridge Model

Hydrogeologic Unit	Parameter	Number of Parameters	Avg Hydraulic Conductivity (m/s)		
			Base Case	Optimized	Multiplier
Conductance	Horizontal Hydraulic Conductivity	10	2.33E-5	4.75E-5	2.04
	Vertical Hydraulic Conductivity	0			
Grand River Outwash; Port Stanley Till	Horizontal Hydraulic Conductivity	4	3.31E-5	5.09E-5	1.53
	Vertical Hydraulic Conductivity	0			
Weathered Bedrock	Horizontal Hydraulic Conductivity	2	2.71E-4	5.64E-4	2.01
	Vertical Hydraulic Conductivity	1	5.00E-5	5.47E-5	1.09
Upper Waterloo Moraine Sediments	Horizontal Hydraulic Conductivity	2	1.22E-4	6.90E-5	0.56
	Vertical Hydraulic Conductivity	1	3.05E-5	3.44E-6	0.12
Maryhill Till	Horizontal Hydraulic Conductivity	1	5.00E-7	8.17E-7	1.63
	Vertical Hydraulic Conductivity	1	5.00E-8	8.18E-8	1.64
Pre-Catfish Creek Outwash; Weathered Rock	Horizontal Hydraulic Conductivity	1	1.72E-4	4.74E-4	2.75
	Vertical Hydraulic Conductivity	0			
Contact Zone	Horizontal Hydraulic Conductivity	10	2.68E-4	1.96E-4	0.73
	Vertical Hydraulic Conductivity	10	8.07E-6	5.89E-6	0.73
Guelph Formation	Horizontal Hydraulic Conductivity	41	7.65E-6	4.6E-6	0.60
	Vertical Hydraulic Conductivity	40	2.43E-7	1.38E-7	0.57
Reformatory Quarry	Horizontal Hydraulic Conductivity	14	1.69E-4	1.70E-4	1.00
	Vertical Hydraulic Conductivity	14	3.89E-5	3.46E-5	0.89
Vinemount Member	Horizontal Hydraulic Conductivity	5	1.48E-5	9.09E-5	0.61
	Vertical Hydraulic Conductivity	5	1.48E-5	9.08E-6	0.61
Goat Island	Horizontal Hydraulic Conductivity	11	1.07E-5	1.44E-5	1.34
	Vertical Hydraulic Conductivity	11	9.51E-7	1.08E-6	1.13
Upper Gasport	Horizontal Hydraulic Conductivity	14	1.15E-5	8.68E-6	0.76
	Vertical Hydraulic Conductivity	12	3.15E-6	2.57E-6	0.83
Middle Gasport	Horizontal Hydraulic Conductivity	14	4.05E-5	3.24E-5	0.80

Hydrogeologic Unit	Parameter	Number of Parameters	Avg Hydraulic Conductivity (m/s)		
			Base Case	Optimized	Multiplier
	Vertical Hydraulic Conductivity	10	7.17E-6	6.22E-6	0.73

In total, 27 horizontal hydraulic conductivity zone values and 3 anisotropy ratios were adjustable for the overburden materials. The changes in hydraulic conductivity values from the base case model were relatively small for most zones, and were in a similar pattern with the changes in Realizations 1 and 2.

The horizontal and vertical hydraulic conductivity zone values along the middle portion of Mill Creek increased by approximately one order of magnitude. This was consistent with the conceptual understanding of this portion of the creek.

The hydraulic conductivity zone value of the Wentworth Till at ground surface, in the eastern portion of the model domain, was increased to its upper bound value. Similar increases also occurred in Realizations 1 and 2. The higher hydraulic conductivity value was within the expected range of values in the Cambridge East area. The increase was inferred to allow increased recharge to reach the underlying groundwater flow system.

The hydraulic conductivity zone values of the Grand River Outwash and Pre-Catfish Creek Outwash sediments were increased. The magnitudes of the increases in hydraulic conductivity values were larger in this Realization than in Realization 2. The hydraulic conductivity of the weathered bedrock was increased to a similar degree as in Realization 2.

The hydraulic conductivity zone value of the Upper Waterloo Moraine material occupying portions of the Cambridge East area, decreased to near its lower bound. The magnitude of the decrease was larger than the decrease in Realization 2. The hydraulic conductivity value of the Upper Waterloo Moraine material occupying the southwestern portion of the model domain increased, and this may correspond to the increase in recharge in the area.

Other zones that had relatively significant changes to their hydraulic conductivity zone values included those representing the Maryhill Till and the Waterloo Moraine Sediments and equivalents (model layers 4, 5, and 6). These units are situated in the northeastern portion of the model domain where detailed overburden hydrostratigraphic information was not available. This area is upgradient of the City of Cambridge. It was inferred that these zones were relatively insensitive to groundwater level elevations changes at the urban well fields, which was why the optimization was able to make relatively significant changes to their hydraulic conductivity values without impacting the model calibration.

Both the horizontal hydraulic conductivity values and anisotropy ratios of 10 zones in the Contact Aquifer were adjustable in Realization 3 and the changes in the values of most parameters were relatively small. The exception was a zone within the Pinebush Well Field. The increased hydraulic conductivity helped sustain the pumping at Well G5, which primarily extracts water from the Contact Aquifer.

In total, 41 horizontal hydraulic conductivity zone values and 40 anisotropy ratio parameters were adjustable for the Guelph Formation. The parameter values for the refined representation of the Guelph Formation were adjusted to improve the simulated fit to vertical groundwater level elevation differences within the formation. A large (approximately 10 m) vertical groundwater level elevation difference was observed in the Guelph Formation in the Dunbar Road Well Field area. The hydraulic conductivity values of the three layers representing the Guelph Formation, were increased by about half an order of magnitude in the top layer, remained consistent with the base case value in the middle layer, and decreased by about a quarter an order of magnitude in the lower layer. The net effect of the these changes improved the simulated fit to the vertical groundwater level elevation differences within the Guelph Formation local to the Dunbar Road Well Field.

At the Blair Road Well Field in the base case model, there was no simulated vertical groundwater level elevation difference within, or across, the Guelph Formation. However, large groundwater level elevation differences were observed in field data across the Guelph Formation, suggesting the Guelph Formation (in this area) acts as a vertical barrier to flow. In this Realization, the optimization decreased the hydraulic conductivity values relative to the base case model. The upper and middle Guelph Formation layers decreased by approximately 50% while the lowermost layer decreased by approximately one order of magnitude relative to the base case.

At the Middleton Street Well Field, the values for most hydraulic conductivity zones representing the refined structure of the Guelph Formation were adjusted to improve the simulated fit to vertical groundwater level elevation differences within this formation. Northwest of the Middleton Street Well Field, the hydraulic conductivity of the upper Guelph Formation layer was decreased by more than an order of magnitude, whereas the middle and bottom Guelph Formation layers remained consistent with the base case model. In the western area of the Middleton Street Well Field, the hydraulic conductivity values for all layers increased, with a greater increase occurring in the top and middle layers. At the centre of the well field, the hydraulic conductivity of the top layer increased by approximately one order of magnitude, whereas the middle and bottom layers decreased by approximately half an order of magnitude. Toward the east of the well field, the hydraulic conductivity values for all three model layers were decreased.

For the Cambridge East area, at the Pinebush and Clemens Mill well fields, the hydraulic conductivity zone values of the top and middle layers were consistent with the base case model, whereas the bottom layer was reduced to approximately 60% of its base case value.

In total, 15 horizontal hydraulic conductivity zone values and 15 anisotropy ratio parameters for the Reformatory Quarry Member were adjustable. The spatial locations of the 15 hydraulic conductivity zones were around the Middleton Street, Dunbar Rd., Blair Rd., and Elgin Street well fields, as well as the

Cambridge East area. Similar change patterns as Realization 2 were observed for most of the hydraulic conductivity zones, with some exceptions that were likely due to differences in conceptual design for this realization.

The hydraulic conductivity zone values of 8 zones in close proximity to the Middleton Street Well Field were varied. The changes in hydraulic conductivity zone values at the 8 zones were similar to the changes made in Realization 2, although the magnitudes of the changes differed slightly. One small zone located north of the Middleton Street Well Field reached its upper bound, whereas another zone that surrounds the immediate vicinity of the Middleton Street Well Field reached its lower bound. This was due to the tight parameter ranges applied to the setup of this realization to ensure consistency with its design. Two zones occupying the area between the Middleton Street and Willard well fields, and in the immediate vicinity of Wells G2 and G3, were increased for this realization, but decreased in Realization 2. The increase in hydraulic conductivity values for these two zones was likely a result of the decrease in hydraulic conductivity applied to the overlying Guelph Formation.

Five hydraulic conductivity zones were adjustable for the Vinemount Member in Realization 3. They were located in the vicinity of the Middleton Street and Elgin Street well fields. The optimized hydraulic conductivity values were similar to those of Realization 2.

The adjustable hydraulic conductivity zone values for the Goat Island Formation were located in the vicinity of the Cambridge East and Middleton Street well fields. In total, 11 hydraulic conductivity zones were adjustable. The changes in hydraulic conductivity zone values for all 11 zones were similar to those observed in Realization 2. The final hydraulic conductivity values for five zones in the Goat Island Formation, near the Middleton Street Well Field, were similar to the values obtained in Realization 2.

The change patterns in the adjustable zones in the Cambridge East Well Field were similar with those of Realization 2. As the vertical and horizontal hydraulic conductivity values were changed independently in this realization, this section outlines the changes made to the horizontal conductivity values and the vertical anisotropy values. The optimized horizontal hydraulic conductivity values of the zone around the Hespeler Well Field, and of the zone east and southeast of the Pinebush Well Field, remained similar to that of the base case model, but their vertical anisotropy ratios had relatively larger changes. The horizontal hydraulic conductivity of the small zone around Wells G5, P9 and P15, increased about one order of magnitude. The horizontal hydraulic conductivity values of the zones around the Clemens Mill and Shades Mill well fields were doubled. The hydraulic conductivity of the zone in the Clyde Park area was reduced by about 30%, relative to the base case model.

In total, 15 zones were allowed to be adjustable for both horizontal hydraulic conductivity and anisotropy ratio parameters in the Upper Gasport Formation. These zones were broadly defined and occupied most of the model domain. The changes in hydraulic conductivity were generally small, and showed similar patterns to the results of Realization 2, although the magnitudes of their changes were slightly different. The exception was in the vicinity of the Middleton Street Well Field; in Realization 2, the hydraulic conductivity of this zone was increased nearly three times the base case value and in Realization 3, the hydraulic conductivity value was reduced.

The horizontal hydraulic conductivity values of two Upper Gasport Formation zones reached their upper bounds. One zone represented a transition area to a tongue-shaped, high hydraulic conductivity feature between Guelph and Cambridge, whereas the other represented a narrow west-east zone south of Well G16 and the Clyde Park area.

The horizontal hydraulic conductivity values of two zones in the Gasport Formation reached their lower bounds. One zone represented a feature of low permeability between the Shades Mill and Middleton Street well fields, whereas the other was a small zone located in the immediate vicinity of Well G18 (Pinebush Well Field). These parameters reached their lower bounds in part due to the narrower range of parameter values applied to the setup of this realization.

A narrower range of parameter bound values were applied to the setup of this realization, to prevent PEST from applying unreasonable values to parameters for zones that may be insensitive. During the optimization of Realization 2, the horizontal hydraulic conductivity of the tongue-shaped high permeability zone in the Gasport Formation, that extends from Guelph to Cambridge, was increased nearly 2 orders of magnitude to $4x10^{-3}$ m/s. Wide bounds were applied for parameters to provide the flexibility needed to search for an optimum solution; in this case the optimized parameter value was greater than the conceptualized upper bound for this (bedrock aquifer) parameter. As a result, a narrower bound was applied to Realization 3, which forced PEST to find an alternative set of parameter values to match the observations.

In total, 14 parameters zones were allowed to be adjustable for both horizontal hydraulic conductivity and anisotropy ratio in the Middle Gasport Formation. These zones were broadly defined and occupied most of the model domain. For most of these parameters, the optimized values showed a similar pattern as the result of Realization 2, even though the magnitudes of the parameter value changes were slightly different. The exceptions were two hydraulic conductivity zones; one at the Middleton Street Well Field and the other near the Shades Mill Well Field. In Realization 2, the optimized values for these parameters remained similar to their base case values. However, for this realization, PEST reduced the hydraulic conductivity values of zones at the Middleton and Shades Mill well fields to be approximately 50% and 30% of their base case values, respectively.

The horizontal hydraulic conductivity values at three zones reached or nearly reached their respective upper bounds. They were the tongue-shaped, high hydraulic conductivity feature extending from Guelph to Cambridge, a small zone north of the Middleton Street Well Field, and a zone in the northeast of the model domain near the boundary. The horizontal hydraulic conductivity at two other zones reached their lower bounds. One zone occupied a broad region in the western portion of the model domain, whereas the other represented a high permeability feature near the Clyde Park area. These parameters reached their lower bounds because of the narrow range of parameter bounds applied to this realization.

4.3.5 Realization 3 - Overall Impression and Understanding

Overall, the optimized recharge and hydraulic conductivity zone values were consistent with the conceptualization of Realization 3. Sub-dividing the Guelph Formation into three separate model layers gave PEST the flexibility to optimize the aquifer parameters. The hydraulic conductivity values of some portions of the Guelph Formation at the Dunbar Road, Blair Road and Middleton Street well fields were decreased to provide increased resistance to vertical flow and an improved simulated fit to observed vertical groundwater level elevation differences within the Guelph Formation. In turn, the hydraulic conductivity values of adjacent formations were also varied. The hydraulic conductivity values of the deep bedrock aquifers were similar to the results from Realization 2.

The optimization process achieved an improved match to the groundwater level elevation differences observed within the Guelph Formation, but also improved the calibration to the observed data at the regional and well field scales. As a result, the simulation should be included as a realization in the Risk Assessment.

4.4 Summary and Conclusions

The base case model was developed based on detailed characterization studies and an exhaustive calibration effort. It was recognized that the base case model contained parameter uncertainty stemming from a complex conceptual model, limited data and data gaps. This parameter uncertainty propagated through predictions made by this modelling tool to answer ‘what-if’ type questions, such as those of the risk assessment scenarios. To help understand and quantify the range of uncertainty in model predictions (resulting from uncertainty in parameter values), three alternative conceptual models were developed.

Three realizations were defined that embodied the numeric representation of three distinct alternative conceptual models. Realization 1 built on the conceptualization of the base case and emphasized adjusting parameter values to better reflect the responses of the groundwater flow systems under typical, long-term operating conditions. This was a fine tuning of base case parameter values. Realization 2 estimated how leaky the bedrock aquitards could be. Overall, this resulted in a reduced contrast of hydraulic conductivity zone values between aquifers and aquitards, while maintaining a good model calibration. Realization 3 examined the stratification with the Guelph Formation and attempted to introduce intra-formation vertical heterogeneity to better match groundwater level elevation differences within the formation. The optimization process of Realization 3 was able to achieve an improved calibration to vertical groundwater level elevation differences observed within the Guelph Formation, and also improved the match to other observation data at both the regional and well field scales.

For each realization, the parameter values were consistent with the conceptual model and the level of calibration was maintained as compared to that achieved with the base case model. Given this, each of the three realizations was considered acceptable and suitable for inclusion as uncertainty realizations to evaluate the Risk Assessment scenarios.

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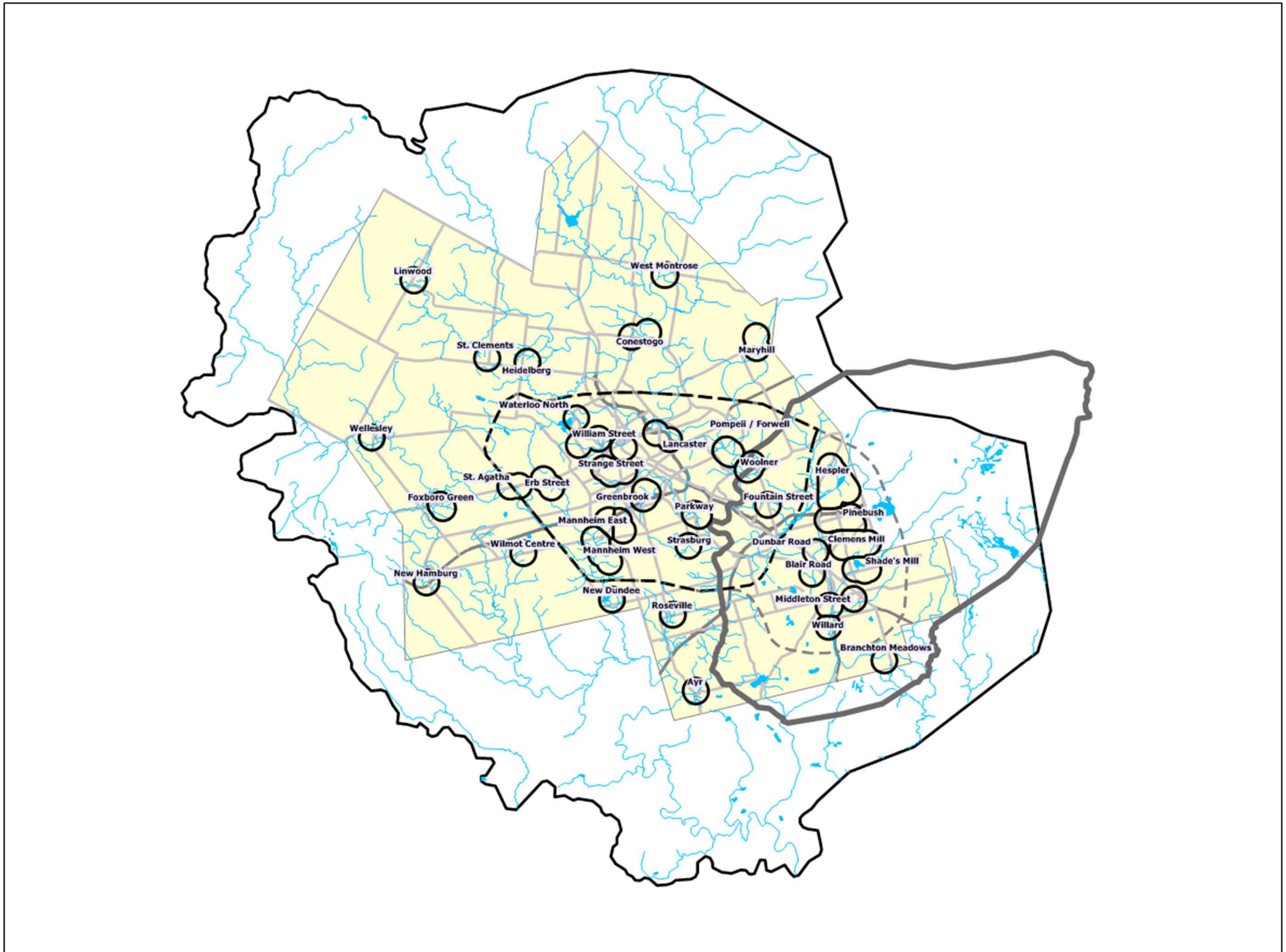

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

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Figure 1: Model Study Area for Regional and Cambridge Models

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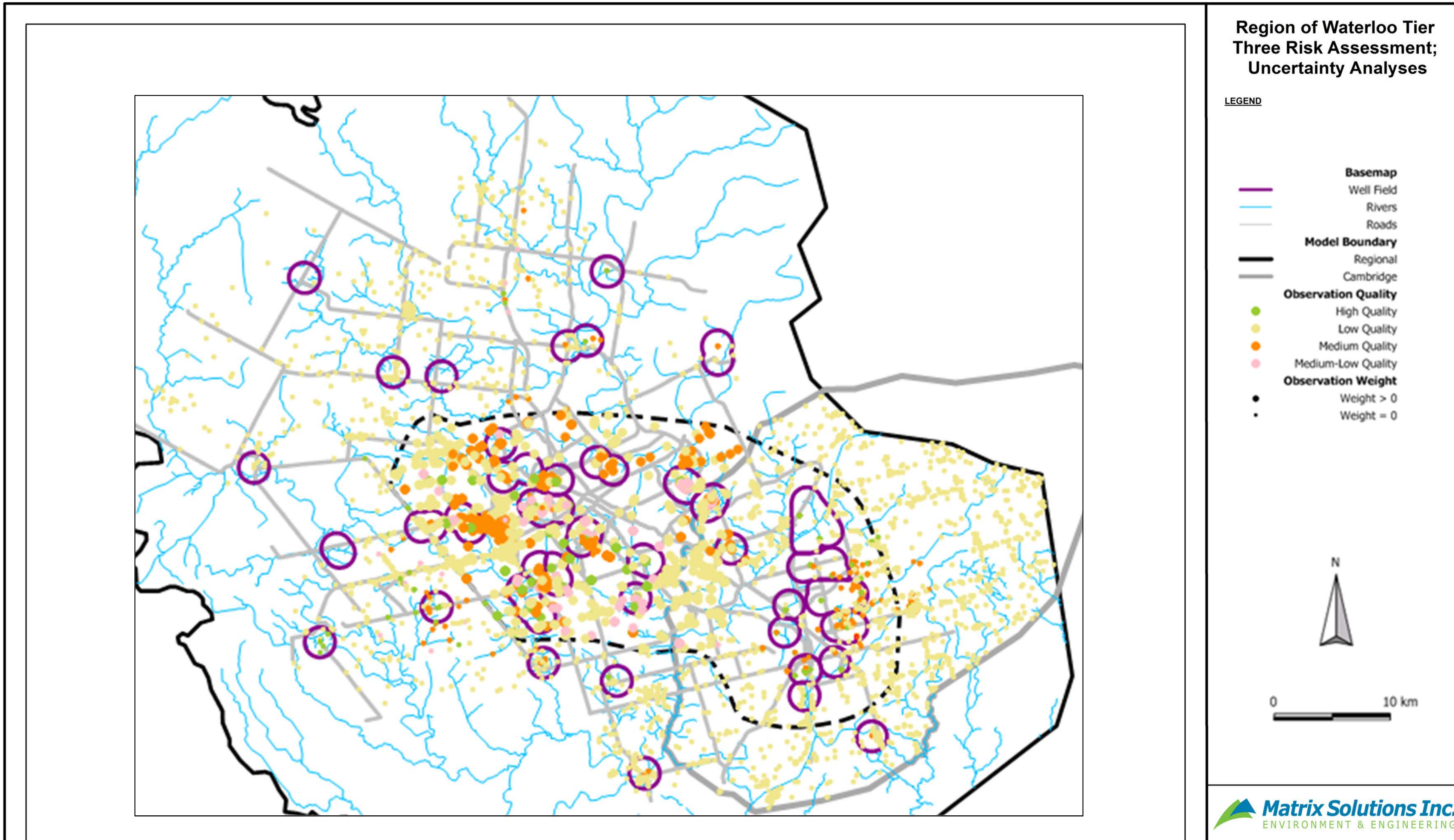

Figure 2: Steady Groundwater Level Elevation Observations - Regional Model

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Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

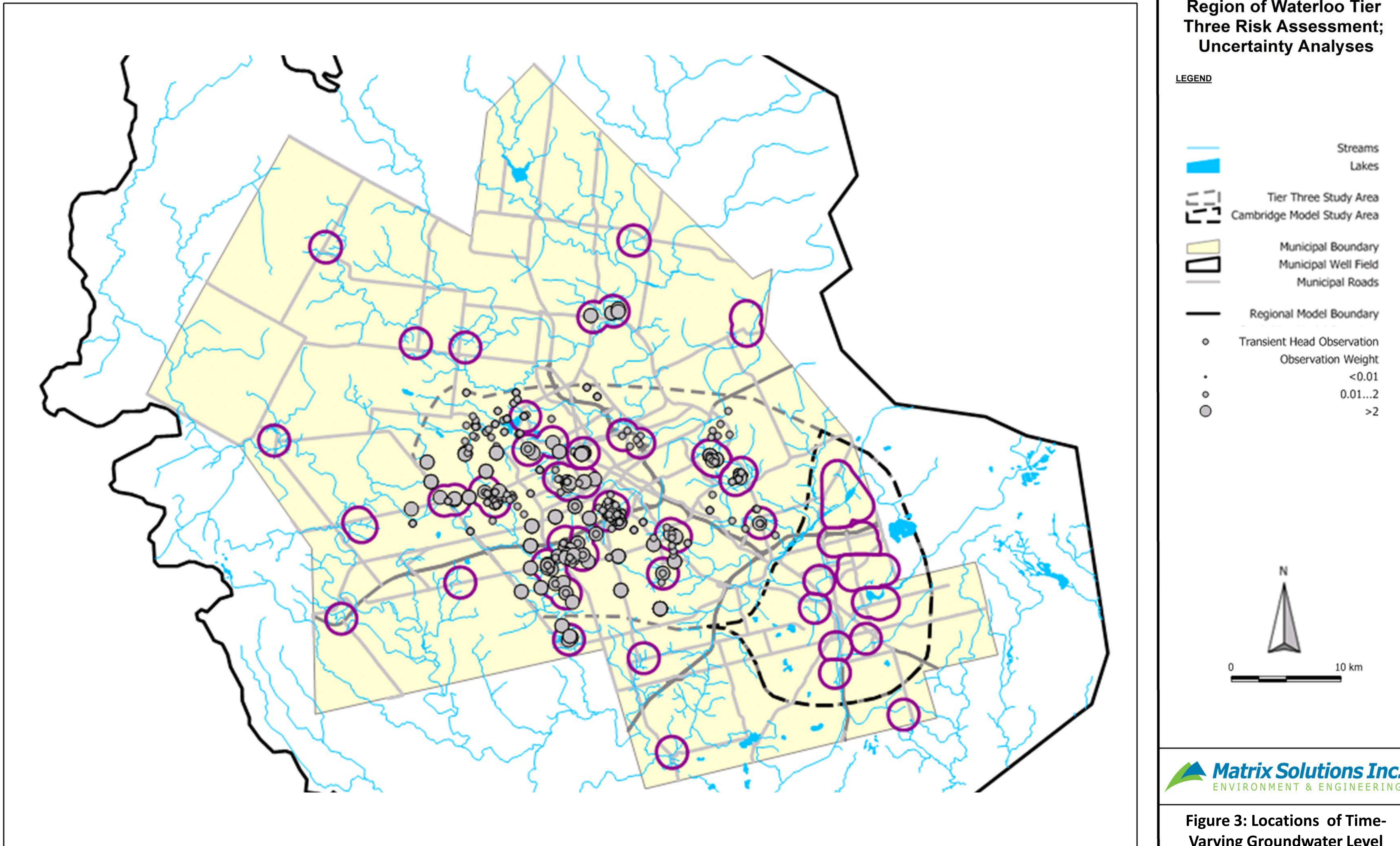

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Figure 3: Locations of Time-Varying Groundwater Level Elevation Data – Regional Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

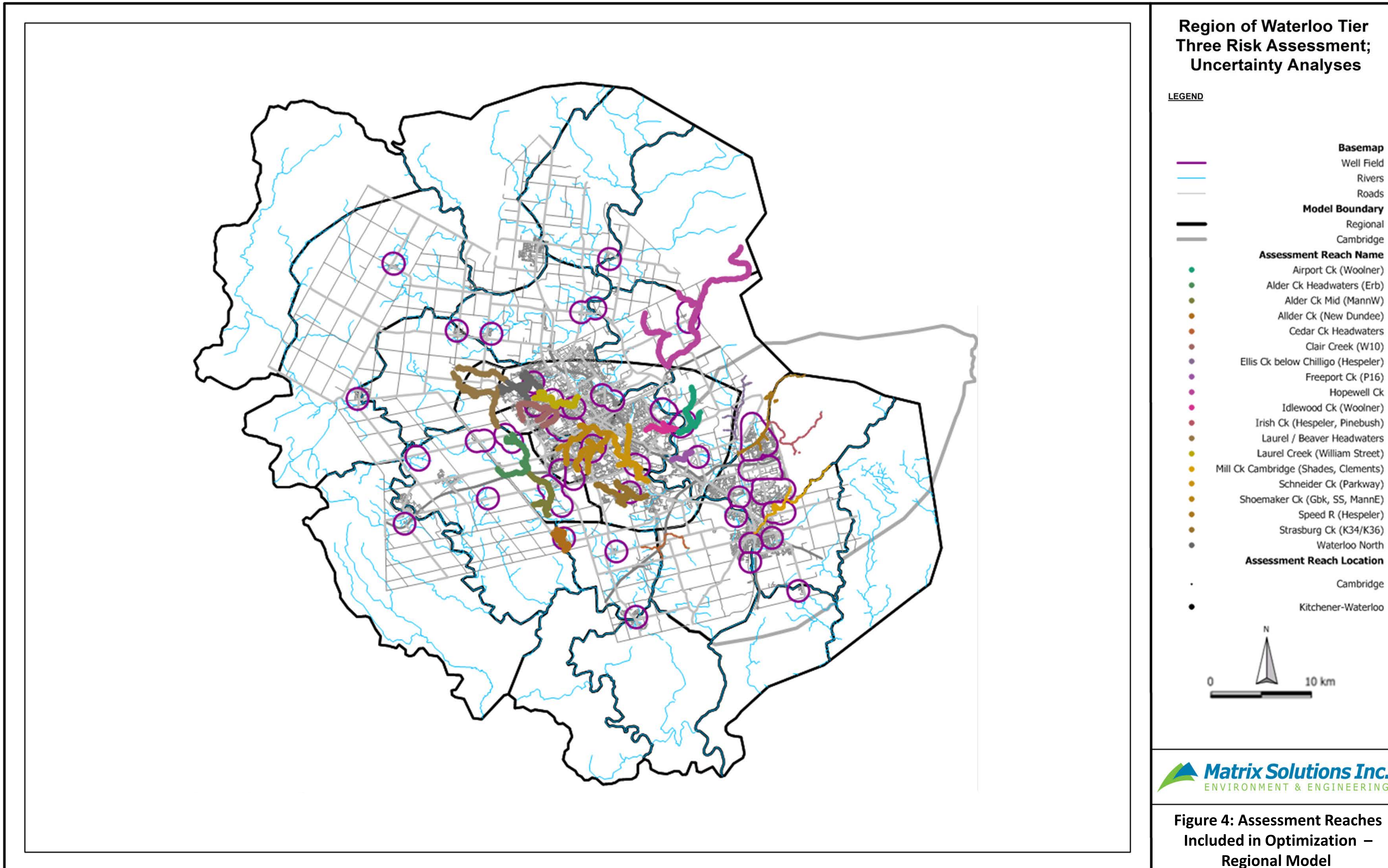

Figure 4: Assessment Reaches Included in Optimization – Regional Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

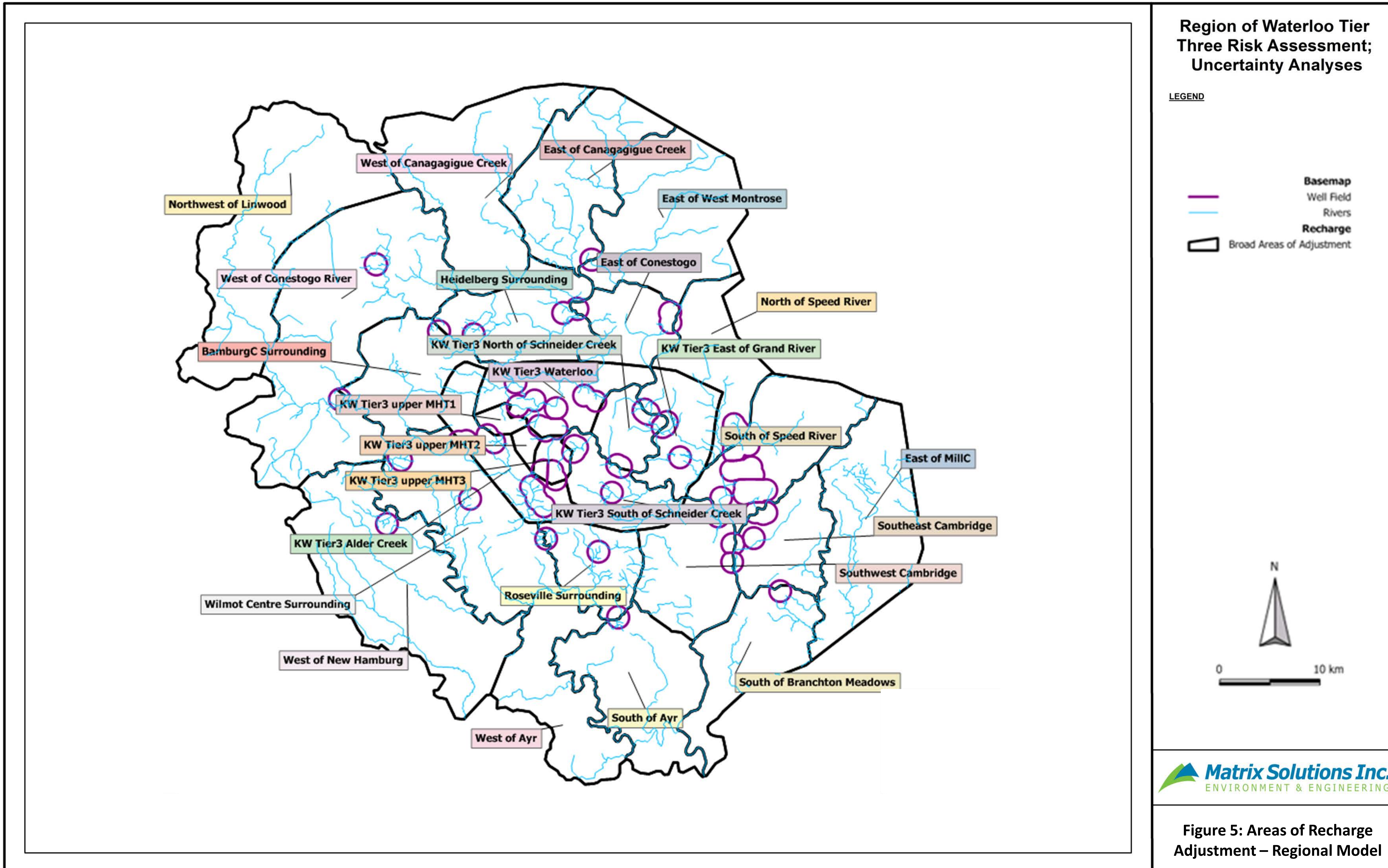

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Figure 5: Areas of Recharge Adjustment – Regional Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

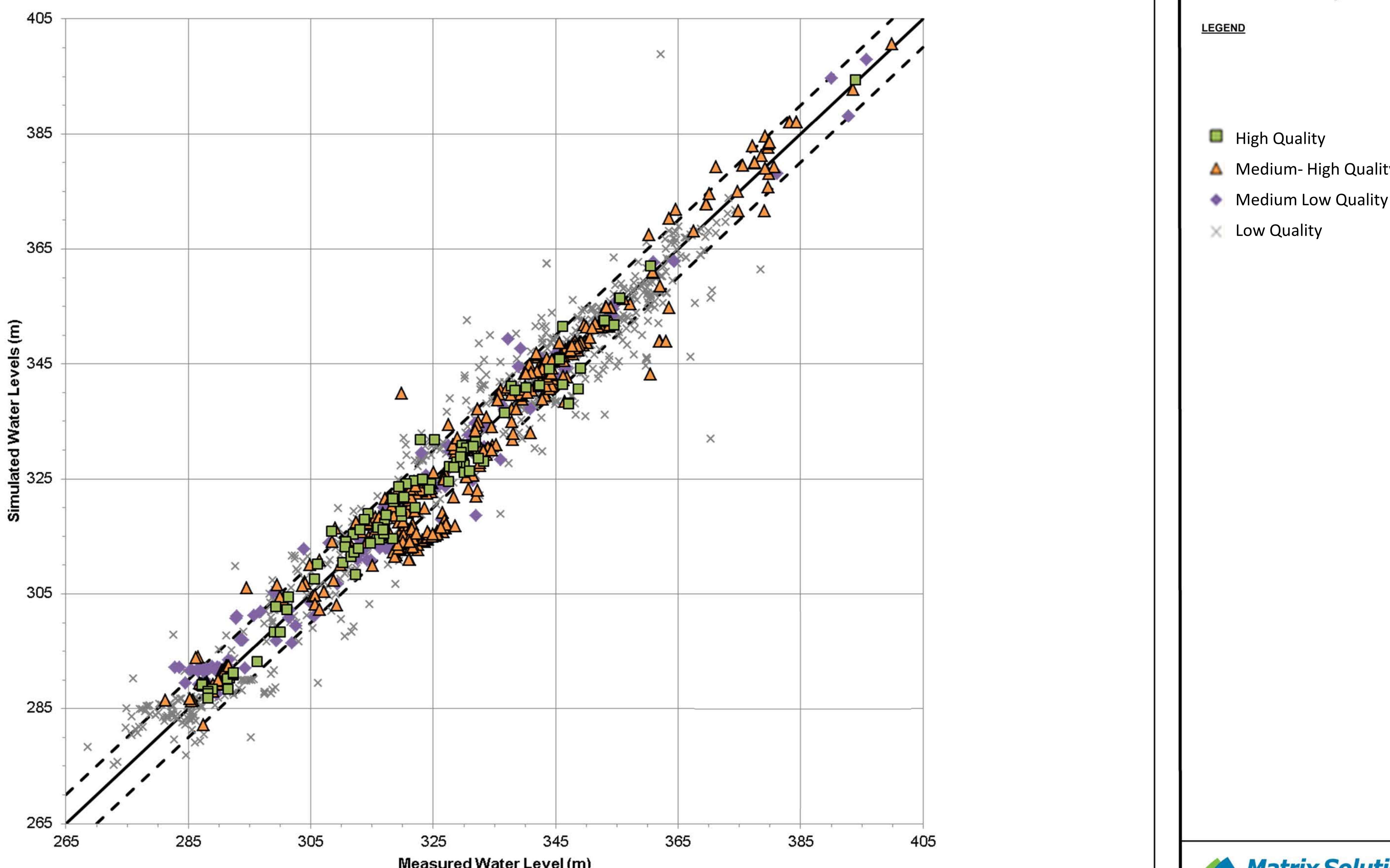

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Figure 6: Simulated vs Observed Groundwater Level Elevations– Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

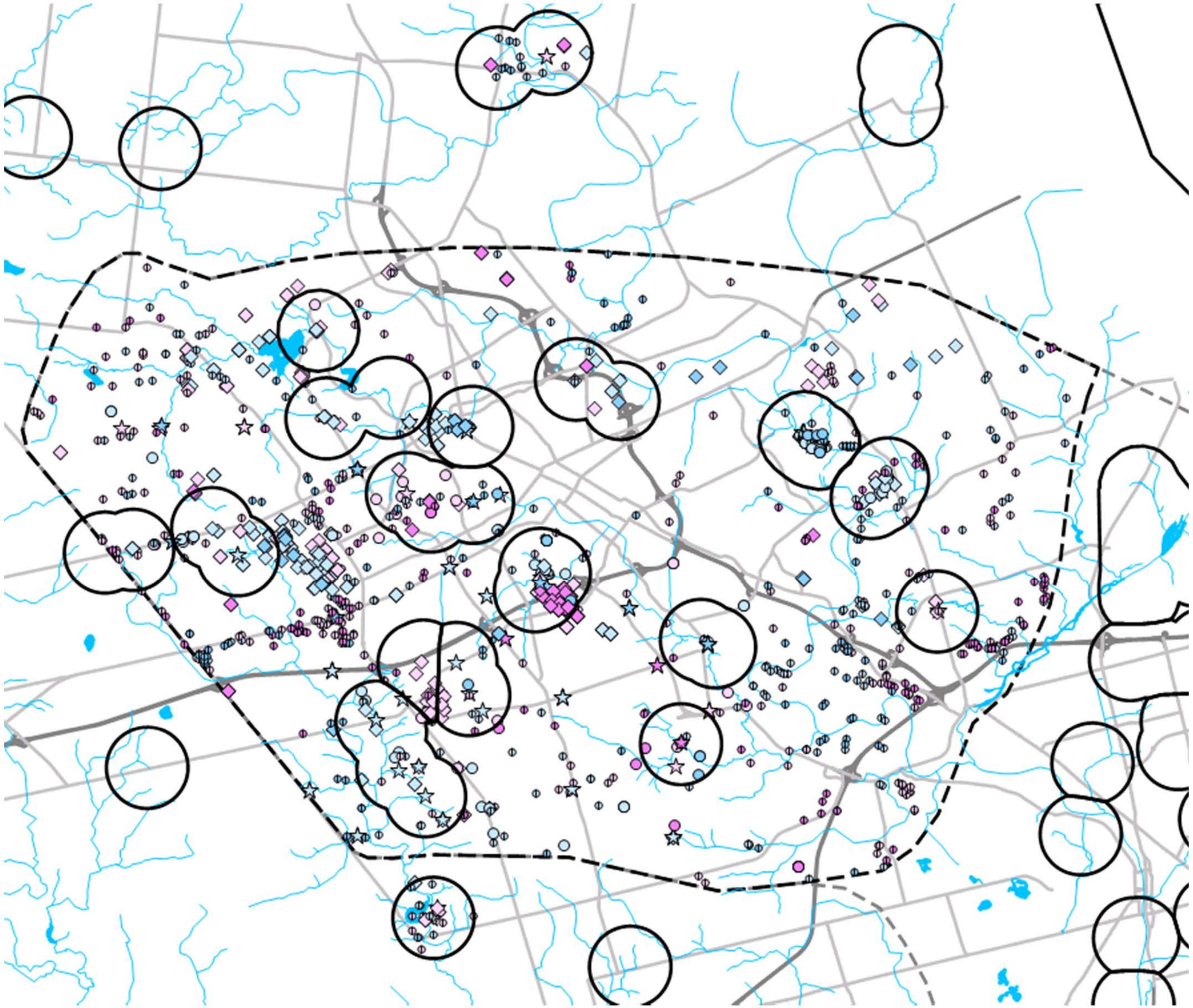

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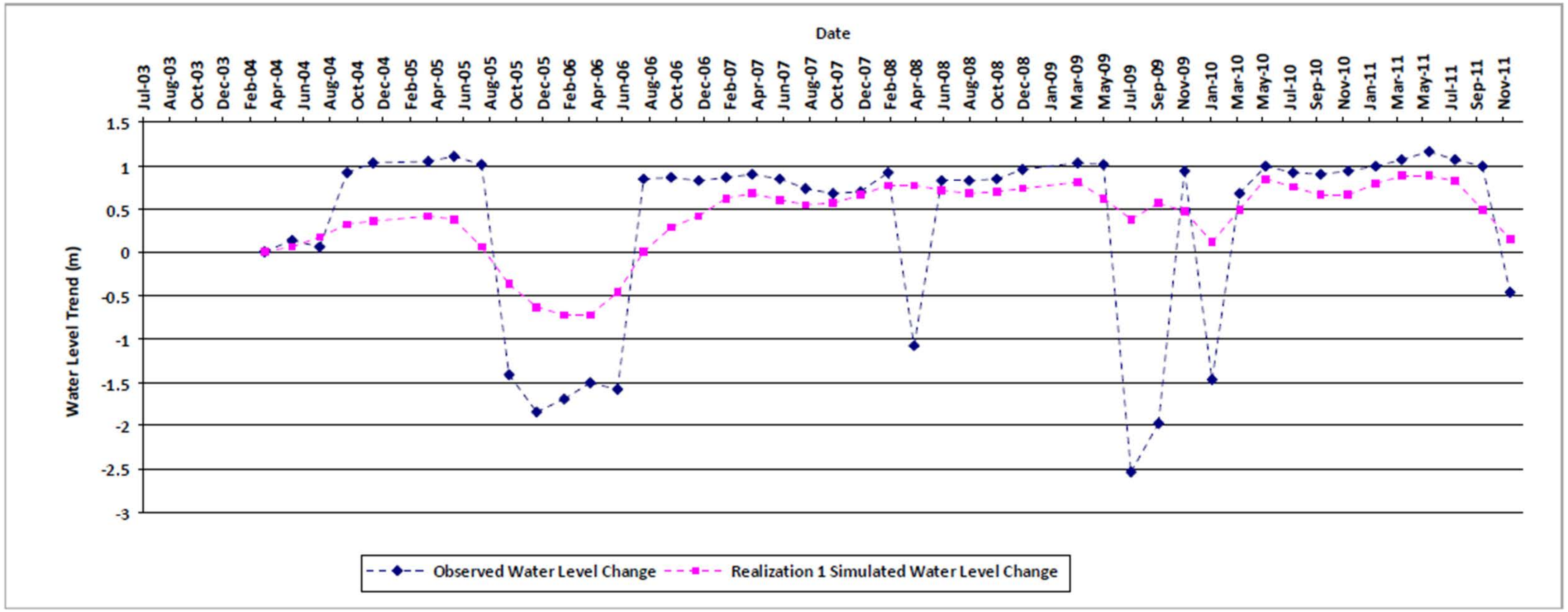
Figure 7: Spatial Plot of Groundwater Level Elevation Residuals – Realization 1

