Klohn Crippen Berger

The City of Calgary

CoC Bowness Flood Control Barriers

Hydrogeological Characterization and Groundwater Flow Modelling Report

CANADA BEST MANAGED COMPANIES Platinum member

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Klohn Crippen Berger

May 17, 2021

The City of Calgary
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Ms. Amy Stansky, P. Eng.
Project Engineer, Project Engineering – Underground

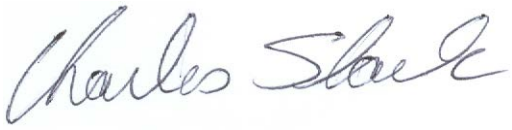
Dear Ms. Stansky:

CoC Bowness Flood Control Barriers
Hydrogeological Characterization and Groundwater Flow Modelling Report

Klohn Crippen Berger Ltd. Is pleased to submit our revised Hydrogeological Characterization and Groundwater Flow Modelling Report for the Bowness Flood Control Barriers Project.

Yours truly,

KLOHN CRIPPEN BERGER LTD.



Chuck Slack, P.Eng.
Principal, Manager – Calgary

TH:AW:JP:ap

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CoC Bowness Flood Control Barriers

Hydrogeological Characterization and Groundwater Flow Modelling Report

EXECUTIVE SUMMARY

Background and Objectives

Klohn Crippen Berger Ltd. (KCB) has undertaken a hydrogeological investigation of the community of Bowness to support The City of Calgary's (CoC) Flood Mitigation Measures Assessment. The assessment concluded that a combination of watershed-level, community-level, and property-level flood mitigation measures should be pursued to reduce Calgary's flood risk (CoC 2016).

The hydrogeological investigation included multi-method geophysical surveying, drilling, monitoring and pumping well installation, hydraulic testing, piezometric monitoring, and groundwater sampling. The compilation and analysis of this data and other relevant data were used to develop a conceptual hydrogeological model for the Bowness area, including a strong understanding of the interaction between the shallow groundwater system and the Bow River, and the development of a *Leapfrog*™ three-dimensional (3D) geological model.

The *Leapfrog*™ model was used as the basis for construction of a 3D groundwater flow model using the *MODFLOW USG* program with a *Groundwater Vistas* pre- and post-processor. The principal objectives of the modelling were to:

- Predict the extent, magnitude, and timing of surface flooding due to overbank flow and groundwater level rises associated with specific Bow River flood events; and
- Assess the effect of the proposed Surface Event Barrier (SEB)[1] on the shallow groundwater system.

Study Methodology

Numerical groundwater modelling was undertaken in general accordance with the guidelines presented in *Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities* (Wels et al. 2012). Numerical model calibration was undertaken using piezometric data collected during the 2019 monitoring program and river level monitoring undertaken by CoC, and simulated Bow River levels using a *HEC-RAS* model (KCB 2020). The groundwater model was calibrated using two separate conditions: an approximate six-month 'long-term' transient model covering the period of greatest river level fluctuation for 2019, and a 'short-term' transient model of four-day duration to evaluate model calibration performance associated with shorter-term changes in river level.

A good calibration with an average Normalized Root Mean Square Error of 1.6% and 2.4% were obtained for the long- and short-term calibrations, respectively. The model was then verified against the 2005 flood event by comparison of areas of high groundwater table (< 2.5 m below ground surface) with anecdotal data gathered regarding basement flooding. The verification showed general correspondence between areas of simulated high water tables and properties where basement flooding was reported.

[1] Also known as Surface Flood Barrier

The 1:200 Attenuated flood hydrograph with Future Upstream mitigation (1:200 Attenuated Event) was used as the basis for assessment of barrier performance. River levels and areas of surface inundation resulting from overbank flow during this event were modelled previously (KCB 2020). As the flood event was considered likely to occur coincident with significant local rainfall, a 1:5 year 24-hour duration rainfall event was simulated at the start of the flooding event. As Bow River flood events are normally driven by coincident Rocky Mountain snowmelt and rainfall events, a 1:5 rain event is the most statistically probable to occur at the same time as a flooding event based on previous City of Calgary studies.

The model was then used to assess the performance of various barrier options in controlling groundwater levels during flood events and their compatibility with the normal groundwater flow conditions in the shallow aquifer system. The barriers were evaluated over a proposed 3900 m long alignment directly adjacent to the Bow River on the right (looking downstream) or south bank.

Study Findings

Hydrogeological Conceptual Model

The Bowness community is underlain by between about 1 m to 21 m of stratified glacial and postglacial sediments, consisting of, from top down, topsoil, silty and clayey fill, alluvial gravel and sand deposits, fine glaciolacustrine sediments, and silty to clayey glacial till. These sediments overly Tertiary-aged Paskapoo Formation bedrock, comprising mostly siltstone and mudstone, with occasional sandstone beds.

The alluvial gravel and sand (Alluvial Aquifer), which also contains appreciable coarser material, including cobbles, is laterally bounded by escarpments comprising of fine-grained lacustrine sediments on the northern and southern margins of the Bow River valley. This unit forms a moderately to highly permeable aquifer, with horizontal hydraulic conductivities estimated to range between about 5×10^{-6} m/s and 2×10^{-3} m/s; hydraulic conductivity within the aquifer tends to increase with proximity to the Bow River. The gravel and sand unit ranges in thickness from about 1 m to 12 m in the Bowness area, based on drilling and geophysical data. The Alluvial Aquifer is mostly unconfined, although portions of the aquifer may become confined by the overlying fine sediments during high water table periods.

The aquifer displays a strong hydraulic connection with the Bow River and past experience, notably the 2005 Flood Event, has shown that high Bow River levels can result in basement flooding through the raising of groundwater levels without surface inundation. During significant flood events, groundwater levels may rise due to three mechanisms: (1) Rainfall and surface runoff recharge; (2) Surface inundation from overbank flow; and (3) High groundwater levels driven by high Bow River levels causing river water to enter the Alluvial Aquifer.

Shallow groundwater flow below Bowness is dominated by the Alluvial Aquifer, and flow is generally northeastward from the southern escarpment to the Bow River in the westernmost portion of Bowness, and northeastward to eastward in the eastern half of Bowness (Figure ES.1). Piezometric and groundwater chemistry data indicate a high degree of mixing of groundwater and river water

within a distance of up to 360 m from the river. River water enters the aquifer during high flow periods and even during normal flow periods within portions of the aquifer proximal to the river, including the point bar on the northeastern end of Bowness.