SpatialArea: Waterloo North

OBJ_NUM & Screen	9201414 A	SCRNTYPE	Single	SCRN_FROM	11.9
CONSLT_ID	MWWN1-02	ObsType	nOW	SCRN_TO	14



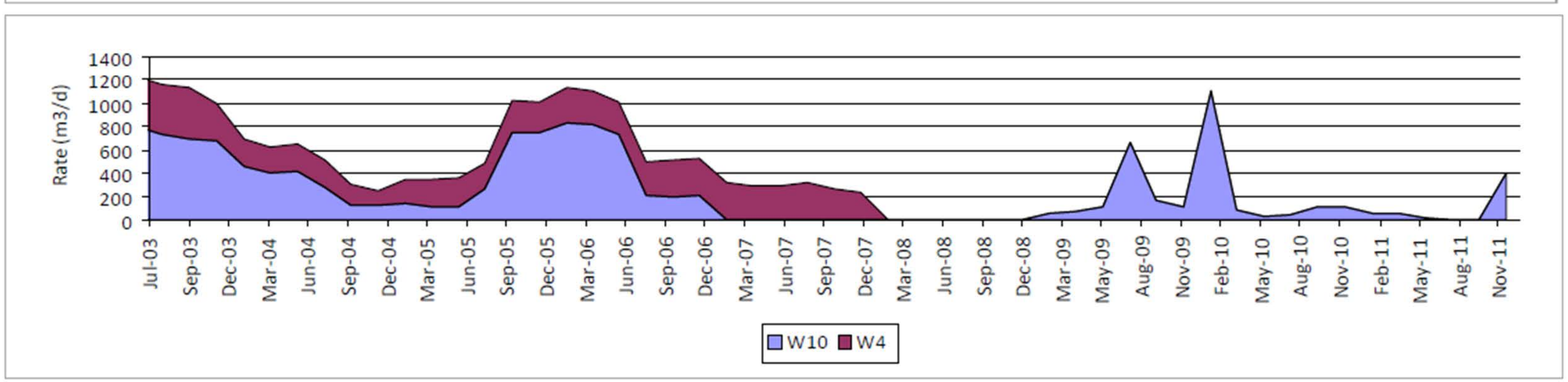


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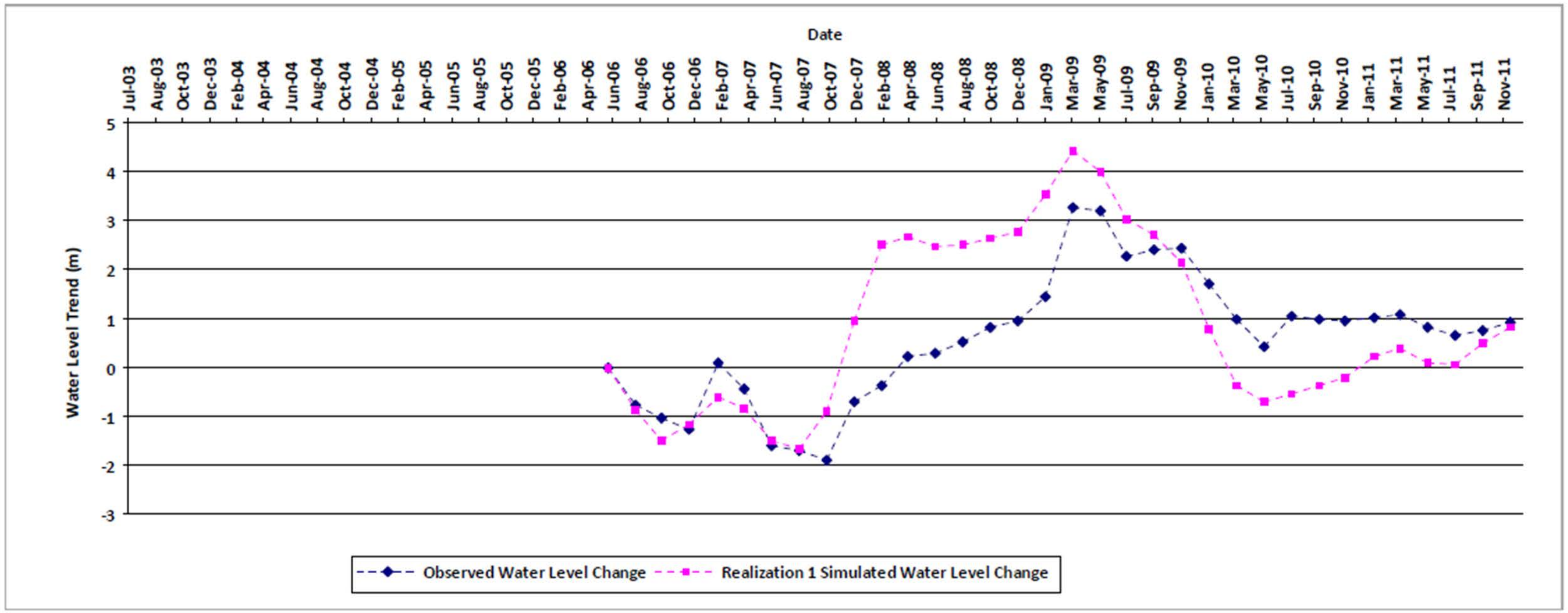
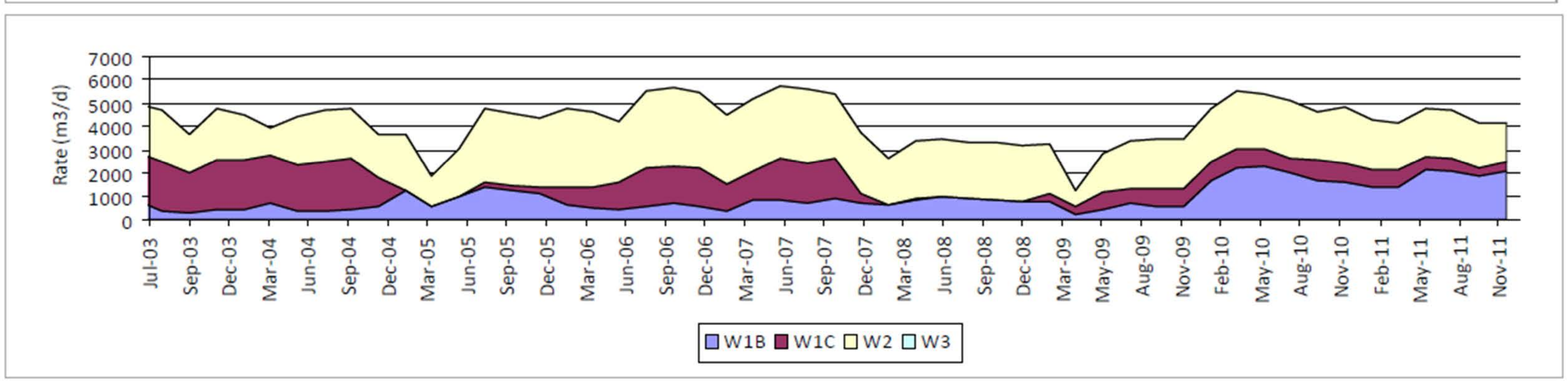
Figure 8: Sample Hydrograph for Waterloo North Well Field – Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

SpatialArea	William Street				
OBJ_NUM & Screen	9202636 A	SCRNTYPE	Single	SCRN_FROM	27.05
CONSLT_ID	OW5A-87	ObsType	nOW	SCRN_TO	27.81





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

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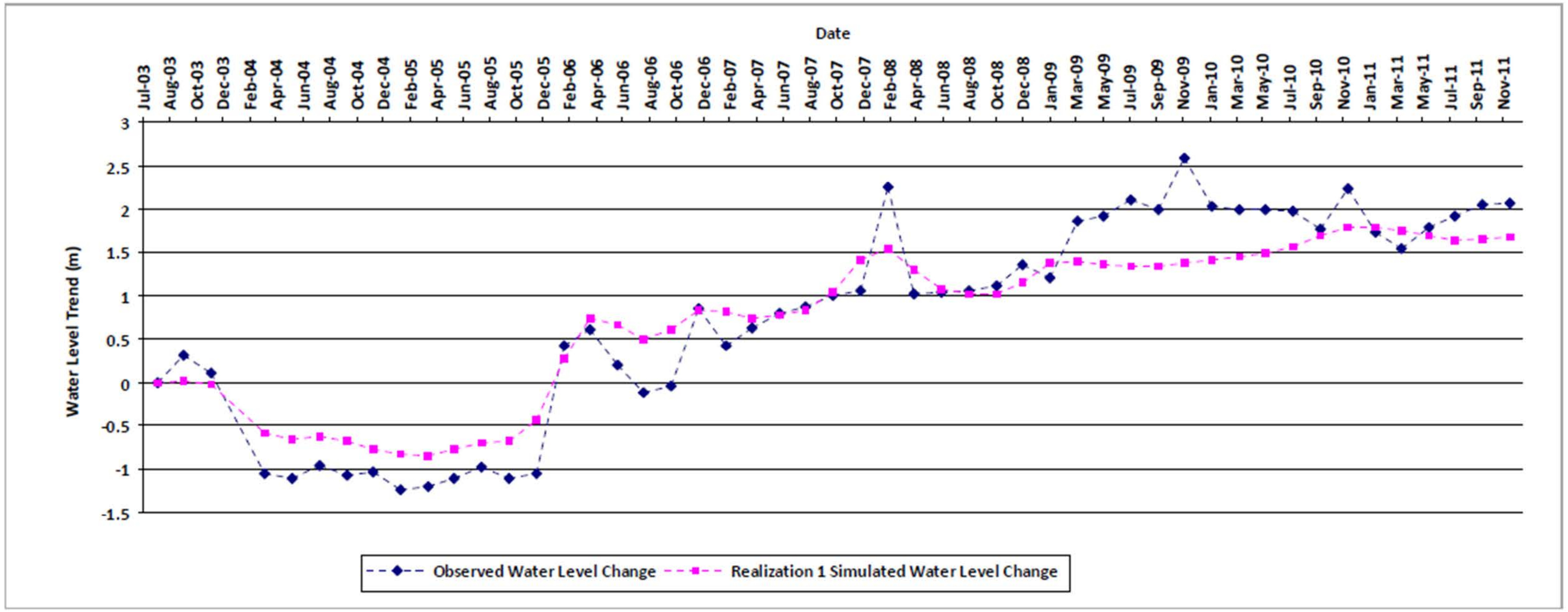
Figure 9: Sample Hydrograph for William Street Well Field – Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

SpatialArea	Erb Street				
OBJ_NUM & Screen	6502375 B	SCRNTYPE	Single	SCRN_FROM	27.33
CONSLT_ID	OW7-57B	ObsType	nOW	SCRN_TO	30.69



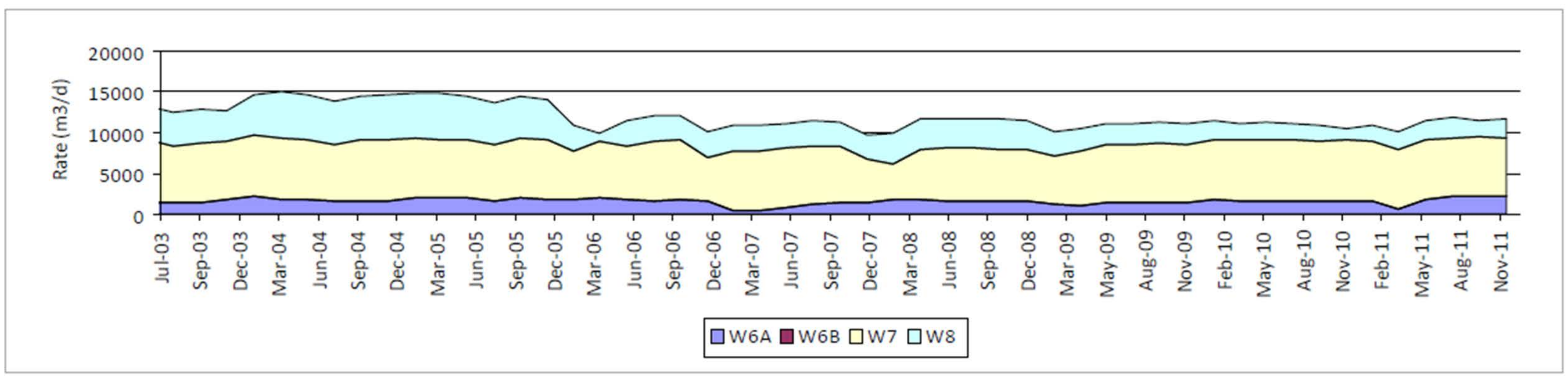


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Figure 10: Sample Hydrograph for Erb Street Well Field – Realization 1

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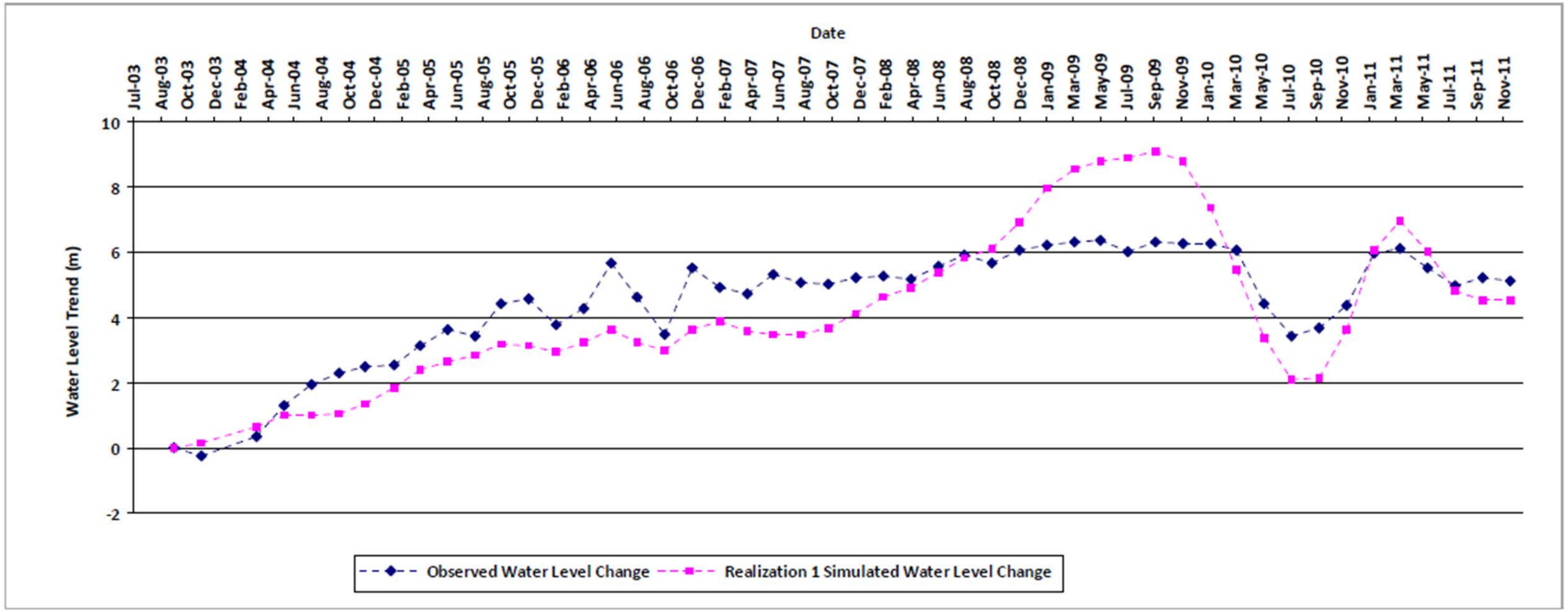
SpatialArea	Strange Street				
OBJ_NUM & Screen	9200064 / A	SCRNTYPE	Single	SCRN_FROM	18.82
CONSLT_ID	OW1-82 (TW10-82)	ObsType	nOW	SCRN_TO	20.62



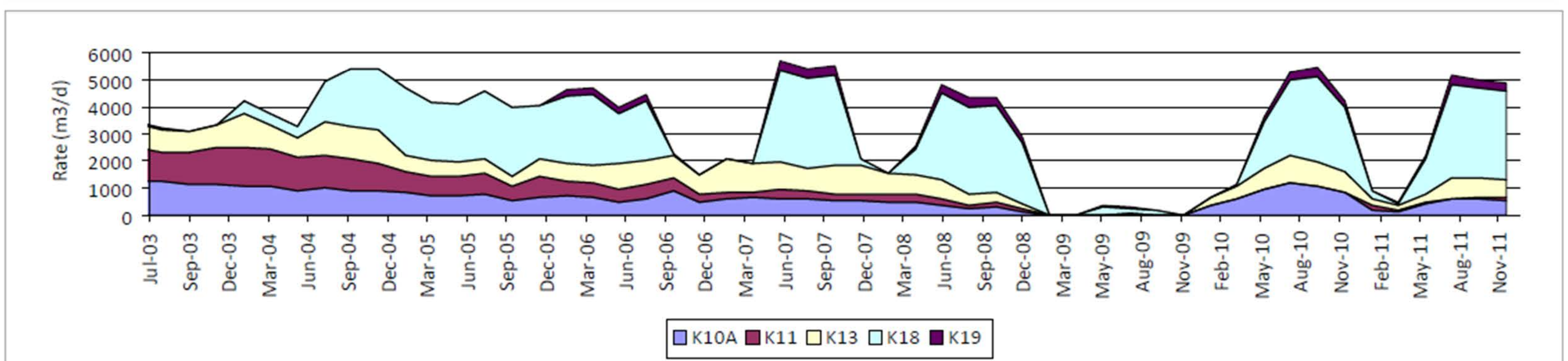


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Figure 11: Sample Hydrograph for Strange Street Well Field – Realization 1

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Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

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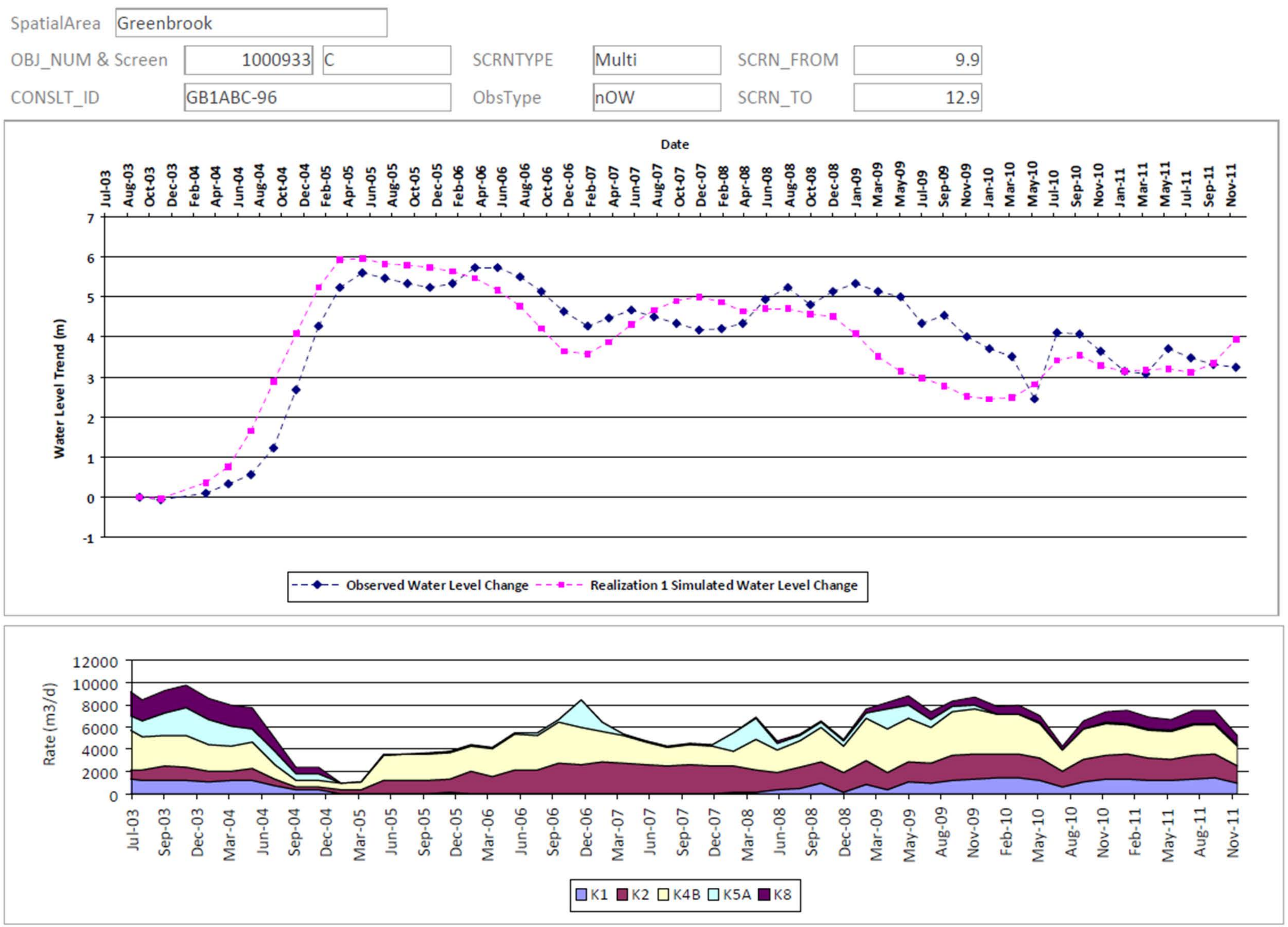

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Figure 12: Sample Hydrograph for Greenbrook Well Field – Realization 1

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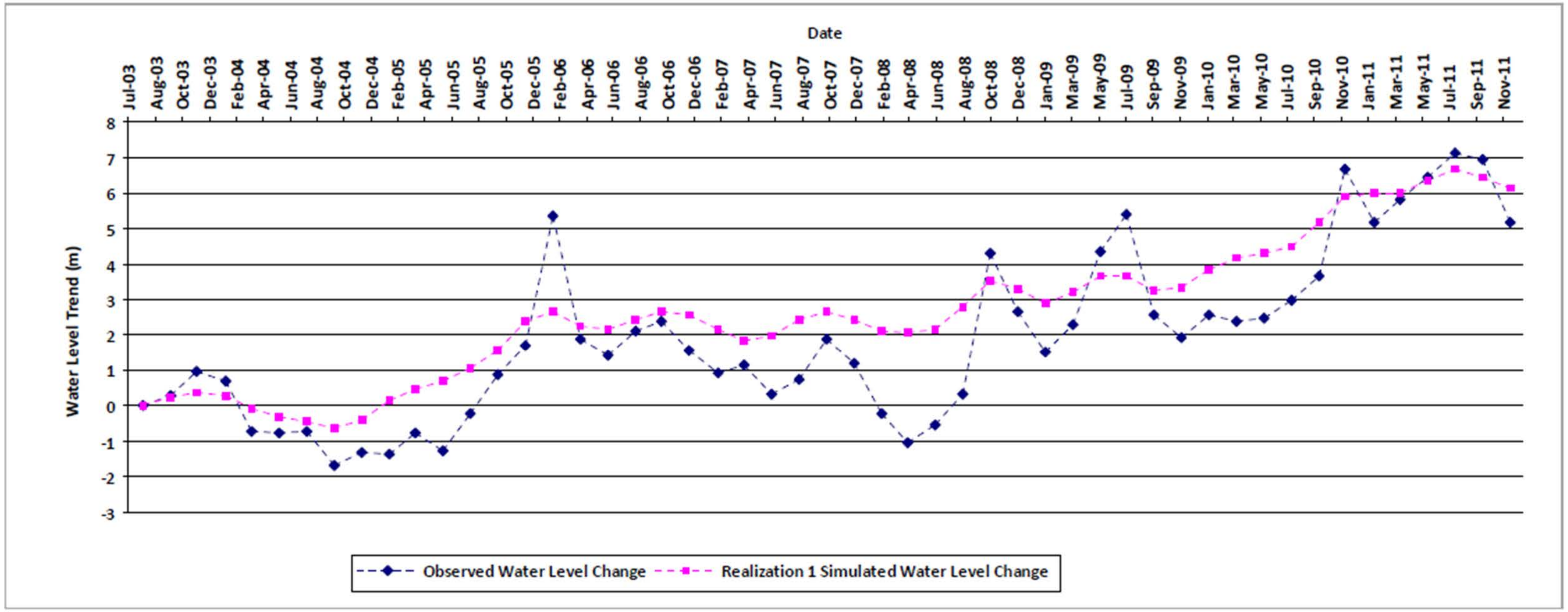
SpatialArea	Parkway				
OBJ_NUM & Screen	1000429 B	SCRNTYPE	Multi	SCRN_FROM	28.35
CONSLT_ID	PK1-95	ObsType	nOW	SCRN_TO	29.87



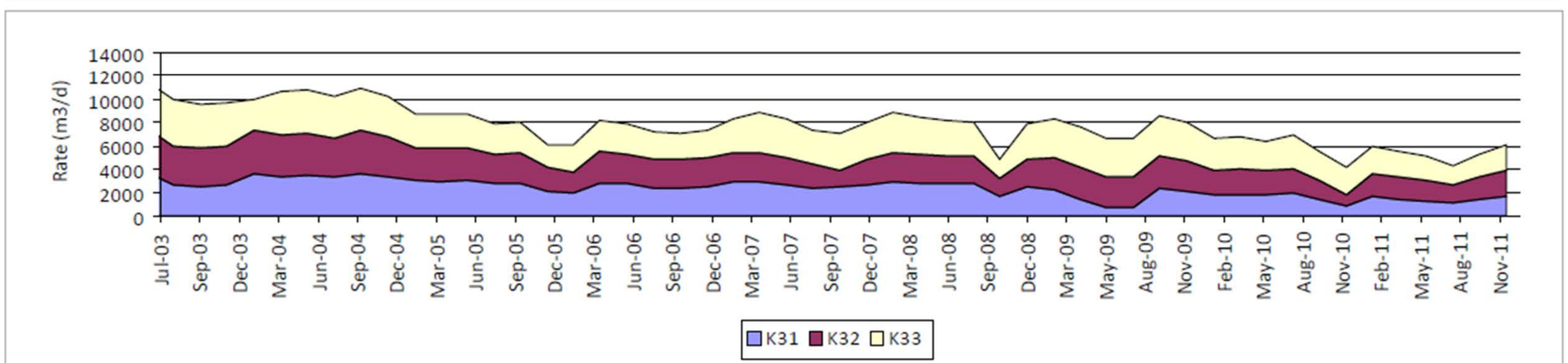


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Figure 13: Sample Hydrograph for Parkway Well Field – Realization 1

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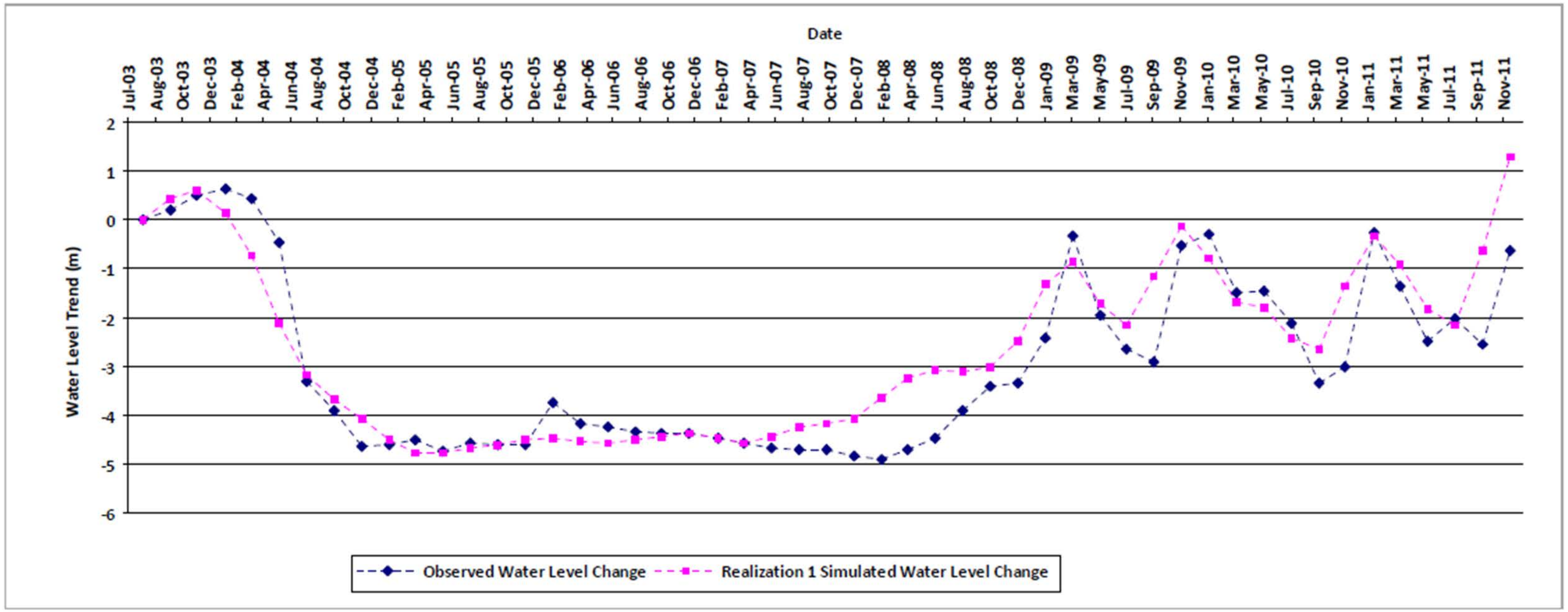
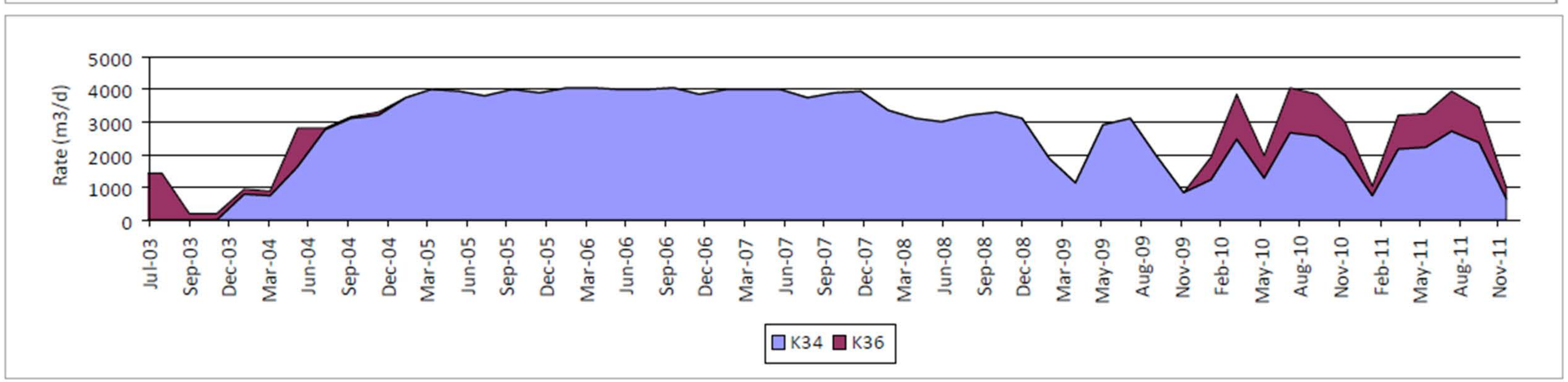
SpatialArea	Strasburg				
OBJ_NUM & Screen	1000433 B	SCRNTYPE	Multi	SCRN_FROM	35.7
CONSLT_ID	PK5-96	ObsType	nOW	SCRN_TO	37.2





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LEGEND

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Figure 14: Sample Hydrograph for Strasburg Well Field – Realization 1

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SpatialArea	Mannheim West				
OBJ_NUM & Screen	6502125 A	SCRNTYPE	Single	SCRN_FROM	21.34
CONSLT_ID	OW8-61	ObsType	nOW	SCRN_TO	24.69

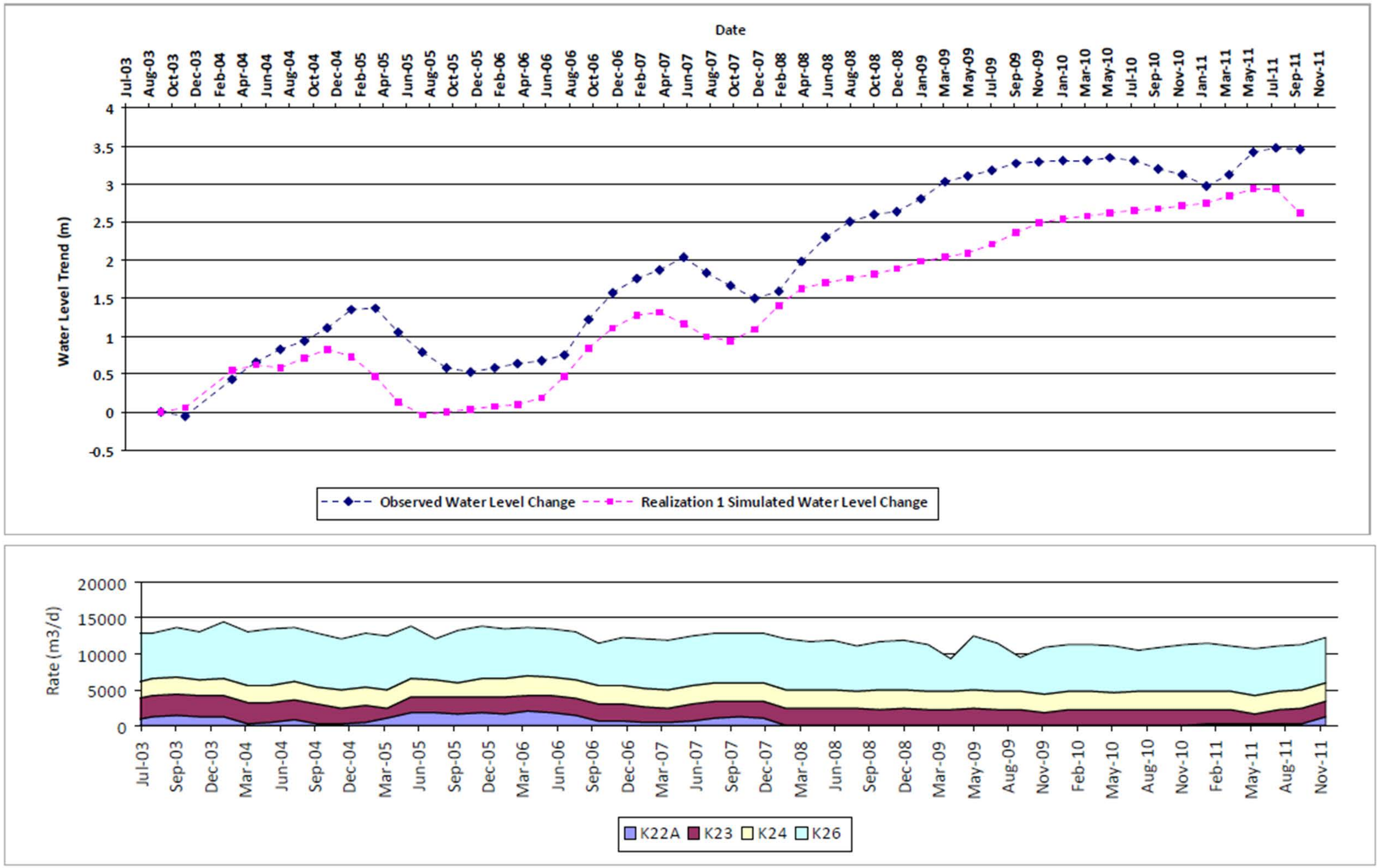

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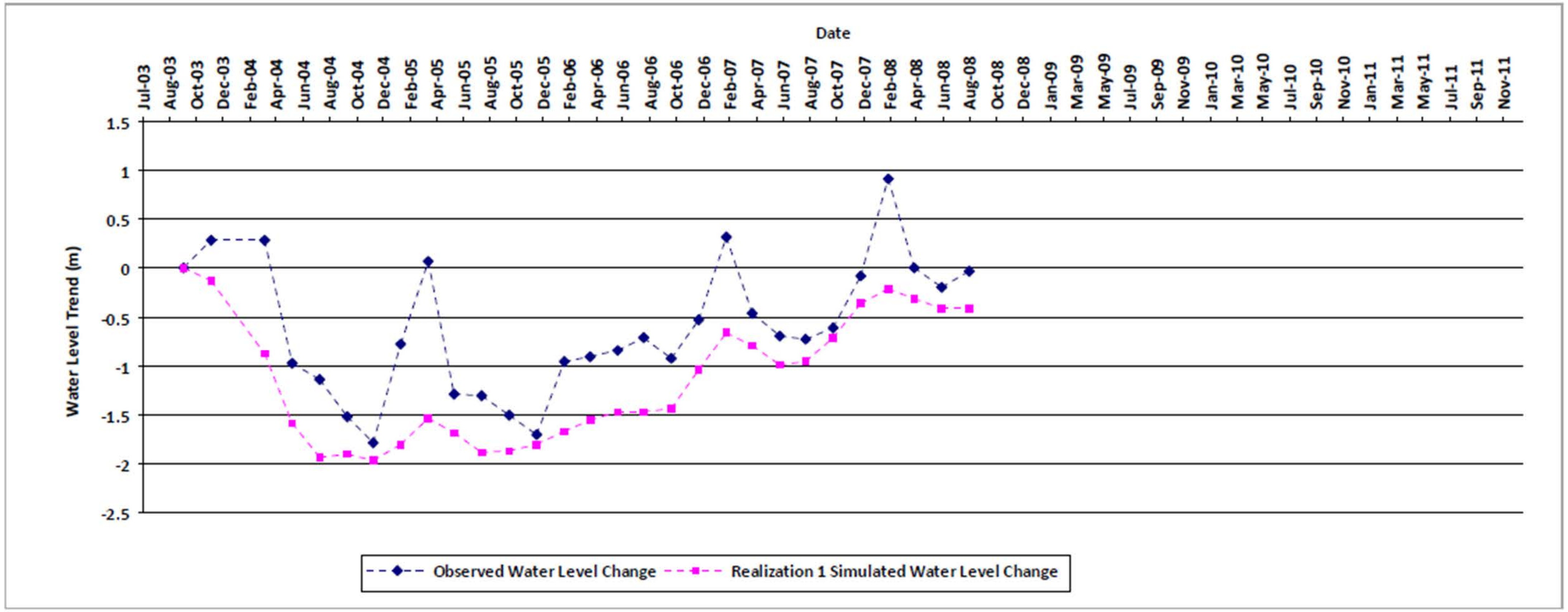
Figure 15: Sample Hydrograph for Mannheim Well Fields – Realization 1

SpatialArea	Woolner				
OBJ_NUM & Screen	6504873 A	SCRNTYPE	Single	SCRN_FROM	4.88
CONSLT_ID	OW12-78	ObsType	nOW	SCRN_TO	7.38



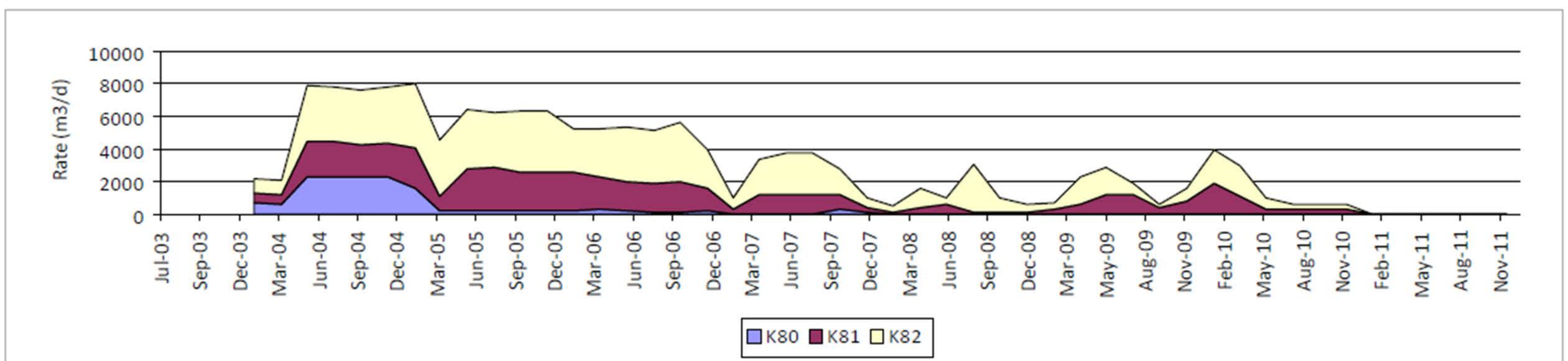


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Figure 16: Sample Hydrograph for Woolner Well Field – Realization 1

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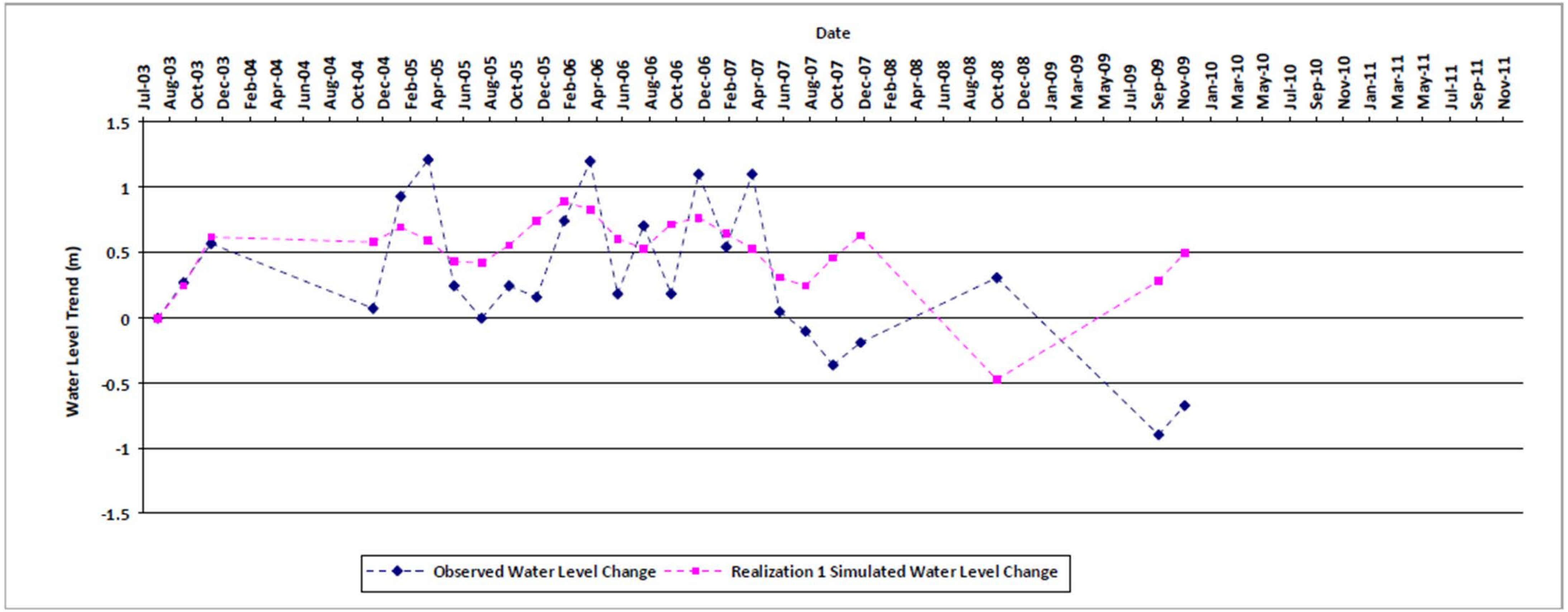
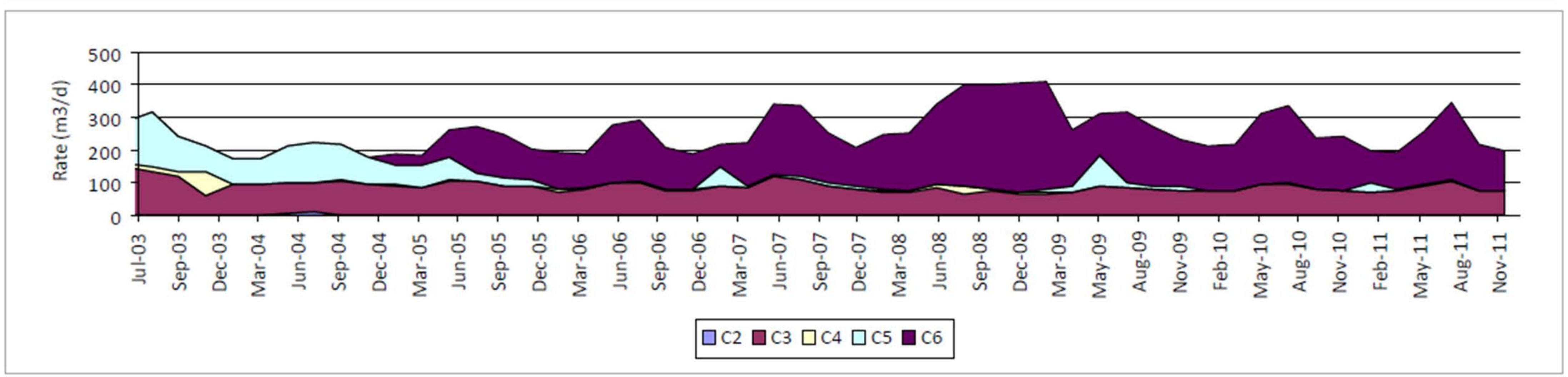
SpatialArea Conestogo

OBJ_NUM & Screen	1000290 A	SCRNTYPE	Single	SCRN_FROM	15.24
CONSLT_ID	C5	ObsType	PW	SCRN_TO	17.67





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LEGEND

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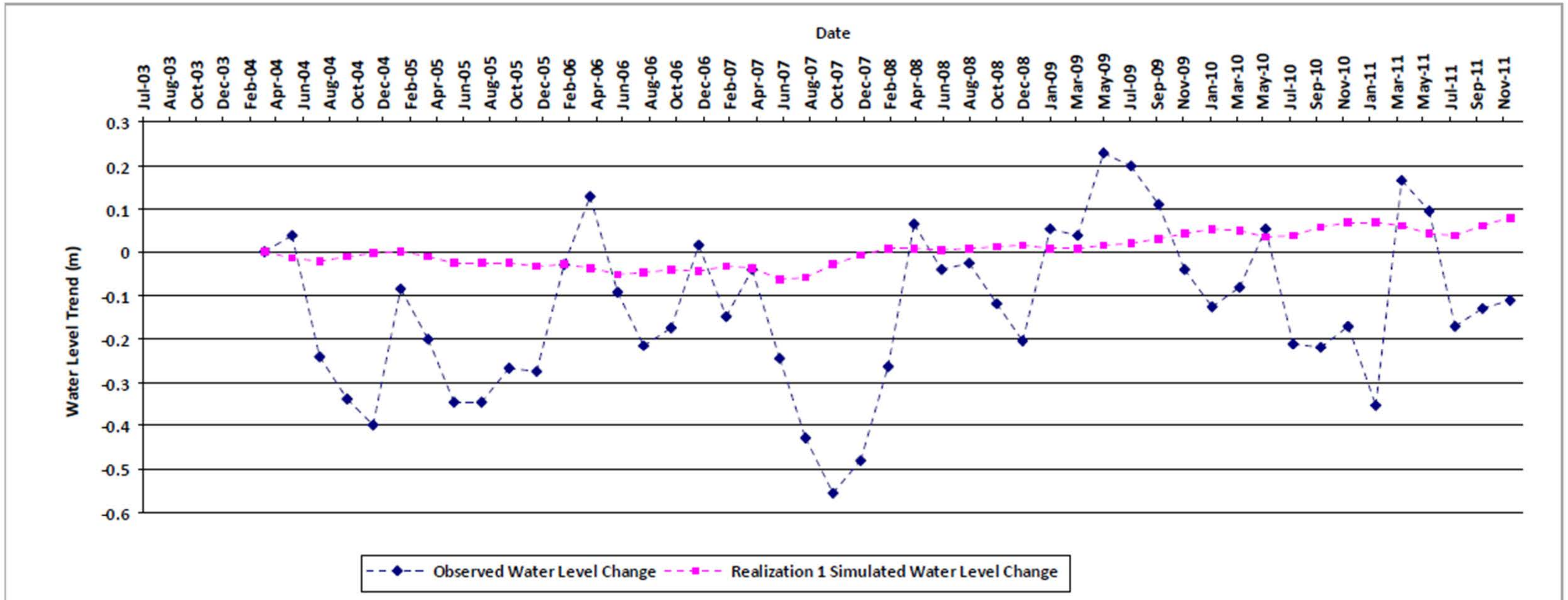
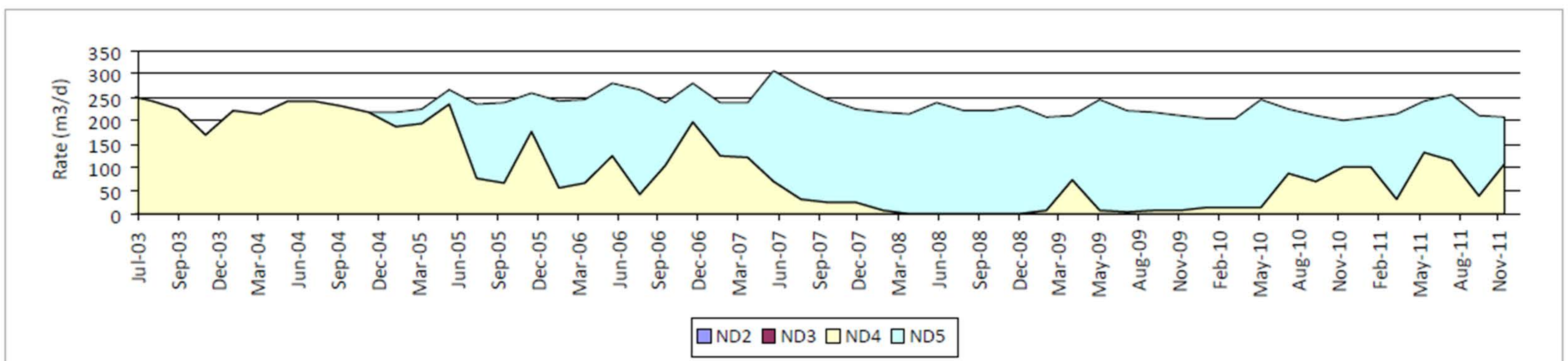
Figure 17: Sample Hydrograph for Conestogo Well Field – Realization 1

SpatialArea	New Dundee					
OBJ_NUM & Screen	9201304	A	SCRNTYPE	Single	SCRN_FROM	13.7
CONSLT_ID	OW1-03		ObsType	nOW	SCRN_TO	16.8





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LEGEND

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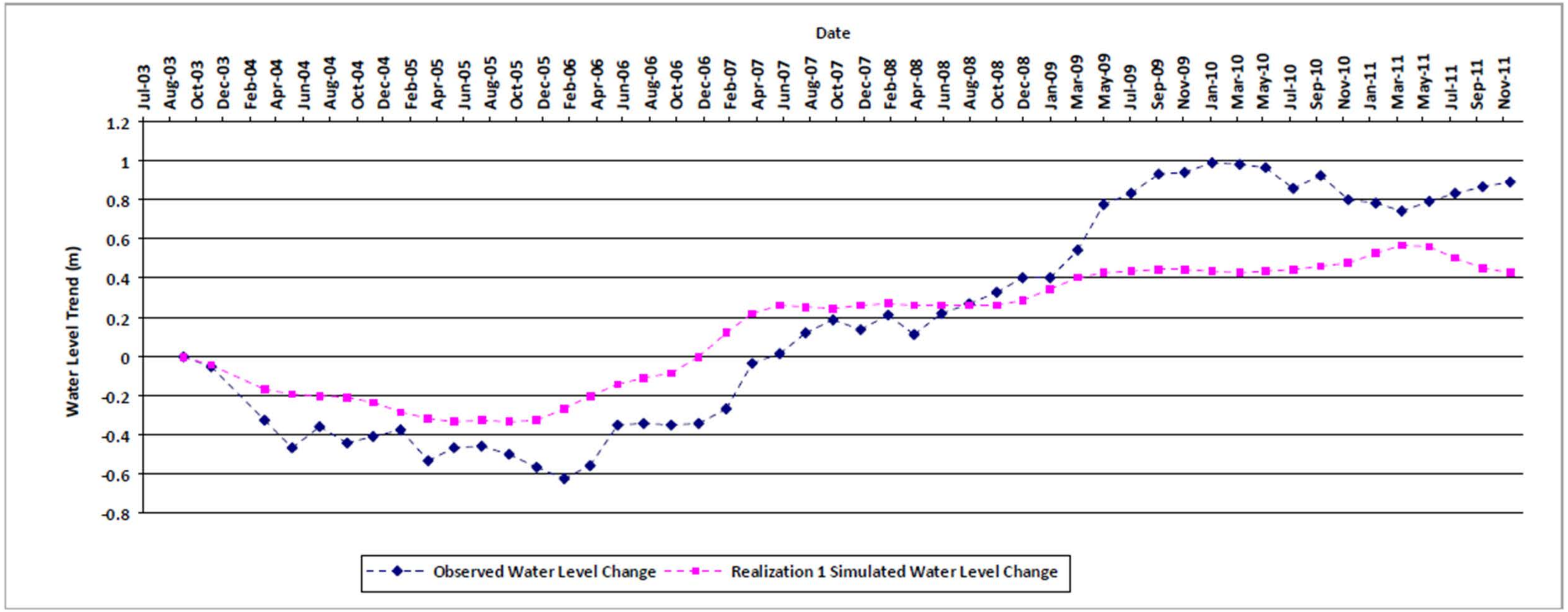
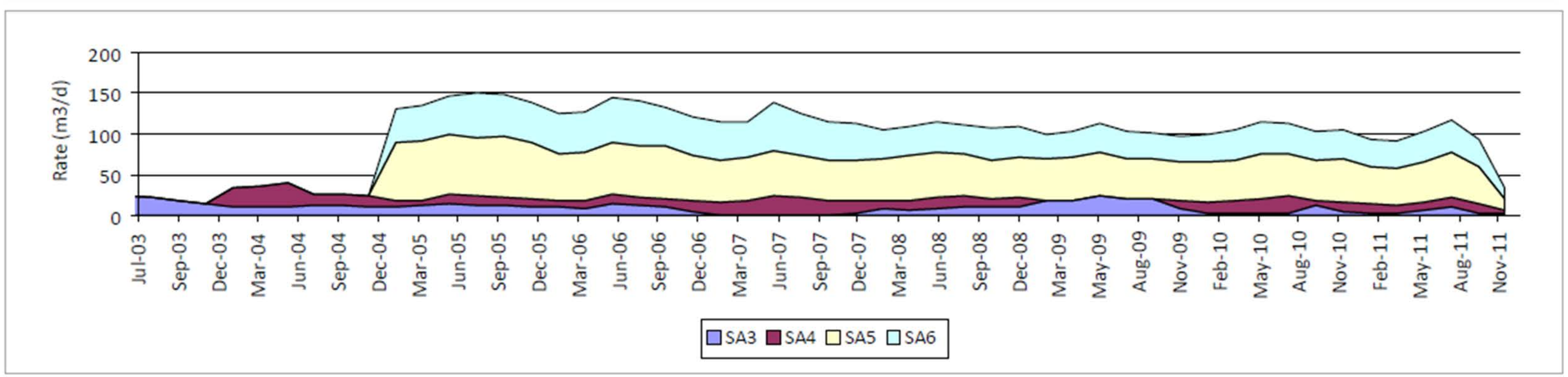
Figure 18: Sample Hydrograph for New Dundee Well Field – Realization 1

SpatialArea St. Agatha

OBJ_NUM & Screen	9200499 B	SCRNTYPE	Multi	SCRN_FROM	53.3
CONSLT_ID	WM2-93	ObsType	nOW	SCRN_TO	56.5





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LEGEND

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Figure 19: Sample Hydrograph for St. Agatha Well Field – Realization 1

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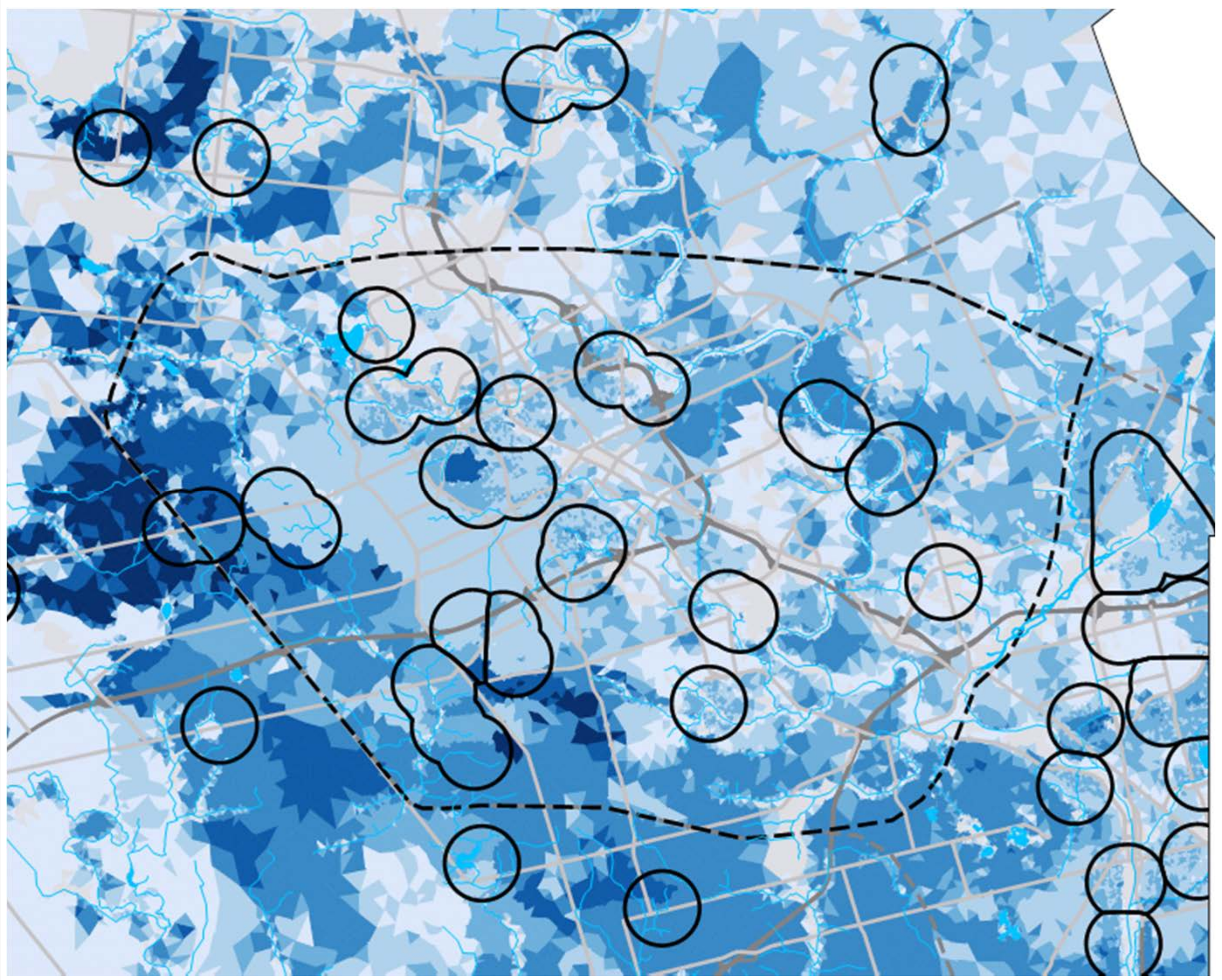
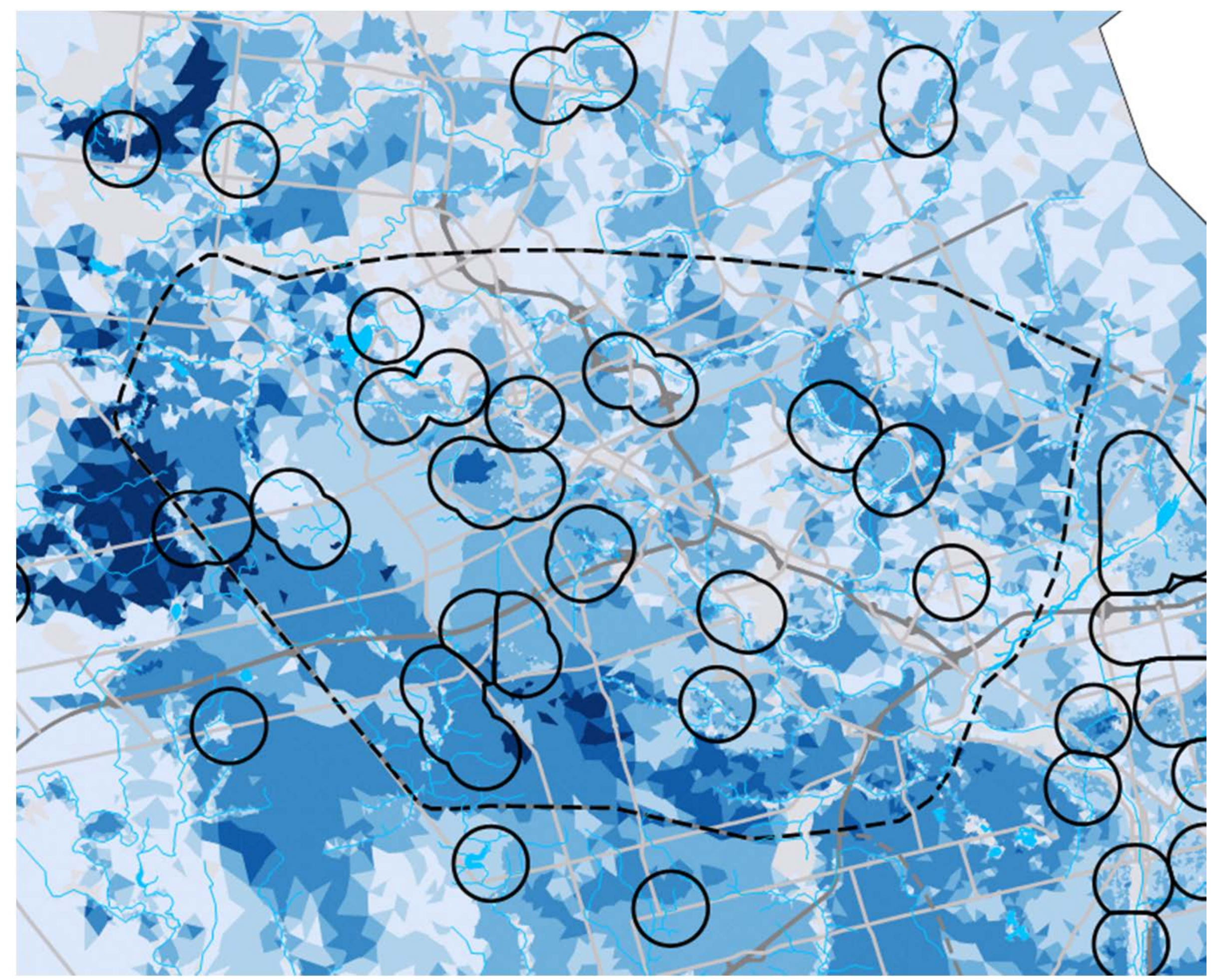
Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

Base Case (Calibrated Model) Recharge Distribution



Optimized Recharge Distribution- Realization 1



LEGEND

Streams
Lakes

Regional Model Study Area
Tier Three Study Area

Recharge (mm/yr)
<50
50...100
100...200
200...300
300...400
400...500
>500

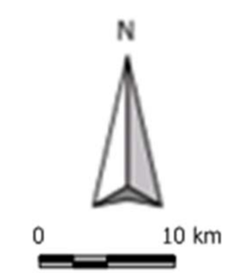


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Figure 20: Base Case and Optimized Recharge Distribution – Realization 1

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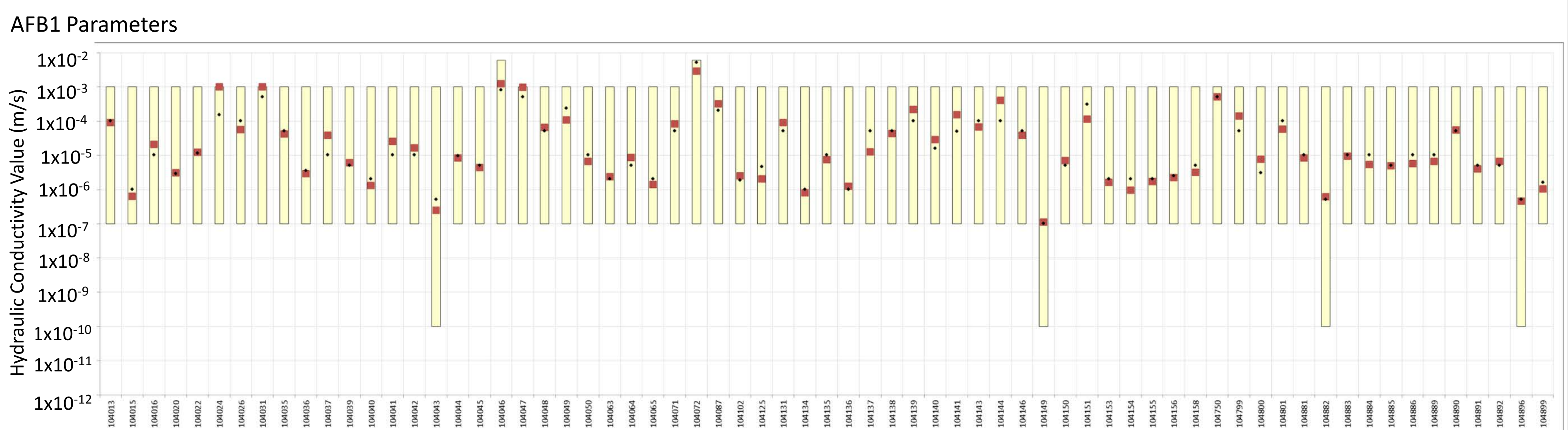

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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Figure 21: Optimized Hydraulic Conductivity for ATB1 and AFB1 – Realization 1

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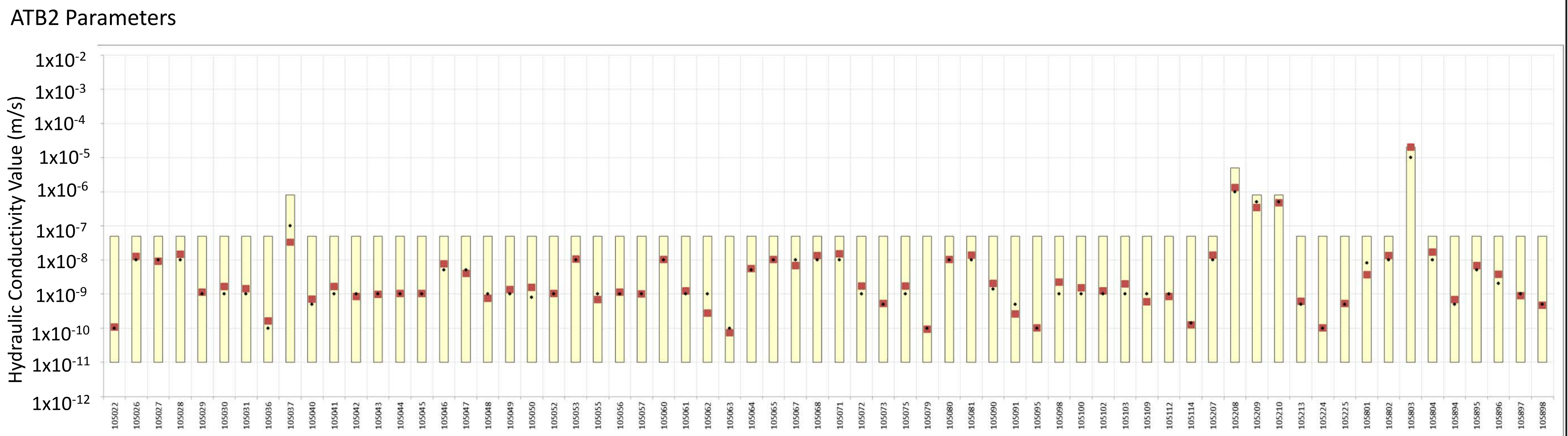

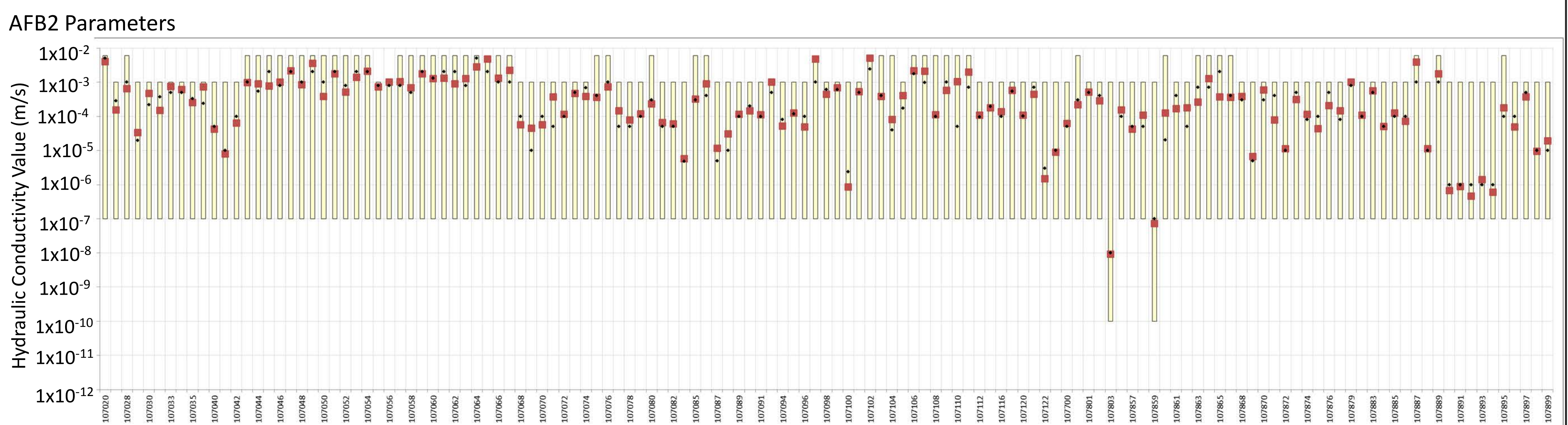

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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Figure 22: Optimized Hydraulic Conductivity for ATB2 and AFB2 – Realization 1

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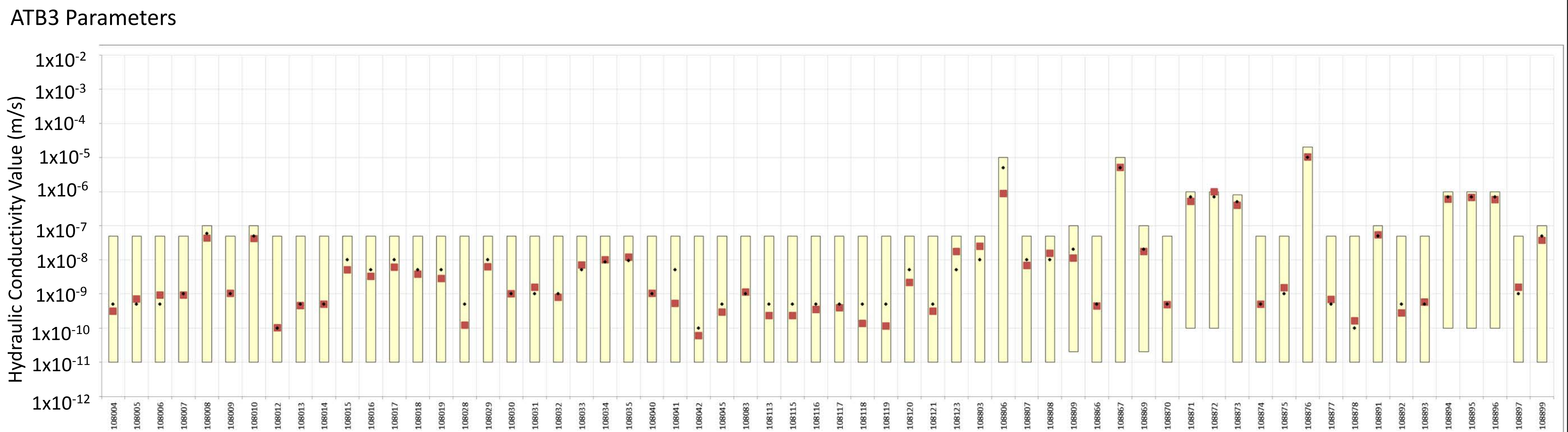

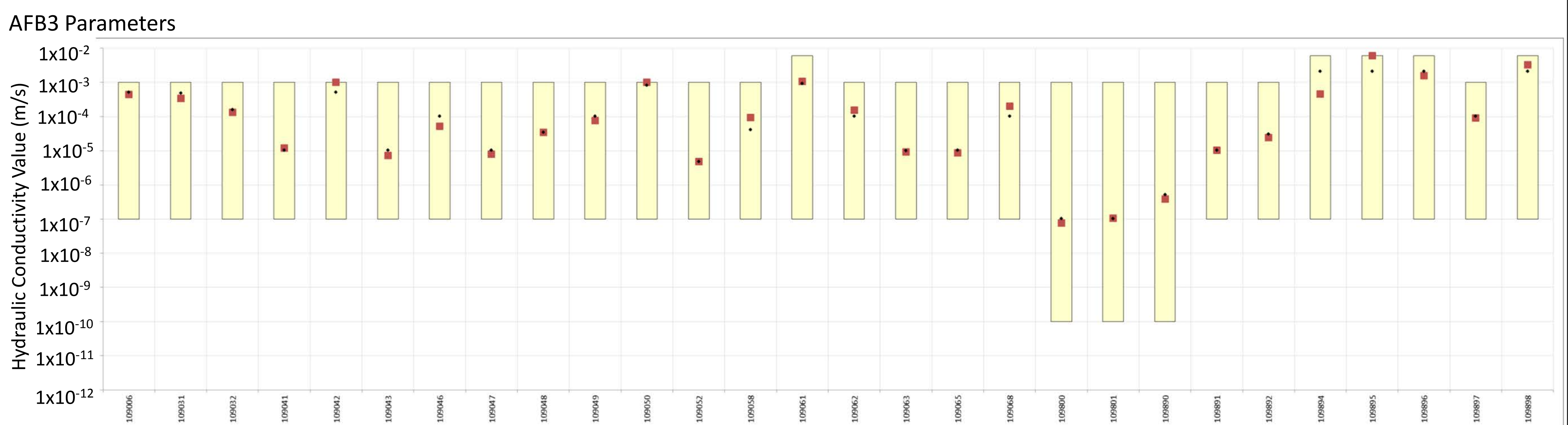

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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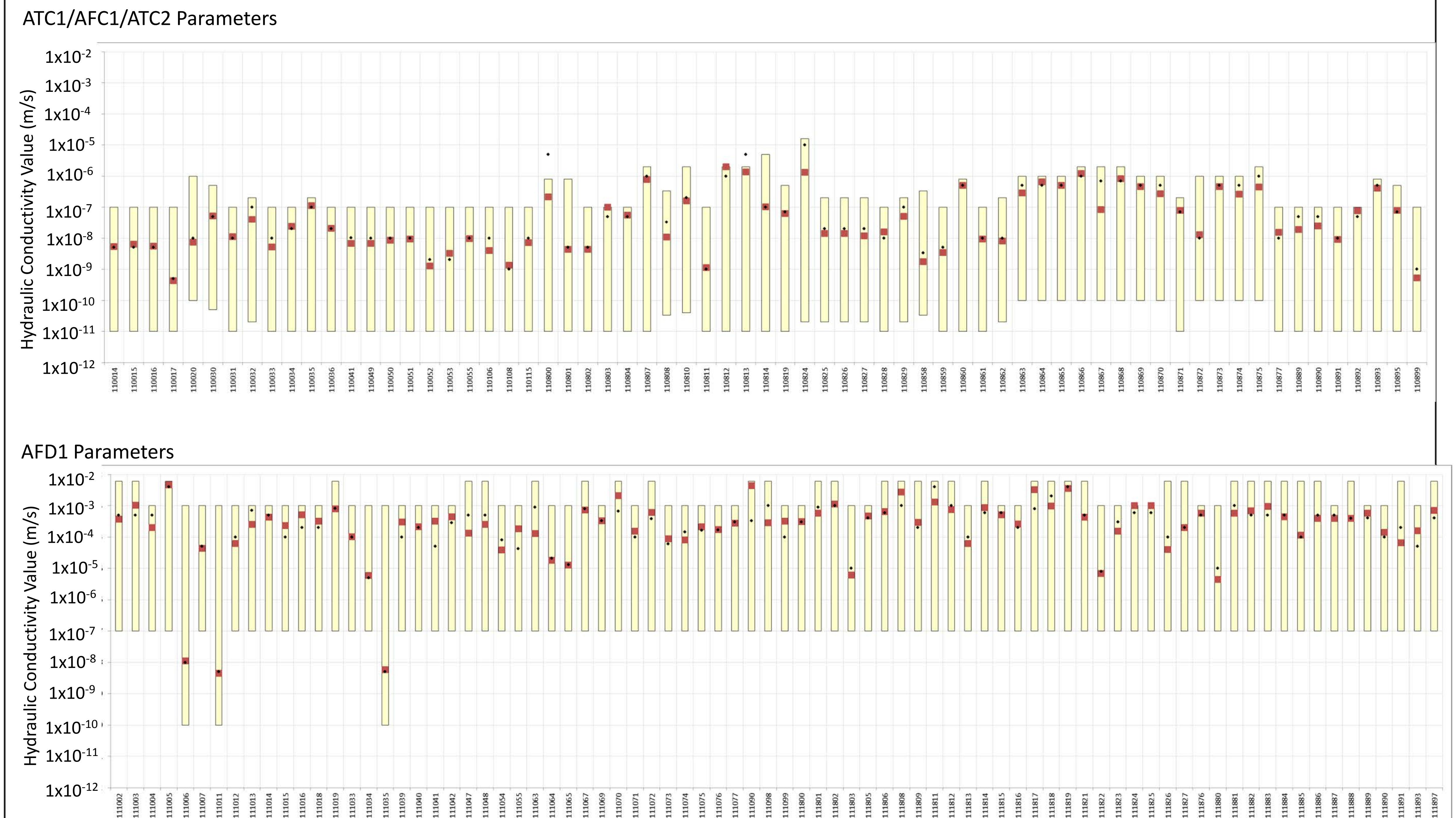
Figure 23: Optimized Hydraulic Conductivity for ATB3 and AFB3– Realization 1



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LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Model Value

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Figure 24: Optimized Hydraulic Conductivity for ATC1/AFC1/ATC2 and AFD1– Realization 1

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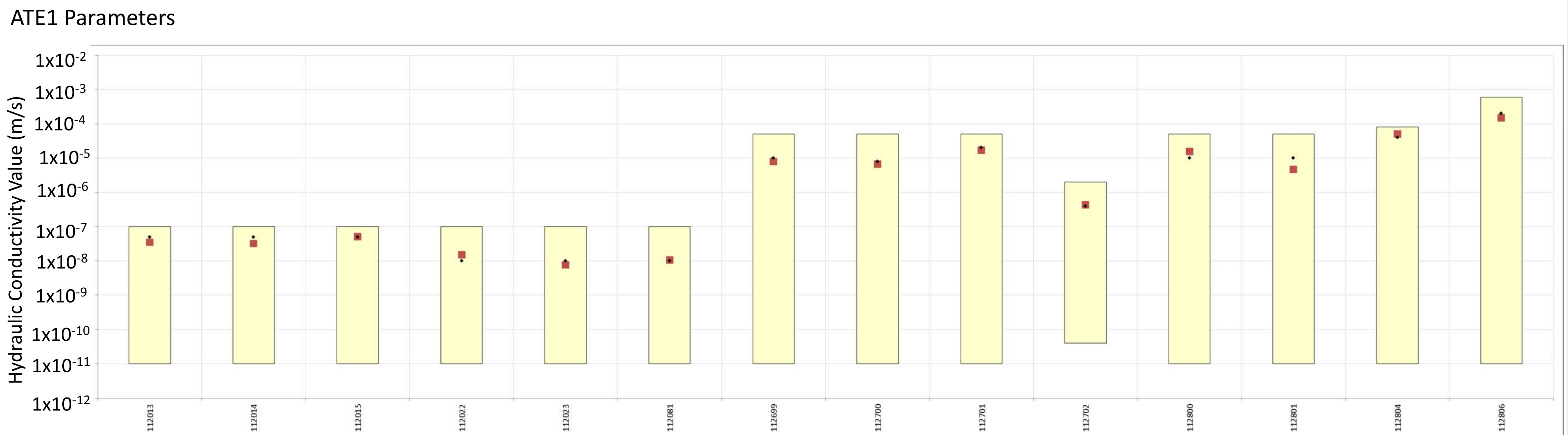

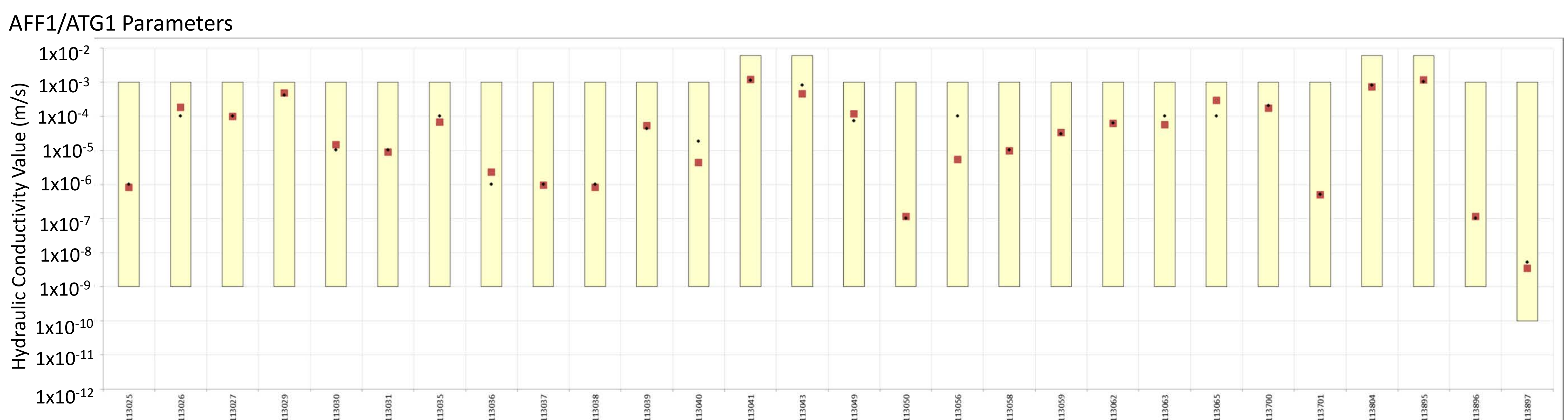

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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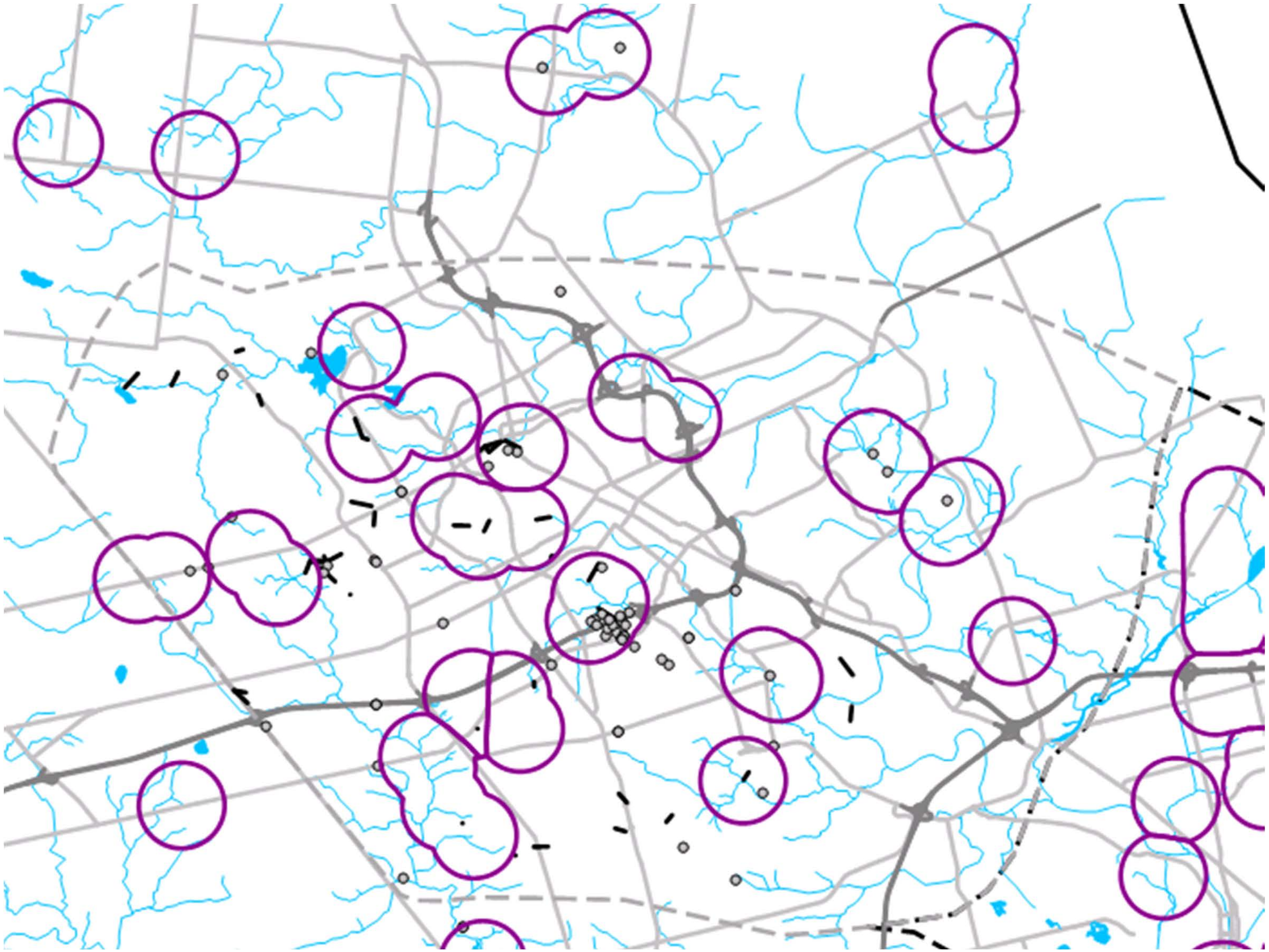
Figure 25: Optimized Hydraulic Conductivity for ATE1 (top) and AFF/ATG1 (bottom) – Realization 1



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

Groundwater Elevation Difference across Aquitard at Multi-level Monitoring Well

Groundwater Elevation Difference across nearby Monitoring Wells

N

0 5 km

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Figure 26: Groundwater Level Elevation Difference Across Aquitards – Regional Model