Figure ES.1 Groundwater Flow within the Alluvial Aquifer, June 25, 2019

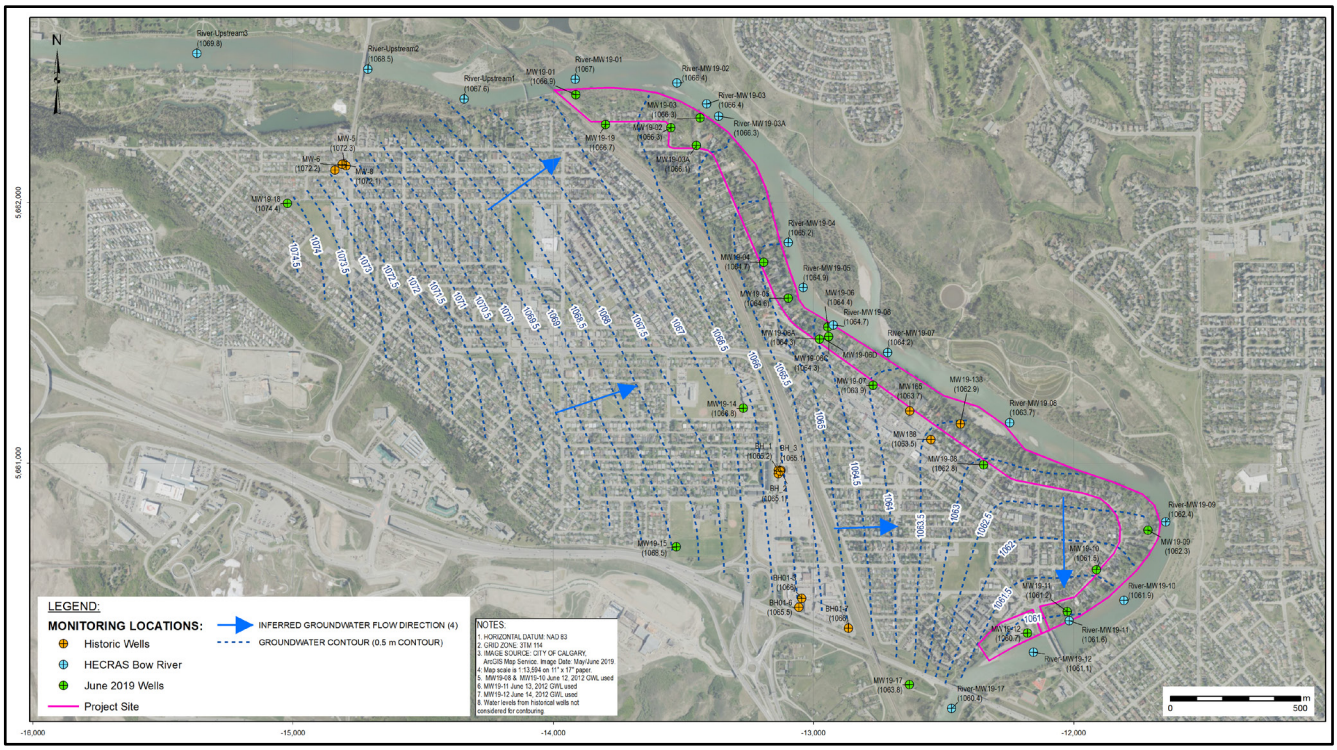
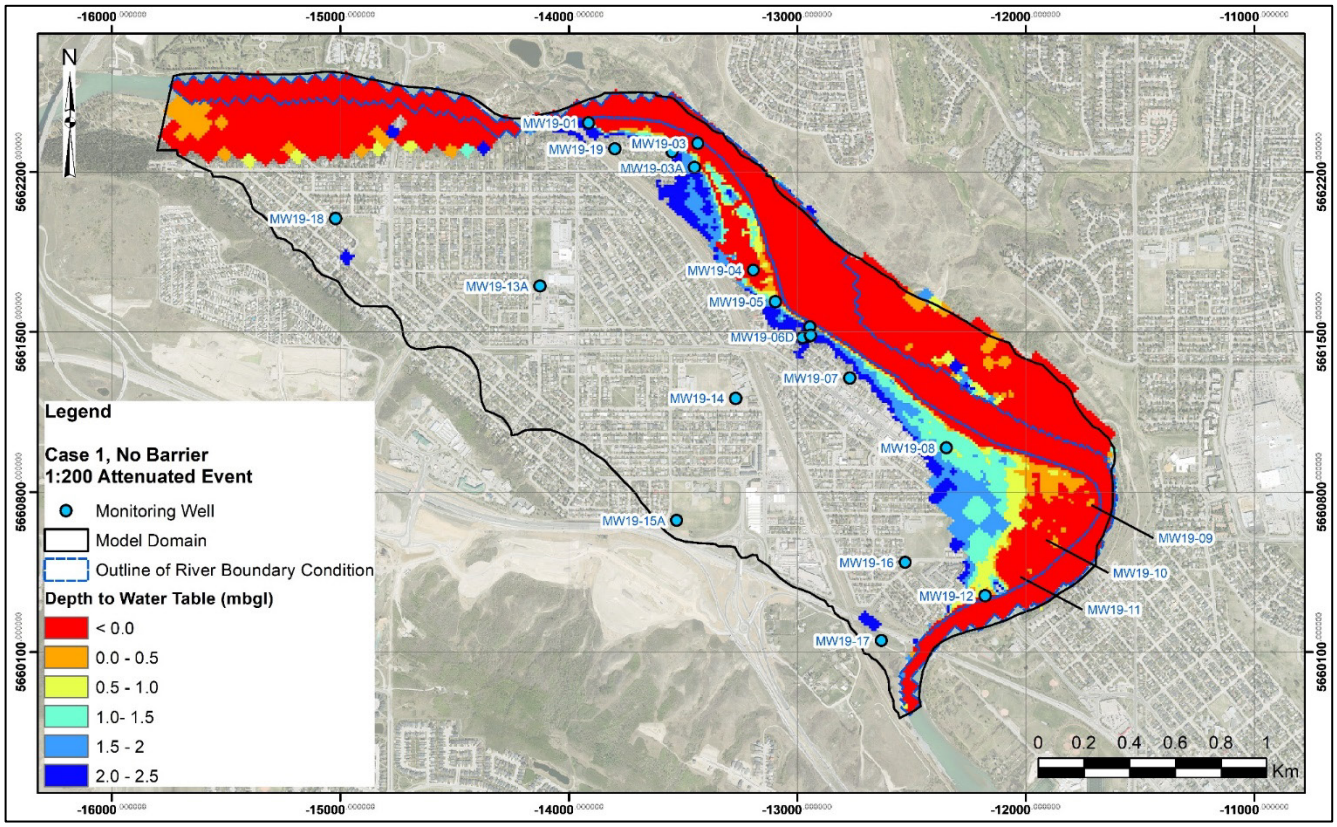


Figure ES.2 shows the simulated peak groundwater levels in the Alluvial Aquifer during the 1:200 year attenuated flood event without any flood mitigation. The groundwater table is predicted to rise to the ground surface in north and northwest Bowness and southeast Bowness, largely due to infiltration of river overbank floodwater.

Figure ES.2 Depth to Peak Groundwater Table, 1:200 Attenuated Event without Flood Mitigation



Surface Event Barrier

Figure ES.3 shows the best estimate peak groundwater table for the 1:200 year attenuated flood event with the Surface Event Barrier (SEB). Simulation of the SEB indicates that the proposed barrier will not result in higher groundwater tables during flood events and will locally reduce peak groundwater levels by between 0 m to 0.8 m during significant flood events (e.g. 1:200 year attenuated flood event) in areas subject to surface inundation. Figure ES.4 shows the predicted peak water table reduction with the SEB in place.