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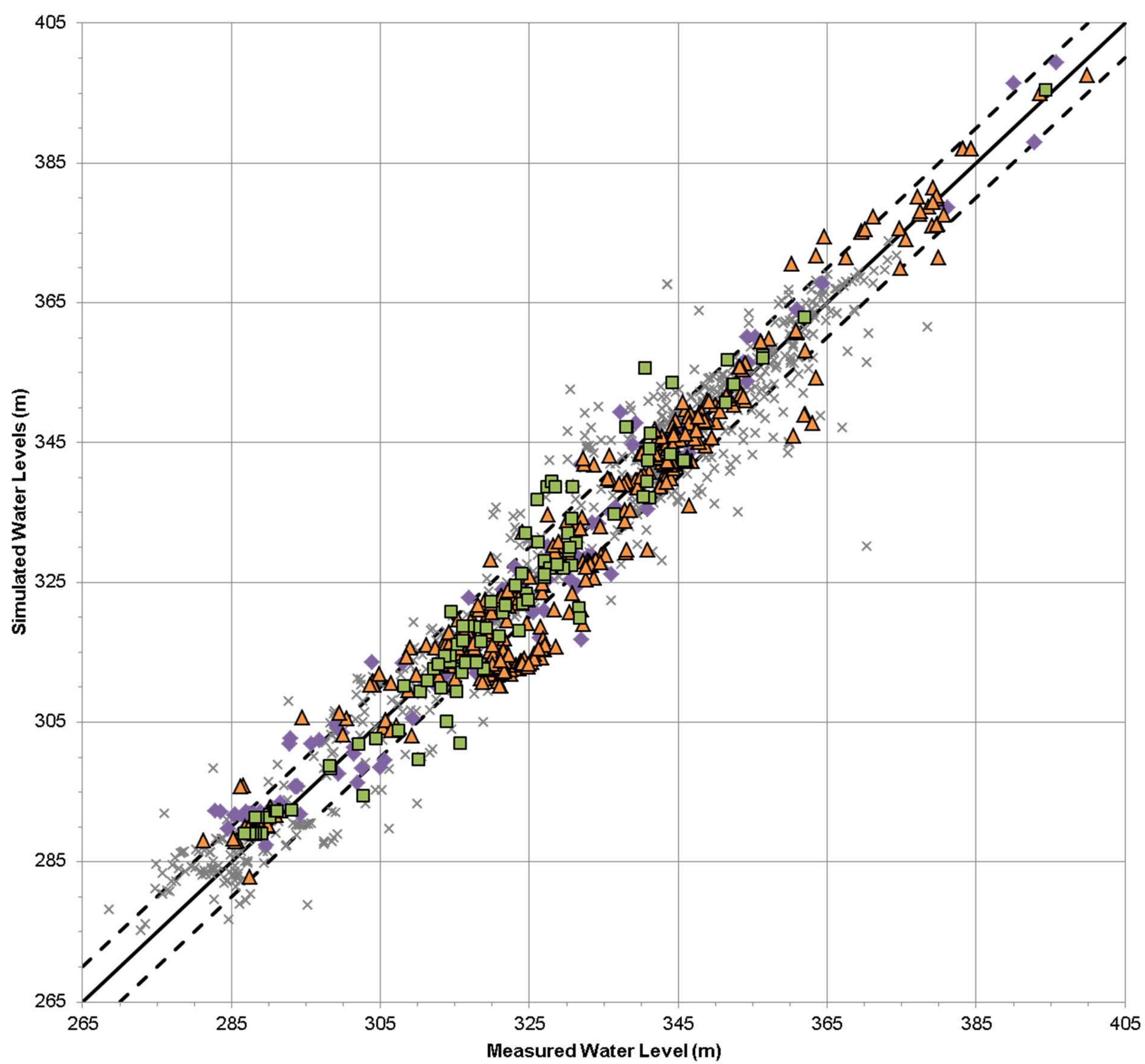

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- High Quality
- Medium- High Quality
- Medium Low Quality
- Low Quality

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Figure 27: Simulated vs Observed Groundwater Level Elevations – Realization 2

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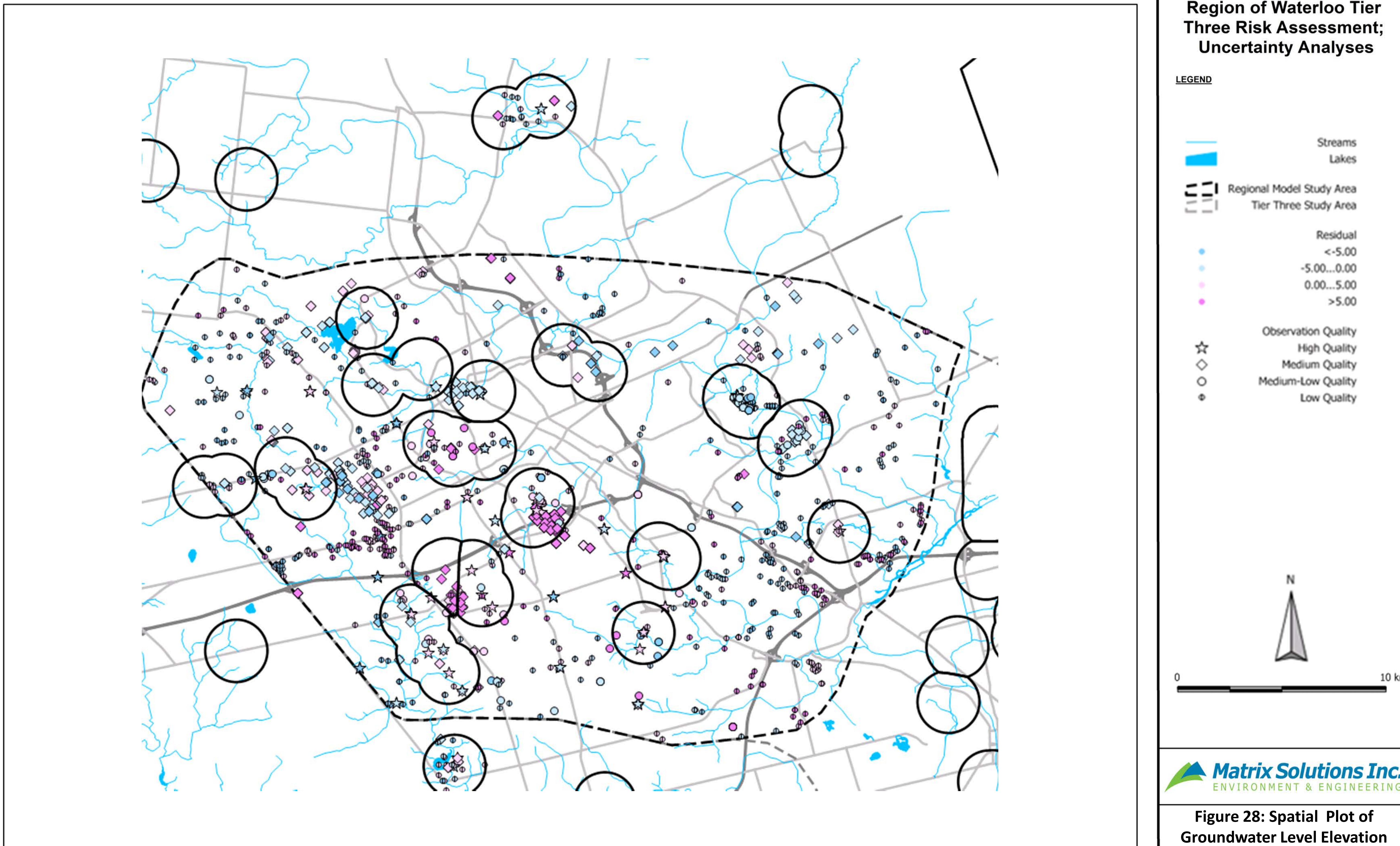

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Figure 28: Spatial Plot of Groundwater Level Elevation Residuals – Realization 2

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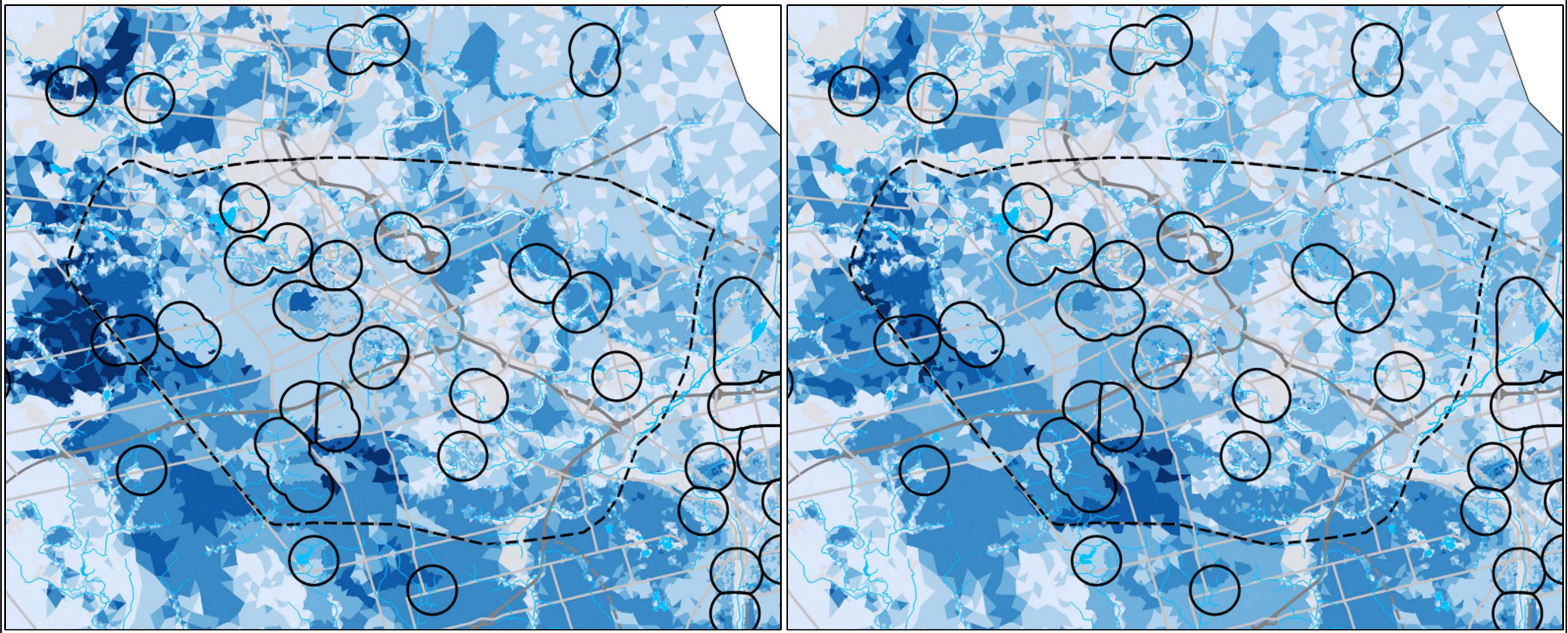
Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

Base Case (Calibrated Model) Recharge Distribution

Optimized Recharge Distribution- Realization 2



LEGEND

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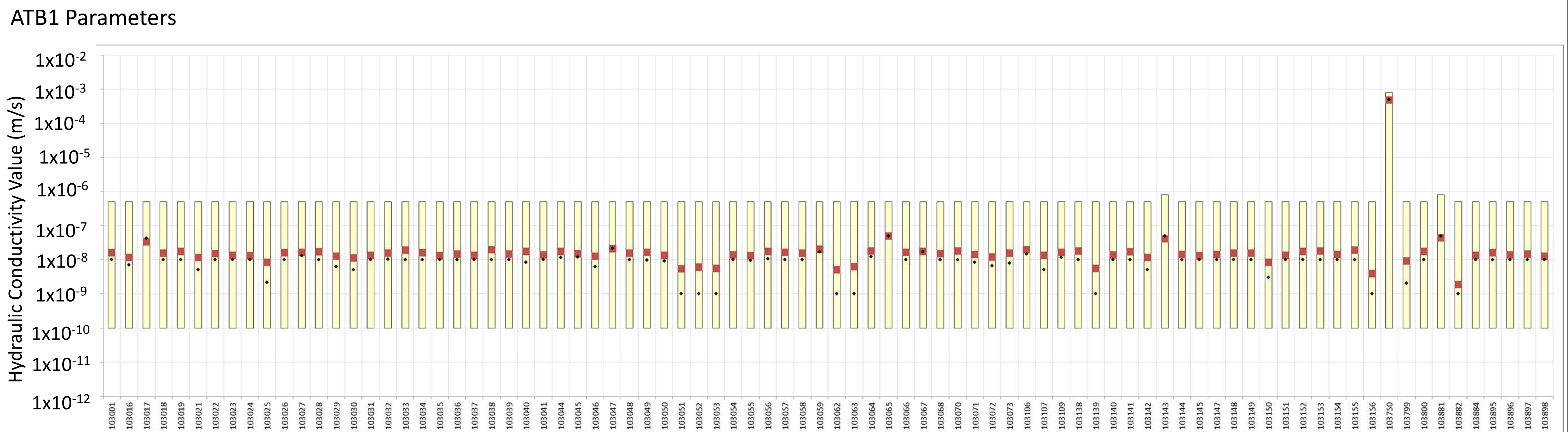
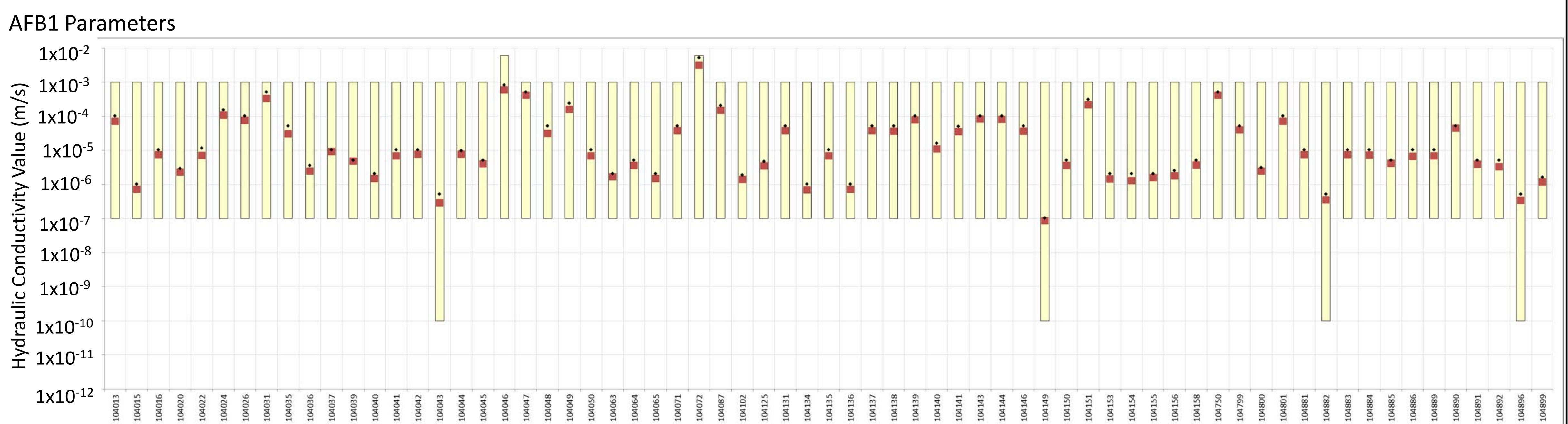
Figure 29: Base Case Model and Optimized Recharge Distribution- Realization 2





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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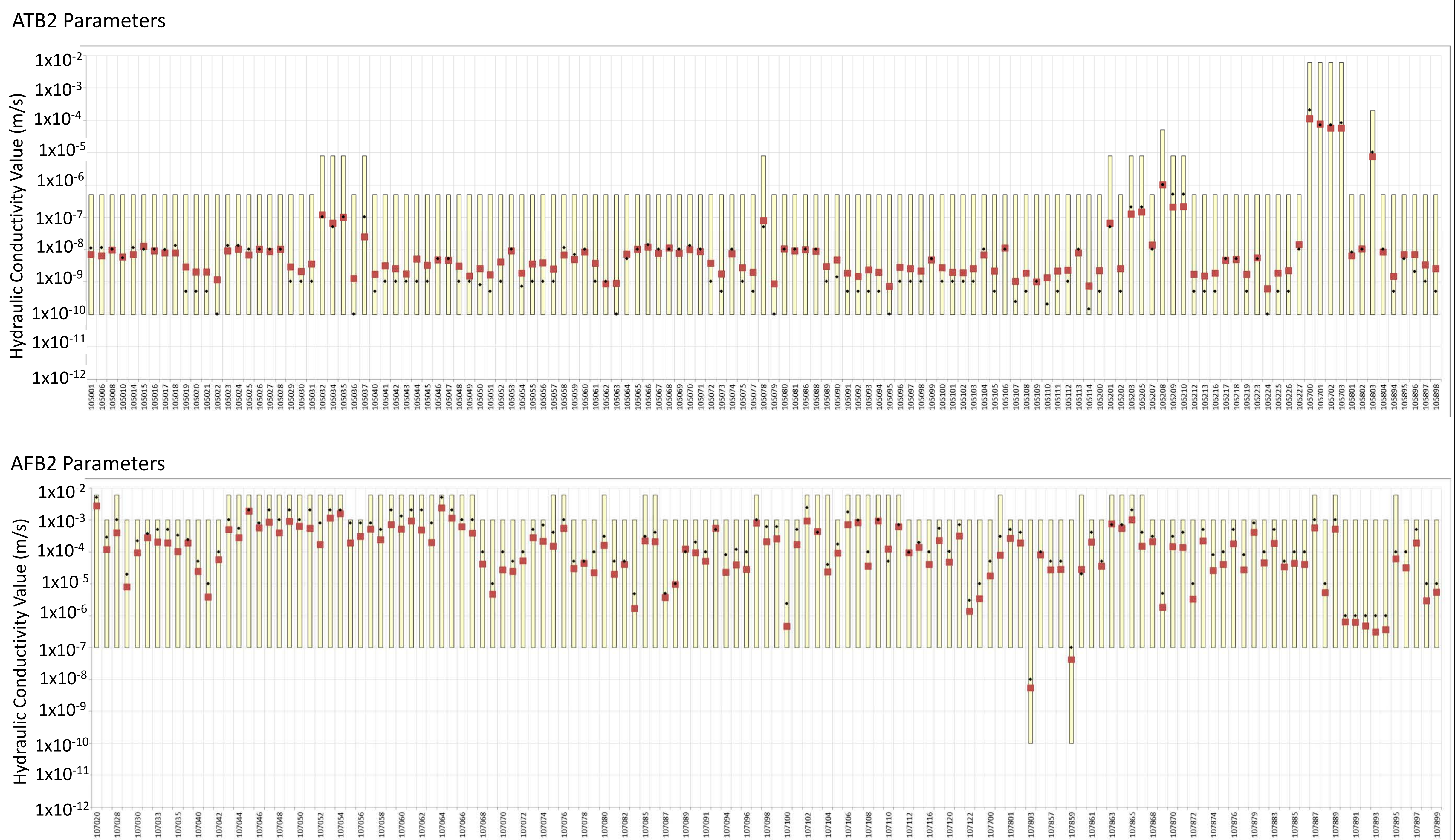
Figure 30: Optimized Hydraulic Conductivity for ATB1 and AFB1– Realization 2



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Model Value

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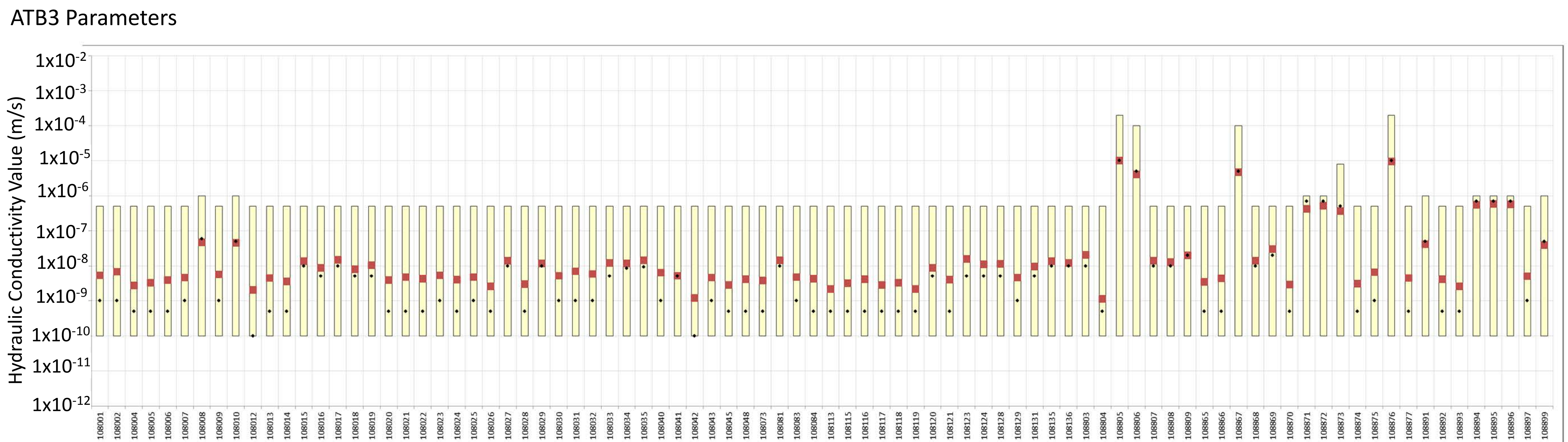
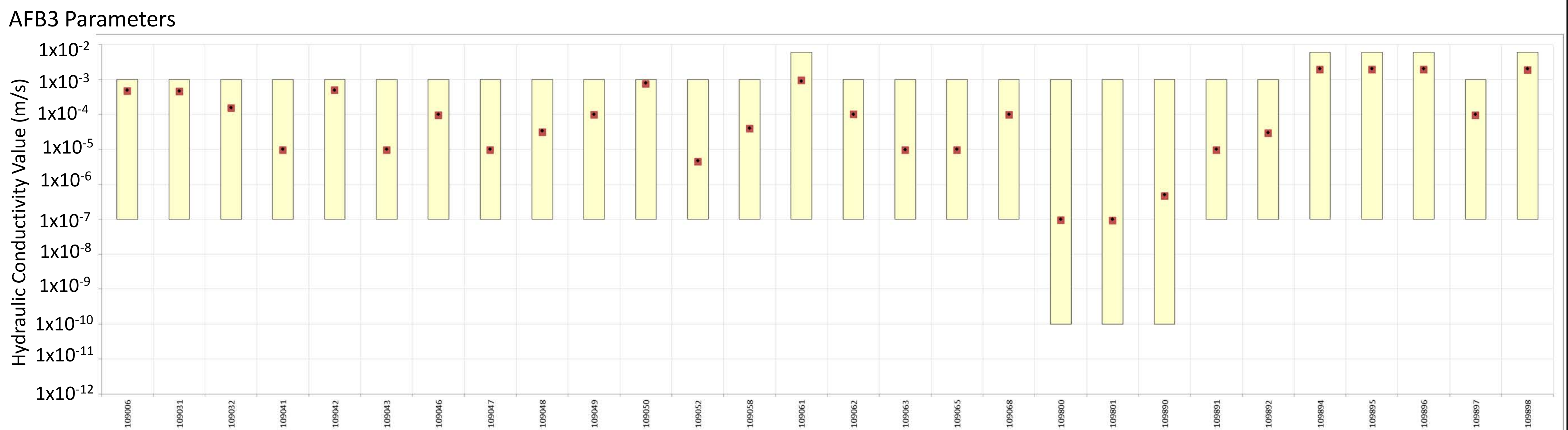
Figure 31: Optimized Hydraulic Conductivity for ATB2 and AFB2– Realization 2





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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Figure 32: Optimized Hydraulic Conductivity for ATB3 and AFB3–Realization 2

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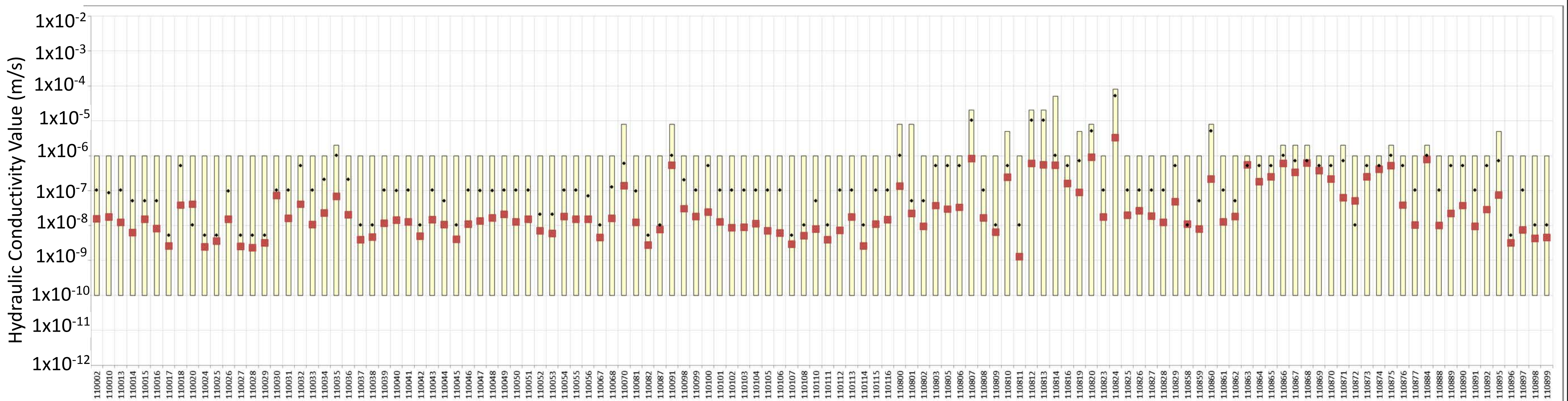
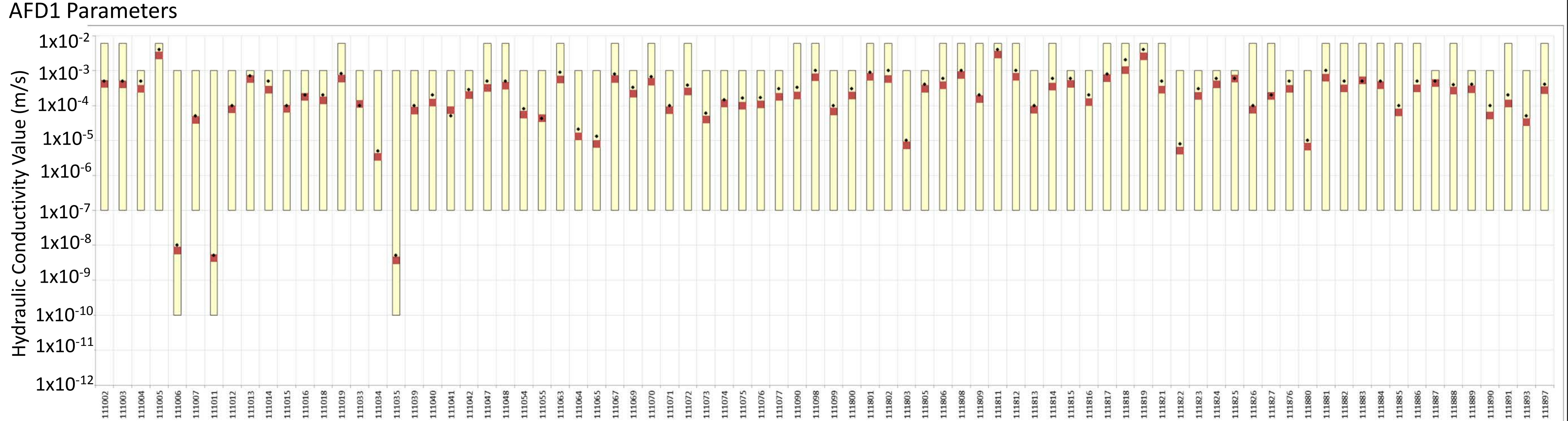
ATC1/AFC1/ATC2 Parameters



AFD1 Parameters



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Model Value

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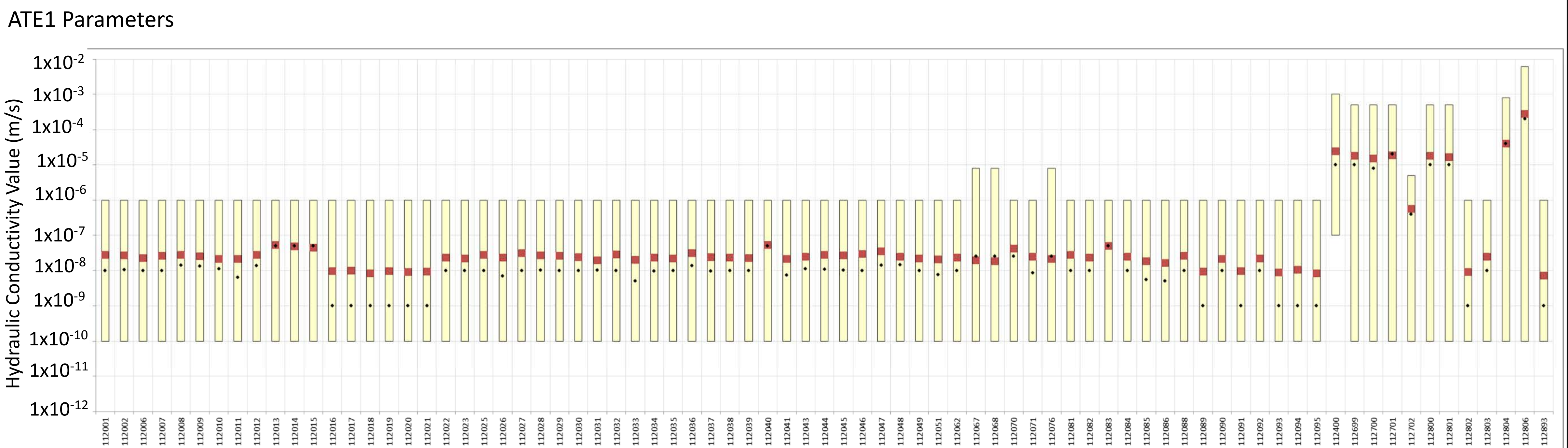
Figure 33: Optimized Hydraulic Conductivity for ATC1/AFC1/ATC2 and AFD1 – Realization 2

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses



LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

Matrix Solutions Inc.
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Figure 34: Optimized Hydraulic for ATE1 – Realization 2

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

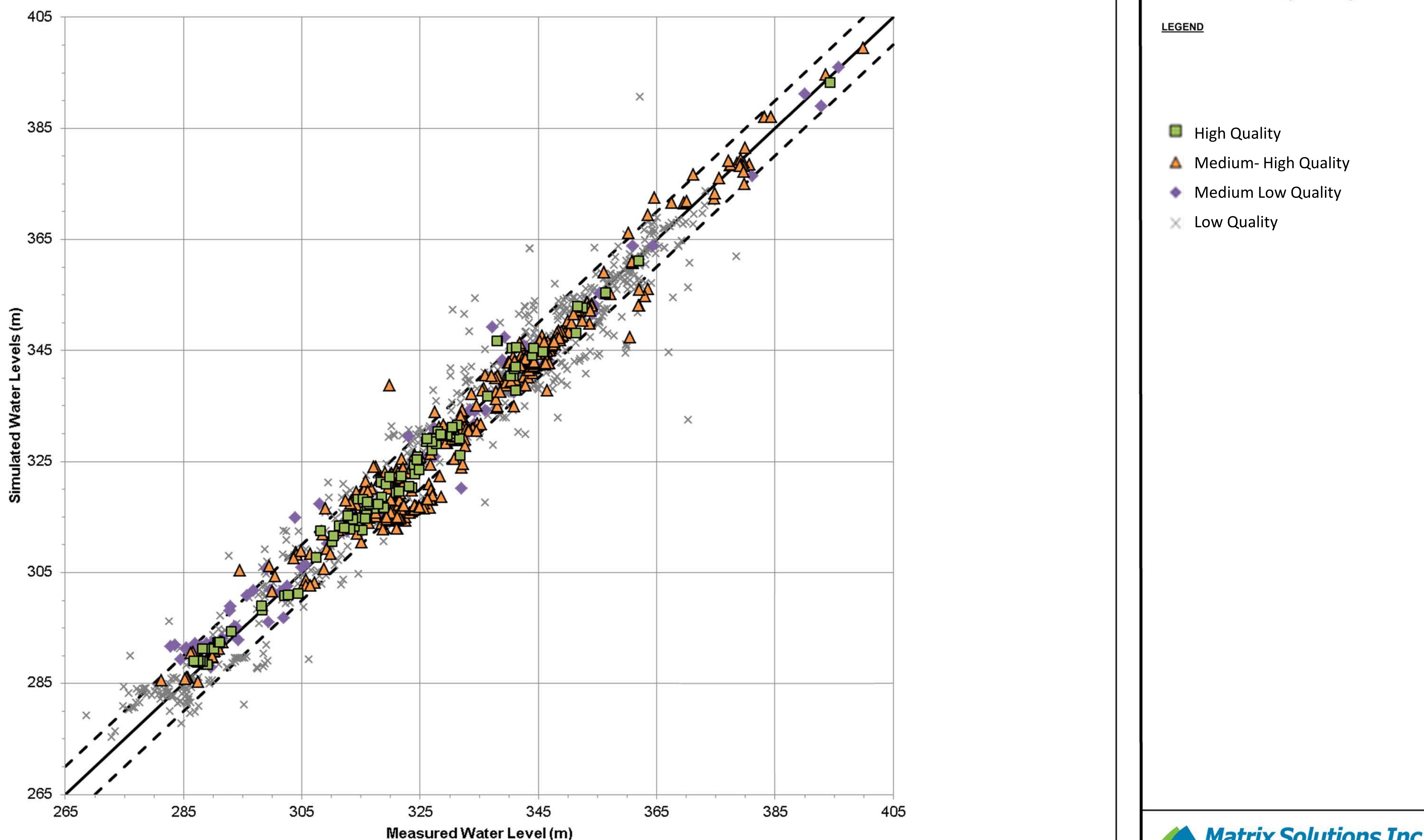

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Figure 35: Simulated vs Observed Groundwater Level Elevations – Realization 3

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

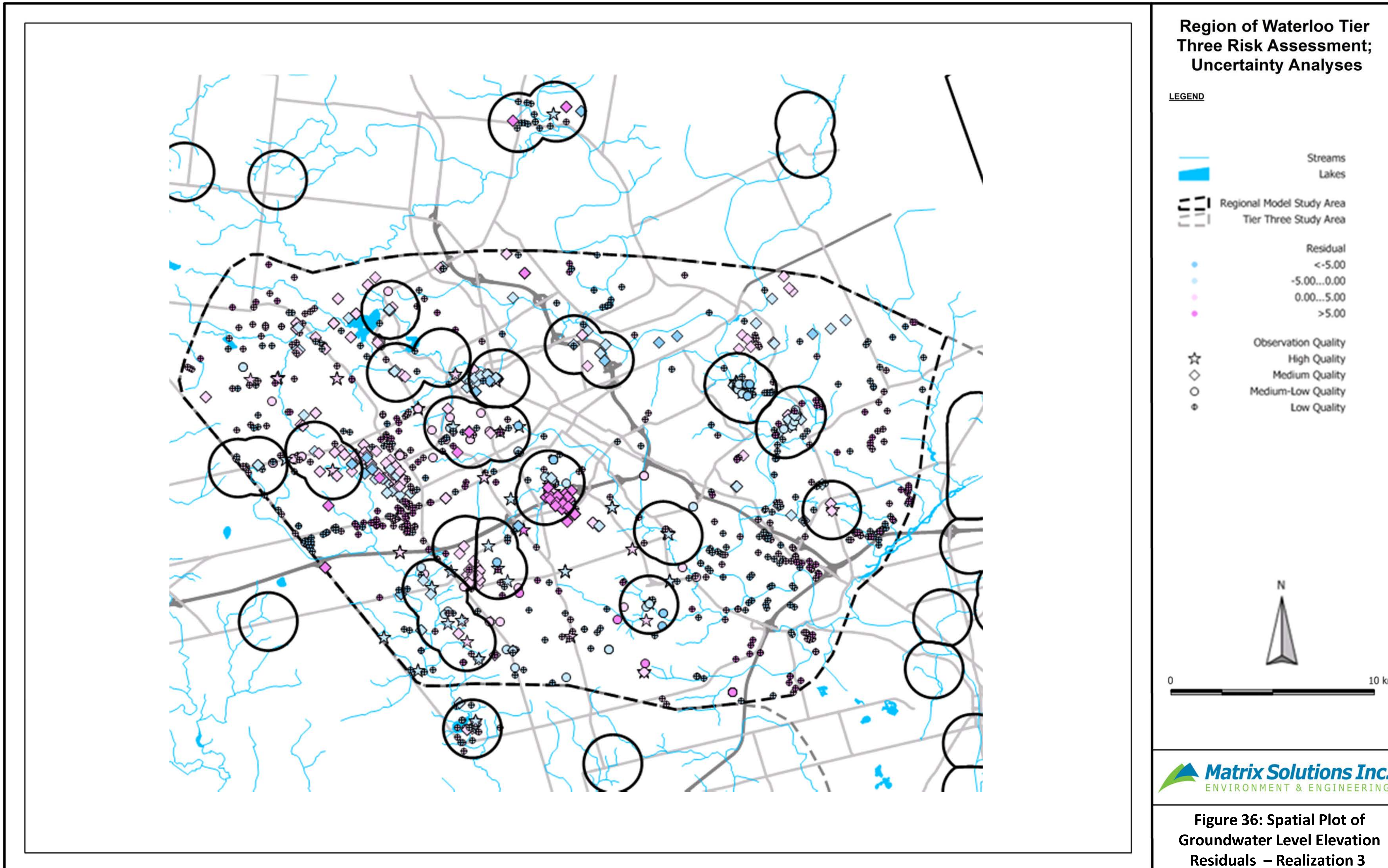
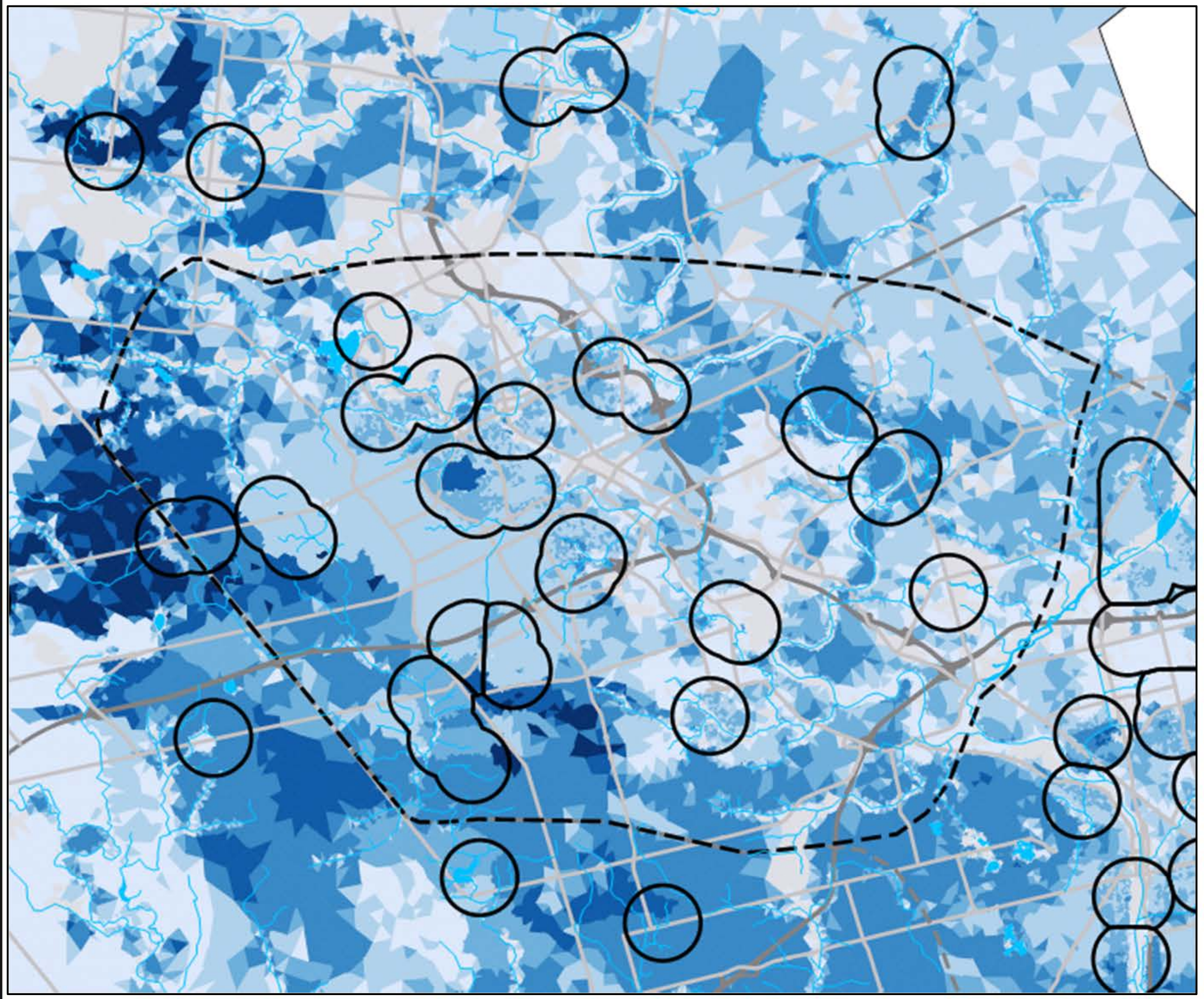
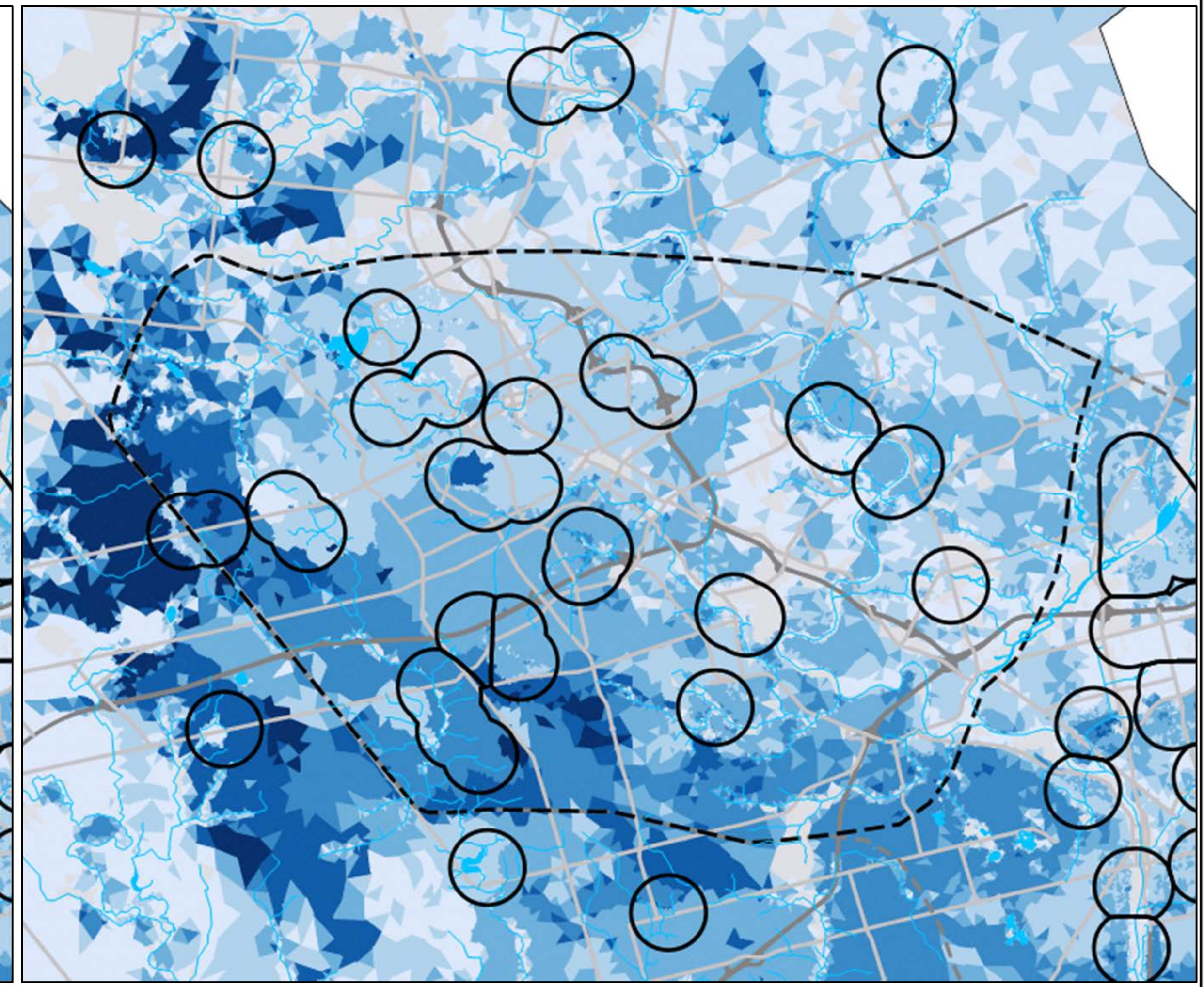