Figure ES.3 Depth to Peak Groundwater Table, 1:200 Attenuated Event With SEB

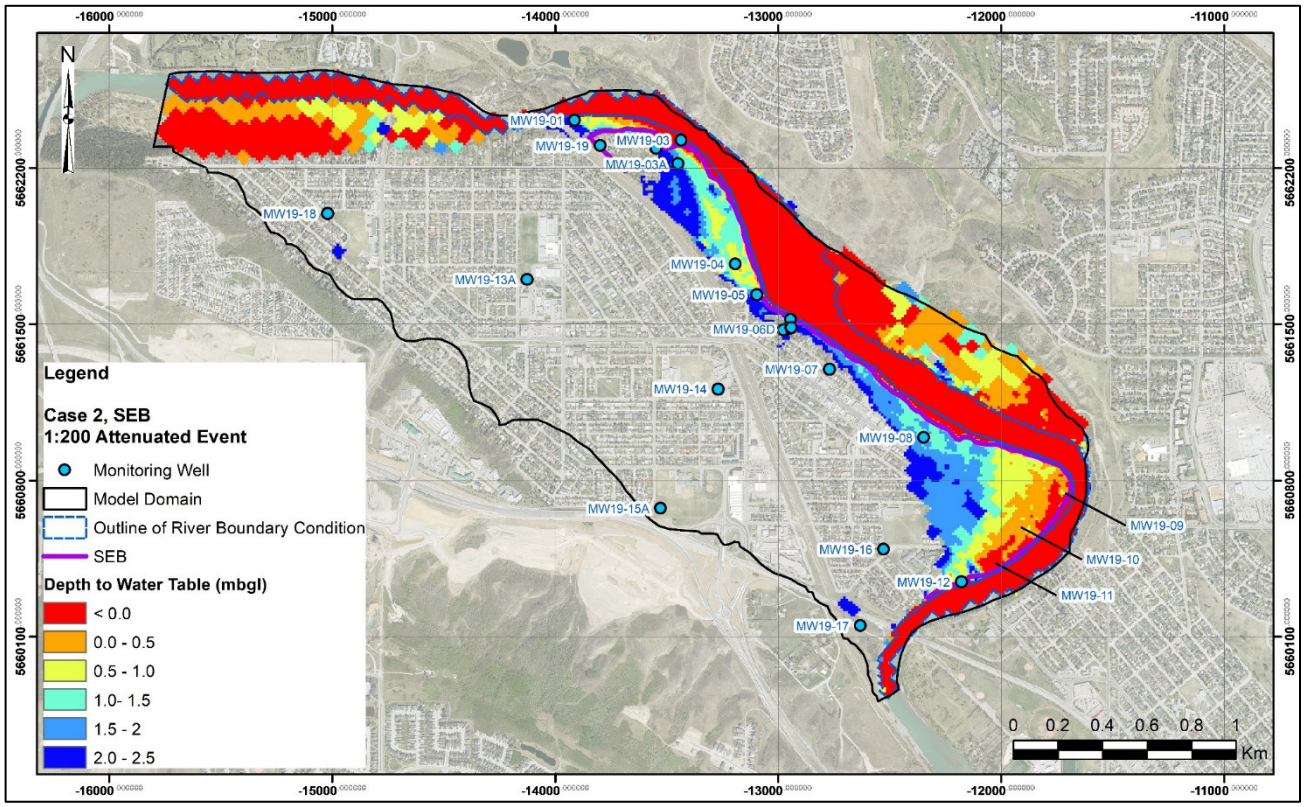
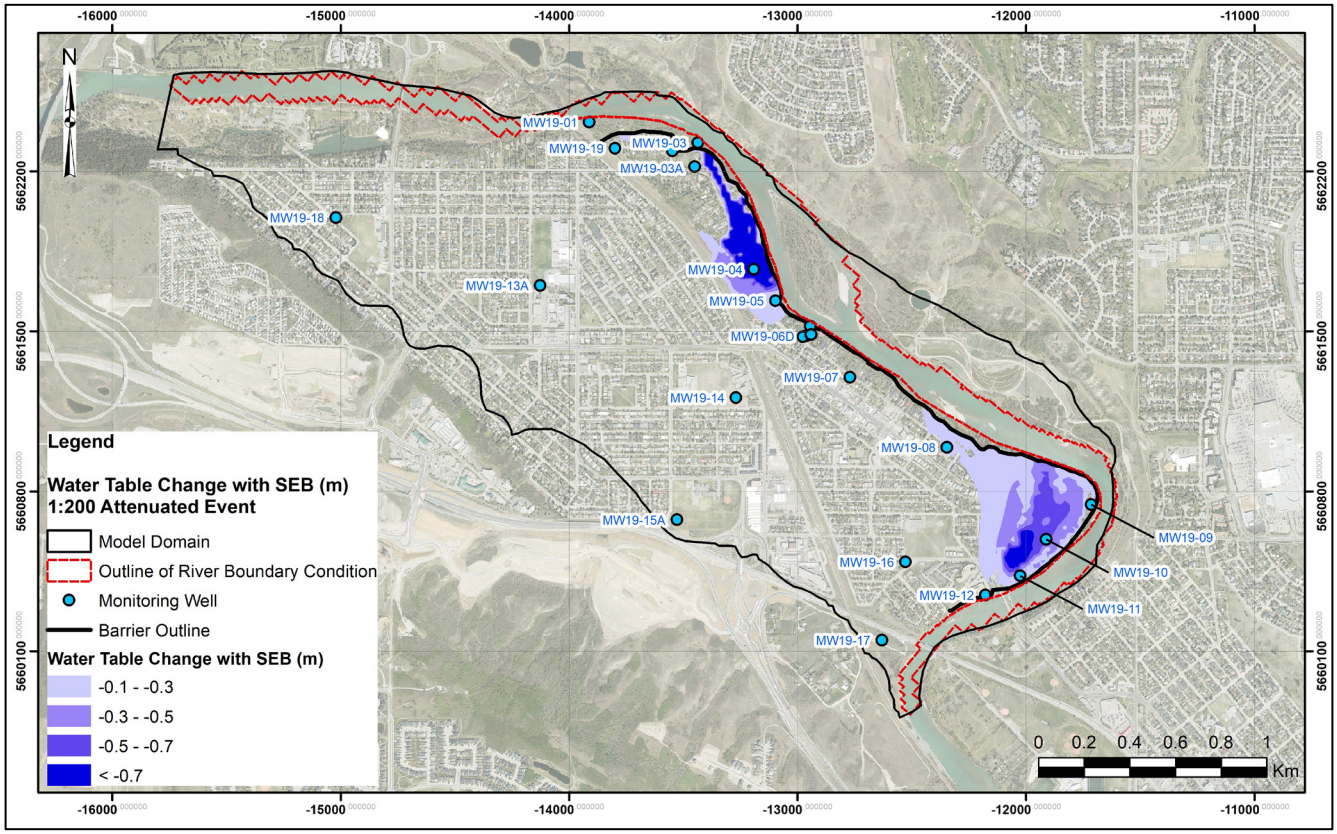


Figure ES.4 Peak Groundwater Table Reduction With SEB, 1:200 Attenuated Event



Recommendations

To meet the design objective of eliminating surface inundation during significant flood events, KCB recommends further investigation of those areas identified as potentially susceptible to groundwater-induced flooding with the SEB in place, within the northwestern and southeastern extents of the proposed barrier alignment. This would include:

- Continue monitoring groundwater levels and water chemistry at select wells within monitoring network. Install pressure transducer/dataloggers in those monitoring wells not instrumented during 2019, which are not dry for significant periods of the year.
- Install, develop and hydraulically test (slug and constant-head testing) three monitoring wells, each screened across the Alluvial Aquifer, one between existing wells MW19-03 and MW19-04, a second between MW19-08 and MW19-09 and a third between MW19-09 and MW19-10.
- Compile and analyse this data and use as input to the next design phase.

GLOSSARY, ACRONYMS AND ABBREVIATIONS

°C	degrees Celsius
µeq/L	micro equivalents per litre
µg/L	micrograms per litre
µS/cm	micro siemens per centimetre
mg/L	milligrams per litre
AEP	Alberta Environment and Parks
Alluvial Aquifer	Fluvial gravel and sand units extending below the Bow River floodplain in the Project Area.
Alluvial fan	A fan-shaped deposit at the mouth of a mountain canyon, where stream gradient abruptly drops. These are usually coarse-grained sediments.
Alluvium	Sediments deposited by or in conjunction with running water in rivers, streams, or sheetwash and in alluvial fans.
Anisotropy	The directional variation of a property, e.g. hydraulic conductivity.
Aquifer	A geological formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to springs and wells.
Aquitard	A geologic material, stratum, or formation of low permeability (a confining unit) that transmits significant amounts of water on a regional scale or over geologic time.
Arithmetic mean	The sum of a set of observed data divided by the count of numbers. Synonymous with ‘average’ or ‘mean’.
Bank storage	Water in an alluvial system that was recharged by the adjacent stream during the rising limb of a streamflow hydrograph.
Baseflow	A groundwater flow to a surface water body.
Bedrock	Consolidated rock which occurs may occur at surface or beneath unconsolidated surficial material.
Borehole	A hole drilled into the earth into which well casing or piezometers may be installed.
Boulder	Soil particle with greater than >250 mm effective diameter (The Canadian System of Soil Classification 1998).

Boundary condition	Specified hydraulic or chemical conditions at the edges or surfaces of a groundwater system.
Bulk	Averaged property for a medium which shows significant variability, for e.g. bulk hydraulic conductivity.
CHB	Constant-Head Boundary (condition)
CO_3	Bicarbonate
Clay	Soil particles with <0.002 mm effective diameter.
Cobble	Soil particle with effective diameter between 80 mm and 25 mm (The Canadian System of Soil Classification 1998).
Conceptual model	A simplified and idealized representation (usually graphical) of the physical hydrogeologic setting and our hydrogeological understanding of the essential flow processes of the system. This includes the identification and description of the geologic and hydrologic framework, media type, hydraulic properties, sources and sinks, and important aquifer flow and surface-groundwater interaction processes.
Cone of depression	A depression of the potentiometric surface in the shape of an inverted cone that develops around a well which is being pumped.
Confined	A condition in which the potentiometric, or piezometric, surface is above the top of the aquifer. Synonymous with artesian.
Confined aquifer	An aquifer that is immediately overlain by a low permeability unit. A confined aquifer does not have a water table.
Datalogger	A device which stores data collected by an electronic instrument.
Deposition	The accumulation of material left in a new position by natural transporting agent such as water, wind, ice or gravity; or by the activity of humans.
DGC	Dual Groundwater Cut-off Wall (simulated Bowness groundwater flood mitigation option)
Discharge	The water leaving a groundwater system by flow to surface water, land surface or to the atmosphere.
Dissolved metals	The content of metal ions in solution, usually after filtration with a 0.45 µm filter.
Drawdown	The vertical distance the water elevation is lowered or the reduction of the pressure head due to the removal of water.

Durov diagram	The trilinear Durov diagram is based on the percentage of major ion milliequivalents. The Cations and Anions values are plotted on two separate triangular plots and the data points are projected onto a square grid at the base of each triangle.
Electrical Resistivity Tomography	The combined application of surface electrical resistivity sounding and profiling surveys to obtain 2D or 3D data. This is normally inverted (interpreted) to provide a 2D or 3D geoelectric interpretation, containing geoelectric units and structures.
Erosion Surface	In the context of the geological modelling program, Erosion Surfaces are similar to deposit surfaces but can 'cut away' other contact surfaces on the older side of the erosion contact surface.
ERT	Electrical Resistivity Tomography
ESAR	Environmental Site Assessment Repository
Exceedance	The measure of an ambient concentration that has a measured value greater than applicable government regulations.
FHT	Falling head test
Flood	An overflow or inundation from a river or other body of water that causes or threatens damage.
Floodplain	The low-lying areas adjacent to a river that are occasionally, are predicted to be, or have been covered by water when the river over tops its bank.
Flow path	The path a molecule of water takes in its movement through a porous medium.
Formation	A body of rock strata that consists of a certain lithology or combination of lithologies; a lithological mappable unit.
Fractured formation	A fractured porous medium in which flow rates in the matrix can be assumed to be negligible. Compare with a purely fractured medium and a double porosity medium.
Freshet	Surface water runoff associated with snowmelt.
Freshwater	Water with salinity <1000 mg/L; drinkable or potable was is implied.
Friable	Easily crumbled. Friable is used in description of soil and drill cuttings.
Gauging station	A location on a stream, lake or canal where data, usually stage height and or discharge, are collected.