Figure 36: Spatial Plot of Groundwater Level Elevation Residuals – Realization 3

Base Case (Calibrated Model) Recharge Distribution



Optimized Recharge Distribution- Realization 3



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

Streams
Lakes
Regional Model Study Area
Tier Three Study Area

Recharge (mm/yr)
<50
50...100
100...200
200...300
300...400
400...500
>500

N

0 10 km

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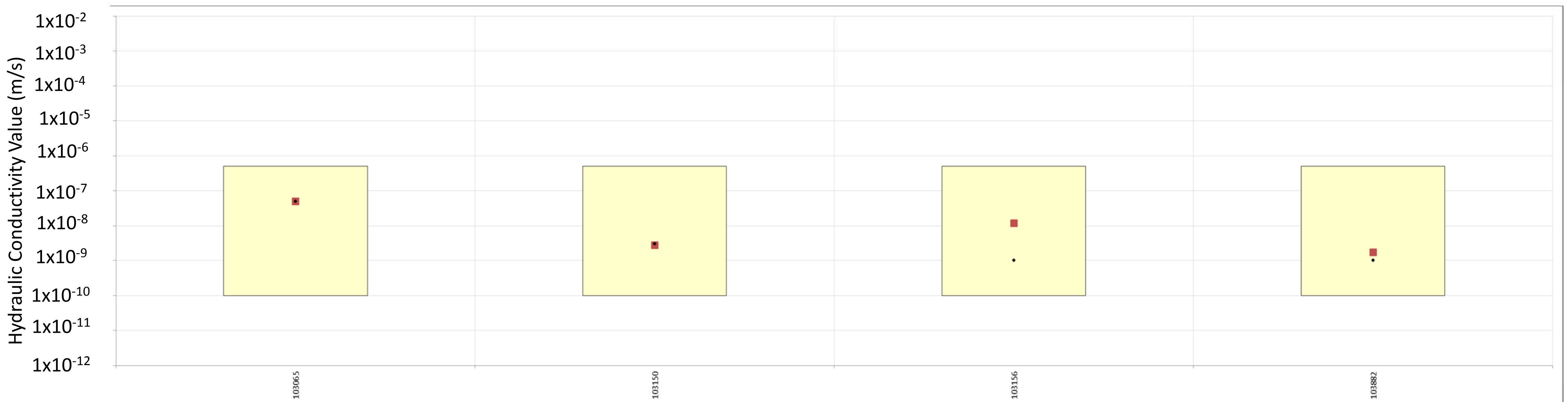
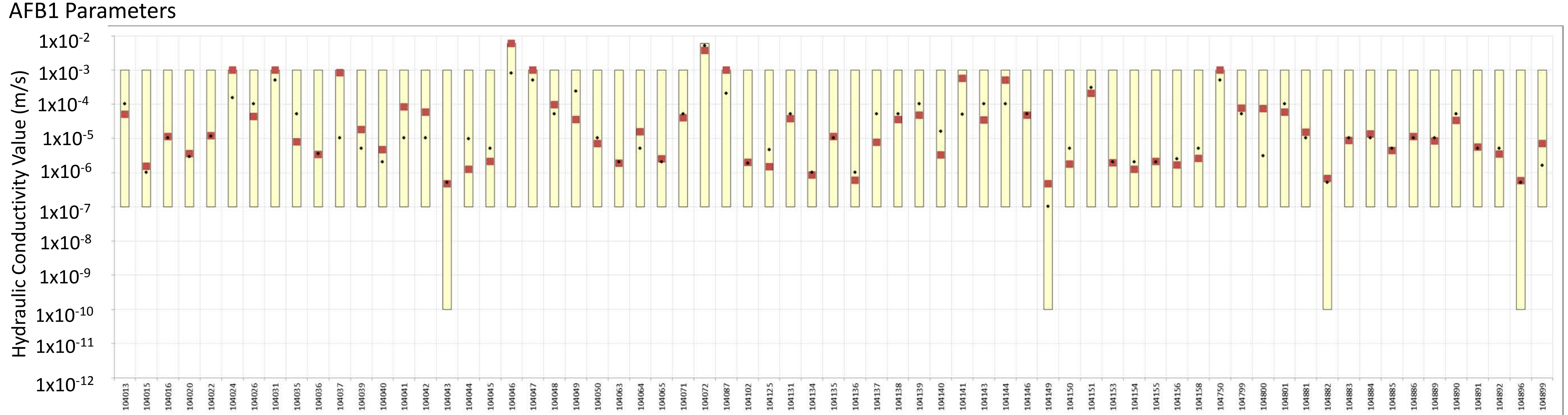
Figure 37: Base Case Model and Optimized Recharge Distribution– Realization 3

ATB1 Parameters



AFB1 Parameters



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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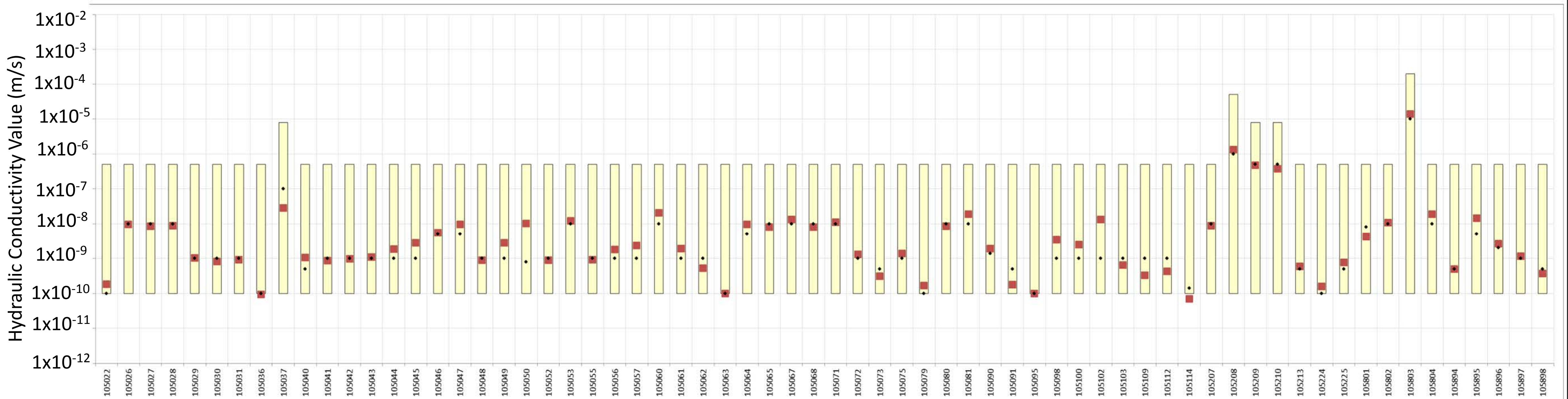
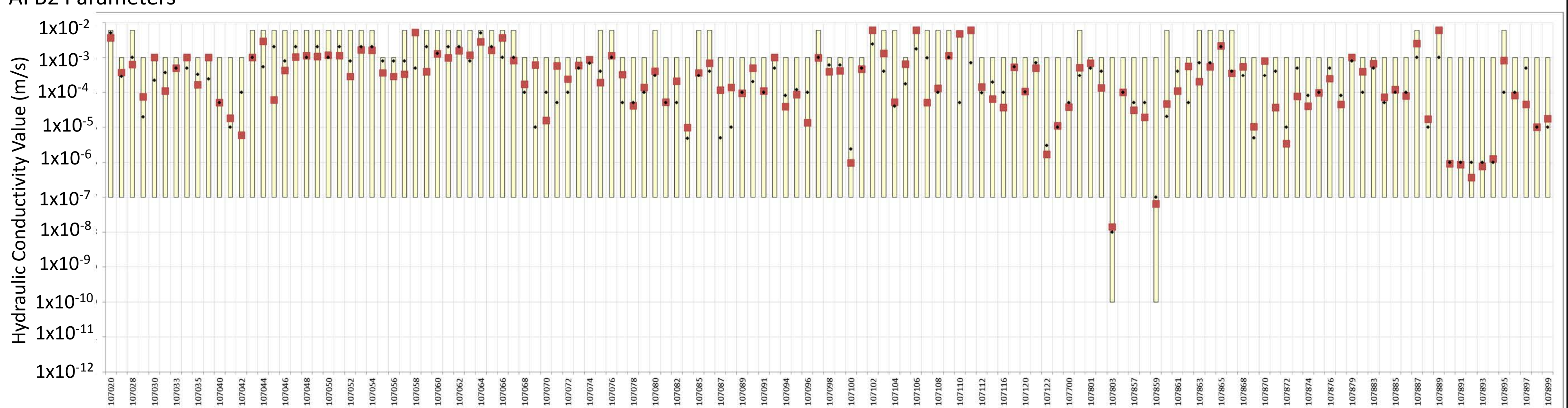
Figure 38: Optimized Hydraulic Conductivity for ATB1 and AFB1– Realization 3

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

ATB2 Parameters



AFB2 Parameters



LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Model Value

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Figure 39: Optimized Hydraulic Conductivity for ATB2 and AFB2– Realization 3

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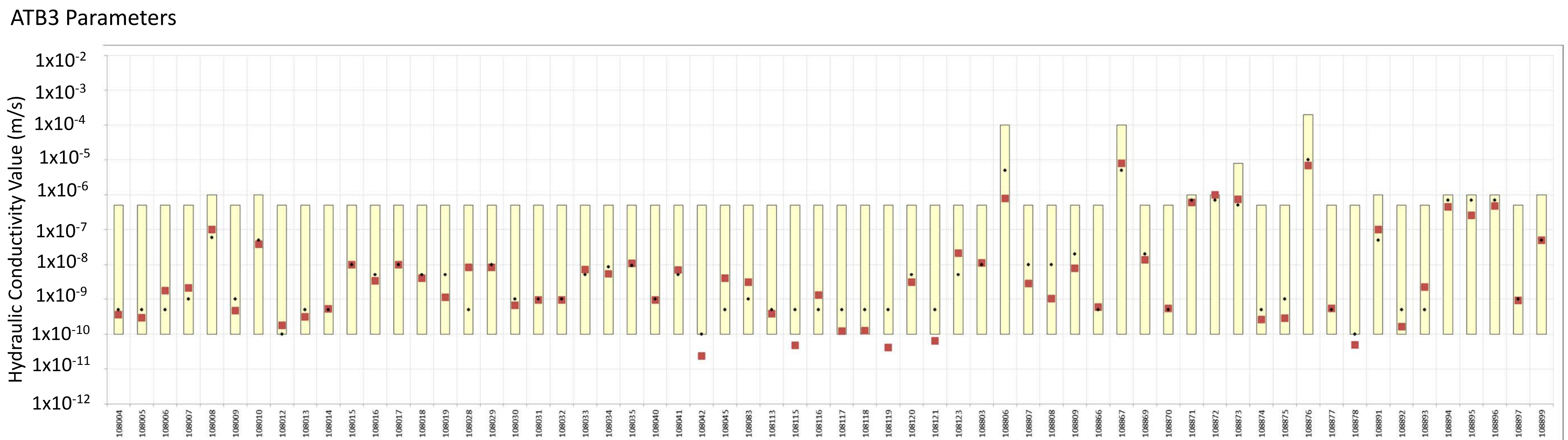
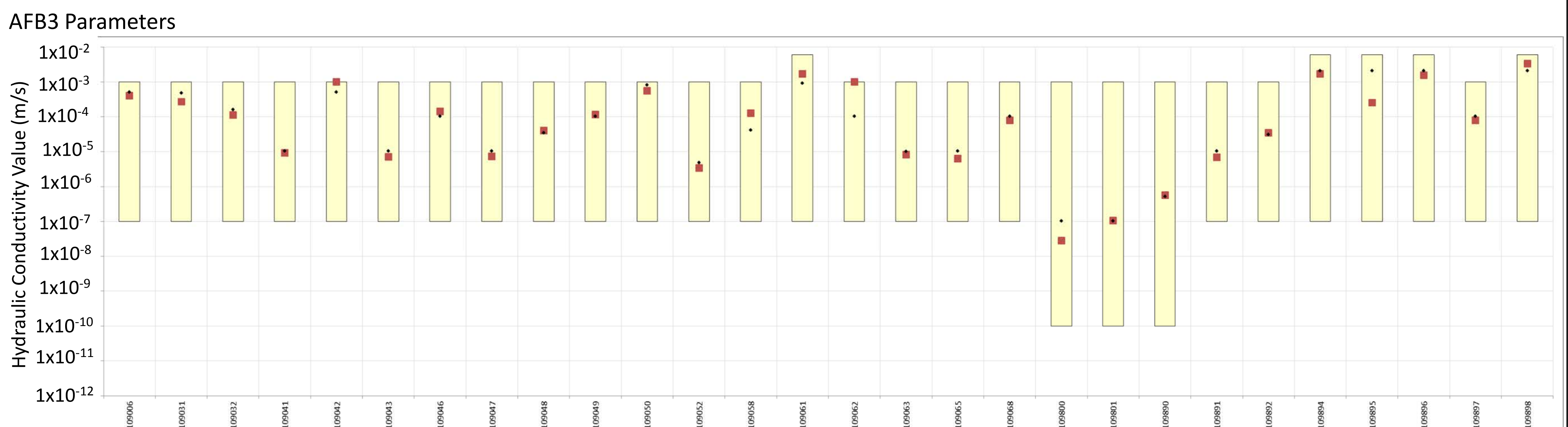
Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses





LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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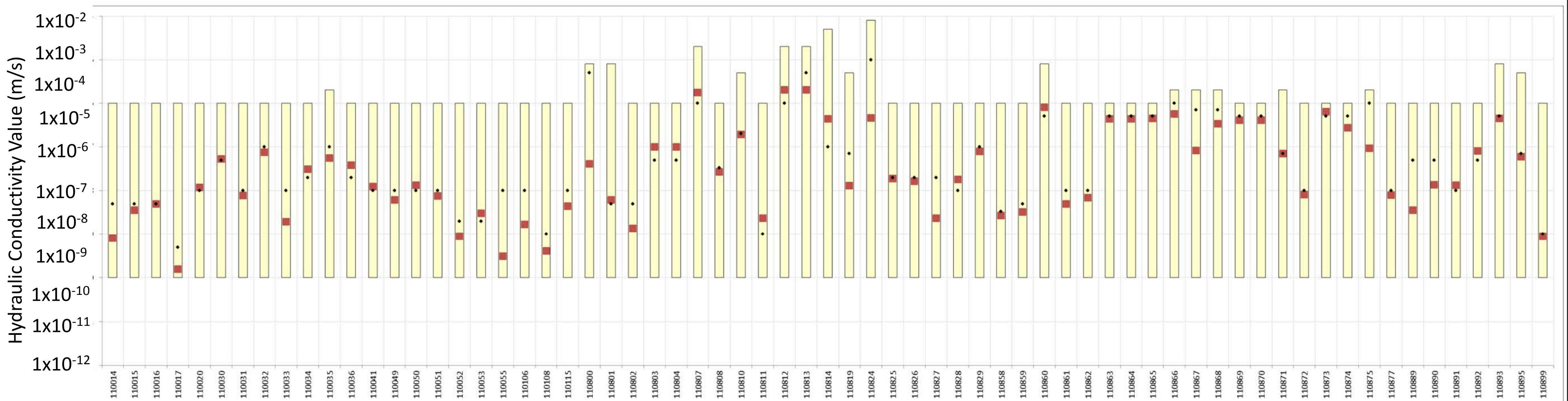
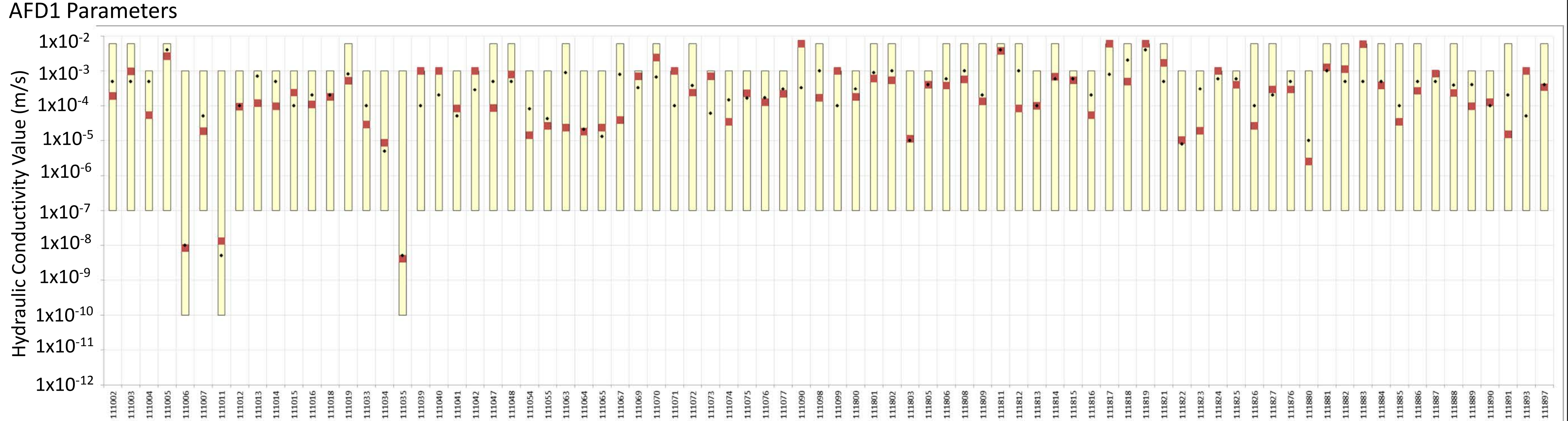
Figure 40: Optimized Hydraulic Conductivity for ATB3 and AFB3–Realization 3

ATC1/AFC1/ATC2 Parameters



AFD1 Parameters



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Model Value

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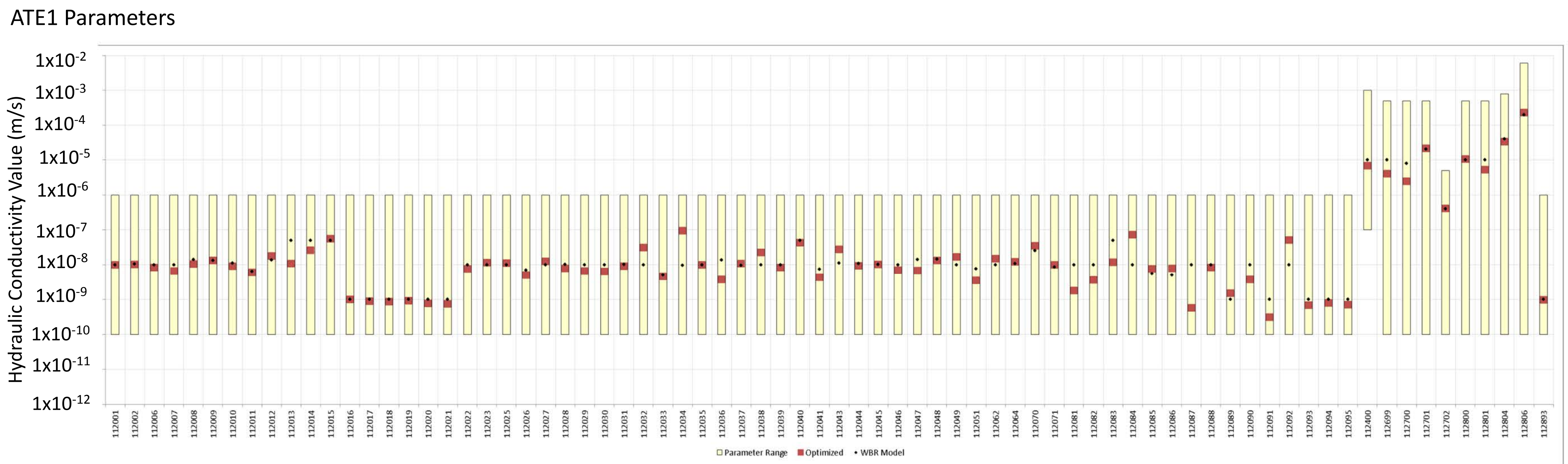
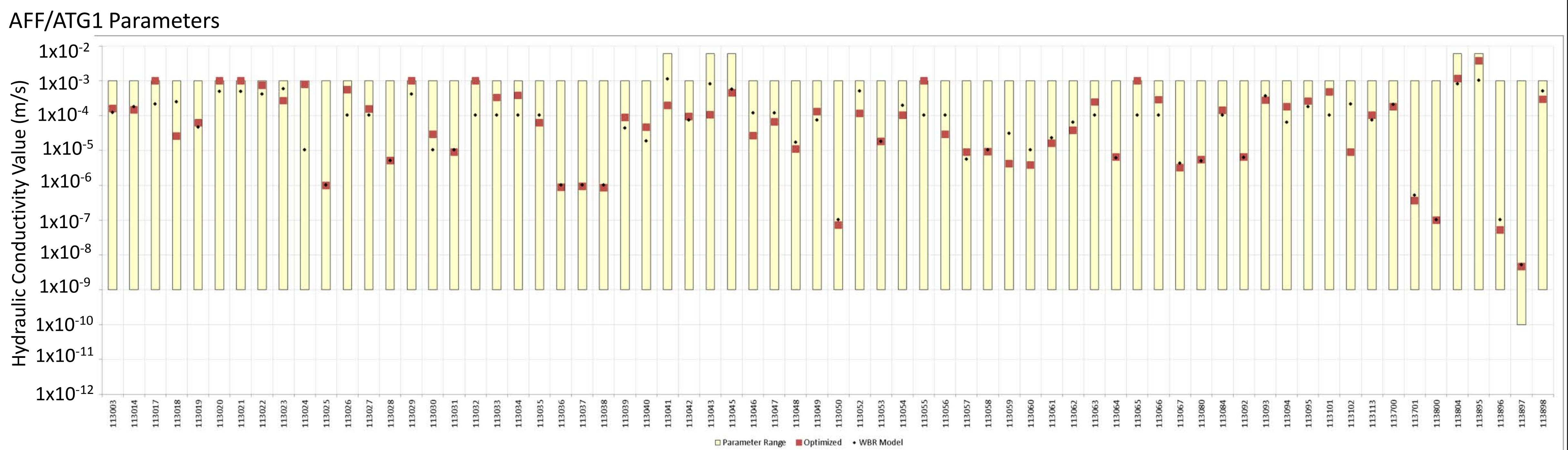
Figure 41: Optimized Hydraulic Conductivity for ATC1/AFC1/ATC2 and AFD1 – Realization 3





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Model Value

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Figure 42: Optimized Hydraulic Conductivity for ATE1 and AFF/ATG1– Realization 3

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Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

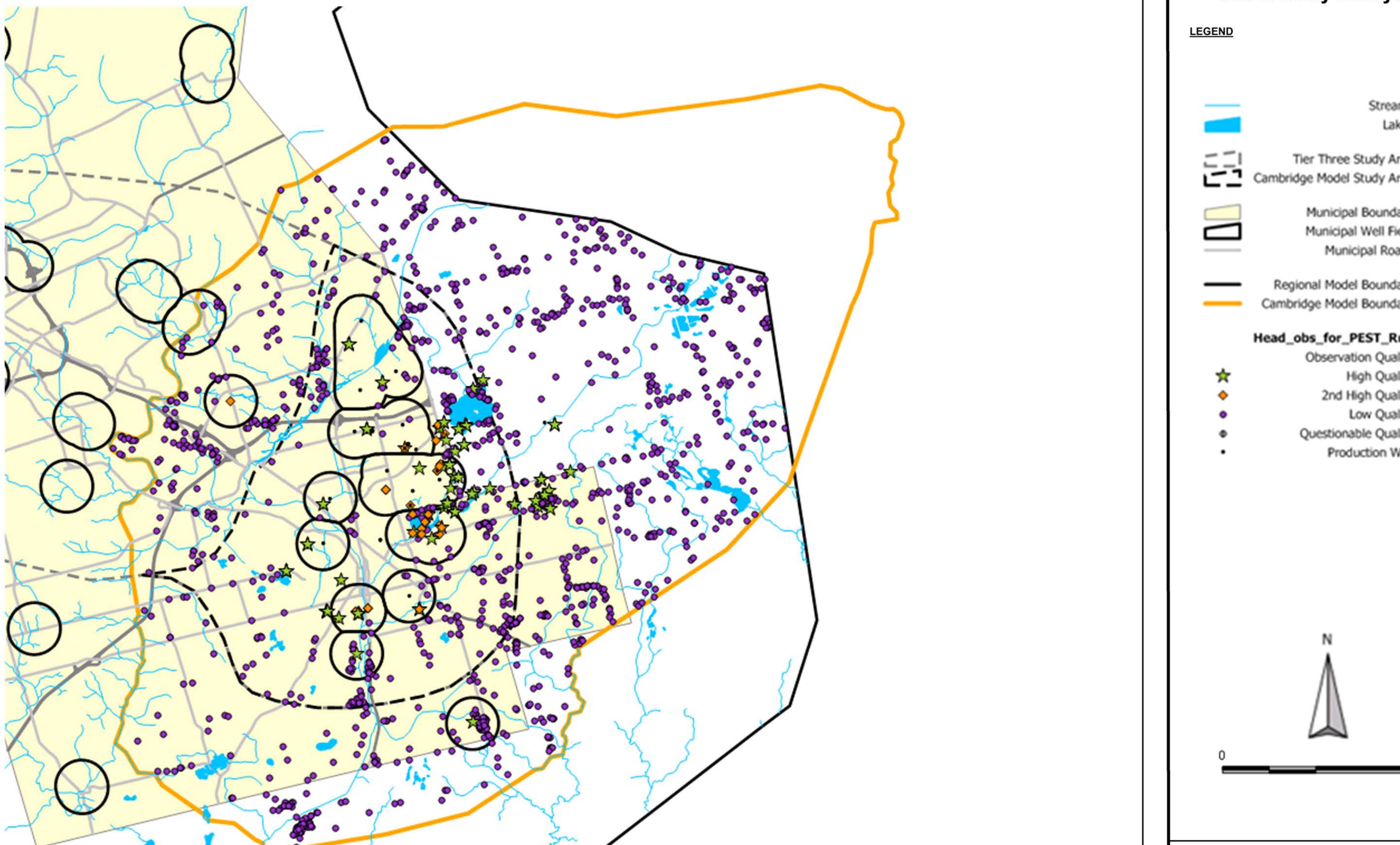

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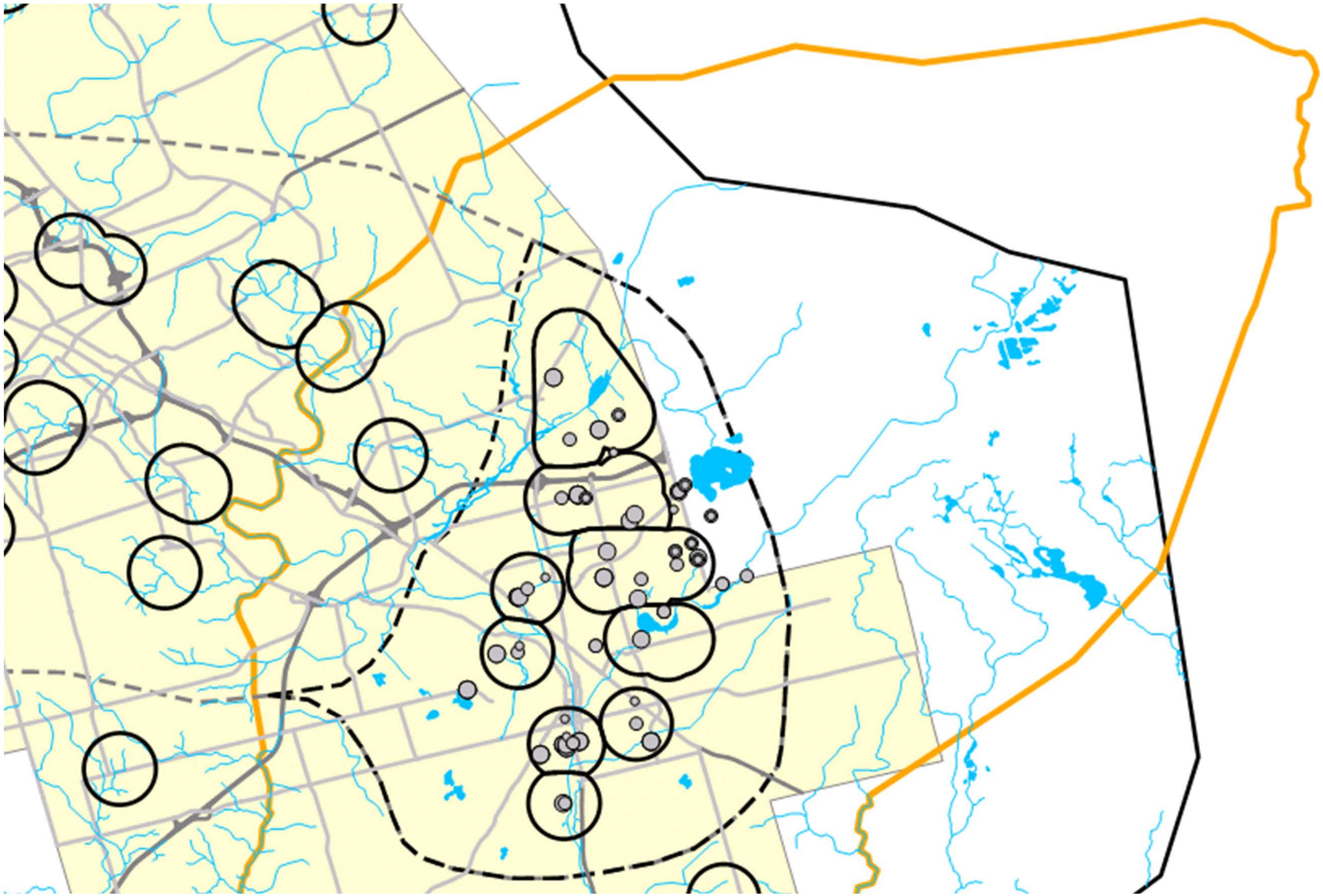
Figure 43: Steady-State Groundwater Level Elevations– Cambridge Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses



LEGEND

Streams
Lakes
Tier Three Study Area
Cambridge Model Study Area
Municipal Boundary
Municipal Well Field
Municipal Roads
Regional Model Boundary
Cambridge Model Boundary
Transient Head Observation
Observation Weight
<2
2...5
5...10
>10

N

0
10 km

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Figure 44: Location of Time-Varying Groundwater Level Elevation Data- Cambridge Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

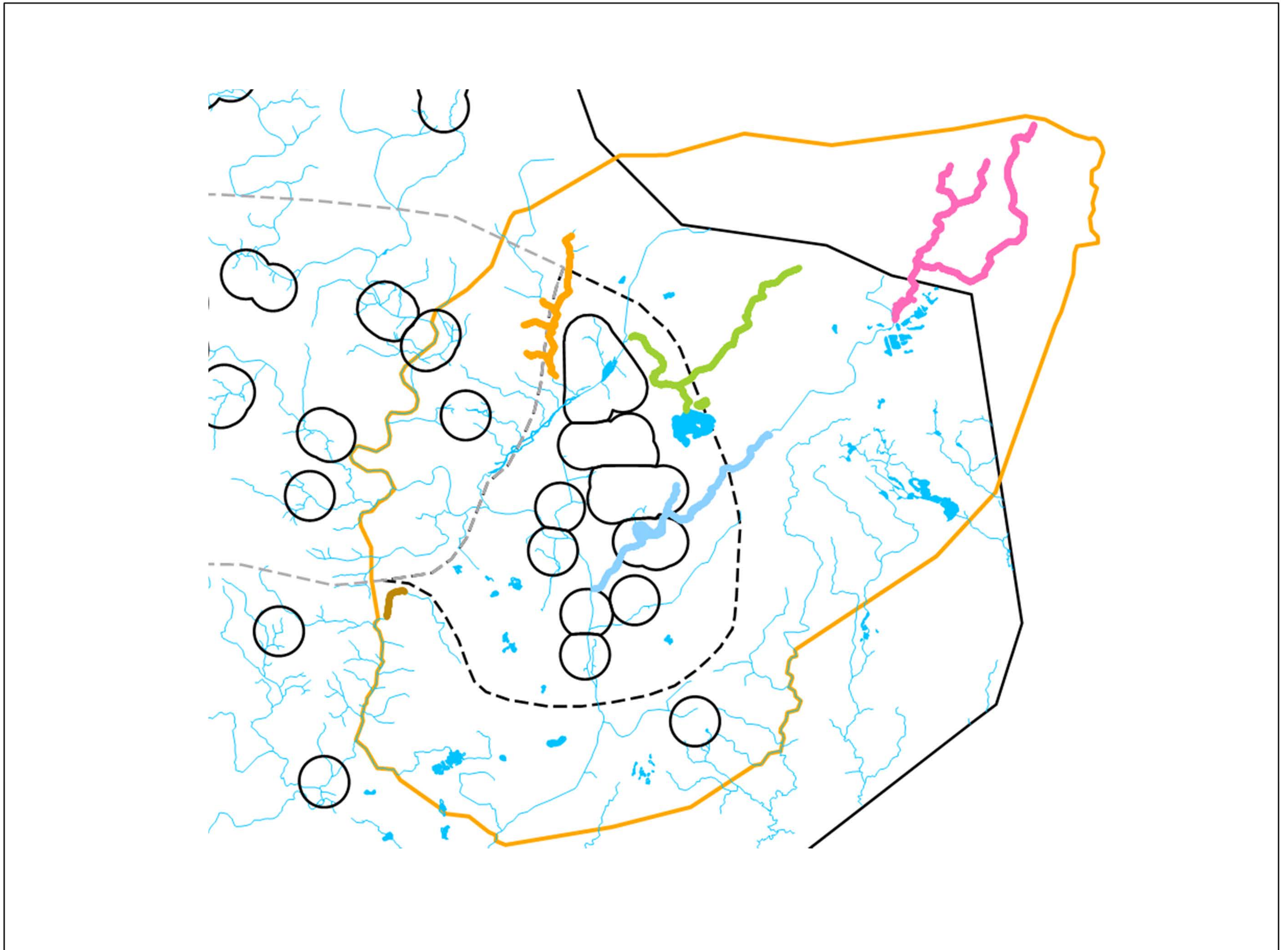

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Figure 45: Assessment Reaches Included in Optimization – Cambridge Model

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

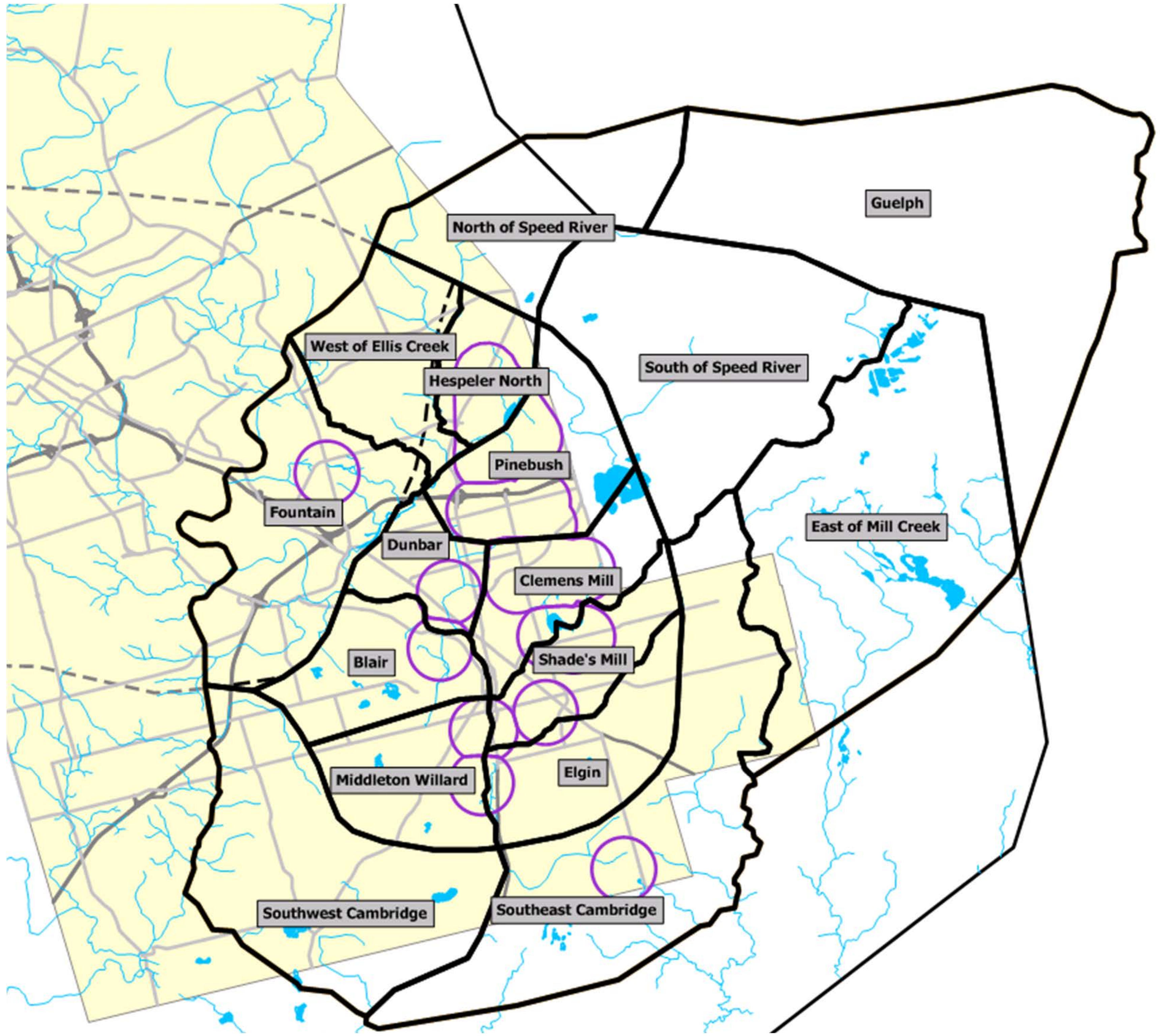

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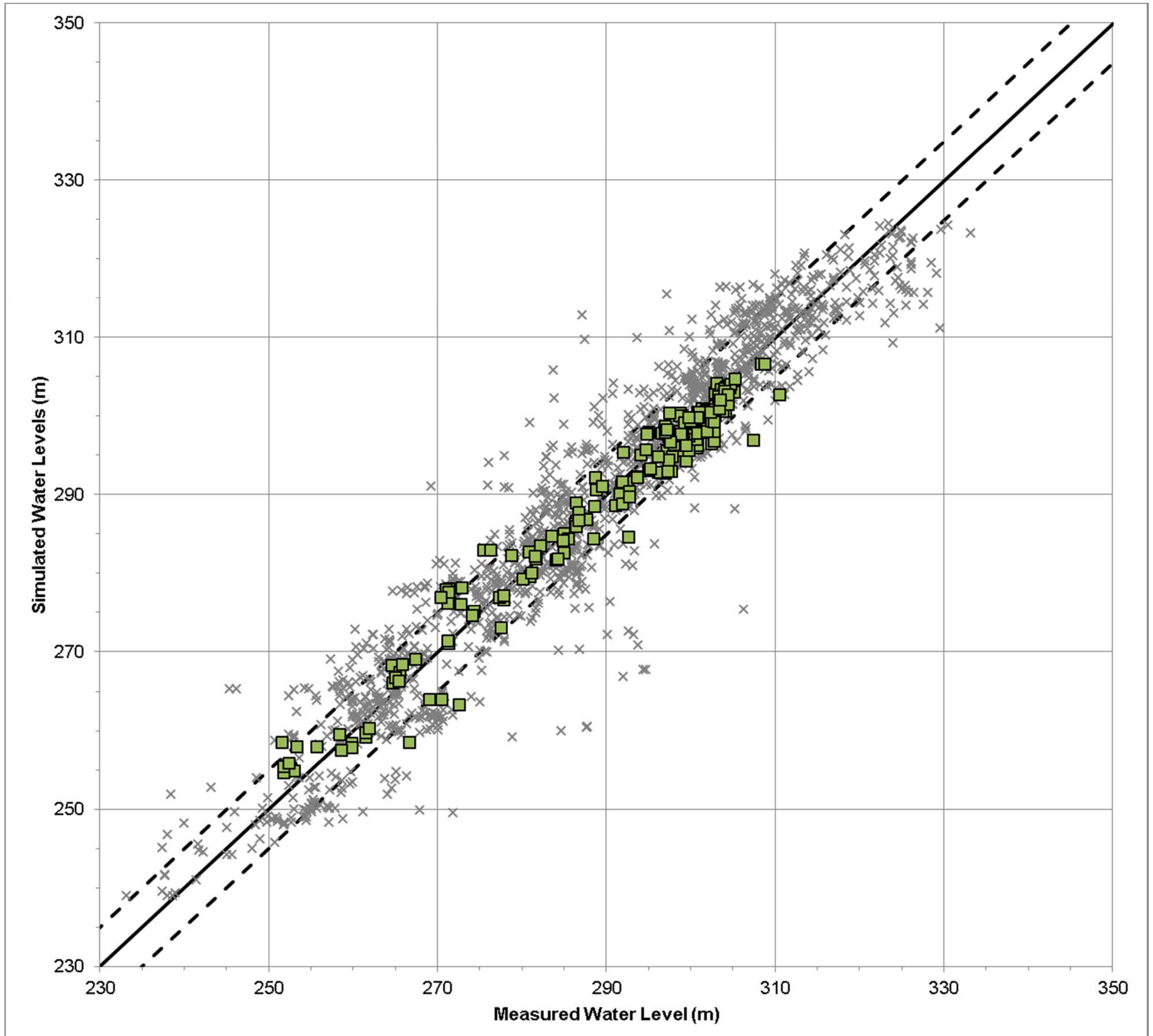
Figure 46: Broad Areas of Recharge Adjustment – Cambridge Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

Low Quality

High Quality

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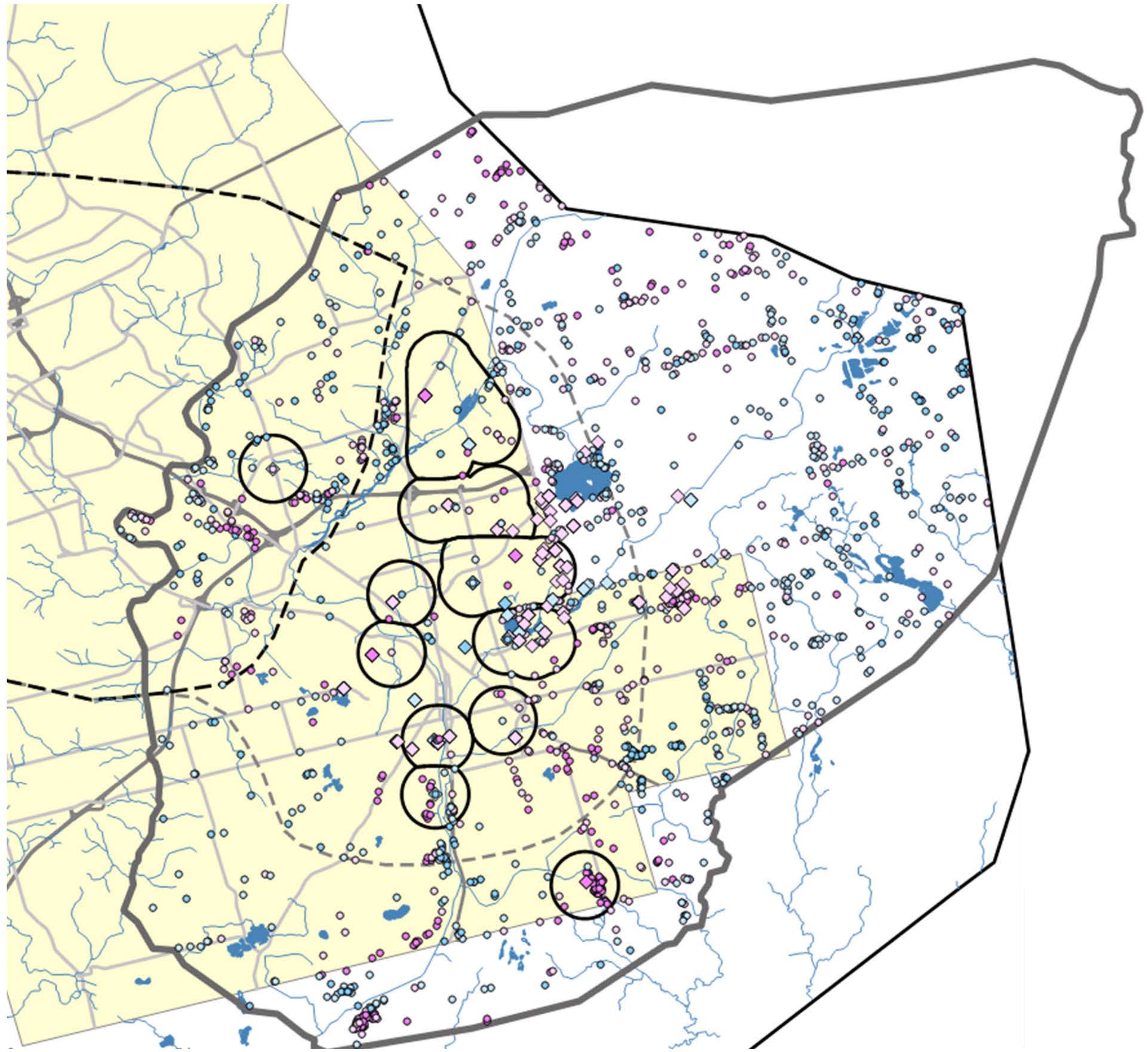
Figure 47: Simulated vs Observed Groundwater Level Elevations– Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

Streams
Lakes
Regional Model Study Area
Tier Three Study Area
Residual
<-5.00
-5.00...0.00
0.00...5.00
>5.00
Observation Quality
High Quality
Low Quality