Geographic Information System (GIS)	Computer based software package for storing, displaying and querying location and attribute data.
Geometric mean	The geometric mean, sometimes referred to as geometric average, is an average calculated by multiplying a set of positive values and taking the nth root, where n is the number of values.
Geotechnical	Of, or relating, to practical applications of geological science in civil engineering, mining, etc.
GHB	General-Head Boundary (condition)
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
Gravel	Soil or rock particles with an effective grain diameter between 2 mm and 64 mm.
Groundwater	Generally, all water beneath the land surface.
Hydraulic conductivity	The rate at which water of a specified density and kinematic viscosity can move through a permeable medium. Synonymous with 'permeability', but not 'intrinsic permeability'.
Hydraulic gradient	The change in hydraulic head with direction.
Hydraulic head	The elevation in a well in reference to a specific datum.
Hydraulic tests	Field or laboratory tests undertaken to determine the hydraulic properties of a geologic material.
Hydrochemistry	The study of the chemical characteristics of water.
Hydrogeology	The study of subsurface water including it physical and chemical properties, geological environment, its role in geologic processes, natural movement, recovery, contamination, and utilization.
Hydrograph	A chart depicting either discharge or water level as a function of time for streams, rivers or wells.
Hydrostratigraphic Unit (HSU)	Any soil or rock unit, or units, or zone, which by virtue of its hydraulic properties has a distinct influence on the storage or movement of groundwater. Broadly synonymous with 'hydrogeologic unit'.
Impermeable	A material with no permeability. In practice, 'impermeable' is often used to apply to materials of very low permeability.

In-situ	Measurements of components or processes in the field rather than in a laboratory.
Infiltration	The movement of water from the surface of the land into the subsurface (vadose zone).
Infiltration rate	The rate of water entry into the soil. The infiltration rate can change with time but cannot exceed the infiltration capacity.
Ion	A charged molecule in solution.
Isopach	Pertaining to a map of the thickness of a geologic unit.
Kinematic viscosity	The property of fluid describing its resistance to flow.
Lacustrine	Pertaining to, produced by, or formed in a lake.
LiDAR	Light detection and ranging
Major ions	Pertaining to the most abundant ions present in natural water solution, typically including bicarbonate, carbonate, sulphate, chloride, calcium, magnesium, sodium and potassium.
m/s	metres per second
m^3/s	cubic metres per second
masl	metres above sea level
mbgs	metres below ground surface
mbTOC	metres below Top of Casing (well)
Model domain	The region for which a numerical model predicts results.
Model	A simplified representation of a relationship or system of relationships.
Monitoring well	A well-used to monitor water level or water quality opposed to a well-used to produce water. Synonymous with standpipe or Casagrande piezometer.
NRMSE	Normalized Root Mean Square Error (model calibration statistic)
Particle size distribution	The grain size distribution in a soil sample, usually as a cumulative plot, based on sieve and hydrometer analyses and summarized as a percentage of gravel, sand, silt and clay.
Permeability	The property of a porous medium to transmit fluids under a hydraulic gradient. Often used synonymously with ‘hydraulic conductivity’.

pH	A measure of acidity of a solution, based upon the negative logarithm of the hydrogen ion concentration.
Piezometer	A device used to measure groundwater pressure head at a point in the subsurface.
Piezometric	An imaginary surface representing the static head of groundwater and defined by the level to which water will rise in a tightly cased well. Synonymous with potentiometric or hydraulic.
Piper diagram	A graphical means of displaying the ratios of the principal ionic constituents in water.
Plastic	The characteristic of measure of the expansive nature of a soil, in general the more plastic a soil is, the higher the clay content.
Potentiometric	An imaginary surface representing the static head of groundwater and defined by the level to which water will rise in a tightly cased well. Synonymous with potentiometric.
Pressure transducer	An instrument which measures fluid pressure.
Pumping test	A technique used to evaluate the hydraulic properties of an aquifer by observing how water level change with space and time when water is pumped from the aquifer.
QA/QC	Quality assurance/quality control
Recharge	The process by which water enters the groundwater system.
Residual Error	The simulated piezometric elevation, or head, minus the observed piezometric elevation, or head at a given observation point at a given time
Runoff	Water from precipitation, snowmelt, or irrigation running over the surface.
Saturated	The zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.
Sand	Soil or rock particle with an effective grain diameter between 0.62 mm and 2 mm.
SEB	Surface Event Barrier (Bowness Surface Flood Barrier)
Seepage	The slow flow of groundwater through a porous medium. Or the groundwater discharge to a surface water body or ground surface.

Silt	Soil particles with an effective grain diameter between 0.004 mm and 0.062 mm.
Specific Electrical Conductance (EC)	The measure of given fluid to conduct an electrical current over a specified distance. Often represented as 'electrical conductivity'.
Specific Storage	The volume of water released from or taken into storage per unit volume of the porous medium per unit change in head.
Specific Yield	The ratio of the volume of water which the porous medium after being saturated, will yield by gravity to the volume of the porous medium.
Stiff diagram	Stiff diagrams are graphical presentations of the cation and anion content of water presented in milliequivalents per liter. By convention, cations are plotted on the left side of the Stiff diagram and anions on the right.
Stress period	Time period used in numerical modelling where boundary conditions are constant.
Subcrop	The surface where consolidated rock occurs beneath unconsolidated sediments.
SWQG	Surface water quality guidelines
TDS	Total dissolved solids
Terrain	A region, tract, or environment under observation.
Till	An unsorted and unstratified accumulation of glacial sediment, deposited directly by glacier ice. Till is a heterogeneous mixture of different sized material deposited by moving ice (lodgement till) or by the melting in-place of stagnant ice (ablation till). After deposition, some tills are reworked by water.
Topography	The general configuration of the land surface or any part of the Earth's surface, including it relief and the position of it natural and man-made features.
Total metals	Metals contained in a water sample, including dissolved ions and suspended particles and complexes.
TSS	Total suspended solids
Transmissivity	The capacity of rock to transmit water under pressure. Transmissivity (T) = Hydraulic Conductivity (K) × Thickness (b)
Unconfined	A condition in which the upper surface of the zone of saturation forms a water table under atmospheric pressure.

Unconfined aquifer	The upper surface of the aquifer is the water table. Water table aquifer are directly overlain by an unsaturated zone or a surface water body.
Unsaturated	A condition whereby the pore spaces contain water at less than atmospheric pressure, as well as air and potentially other gases.
Water table	The upper surface of unconfined groundwater, at the top of the zone of saturation where the fluid pressure is equal to atmospheric pressure.
Watershed	An area of land where all the surface water drains into the same place, whether it's a creek, a stream, a river, or an ocean.
ZOI	Zone of influence

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1 INTRODUCTION

1.1 Background and Purpose of Study

The June 2013 flood in Calgary prompted The City of Calgary (CoC) to conduct a Flood Mitigation Measures Assessment. The assessment concluded that a combination of watershed-level, community-level, and property-level flood mitigation measures should be pursued to reduce Calgary's flood risk (CoC 2016). CoC identified possible community-level measures being required on the Bow River in the historic communities of Bowness, Sunnyside and Inglewood, and in downtown Calgary.

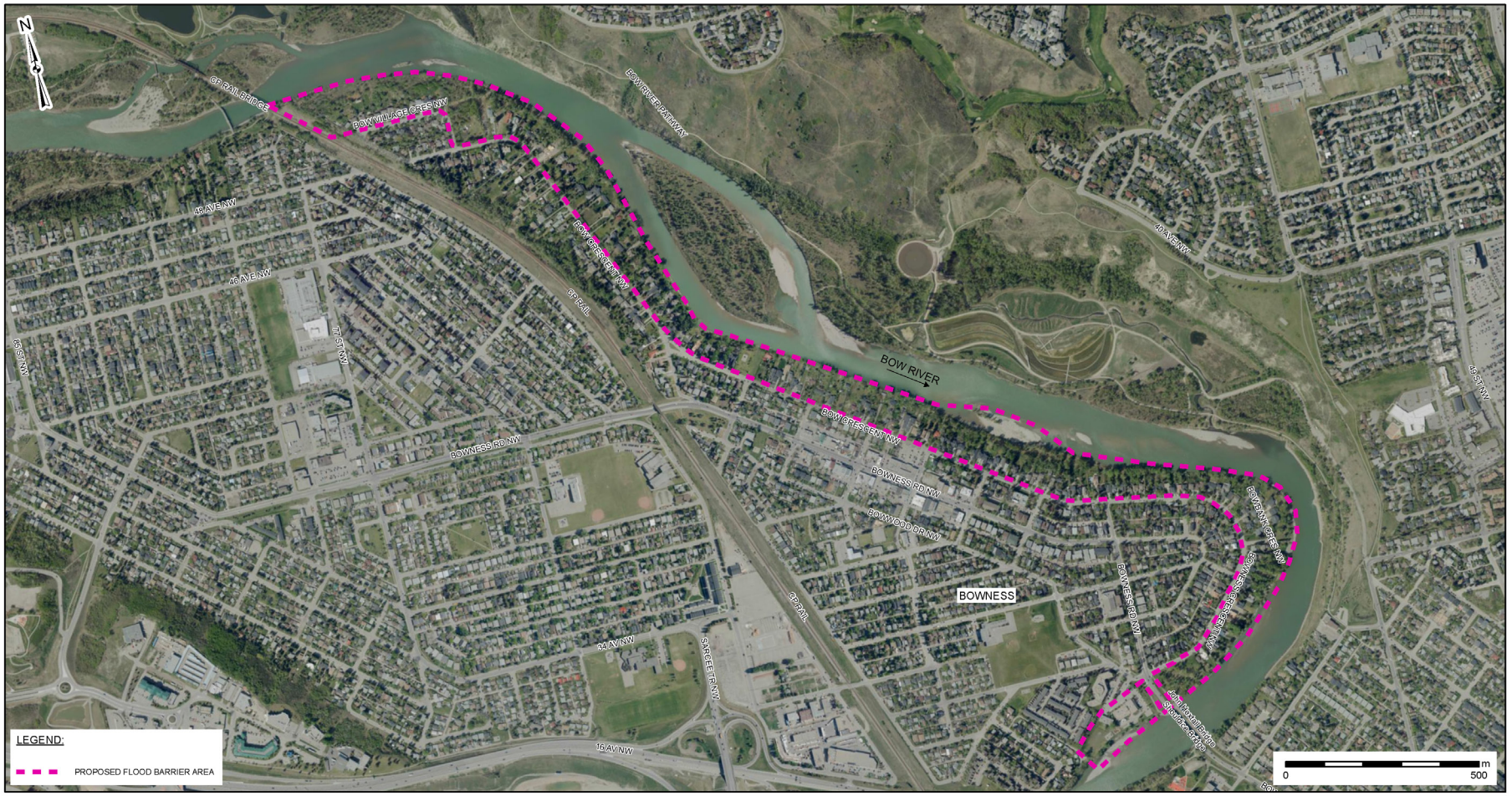
Klohn Crippen Berger Ltd. (KCB) has been commissioned by CoC to conduct a hydrogeological study to support the flood barrier investigation within the riverfront community of Bowness. The proposed flood barrier for Bowness would be located along the Bow River, extending from the CP Railway Bridge downstream to Hextall Bridge (Figure 1.1). The spatial extent of the Project Area was expanded to incorporate all relevant hydrogeological features and the greater Bowness community, and the numerical model domain covers approximately 5.2 km^2. The purpose of the Bowness hydrogeological characterization and groundwater flow modelling study is to:

- Develop and complete a field investigation and monitoring program to collect site-specific geological and hydrogeological data;
- Develop a conceptual model of the geological and groundwater flow system, and its interaction with the Bow River;
- Develop a calibrated three-dimensional (3D) groundwater flow model for the Bowness riverfront community to assess the effect of the proposed Surface Event Barrier (SEB) on the shallow groundwater system;
- Predict the extent, magnitude, and timing of surface flooding due to groundwater level rises associated with specific Bow River flood events and various flood mitigation options; and
- Review potential groundwater mitigation options and present advantages and challenges associated with each option.

Conceptual flood barrier designs provided in the RFP indicate that the construction of the Bowness flood barrier could potentially affect 94 private properties (the total number of properties affected to be confirmed during the Preliminary Design Phase of the project), the Bow River Pathway, public open spaces, the Bowness Road Bridge, and the River Valley School.

The key benefits to the community would be the overall reduction in overland inundation during flood events.

Figure 1.1 Bowness Project Area and Proposed Flood Barrier Alignment Area



1.2 Report Content

This report describes the hydrogeological characterization and numerical groundwater flow modelling undertaken to support the feasibility-level design of a flood barrier protecting the Bowness community. The report is organized as presented in Table 1.1.

1.3 Design Basis

A 3D numerical groundwater flow model was developed to support the Bowness Flood Control Barrier project based on the 3D geological model (*Leapfrog™ Geo*) developed for the Bowness area and conceptual hydrogeological model (CHM) developed for the shallow groundwater system in the Bowness community, to assess the impact of the:

- Proposed flood barrier design(s) on the groundwater system during normal Bow River flows conditions and significant flood events; and
- Potential for groundwater inundation associated with various river flood events, both with and without the flood barrier in place.

Table 1.1 Report Organization

Section		Description
1	Introduction	Background to the current study, report layout, the design basis and objectives of the numerical groundwater modelling, defines the study area and provides a brief summary of previous hydrogeological investigation work.
2	Conceptual Groundwater Model	Describes the current understanding of the climate, geology, hydrology and hydrogeology of the study area as the basis for development of the numerical groundwater model.
3	Numerical Groundwater Flow Model Setup	Describes the construction and setup of the numerical groundwater model, including the use of geological, groundwater modelling and geospatial analysis software and selection of model boundaries and discretization.
4	Model Calibration, Sensitivity Analysis and Verification	Summarizes the calibration methodology employed, the results of model calibration in steady-state and transient mode, model verification and analysis of model sensitivity to various input parameters.
5	Model Predictions	Provides a summary of the predictive simulation methodology utilized and summarizes the modelling results for the impact of a surface water barrier on shallow groundwater. The section also includes a summary of inherent uncertainty in the predictions and limitations of the numerical model for predictive purposes.
6	Model Uncertainty and Limitations	Describes uncertainty analysis undertaken to characterize uncertainty in predictions and discusses remaining model limitations.
7	Summary, Conclusions and Recommendations	Provides a summary of the study findings and provides recommendations for further data collection, monitoring and analysis.
8	Closing	Final comments with respect to use of the report.

A key design aspect of the proposed flood barrier is that the mitigation designs do not have an adverse effect on the Bowness community in terms of groundwater-related flooding. There are benefits to mitigating groundwater-induced flooding. Flood management of the Bow River at the upstream dams operated by TransAlta will also affect the river flood response and the resulting attenuated peak design flows. The magnitude and duration of the river flow during a flood event, whether natural or modified by upstream dams, will be the key design aspect for the proposed Bowness flood mitigation scheme.

1.4 Groundwater Modelling Objectives

The numerical groundwater modelling objectives are as follows:

- To numerically simulate the hydrogeological flow system in the Bowness study area, in a manner which captures the current understanding of shallow groundwater system and groundwater-Bow River interaction, particularly within the alluvial gravel and sand aquifer which borders the river;
- To numerically simulate past and estimated future flooding events to estimate areas affected by groundwater inundation without barriers in place; and
- To simulate the effects of various groundwater flood mitigation measures (i.e., seepage cut-off wall(s), pumping wells and/or interception drains etc.) installed in the alluvial sand and gravel aquifer under both normal and flood flow conditions, notably in terms of the potential for groundwater-induced surface inundation.