N

0 10 km

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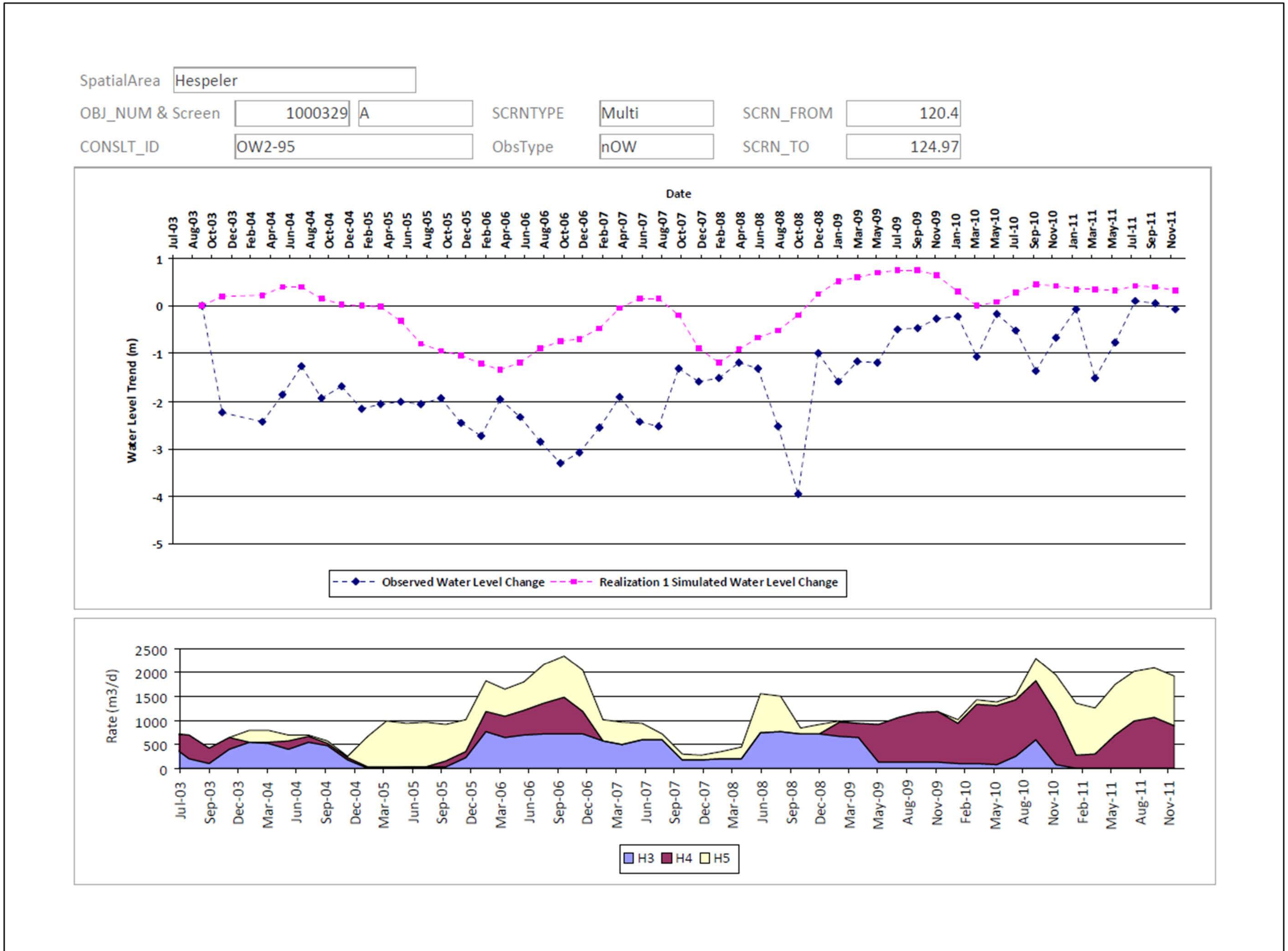
Figure 48: Spatial Plot of Groundwater Level Elevation Residuals – Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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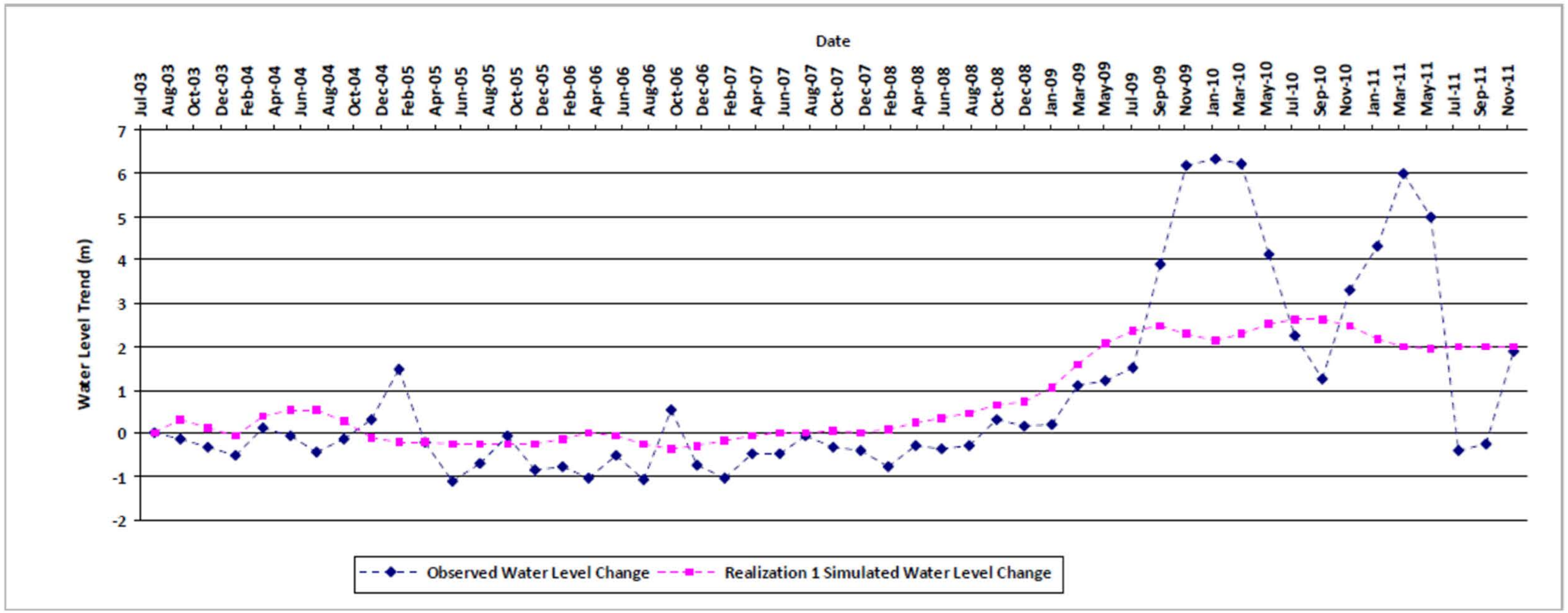
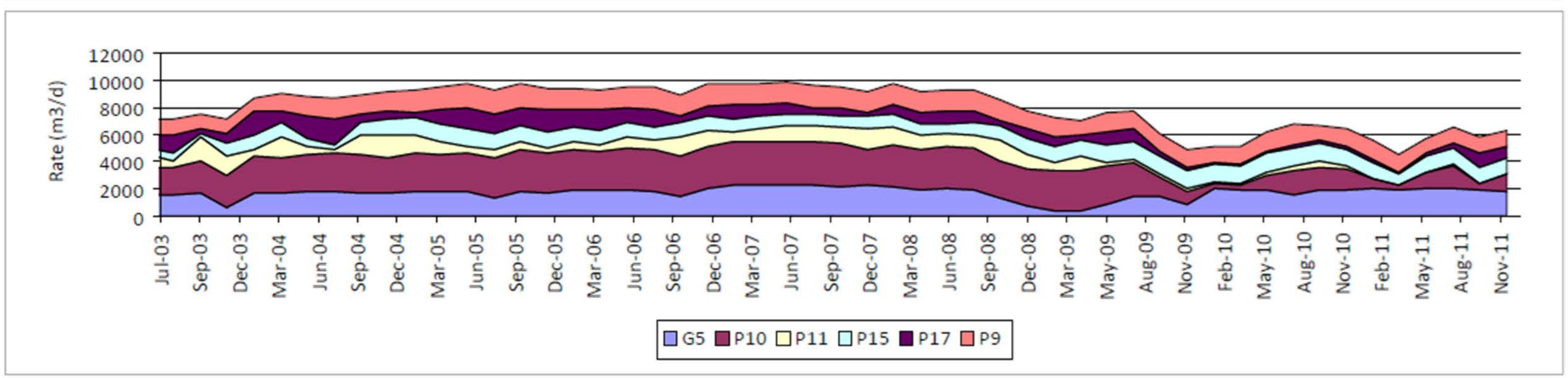
Figure 49: Sample Hydrograph for Hespeler Well Field – Realization 1

SpatialArea | Pinebush

OBJ_NUM & Screen	1000383	A	SCRNTYPE	Single	SCRN_FROM	29.5
CONSLT_ID	CM-OW1A-92		ObsType	nOW	SCRN_TO	84.1





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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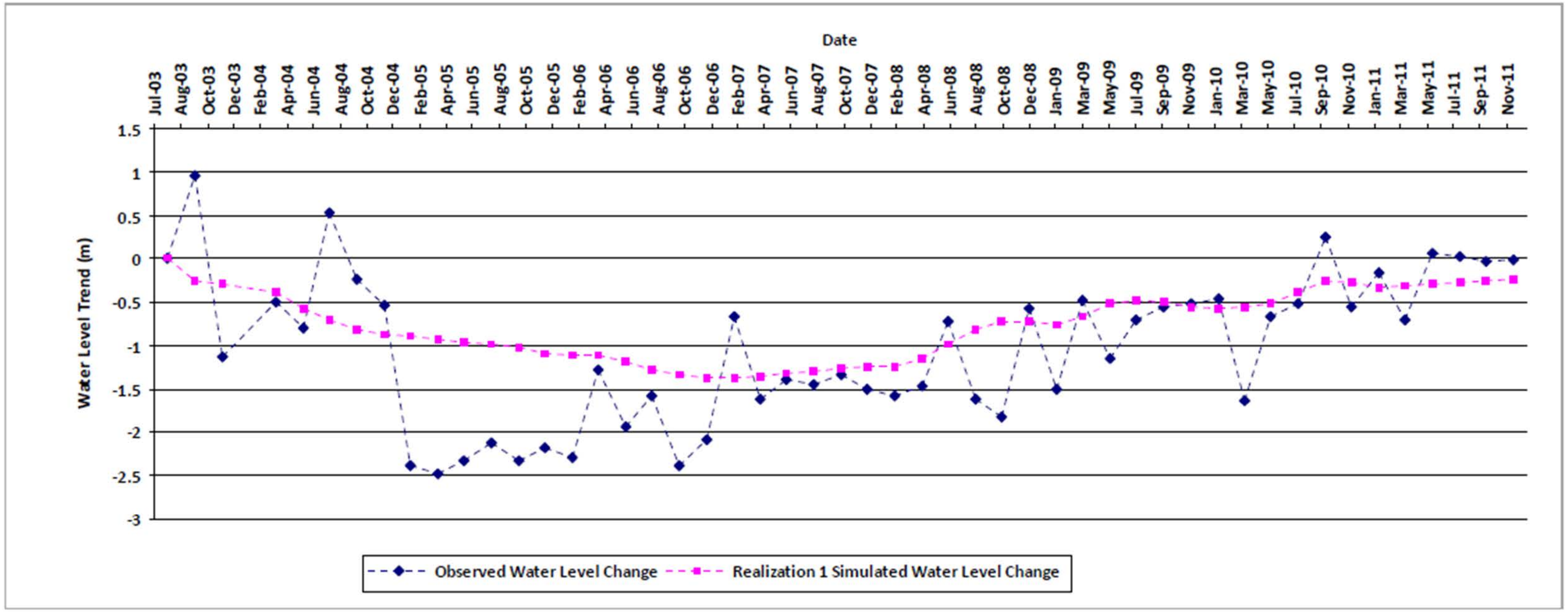
Figure 50: Sample Hydrograph for Pinebush Well Field (Deep) – Realization 1

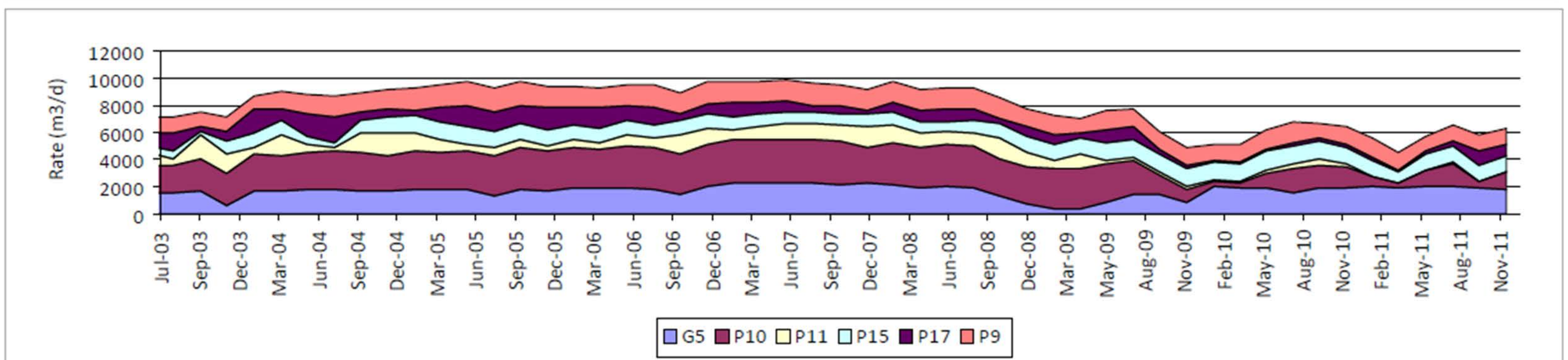
H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

SpatialArea Pinebush

OBJ_NUM & Screen 1000330 D SCRNTYPE Multi SCRN_FROM 47.85

CONSLT_ID OW3-95 ObsType nOW SCRN_TO 52.43





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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Figure 51: Sample Hydrograph for Pinebush Well Field (Shallow) – Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

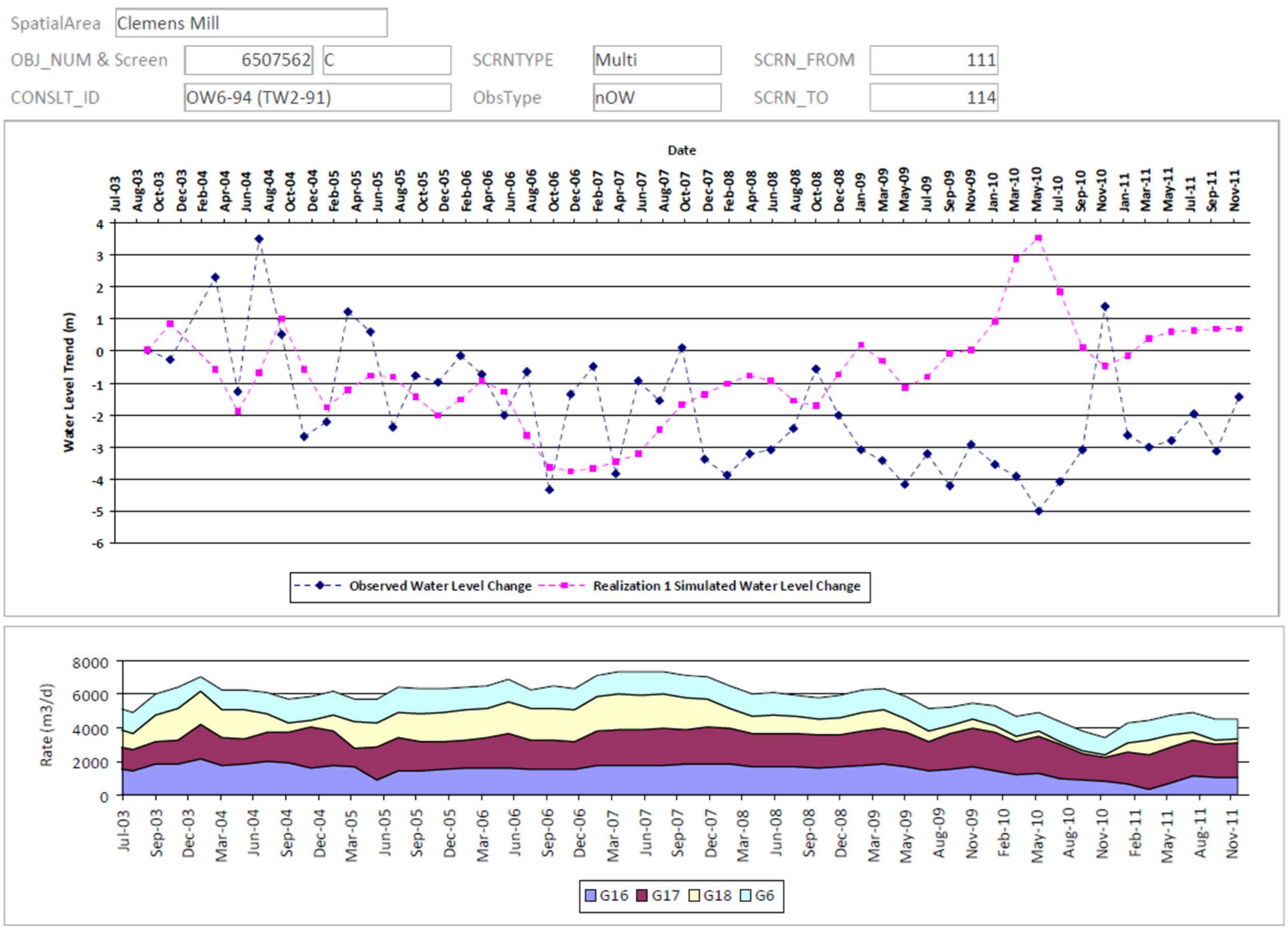

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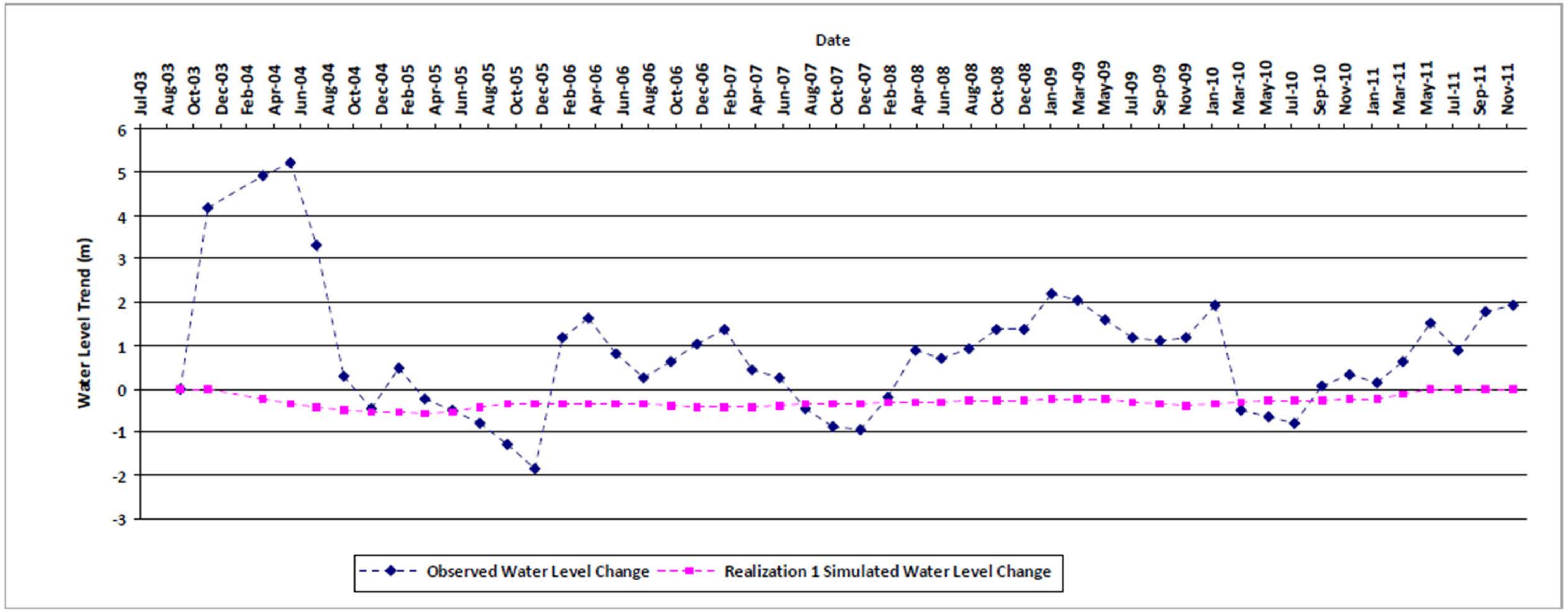
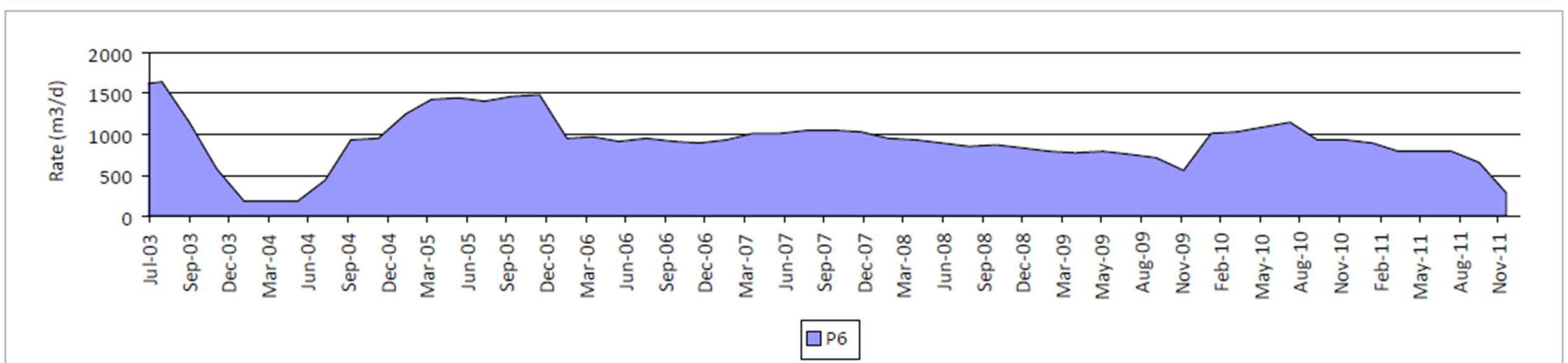
Figure 52: Sample Hydrograph for Clemens Mill Well Field – Realization 1

SpatialArea: Dunbar Road

OBJ_NUM & Screen	1000333 A	SCRNTYPE	Multi	SCRN_FROM	121.92
CONSLT_ID	OW6ABCD-95	ObsType	nOW	SCRN_TO	124.97





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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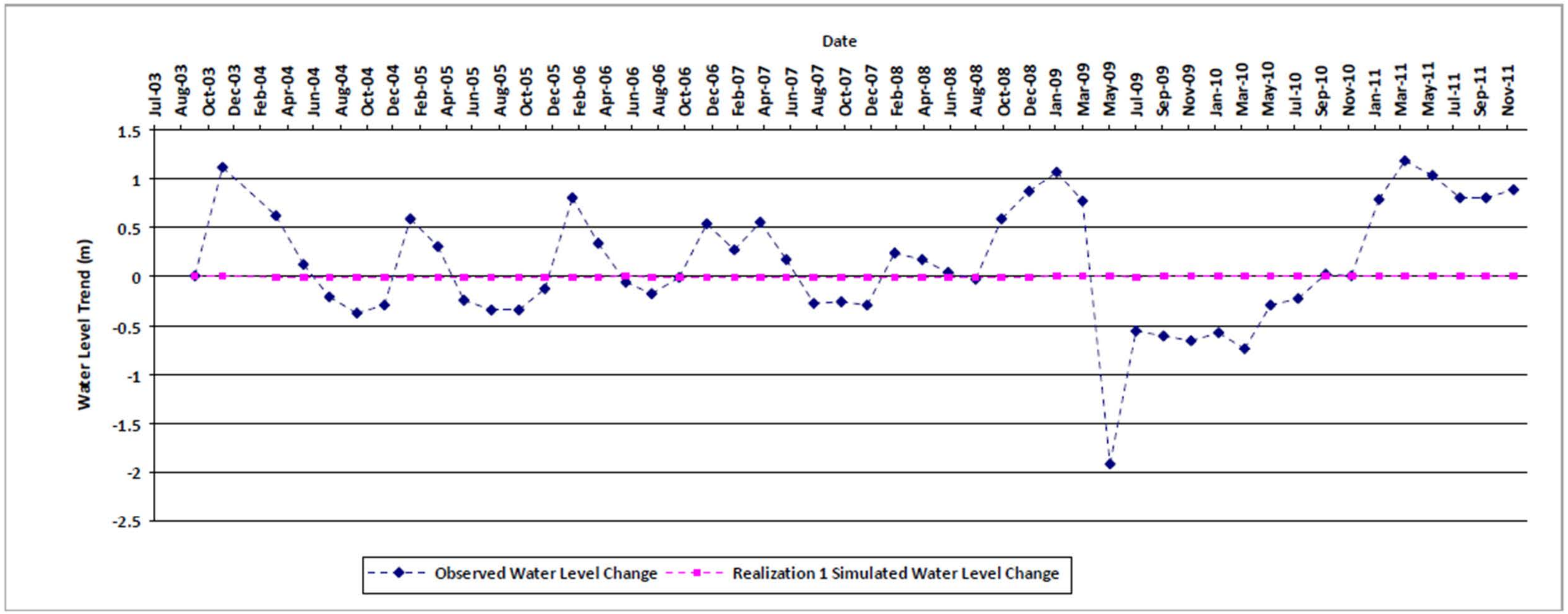
Figure 53: Sample Hydrograph for Dunbar Road Well Field – Realization 1

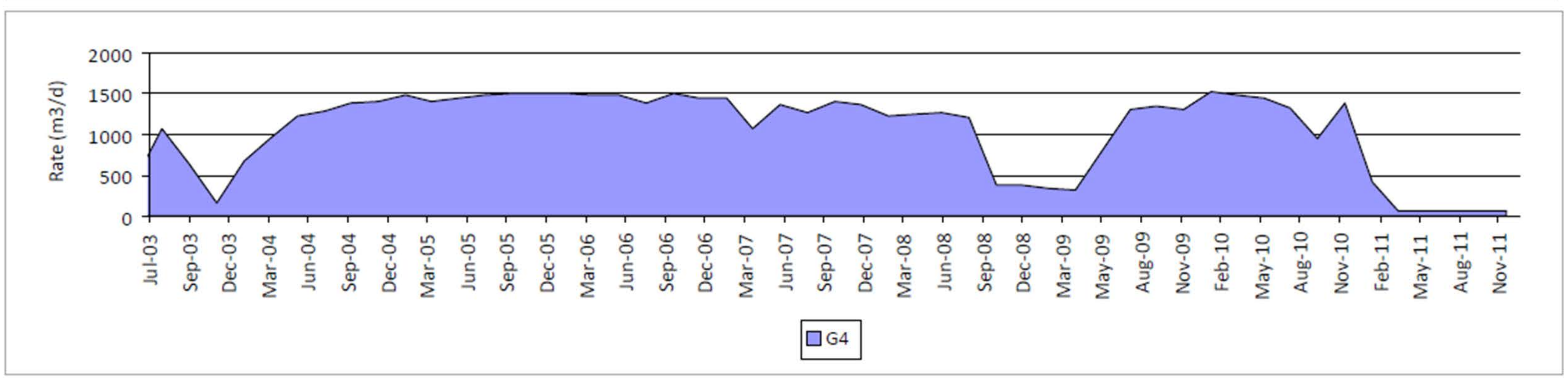
H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

SpatialArea: Blair Road

OBJ_NUM & Screen: 1000332 B | SCRNTYPE: Multi | SCRN_FROM: 102.11

CONSLT_ID: OW5-95 | ObsType: nOW | SCRN_TO: 109.73





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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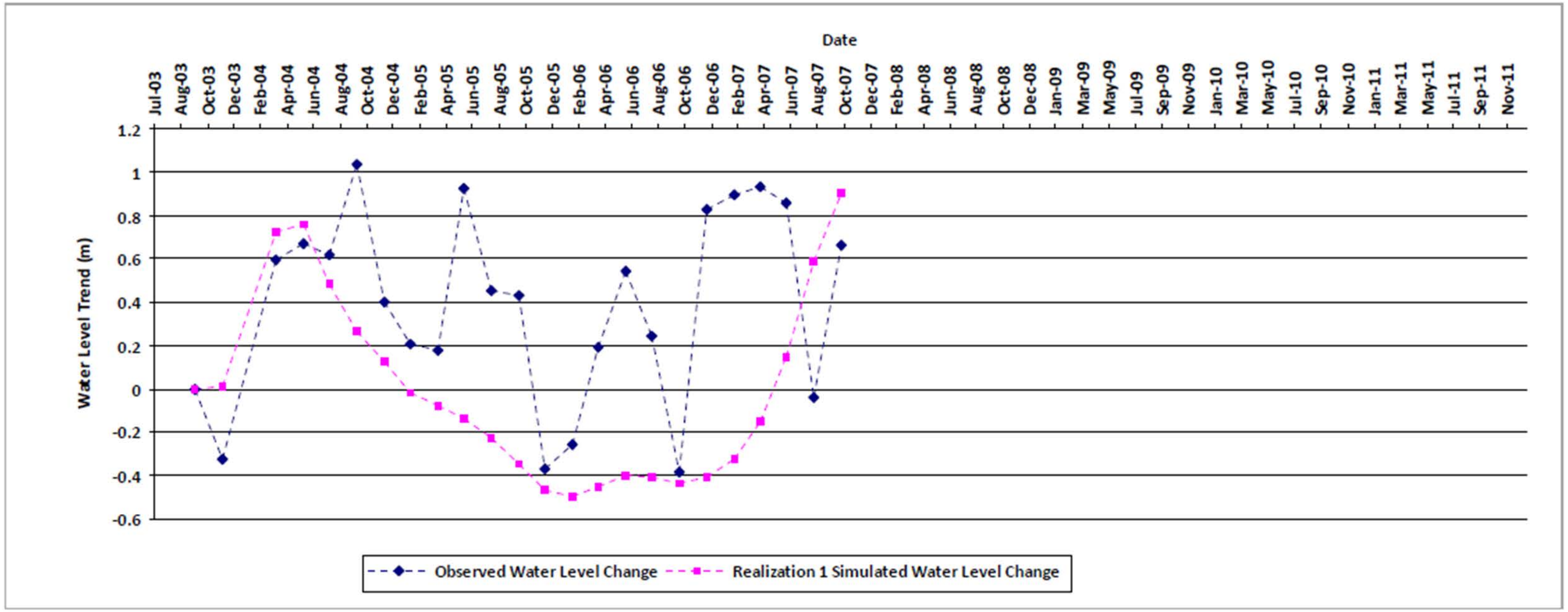
Figure 54: Sample Hydrograph for Blair Road Well Field – Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

SpatialArea	Shade's Mill					
OBJ_NUM & Screen	9200458	A	SCRNTYPE	Multi	SCRN_FROM	24.4
CONSLT_ID	SM3-93		ObsType	nOW	SCRN_TO	137.5



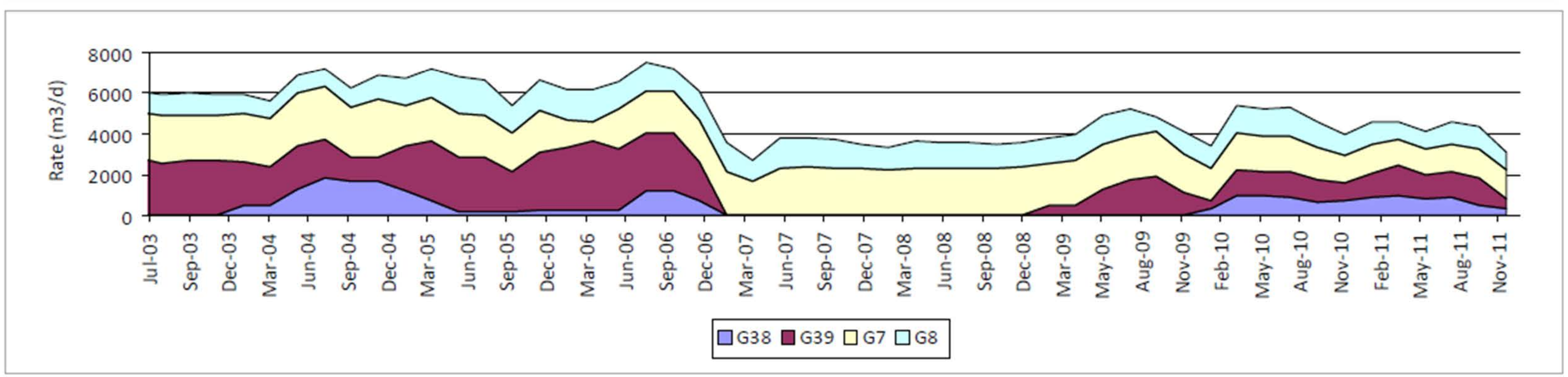


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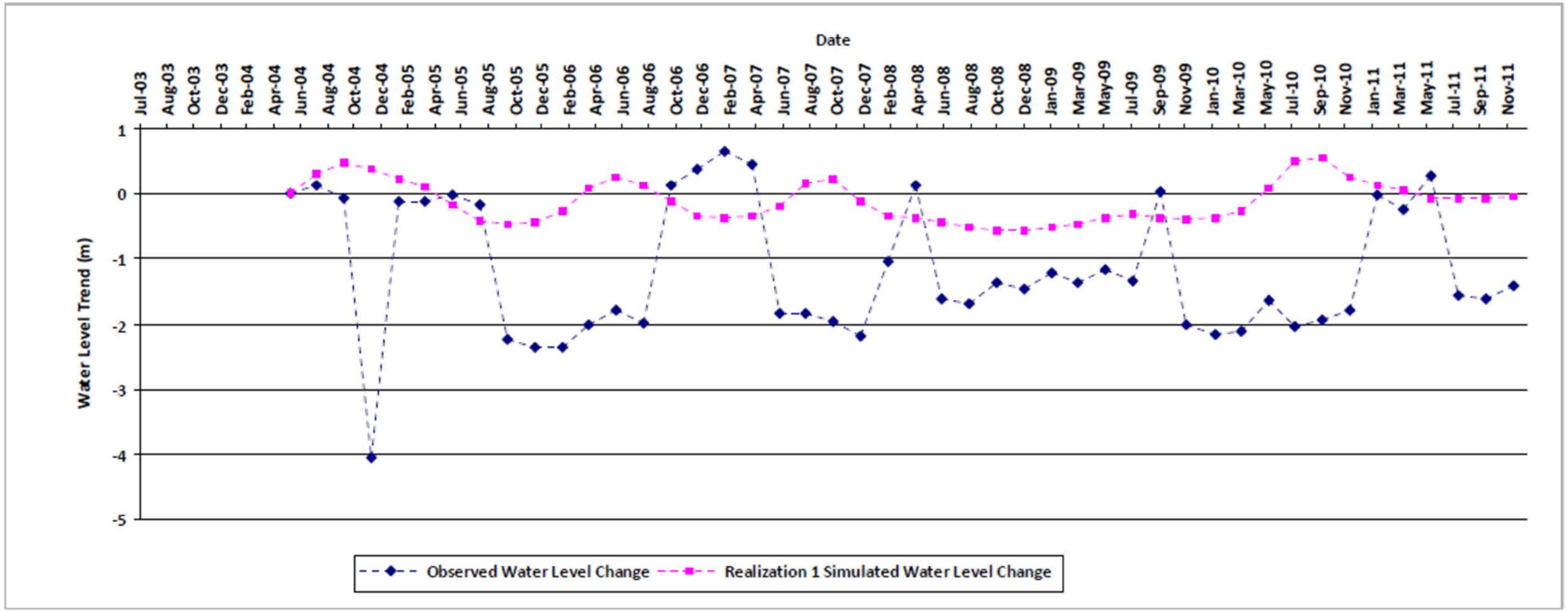
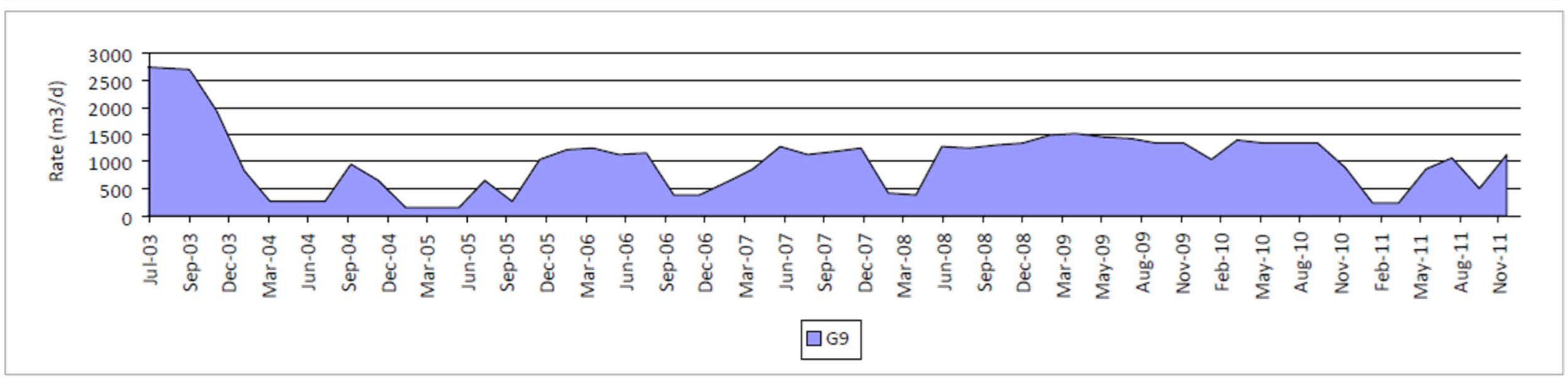
Figure 55: Sample Hydrograph for Shades Mills Well Field – Realization 1

SpatialArea Elgin Street

OBJ_NUM & Screen 1000335 C SCRNTYPE Multi SCRN_FROM 67.05

CONSLT_ID OW8-95 ObsType nOW SCRN_TO 73.15





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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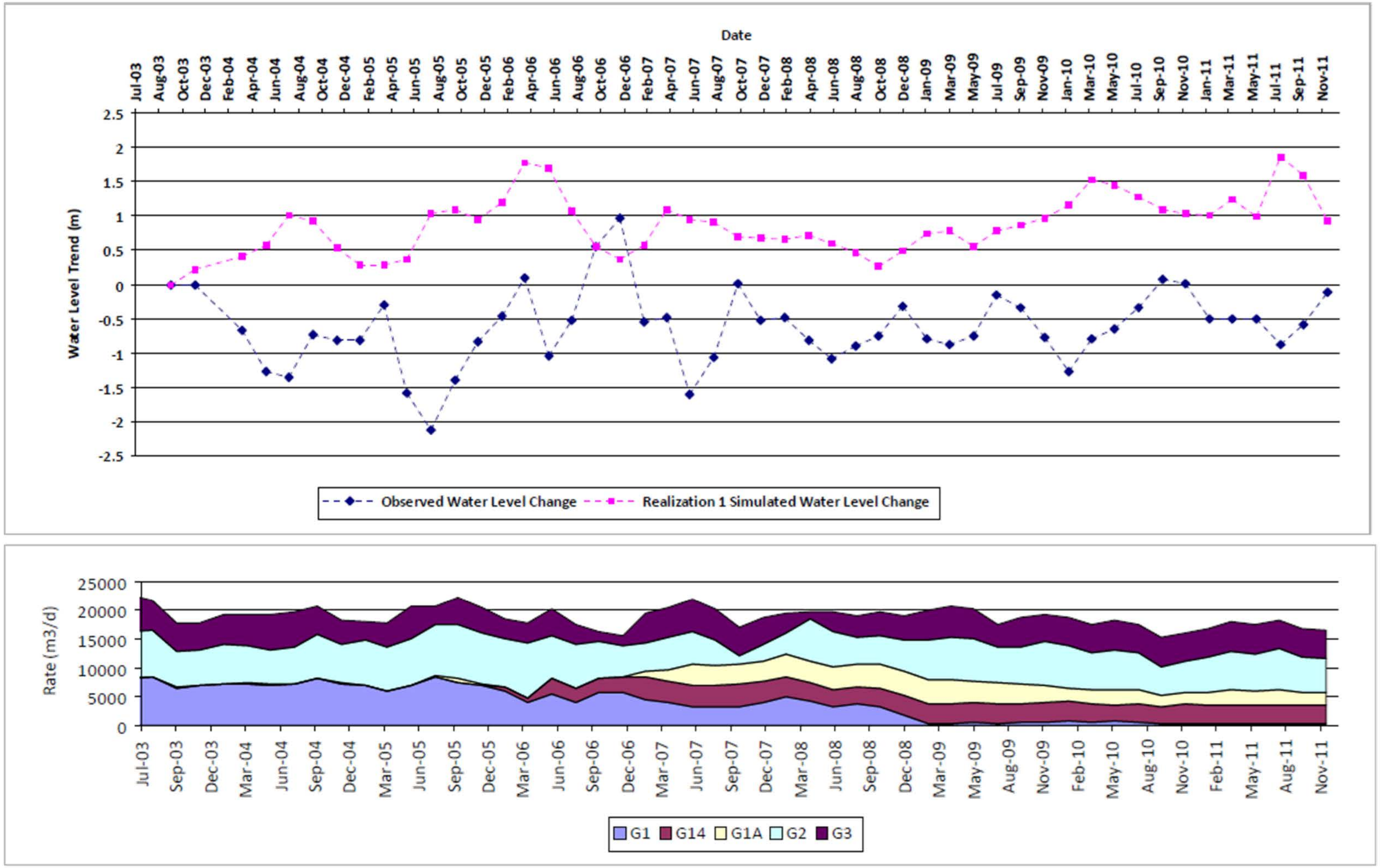
Figure 56: Sample Hydrograph for Elgin Street Well Field – Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

SpatialArea: Middleton Street

OBJ_NUM & Screen: 9200048 C | SCRNTYPE: Multi | SCRN_FROM: 18.5

CONSLT_ID: MI-OW2-92 | ObsType: nOW | SCRN_TO: 21.6



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

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Figure 57: Sample Hydrograph for Middleton Street Well Field – Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