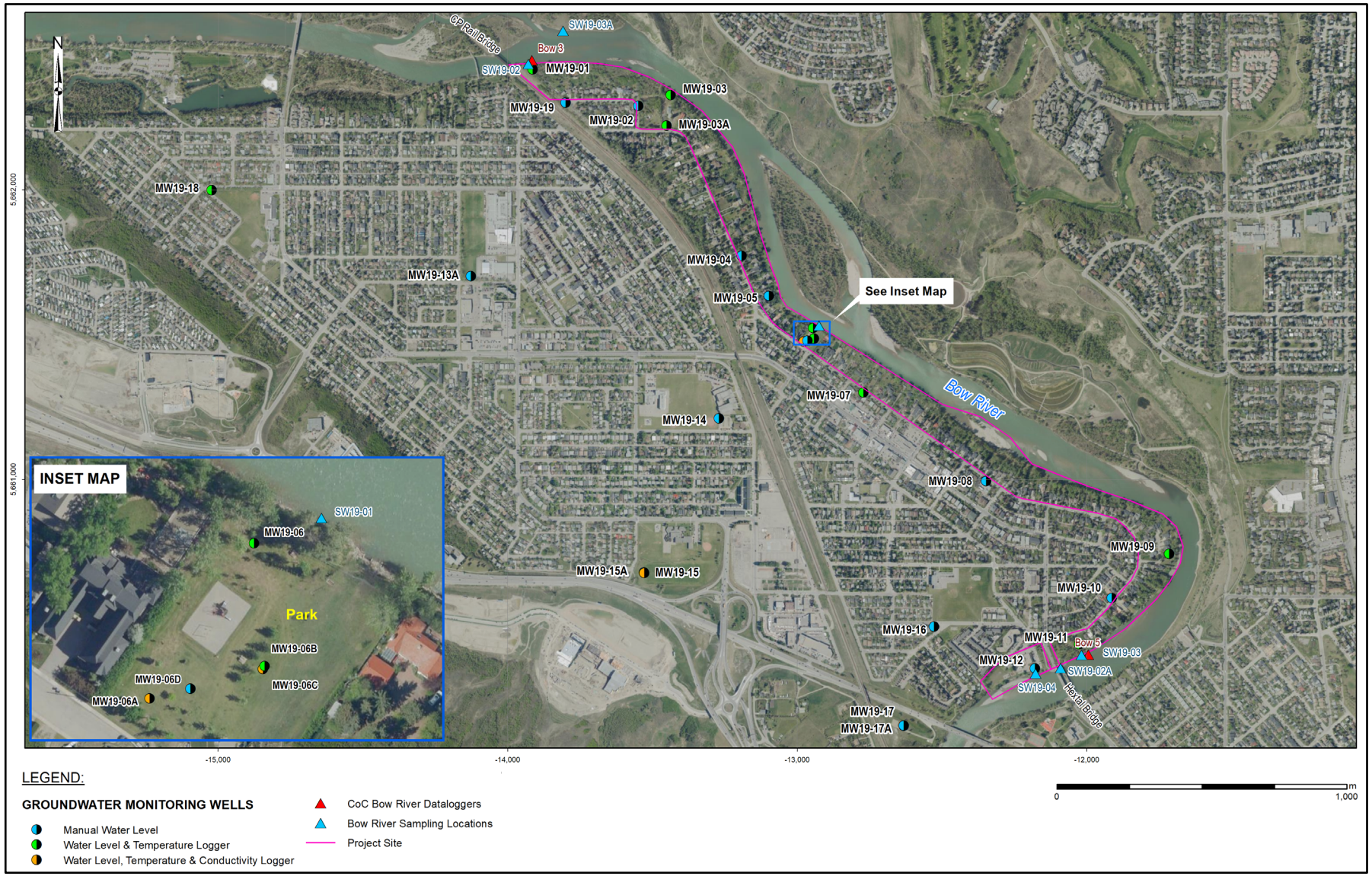
1.5 Previous Investigations

The following groundwater site investigations or well installation programs contributed to the development of a conceptual understanding of hydrogeology of the Bowness area. These are summarized in Table 1.2. Figure 1.2 shows the locations of groundwater and surface water monitoring points within, and adjacent to the Project area, as well as HEC-RAS surface water simulation locations.

Table 1.2 Summary of Relevant Investigations Undertaken to Date

Year	Organization	Investigation Type	Work Undertaken
2019 – 2020	KCB	Hydrogeological	Piezometric monitoring, hydraulic testing, groundwater sampling on 2019 piezometers.
2020	KCB	Hydrotechnical	HEC-RAS modelling of Bow River flood events
2020	Tetra Tech EBA	Geophysical	Electrical Resistivity Tomography (ERT) (land and water), Ground Penetrating Radar, Capacitively Resistivity and Seismic Refraction. Data collected along proposed location of flood barrier and within the Bow River (Marine ERT).
2019	KCB	Geotechnical/ Hydrogeological	Drilling of 27 boreholes and installation of and installation of 1 152 ND PVC pumping well and 25 standpipe piezometers, basic geotechnical index tests. To support flood barrier investigation.
2015 – 2018	CH2M	Hydrogeological/ Environmental	Drilling in excess of 150 boreholes and installation of monitoring wells to support Gas Plus hydrocarbon remediation project. Piezometric monitoring, hydraulic testing, groundwater sampling.
2016	Golder	Hydrogeological	Groundwater flood modelling – development of conceptual model.
-	Alberta Environment and Parks	Hydrogeological	Alberta Water Well Drilling Reports (sourced 2018).

Figure 1.2 Bow River Water Level and Well Monitoring Locations



2 CONCEPTUAL HYDROGEOLOGICAL MODEL

2.1 Topography

The Bowness community lies within the Bow River floodplain. Glaciers and glacial meltwater incised into the sandstone, siltstone and mudstone bedrock to form the Bow River valley system. The earliest available aerial photographs of the Bow River (1924 to 1926) suggest the channel was highly mobile, probably due to several large floods that occurred in preceding years (KCB 2017). The surface riverbed material has a median diameter (D_{50}) in the range of 80 mm to 90 mm.

The Bowness floodplain forms much of the Project area, and ranges in elevation from about 1063 masl to 1087 masl, with little undulation. To the south-southwest, the floodplain is bounded by an erosional scarp formed in underlying fine-grained glaciolacustrine sediments. The scarp ranges in height from about 10 m to 40 m above the adjacent floodplain.

The ground surface topography is shown on Figure 2.1.

2.2 Climate

2.2.1 Temperature

Calgary experiences a humid continental climate with warm summers and cold, dry winters. According to Environment Canada (2020), average daily temperatures in Calgary range from 16.5°C in July to −6.8°C in December. Average monthly temperatures for the Calgary International Airport are presented in Table 2.1, for the period of record 1981 to 2010.

Winters are cold and the air temperature can drop to or below −20°C on an average of 22 days of the year and −30°C on an average of 3.7 days of the year, and are often broken up by warm, dry Chinook winds that blow into Alberta over the mountains. These winds can raise the winter temperature by 20°C, and as much as 30 °C in just a few hours and may last several days.

Freshet typically occurs in May and June. Ground remains frozen through much of this period, limiting groundwater recharge during this period.

2.2.2 Precipitation

Calgary International Airport, in the northeastern section of the city, receives an average of 419 mm of precipitation annually (Table 2.1), with 326.4 mm of that occurring in the form of rain, and 92.4 mm as snow. Highest monthly rainfall typically occurs in June and highest snowfall in March. Thunderstorms can be frequent and sometimes severe with most of them occurring in the summer months.