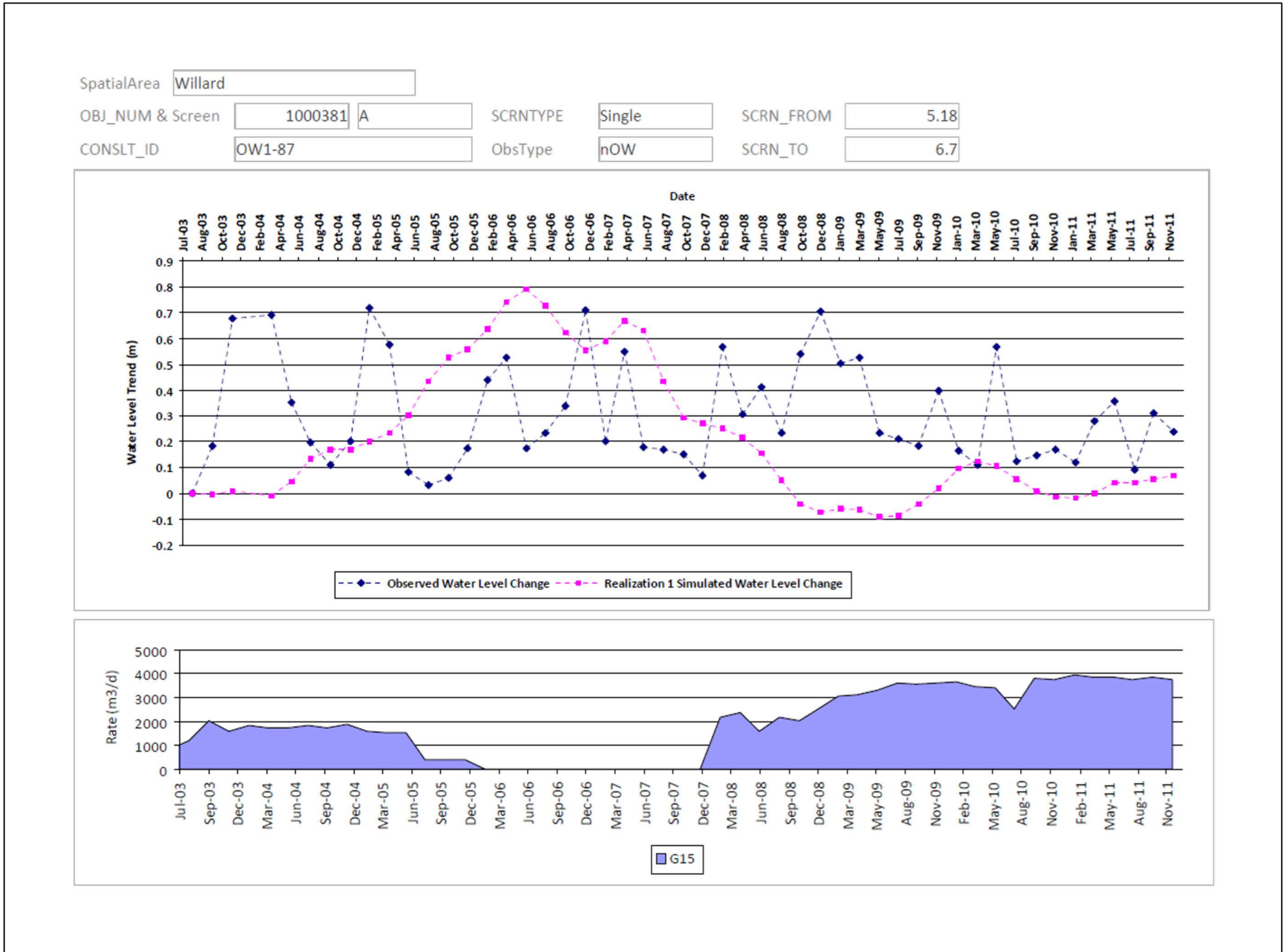

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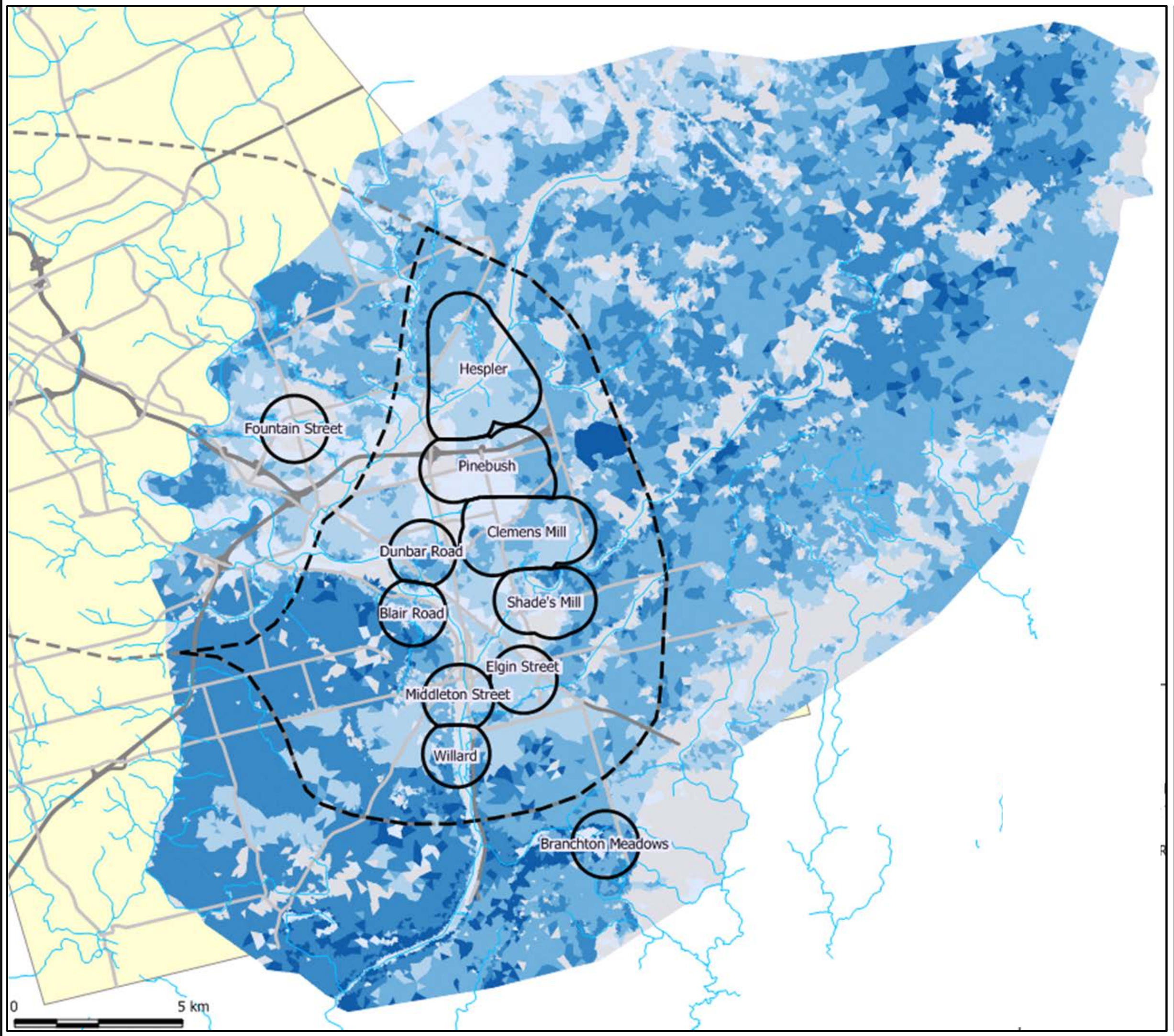
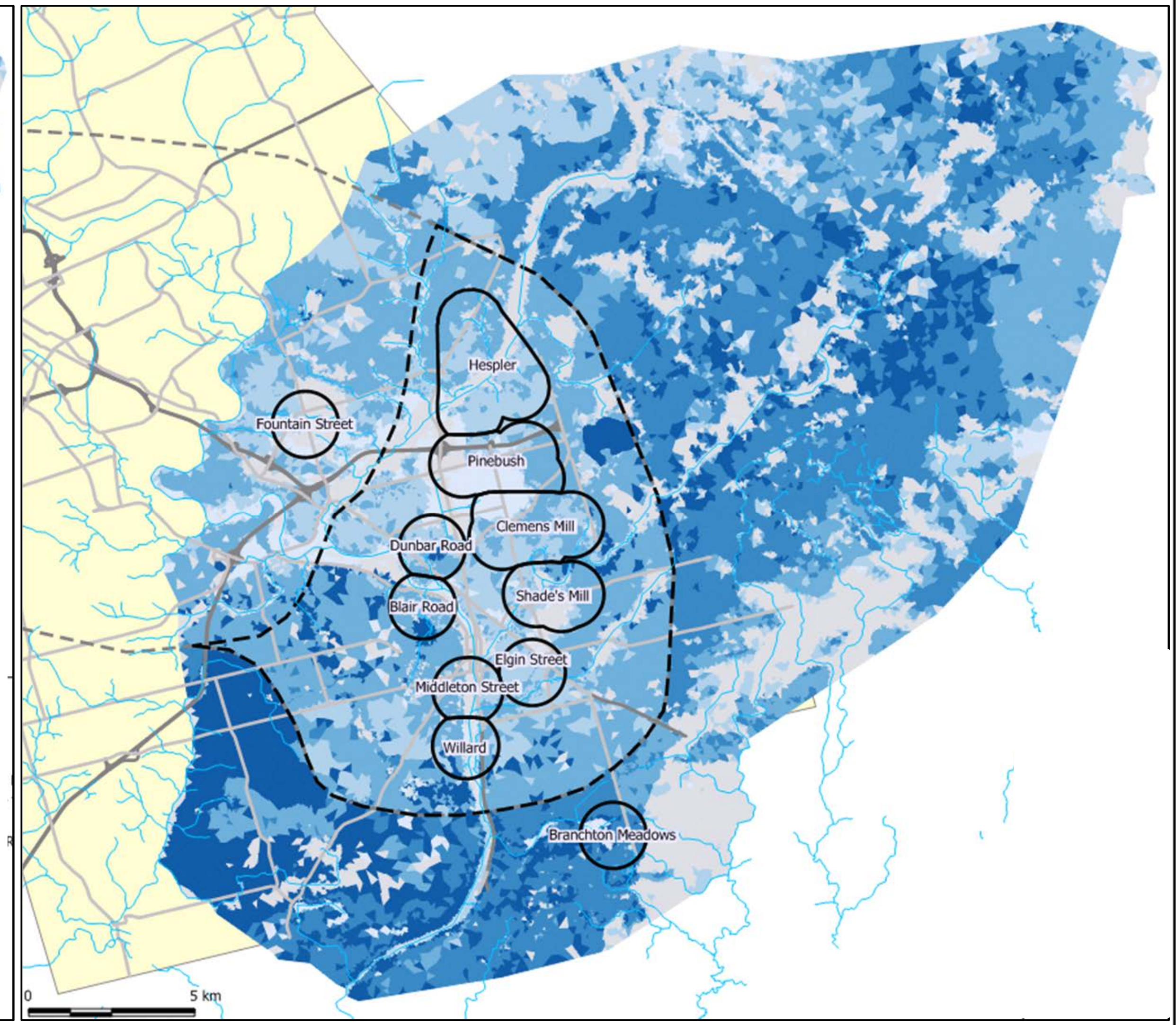
Figure 58: Sample Hydrograph for Willard Well Field – Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

Base Case (Calibrated Model) Recharge Distribution



Optimized Recharge Distribution- Realization 1



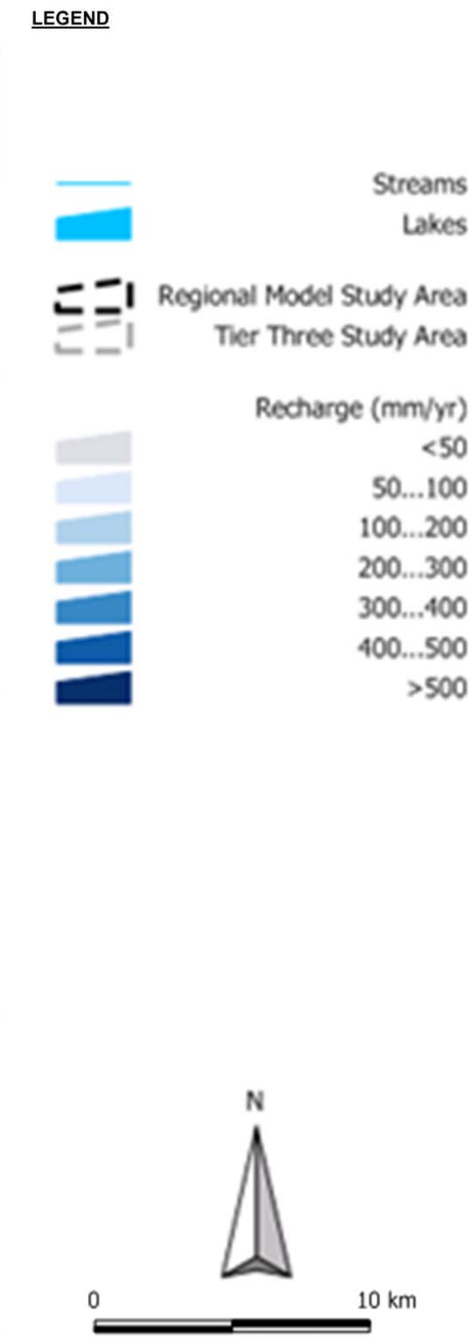


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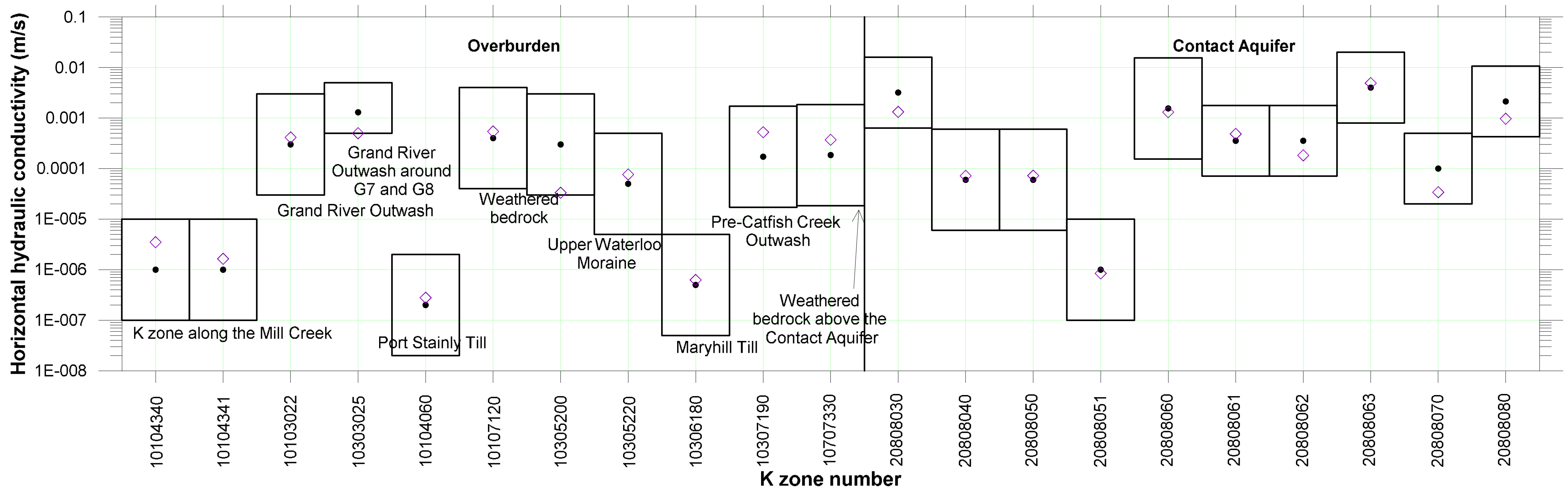
Figure 59: Base Case and Optimized Recharge Distribution – Realization 1

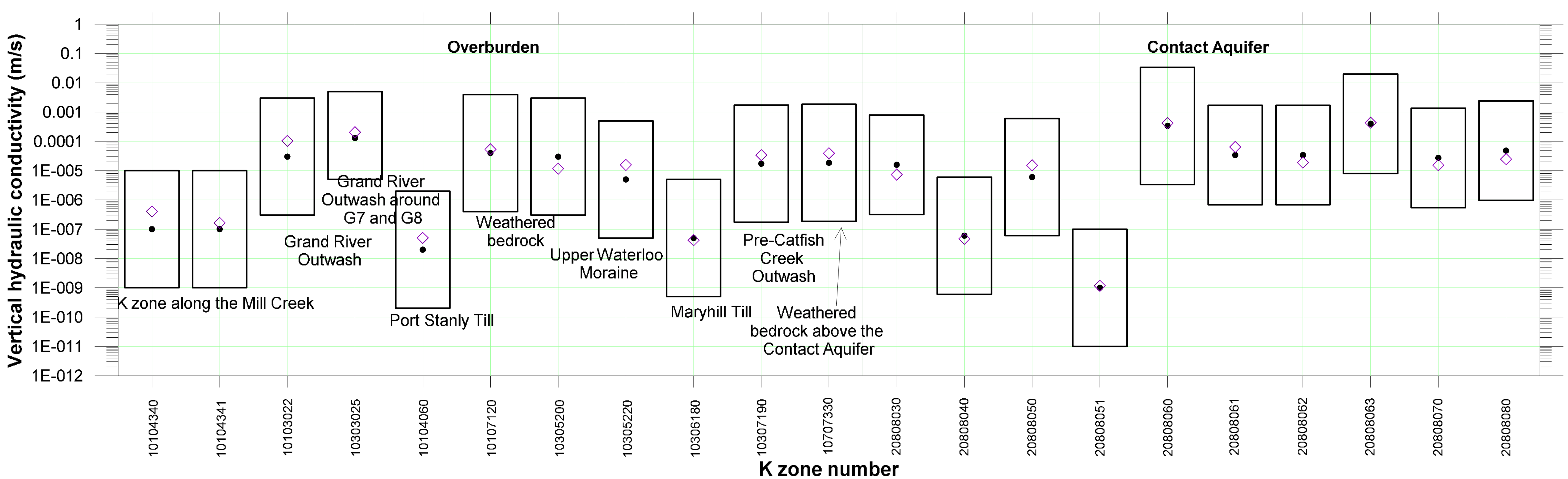
H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

Horizontal Hydraulic Conductivity Parameters



Vertical Hydraulic Conductivity Parameters



LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

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Figure 60: Optimized Hydraulic Conductivity for Overburden Units and Contact Zone – Realization 1

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

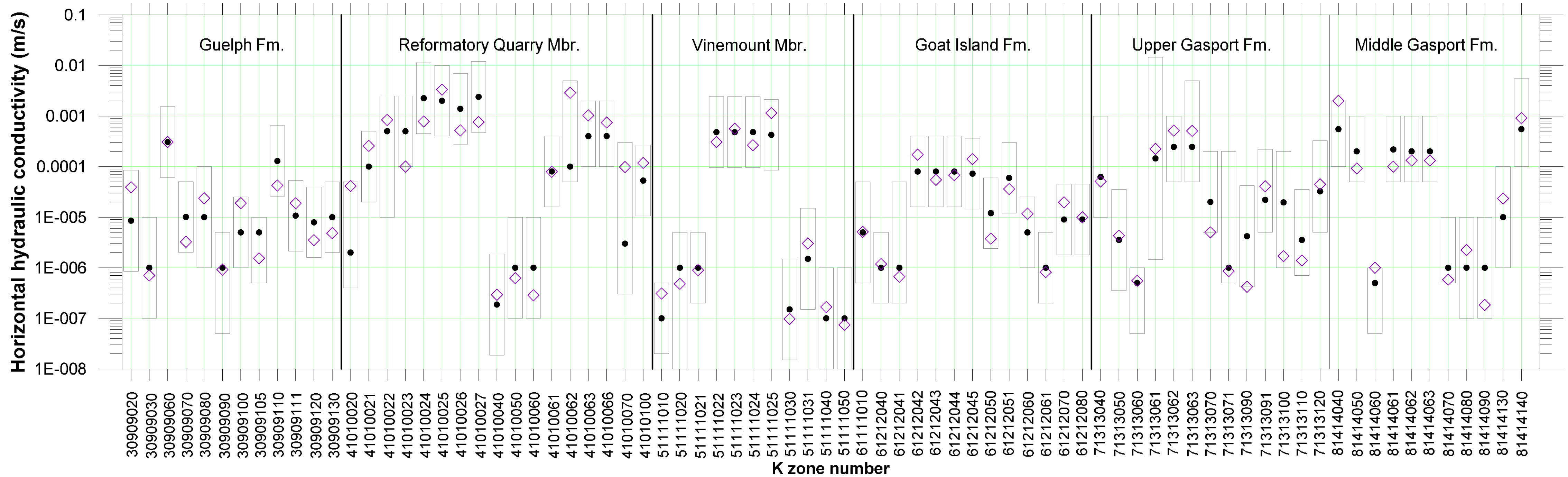
LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

Horizontal Hydraulic Conductivity Parameters



Vertical Hydraulic Conductivity Parameters

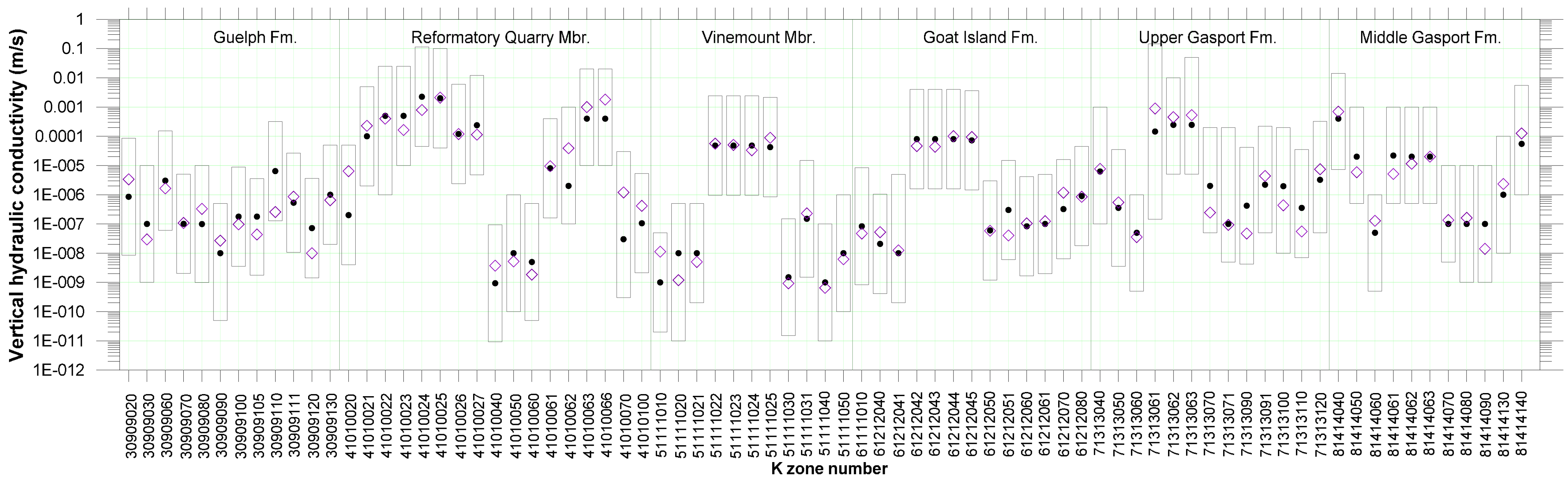


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Figure 61: Optimized Hydraulic Conductivity for Bedrock Units – Realization 1

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

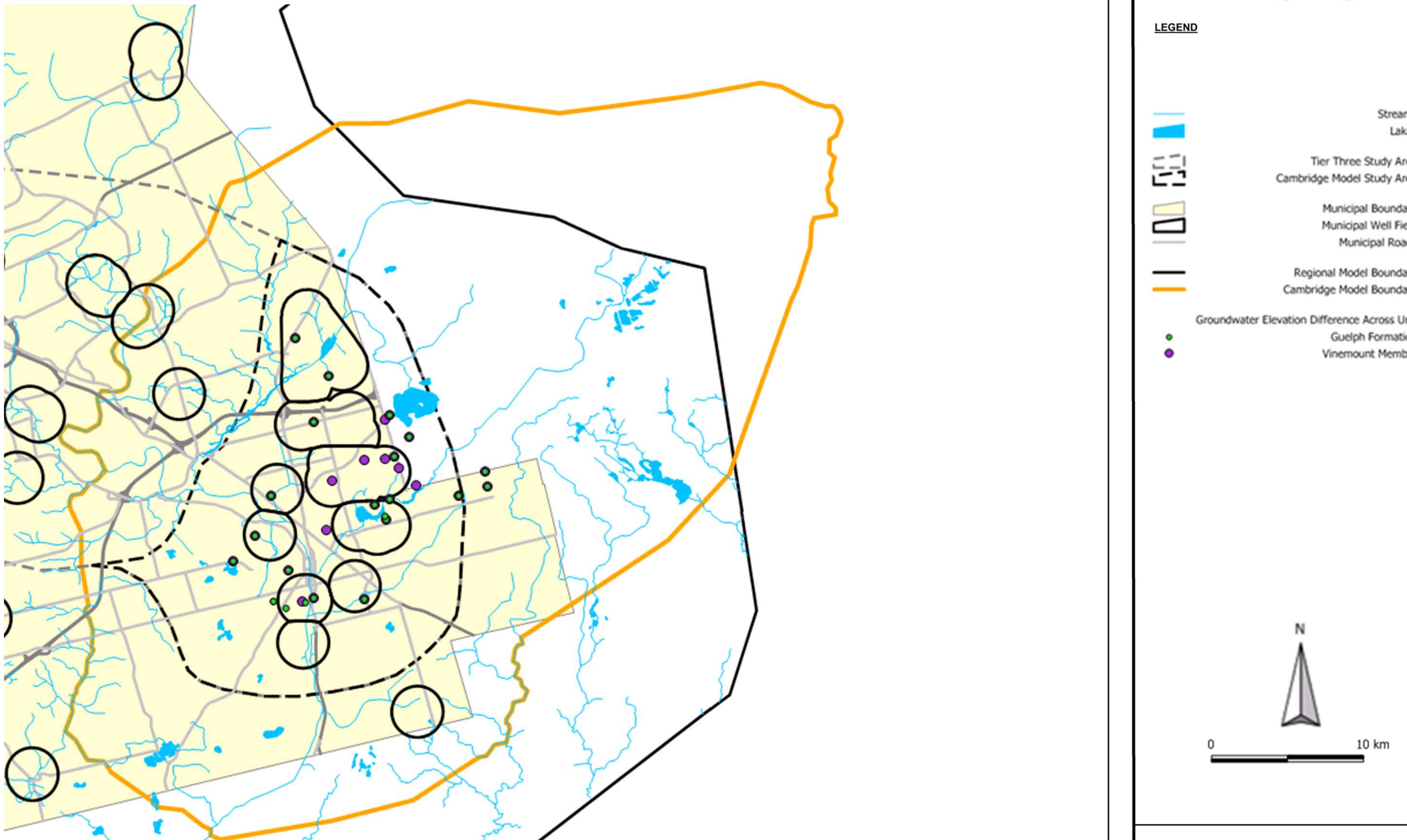

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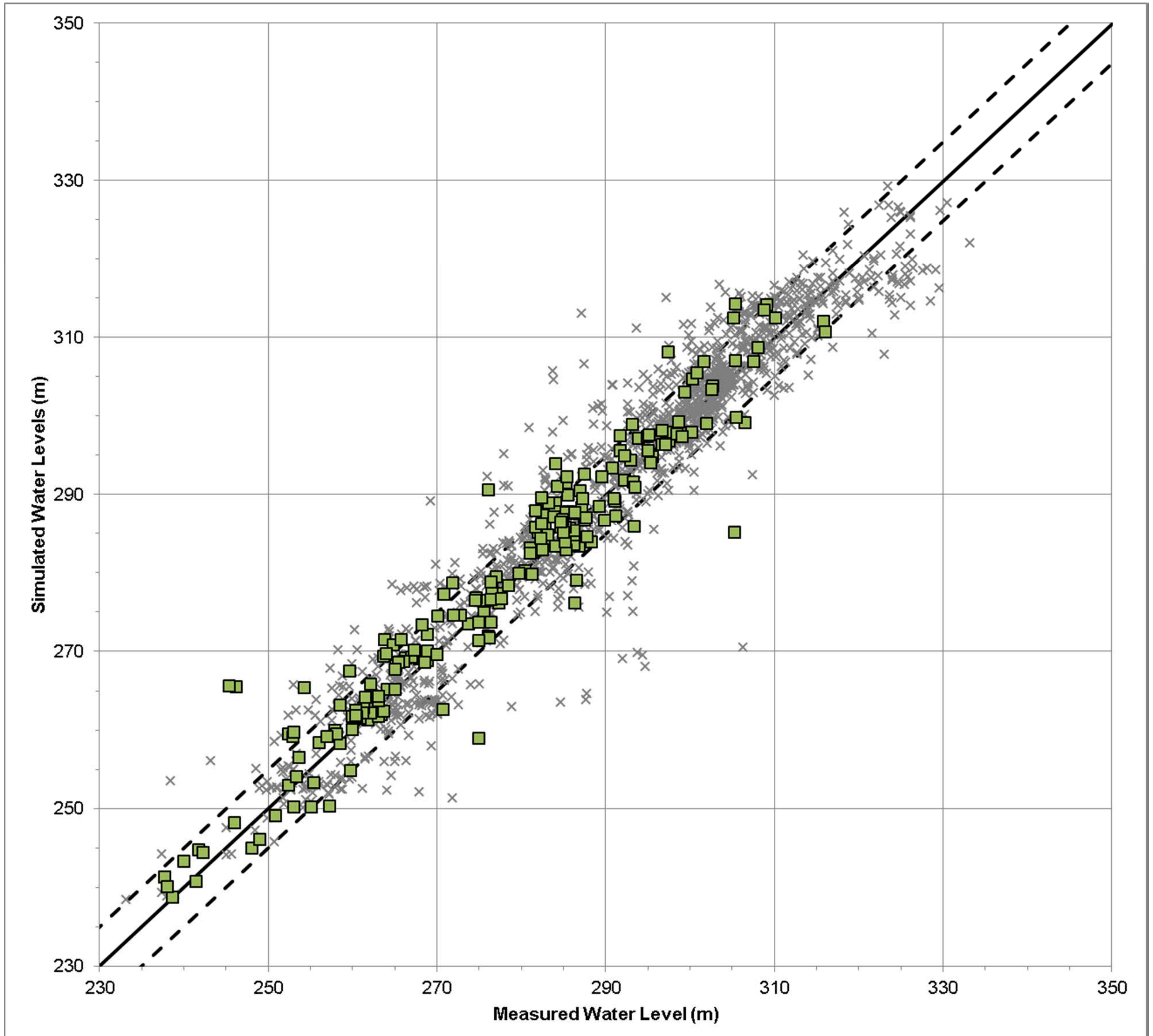
Figure 62: Groundwater Level Elevation Difference Across Aquitards – Cambridge Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

× Low Quality

■ High Quality

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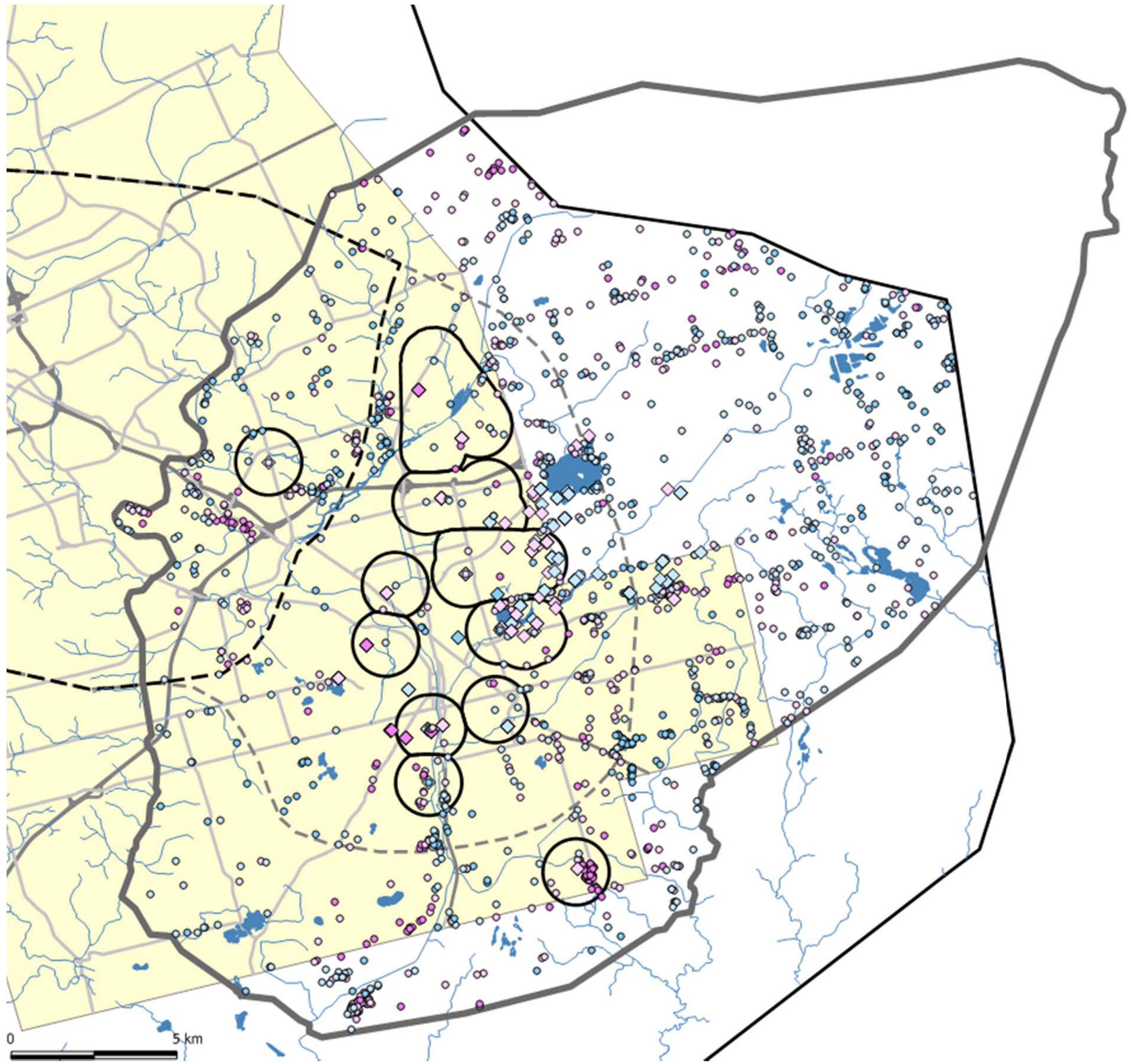
Figure 63: Simulated vs Observed Groundwater Level Elevations – Realization 2

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses



LEGEND

Streams
Lakes
Regional Model Study Area
Tier Three Study Area

Residual
<-5.00
-5.00...0.00
0.00...5.00
>5.00

Observation Quality
High Quality
Low Quality

N
0
10 km

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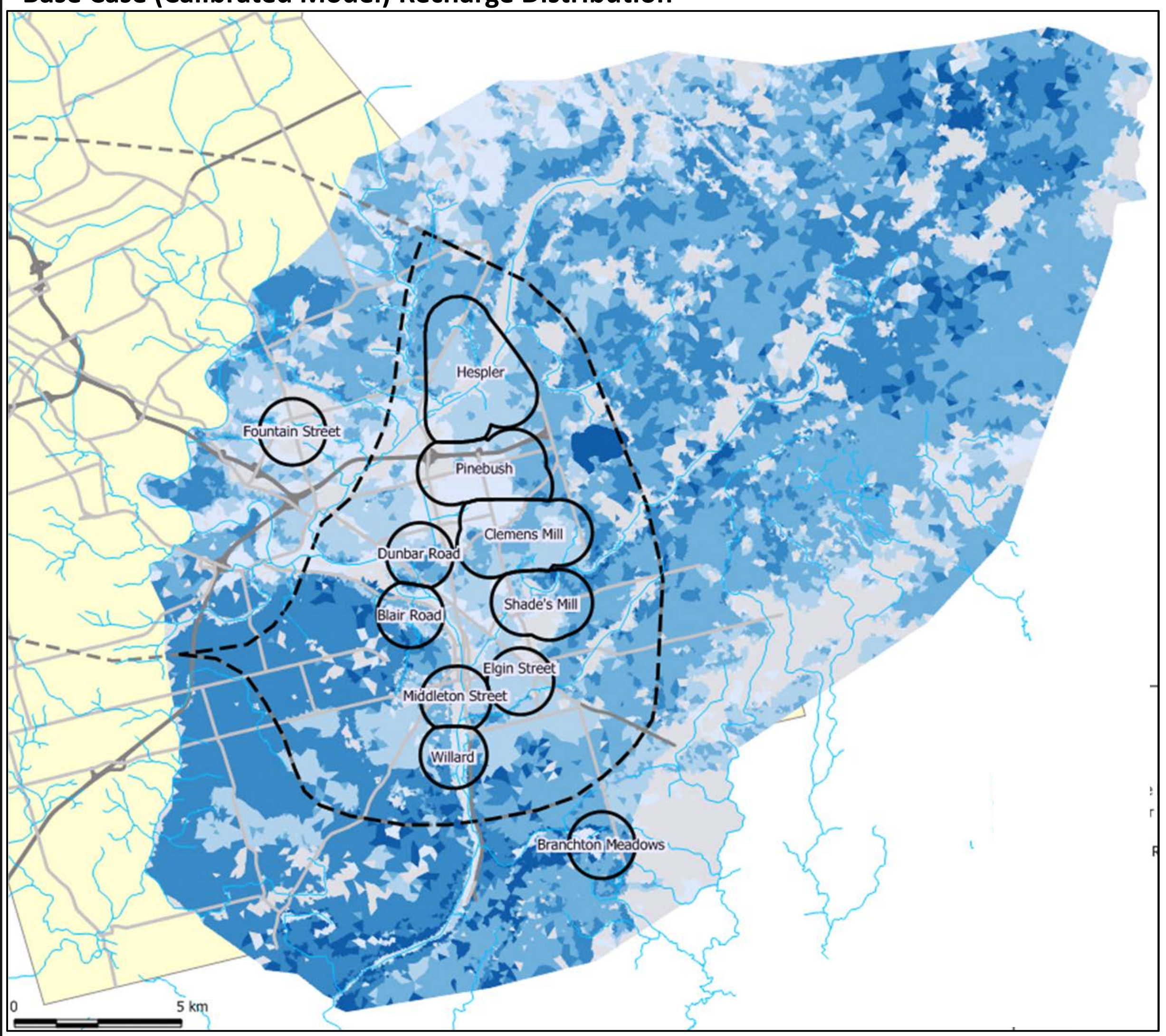
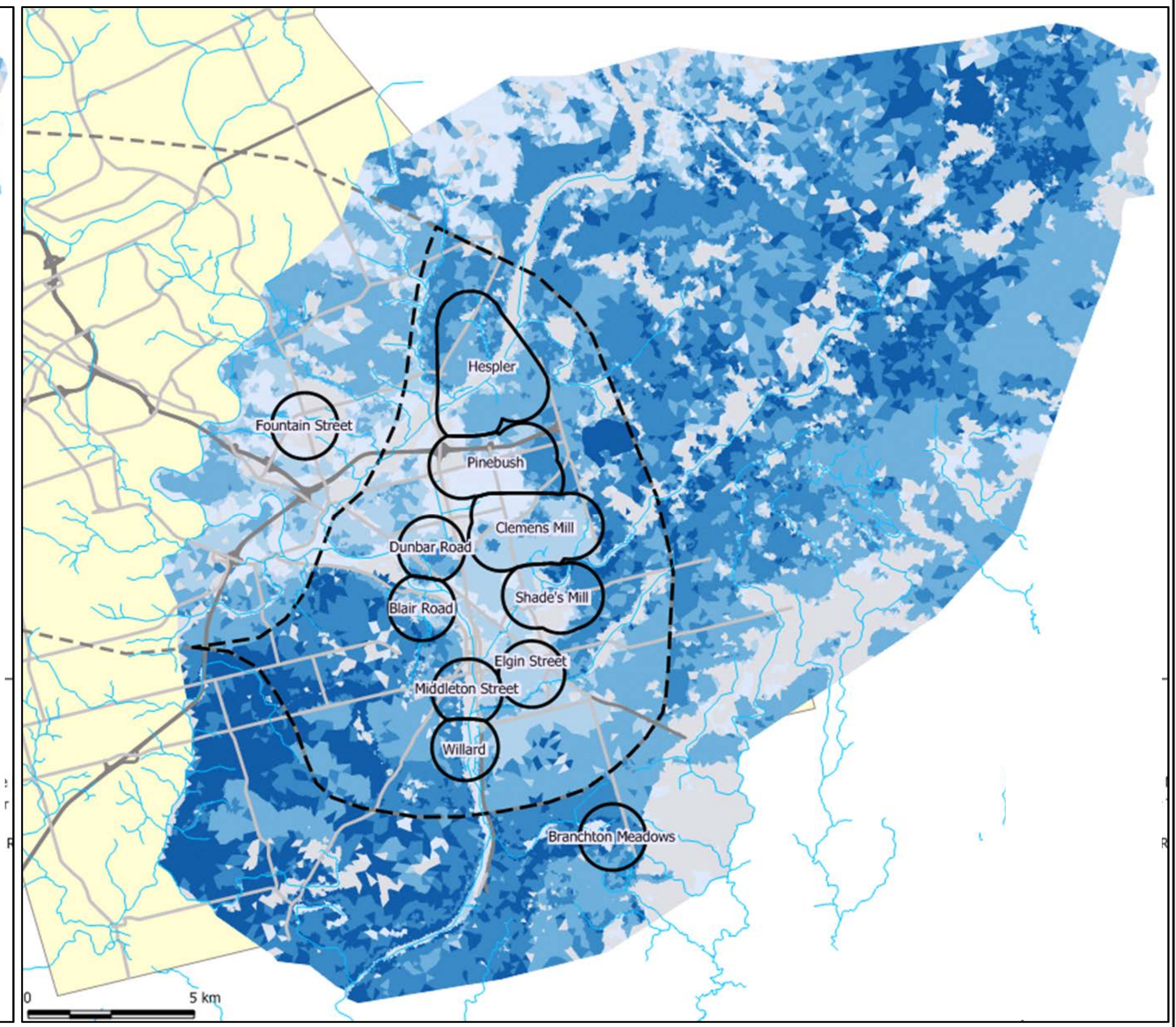
Figure 64: Spatial Plot of Groundwater Level Elevation Residuals – Realization 2

Base Case (Calibrated Model) Recharge Distribution



Optimized Recharge Distribution- Realization 2



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

Streams
Lakes
Regional Model Study Area
Tier Three Study Area

Recharge (mm/yr)
<50
50...100
100...200
200...300
300...400
400...500
>500

N

0 10 km

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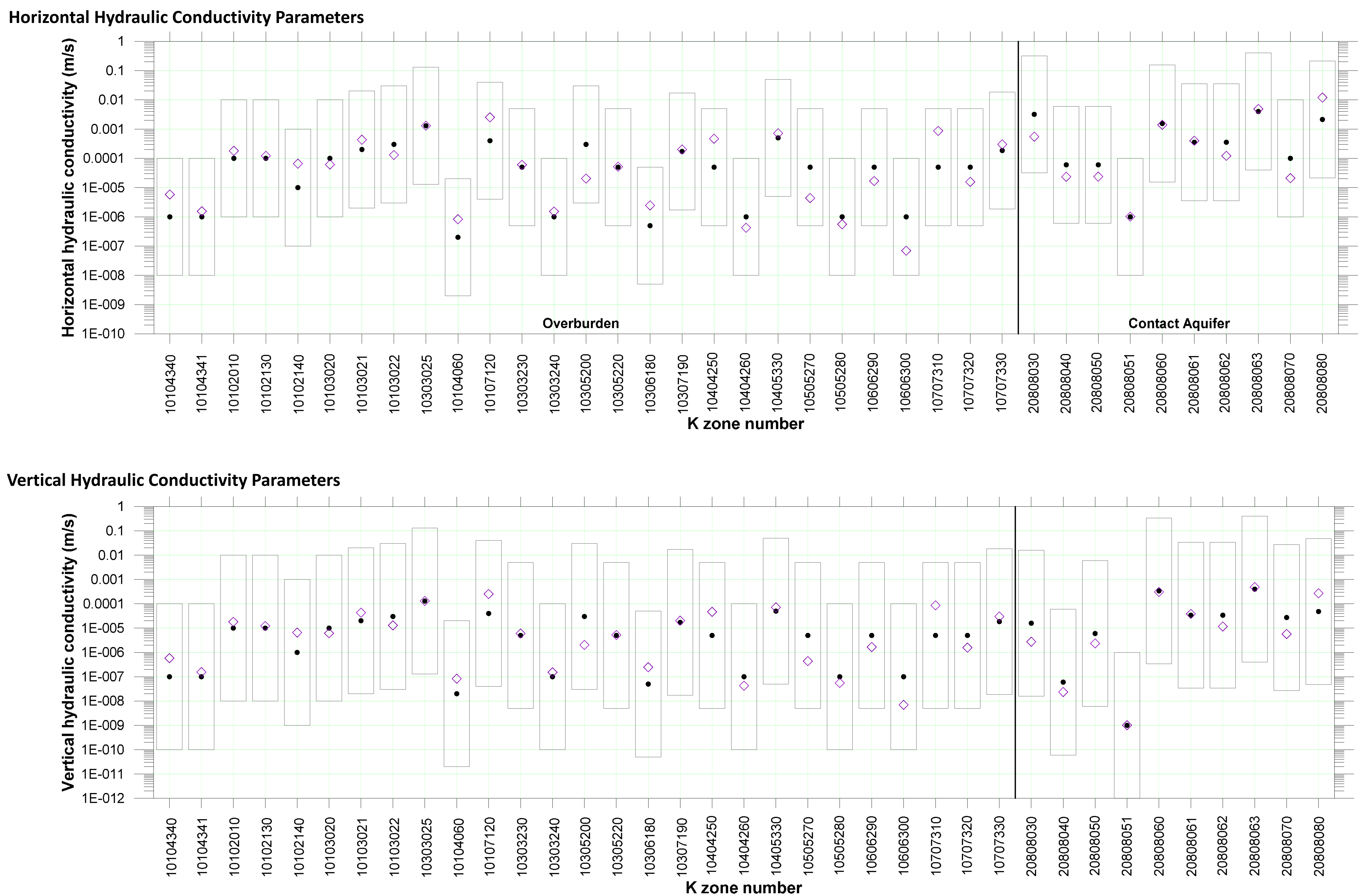
Figure 65: Base Case Model and Optimized Recharge Distribution– Realization 2

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd



Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- PEST Hydraulic Conductivity Range
- PEST Optimized Value
- Calibrated Hydraulic Conductivity Value

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Figure 66: Optimized Hydraulic Conductivity Overburden and Contact Zone – Realization 2

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Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

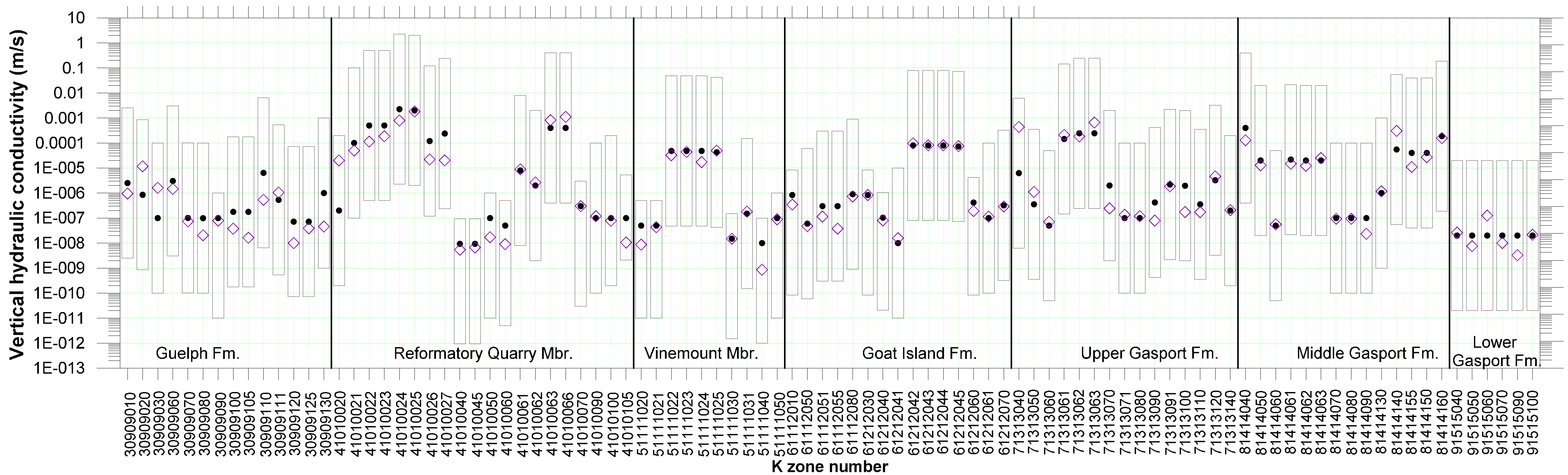
LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

Horizontal Hydraulic Conductivity Parameters



Vertical Hydraulic Conductivity Parameters

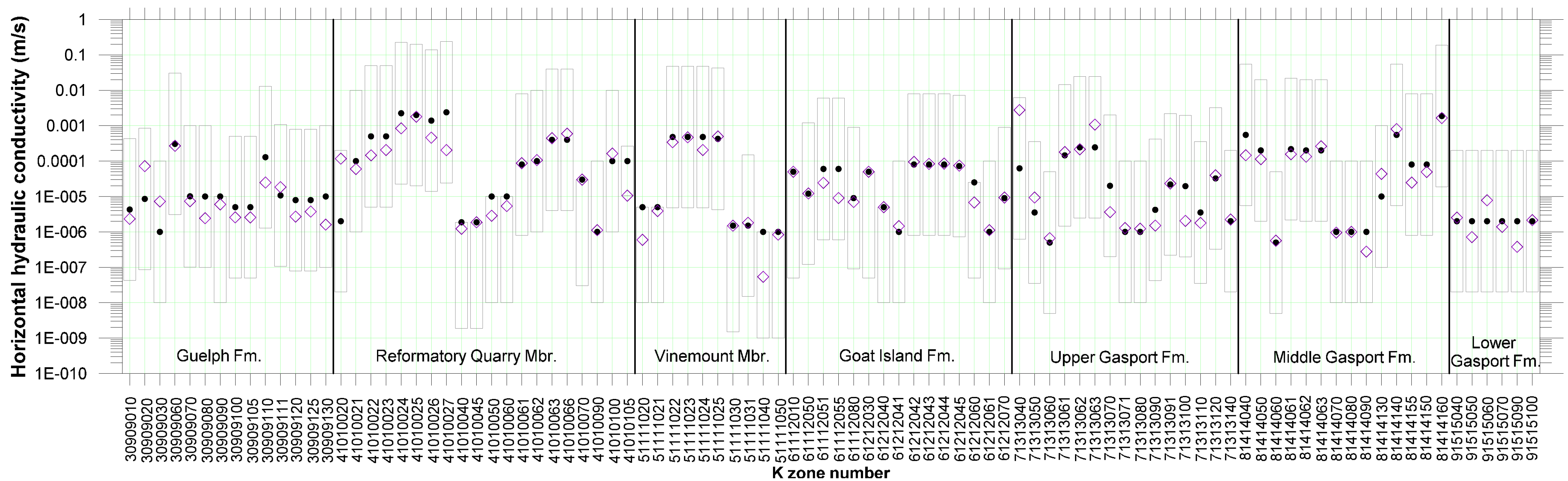


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Figure 67: Optimized Hydraulic Conductivity for Bedrock Units – Realization 2

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

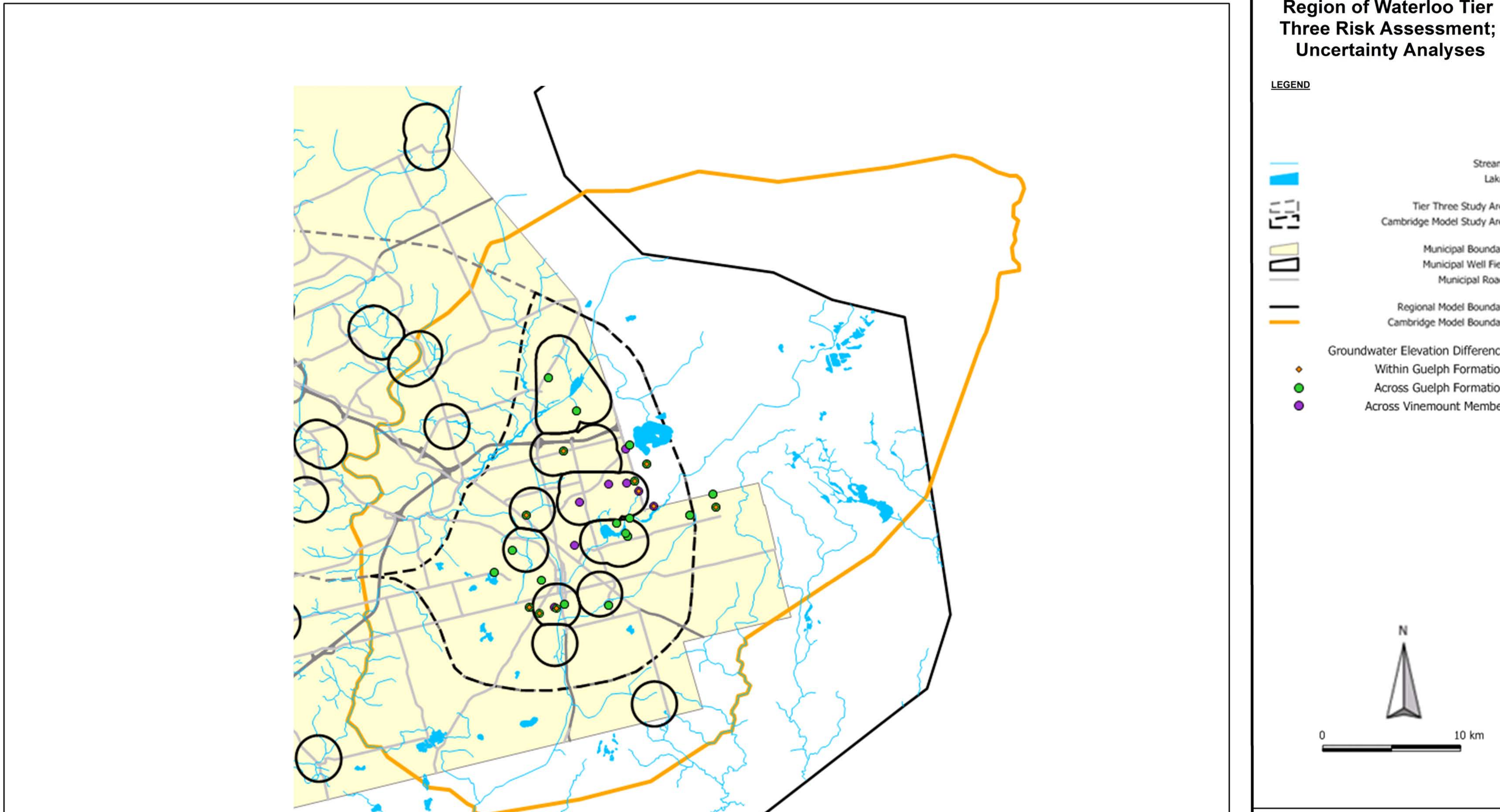

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Figure 68: Groundwater Level Elevation Difference Across Aquitards – Cambridge Model

H:\Projects\2008001_ROW_Tier3\GIS\ArcView\MXDs\Presentation_PPTTemplate\FigX_PPT_Template.mxd

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

× Low Quality

■ High Quality

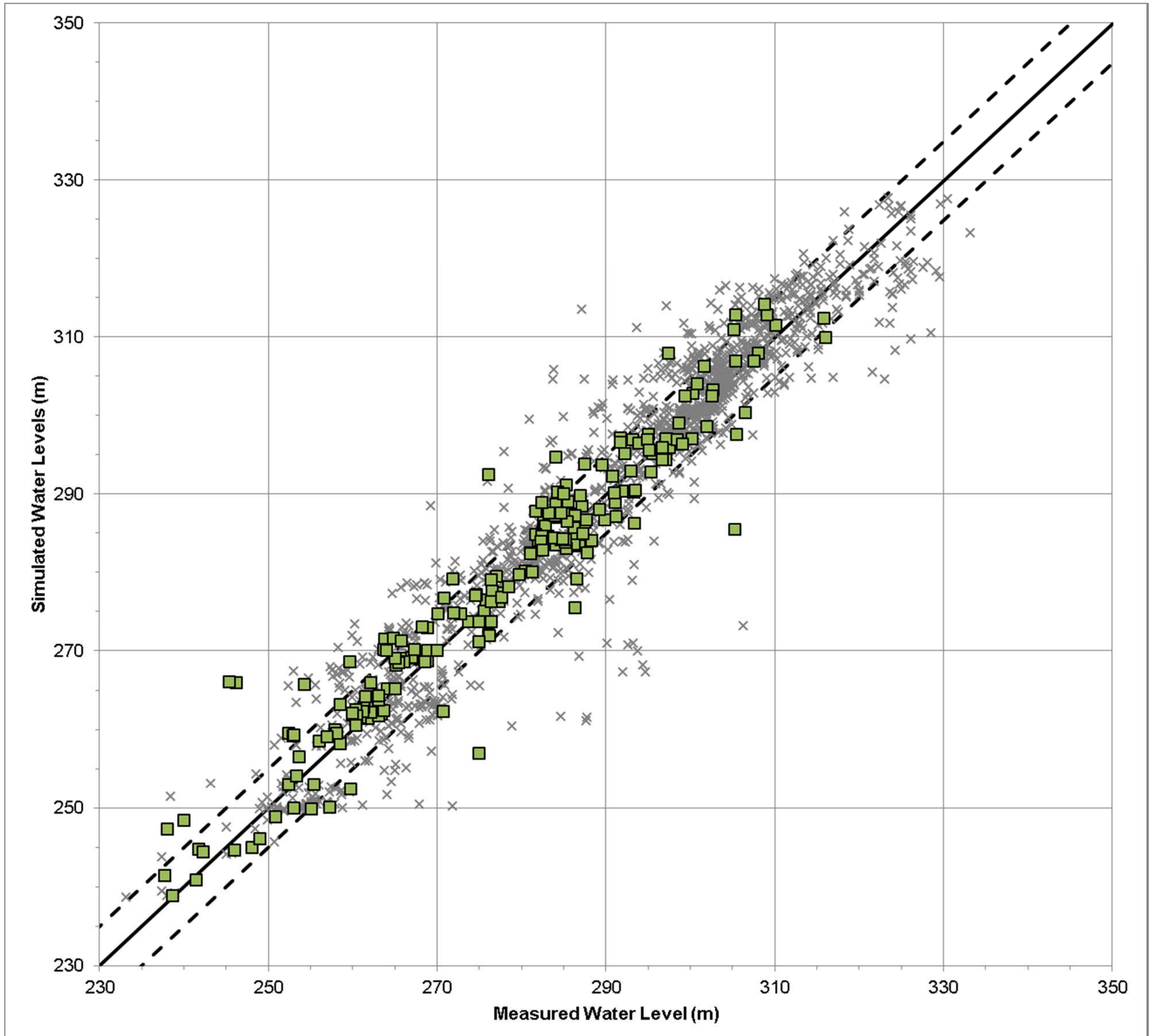

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Figure 69: Simulated vs Observed Groundwater Level Elevations – Realization 3

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

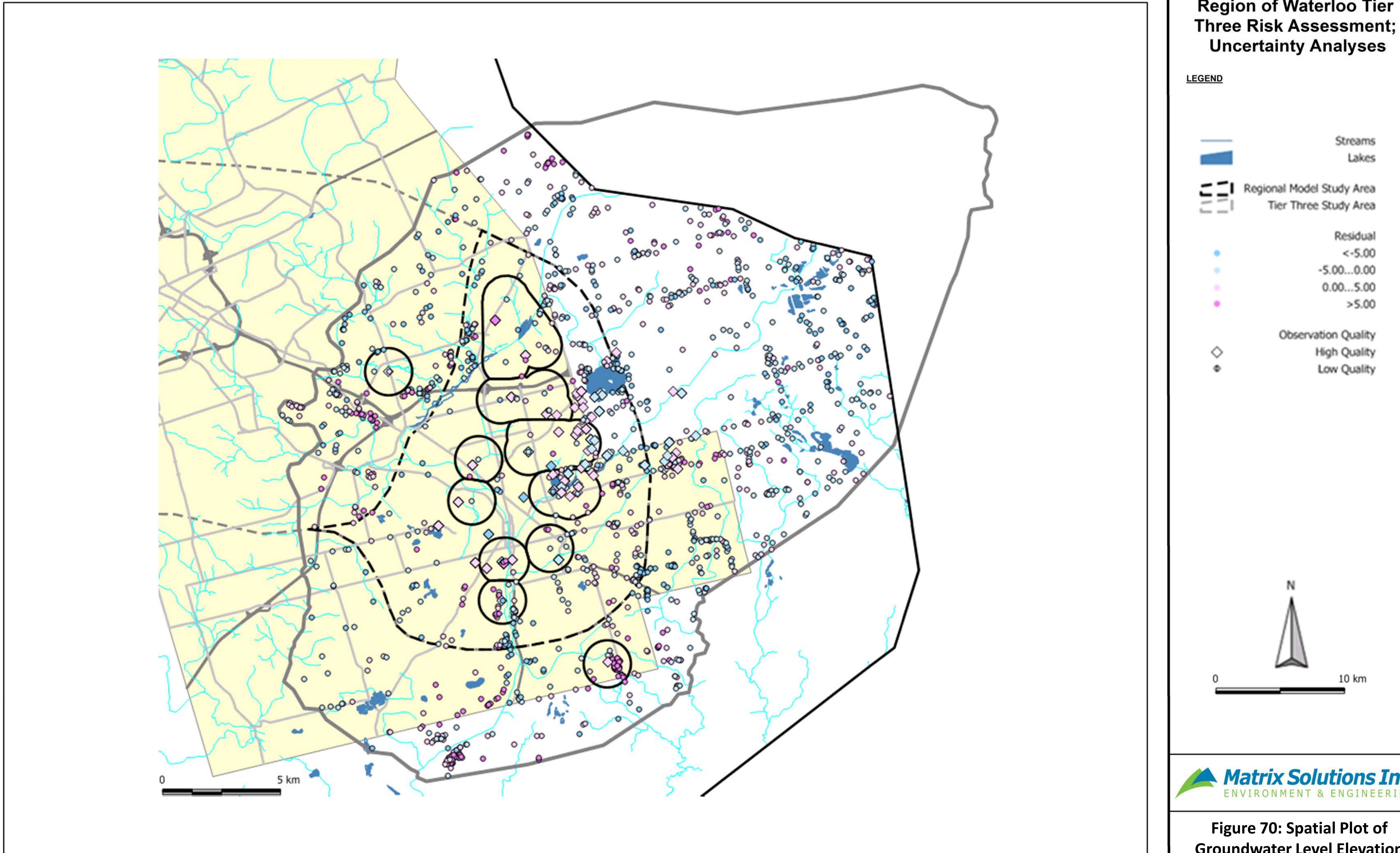

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Figure 70: Spatial Plot of Groundwater Level Elevation Residuals – Realization 3

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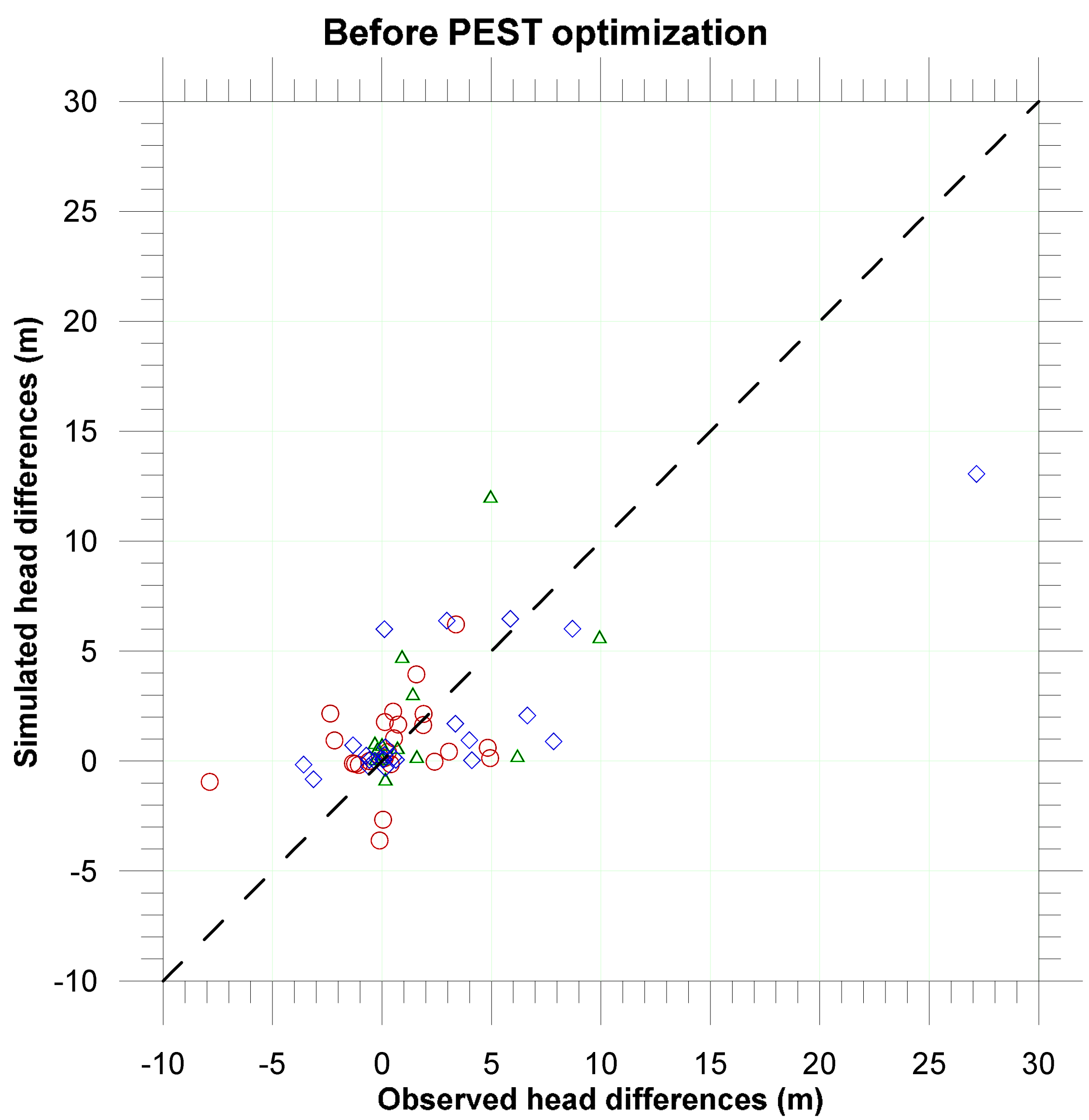

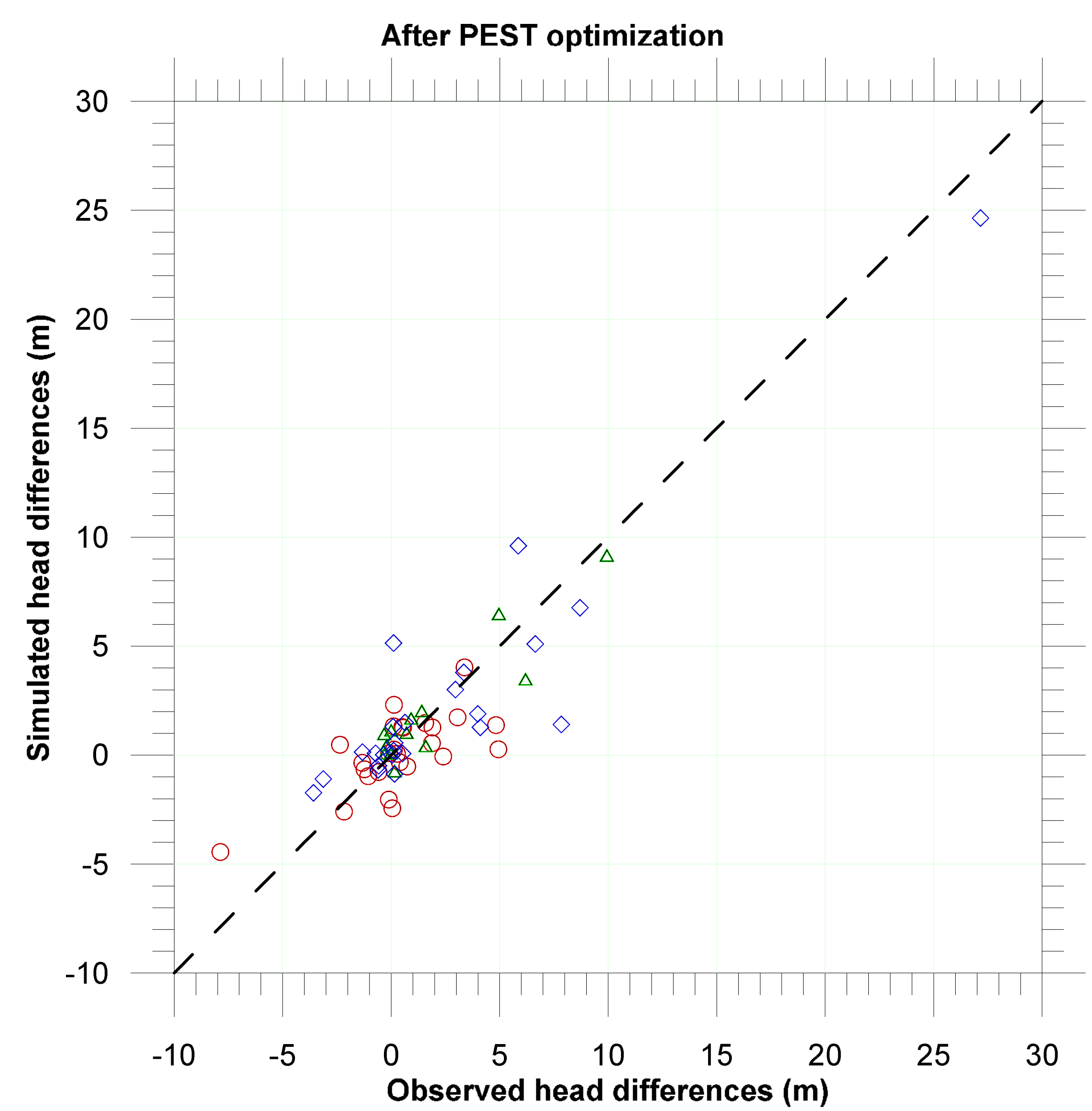

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

- ○ Head Diff. between upper and lower bedrock aquifers
- △ Head Diff within GU
- ◇ Head Diff. between GU and adjacent units

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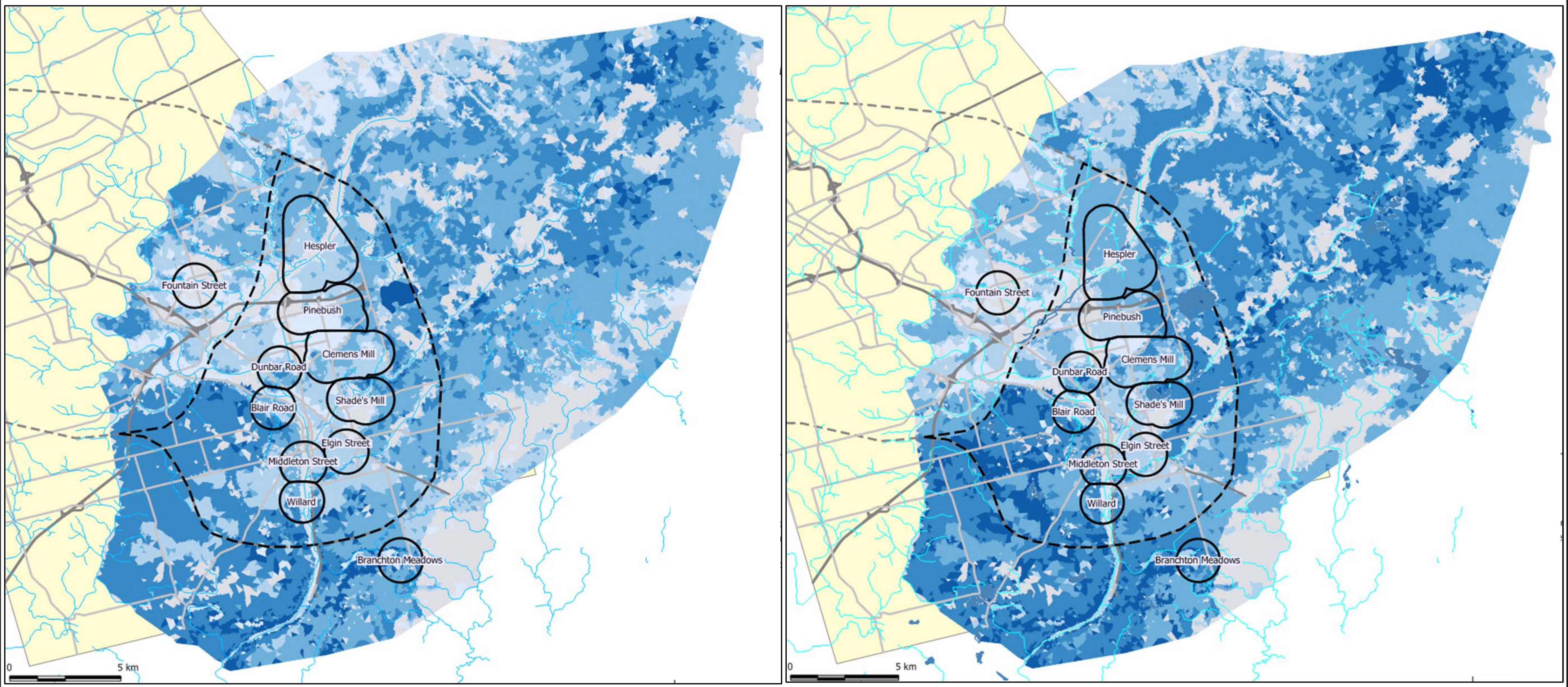
Figure 71: Scatter Plots of Water Level Difference For Base Case and Optimization – Realization 3

Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

Base Case (Calibrated Model) Recharge Distribution

Optimized Recharge Distribution- Realization 3



LEGEND

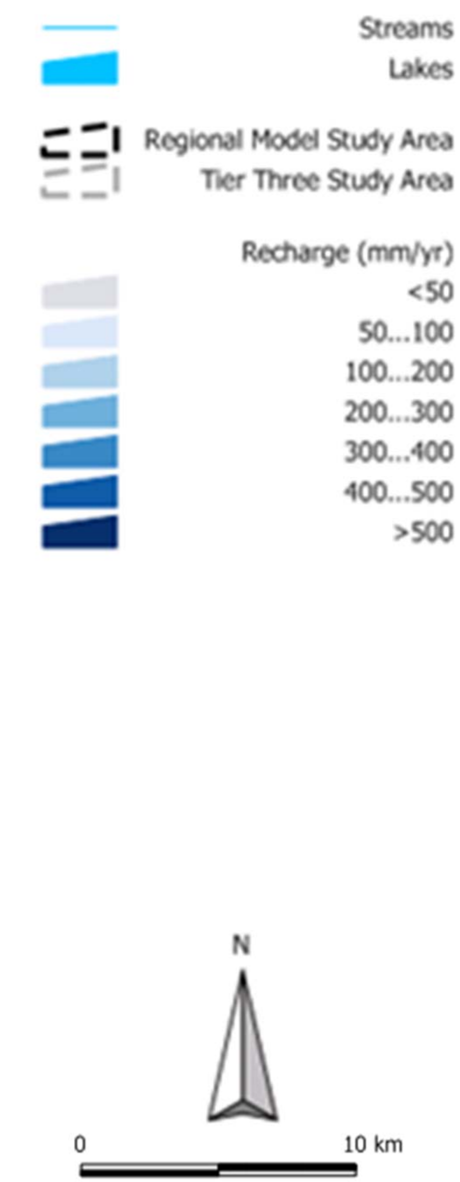


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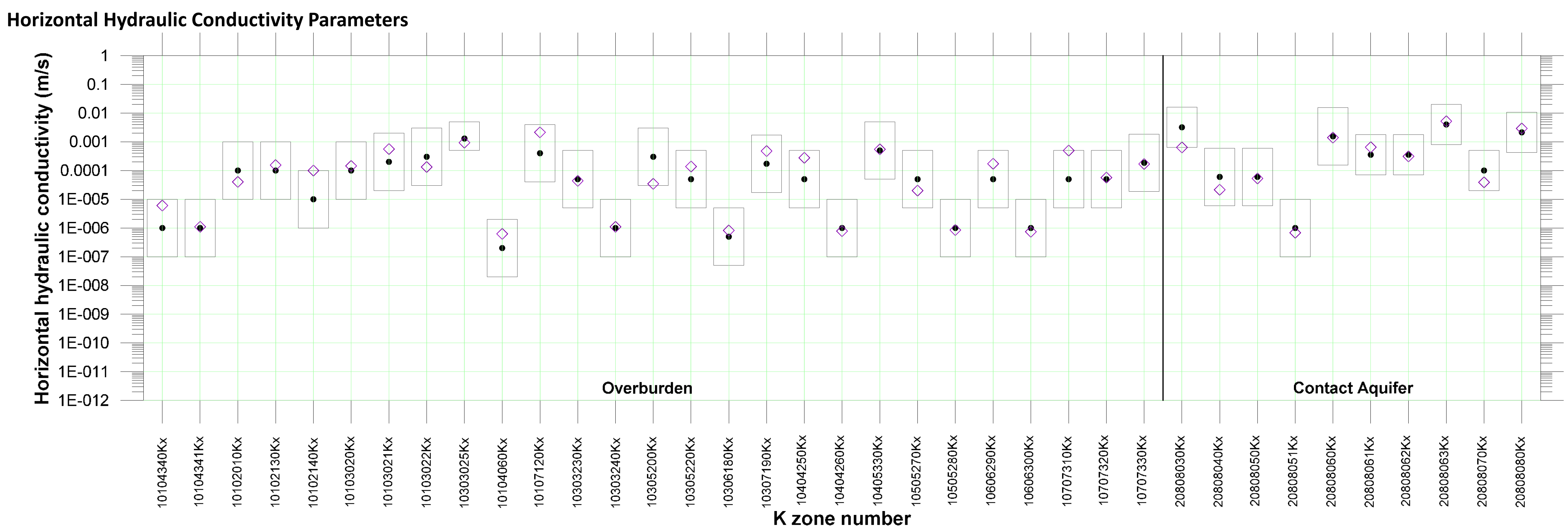
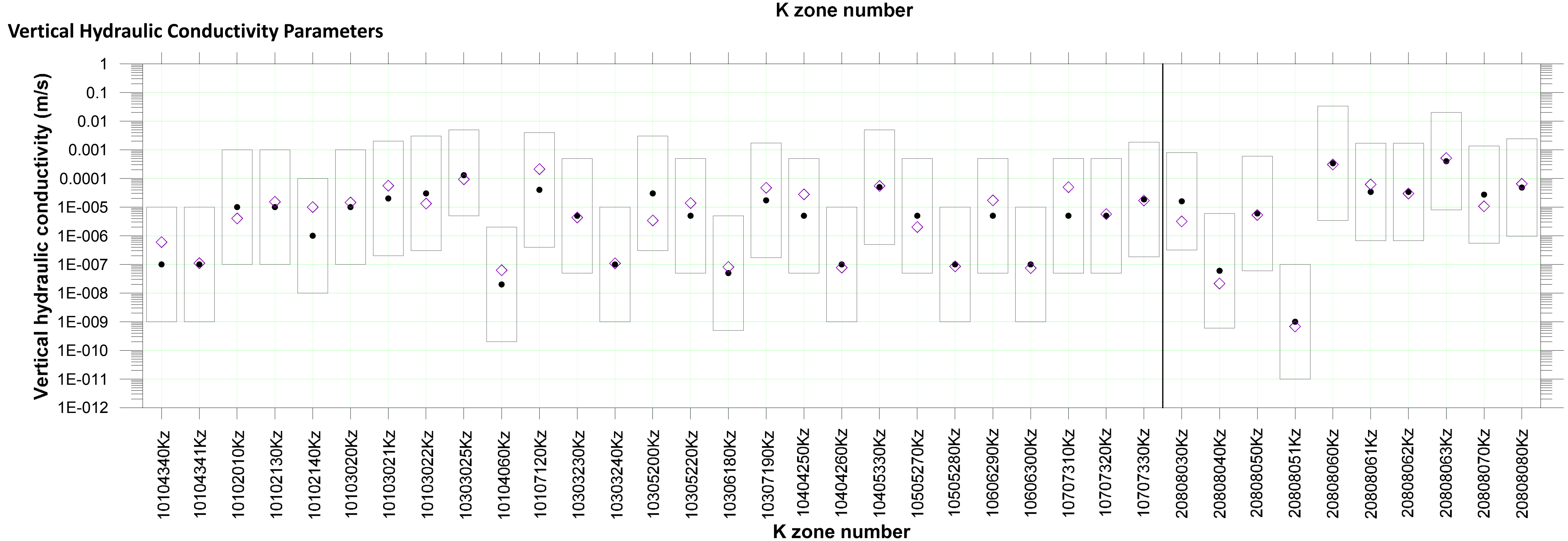
Figure 72: Base Case and Optimized Recharge Distribution- Realization 3





Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses

LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

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Figure 73: Optimized Hydraulic Conductivity Overburden and Contact Zone – Realization 3

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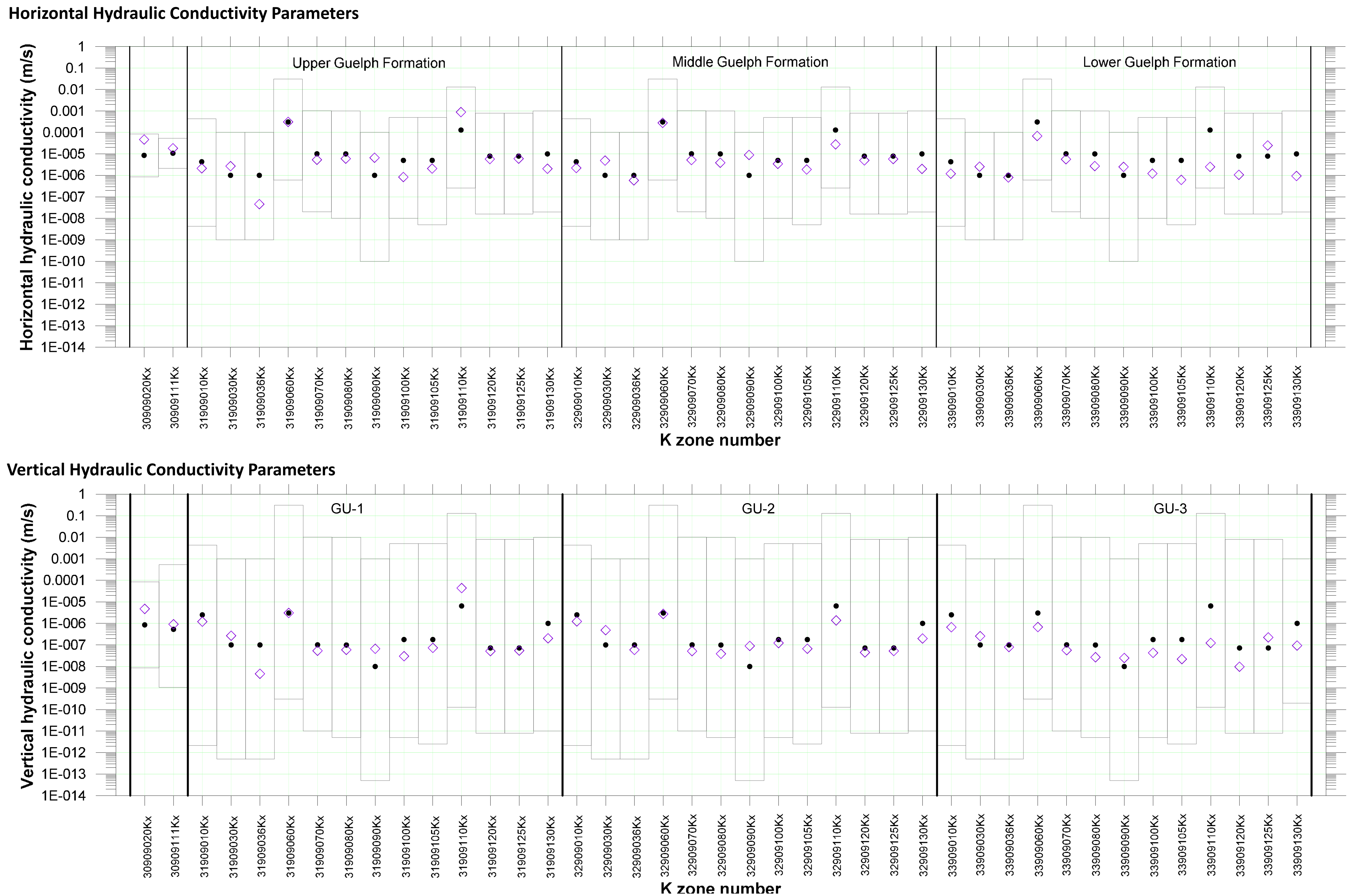
Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses



LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

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Figure 74: Optimized Hydraulic Conductivity for Guelph Formation – Realization 3

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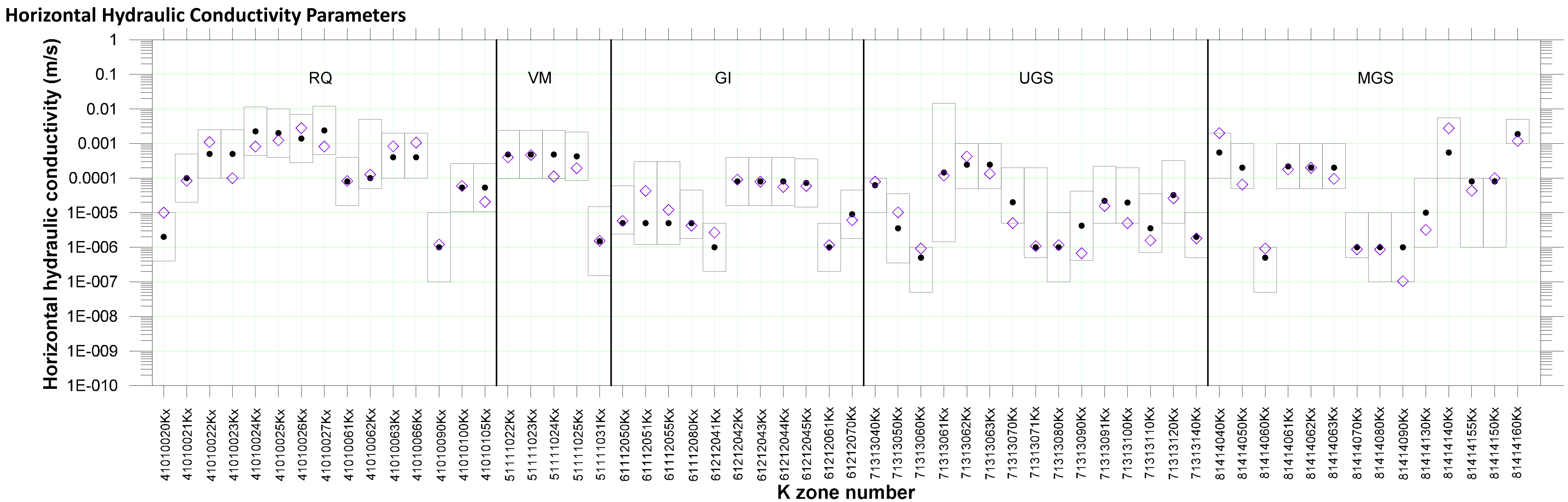
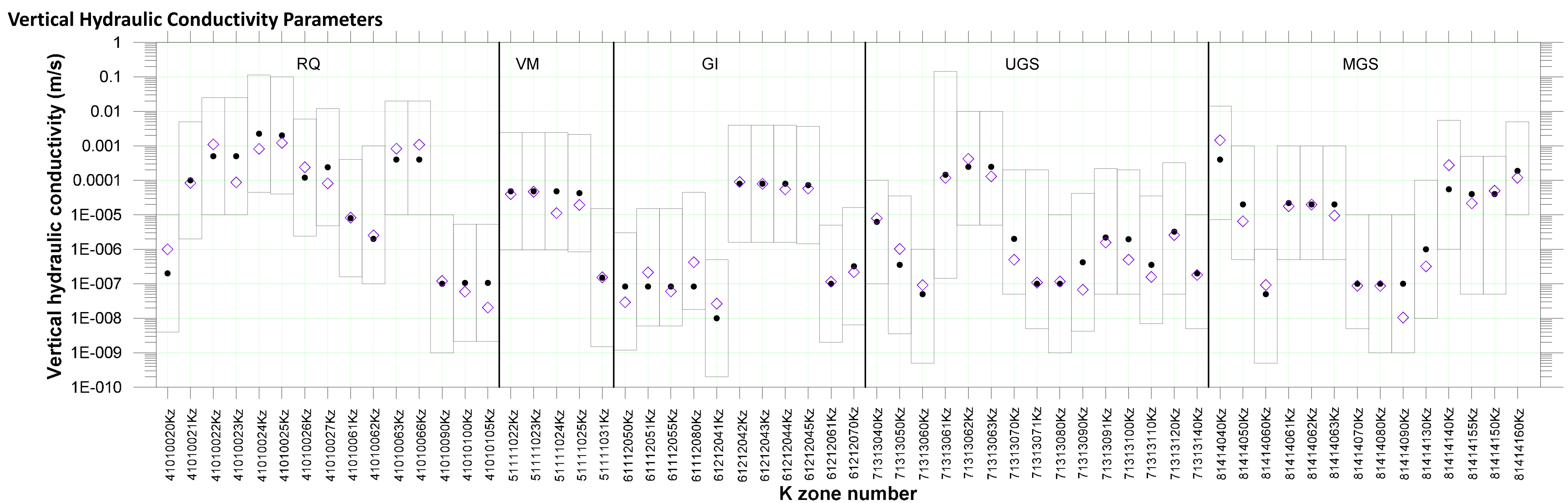
Region of Waterloo Tier Three Risk Assessment; Uncertainty Analyses





LEGEND

PEST Hydraulic Conductivity Range

PEST Optimized Value

Calibrated Hydraulic Conductivity Value

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Figure 75: Optimized Hydraulic Conductivity for Deep Bedrock Units – Realization 3