Figure 2.1 Project Area Topography

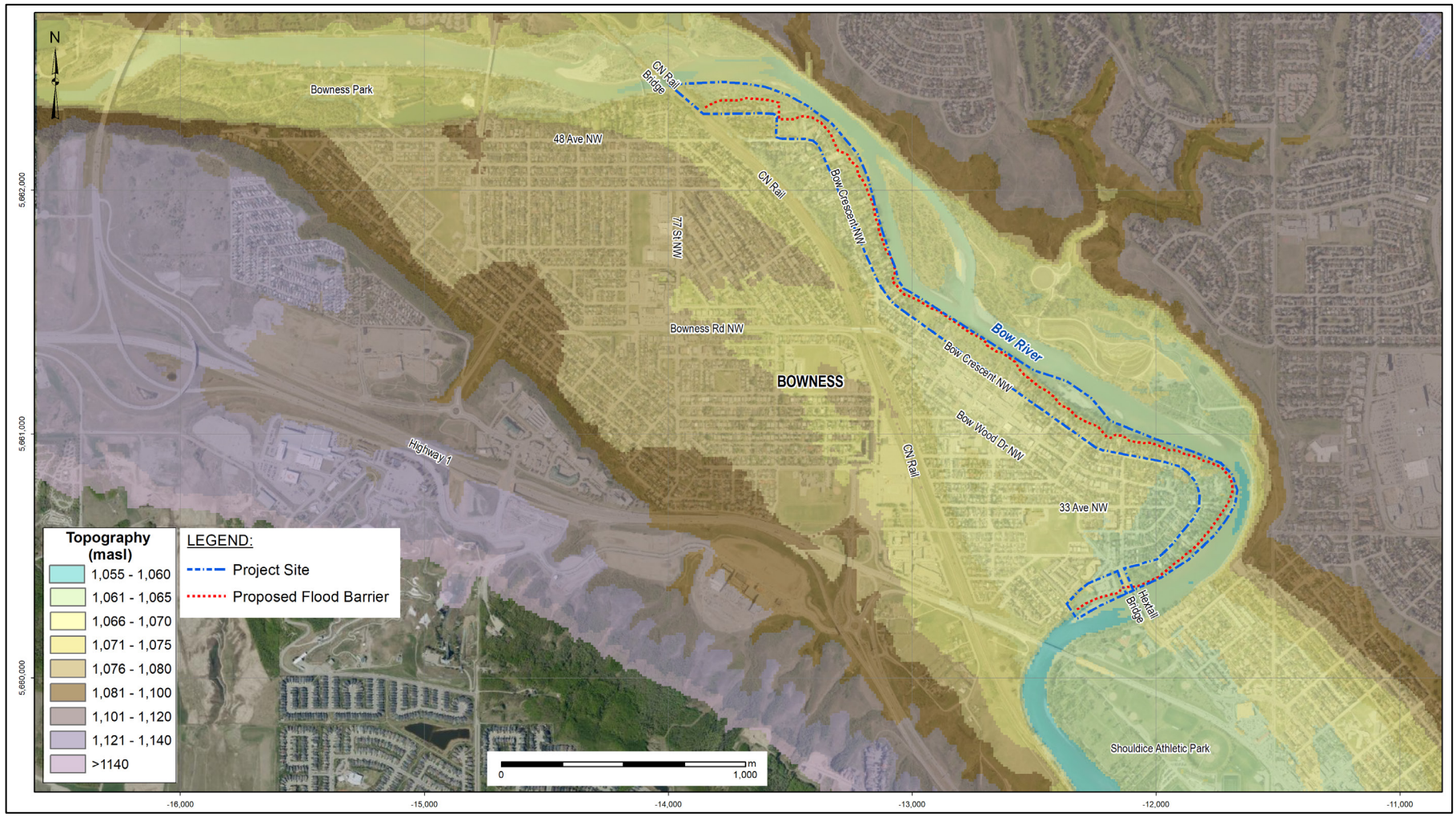


Table 2.1 Average Monthly Temperature, Precipitation, and Potential Evaporation, Calgary International Airport

Month	Average Monthly Temperature[1] (°C)	Average Monthly Precipitation[1] (mm rain or rain equivalent)	Average Monthly Potential Evaporation[2] (mm)
January	-7.1	9.4	2
February	-5.4	9.4	8
March	-1.6	17.8	30
April	4.6	25.2	69
May	9.7	56.8	111
June	13.7	94.0	130
July	16.5	65.5	154
August	15.8	57.0	121
September	11.0	45.1	65
October	5.2	15.3	29
November	-2.4	13.1	7
December	-6.8	10.2	1
Total		**418.8**	**728**

Source: Environment Canada (2020)

2.2.3 Potential Evapotranspiration

Monthly potential evaporation is highest during the summer months, with an average of 154 mm in July, and minimal potential evaporation (< 10 mm/month) during the winter months (Table 2.1). The potential evaporation greatly exceeds the precipitation, resulting in an annual average precipitation 'deficit' of approximately 310 mm.

2.3 Geology

2.3.1 Regional Geology

Surficial geology maps (Moran 1986) reviewed indicate that the Project Area is underlain by 'gravel and minor sand'. Based on our review of the *Urban Geology of Calgary* (Osborn and Rajewicz 1998), it is considered likely that the gravel and minor sand represent post-glacial alluvial deposits and are considered as the original surface of the Bighill Spring Formation. While post-glacial deposits in the Bow Valley typically comprise gravel, these are often interbedded with sand, silt, and lacustrine clay deposits. These gravel and sand deposits form the most significant aquifer in the Calgary area (Osborn and Rajewicz 1998). The deposits are locally interbedded and underlain by lacustrine sand, silt, clay and clayey till deposits.

Osborn and Rajewicz (1998) state that bedrock underlying the city of Calgary typically consists of fine- to medium-grained sandstone and mudstone of Paleocene age. These Paleocene rocks were originally designated as the Paskapoo Formation but were subsequently subdivided into a lower Paskapoo Formation and an upper Porcupine Hills Formation (Osborn and Rajewicz 1998). Based on a review of geological mapping (Hamilton et al. 2004), the bedrock geology within the Project Area is indicated to comprise of a sedimentary bedrock primarily of the Paskapoo Formation. The depth to

bedrock underlying alluvial deposits was recorded at a maximum depth of 18 m, with an average depth of 7 m (Osborn and Rajewicz 1998).

2.3.2 Site Geology

A more detailed description of key geological units relevant to this study is provided below, with reference to the geotechnical drilling program conducted in 2019:

2.3.3 Surficial Geology

The surficial lithological units compiled in the *Leapfrog*™ 3D Geology Model are summarized in the following sections, ordered in general order of occurrence with increasing depth. Figure 2.2 shows the surficial geology of the Project Area (after Moran 1986).

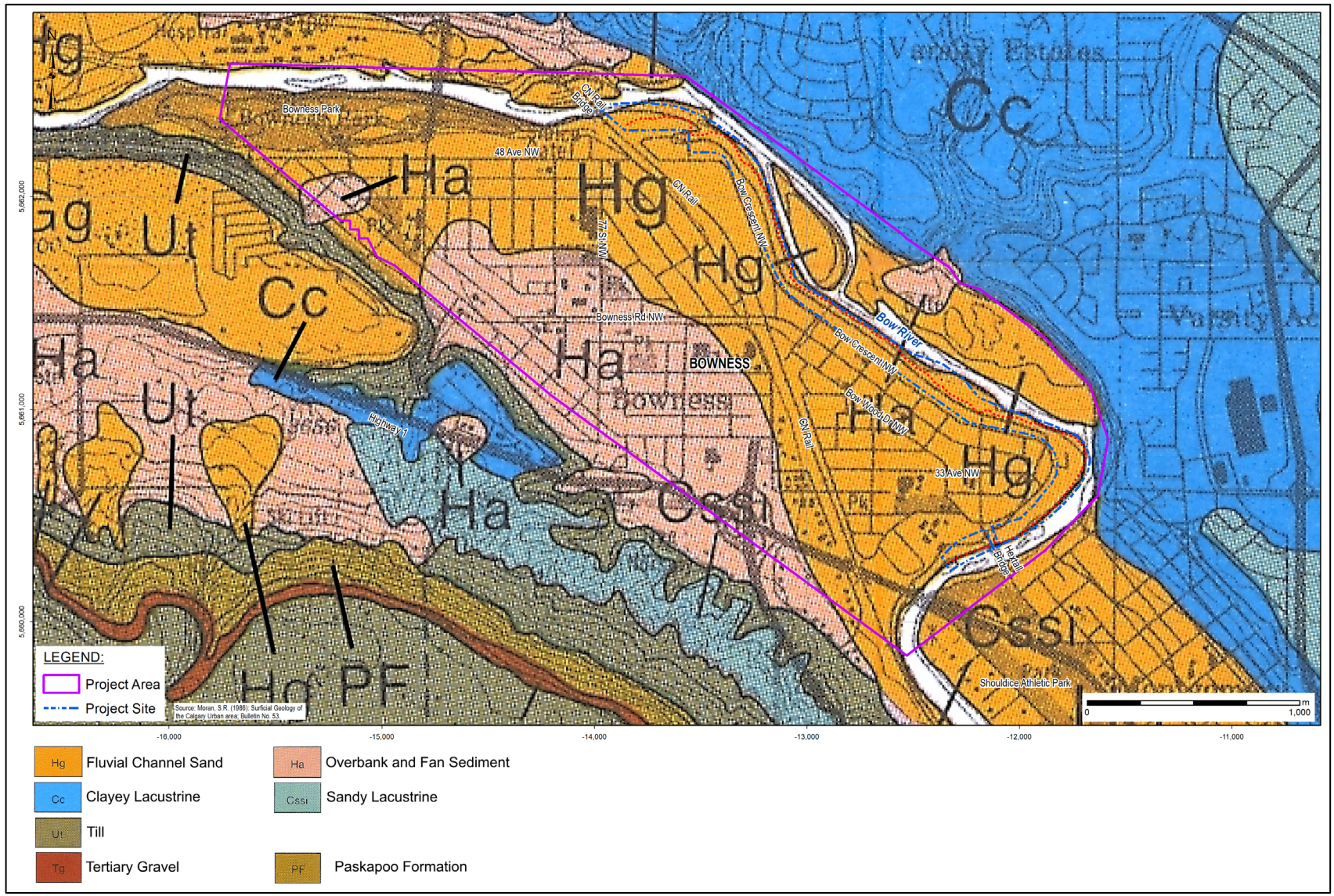
Topsoil/Fill

Topsoil or fill material was encountered from ground surface in each borehole, except for MW19-03, -03A, -07, and MW19-14. In general, the topsoil thickness ranged from 0.1 m to 1.5 m. This material was assigned to either the Silty Topsoil/Fill or Clayey Topsoil/Fill unit in the 3D geology model, depending on overall texture.

Clayey fill material was encountered underlying topsoil in boreholes MW19-09, -11, -15, -17, and MW19-17A (Figure 2.6 through Figure 2.11). The unit extends to depths ranging from 0.6 metres below ground surface (mbgs) to 2.4 mbgs, with thicknesses of 0.3 m to 3.1 m. The material was generally described as brown or black, low plasticity clay with varying granular content. Metal debris was encountered at borehole MW19-11 from 0.3 mbgs to 0.6 mbgs. The clay fill was frozen at the time of drilling from January 2019 through April 2019. The frozen soils indicate that groundwater recharge would be restricted during the winter months. These soils were assigned to the Clayey Topsoil/Fill unit in the 3D geology model.

Low plasticity deposits comprising of either clay or silt were encountered from ground surface or underlying topsoil or clay fill material in boreholes MW19-01, -02, -03, -03A, -05, -08, -09, -12, -13, -13A, -15, -15A, and MW19-19 (Figure 2.6, Figure 2.8 and Figure 2.11). The unit extends to depths ranging from 1.2 mbgs to 4.3 mbgs, with thicknesses of 0.6 m to 4.1 m, and was generally described as brown, low plasticity, sandy, and frozen or moist. These soils were assigned to the Clayey Topsoil/Fill unit in the 3D geology model.

Figure 2.2 Surficial Geology



Gravel and Sand

Sand layers were encountered underlying topsoil or clay fill in boreholes MW19-04, -10, and MW19-11. The sand extends to depths from 1.8 mbgs to 2.3 mbgs, with thicknesses ranging from 1.4 m to 2.0 m. It was generally described as brown, fine-grained, silty, loose or compact, and moist to wet.

Gravel of interpreted alluvial origin was encountered in each of the boreholes located on the Bow River floodplain and extended to depths of 1.8 mbgs to 12.2 mbgs, with thicknesses ranging from 1.0 m to 12.2 m (Figure 2.3). The unit was generally described as brown or grey, sandy, with trace clay, silt, and cobbles; and moist or wet (refer logs provided in Appendix I). Based on freshly fractured, angular gravel drill-cuttings observed throughout the gravel layer, it was inferred that cobbles and boulders are present within the unit. Core loss frequently occurred when drilling through the gravel, likely due to large cobbles or boulders blocking the drill shoe.

The index properties of the gravel are summarized in Table 2.2, which shows a textural variability from Gravel, some Sand to Silty, Sandy Gravel, with an average textural composition of Sandy Gravel.

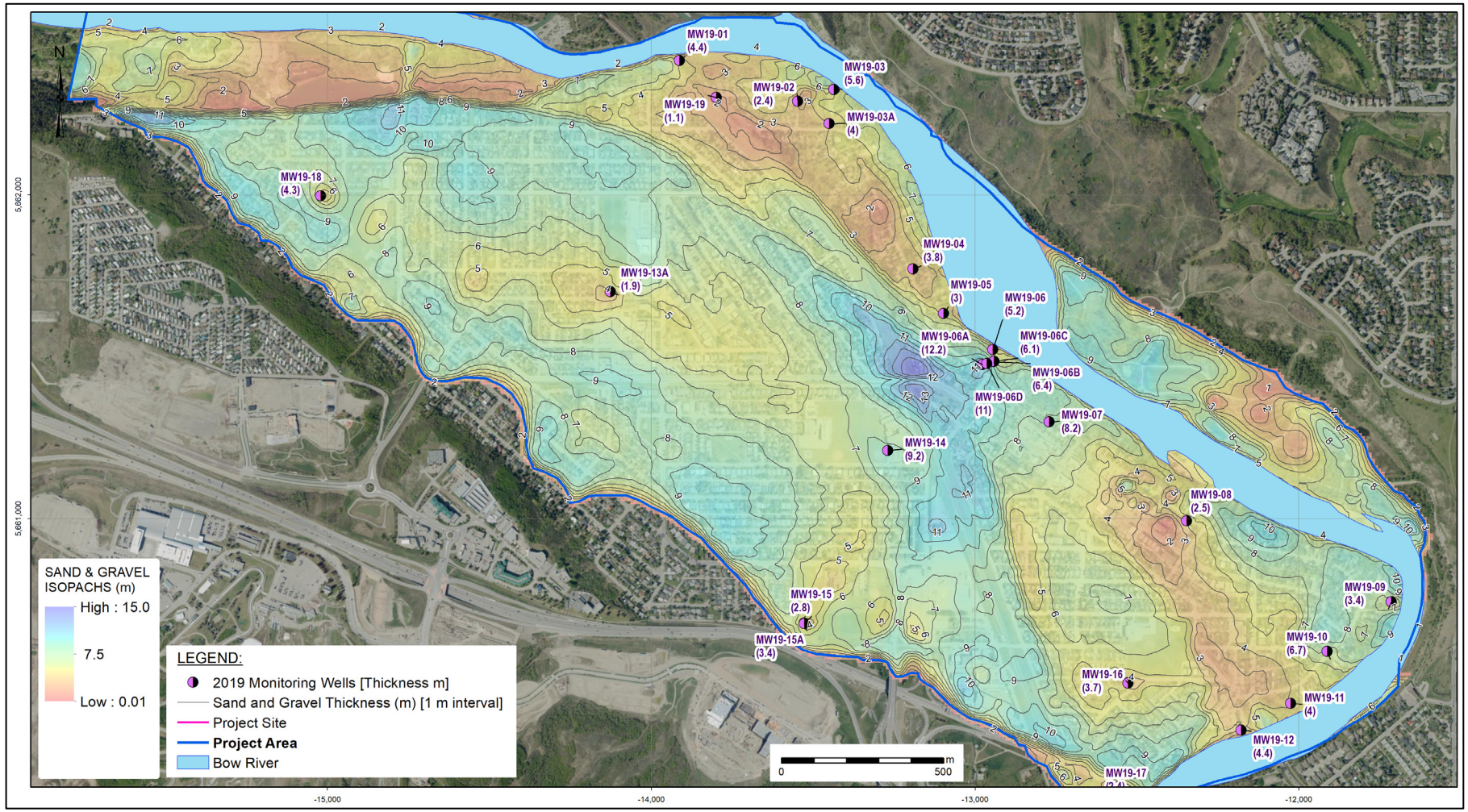
Table 2.2 Summary of Laboratory Index Testing of Gravel and Sand

Borehole ID	Depth (mbgs)	Moisture Content (%)	Particle Size Distribution		
			Gravel (%)	Sand (%)	Silt and Clay (%)
MW19-01	2.1 – 2.4	1.9	73.1	20.5	4.0
MW19-03	4.6 – 5.2	9.0	82.2	16.5	1.3
MW19-04	2.4 – 2.7	5.0	38.5	54.5	7.0
MW19-06A	3.7 – 4.0	4.2	70.2	21.7	8.1
MW19-07	2.1 – 2.4	2.1	81.2	13.8	5.0
MW19-08	5.2 – 5.5	4.0	68.8	24.7	6.5
MW19-09	3.0 – 3.4	15.0	28.7	48.9	22.4
MW19-10	3.7 – 4.0	3.1	70.8	18.8	8.5
MW19-12	3.7 – 4.0	4.0	71.5	26.0	2.5
MW19-13	3.7 – 4.0	1.3	78.0	16.5	5.4

Clayey Till

Clay till was encountered underlying gravel, silt or sand in boreholes MW19-03A, -06, -06A, -06D, -07, -09, -10, -11, -12, -14, -15, -15A, -16, and MW19-17. The clay till extended to depths ranging from 7.6 mbgs to 20.1 mbgs, with thicknesses of 1.0 m to 8.5 m. It was generally described as brown or blue grey, with varying secondary constituents, very stiff to hard, dry to moist, and blocky. This unit was assigned to the Sandy Lacustrine and Till unit in the 3D geology model, for practical purposes.

Figure 2.3 Post-Glacial Gravel and Sand Isopach



Clay

Clay of low to intermediate plasticity was encountered underlying gravel in boreholes MW19-13, -13A, -14, -15, -17, and MW19-17A. The clay was described as brown to grey, trace gravel to gravelly, with trace to some sand, soft to hard, and moist to wet. It extended to depths ranging from 13.3 mbgs to 15.8 mbgs, with thicknesses ranging from 4.8 m to 7.2 m. This was attributed to the Clayey Lacustrine unit in the 3D geology model.

Bedrock

Bedrock was encountered in all boreholes except for MW19-06C, -06D, -13, and MW19-17A at depths ranging from 4.3 mbgs to 20.1 mbgs and extended to the termination depth of the boreholes. The bedrock was generally described as blue grey, fresh to completely weathered, and extremely weak to weak siltstone and mudstone. Moderately to completely weathered, weak sandstone was encountered at MW19-02 and MW19-06B.

Boreholes advanced between 61 Street NW and 64 Street NW along Bow Crescent NW (central bedrock high) generally encountered relatively shallow bedrock. Weathered sandstone intersected was described as silty, dry, poorly cemented, and friable. Competent sandstone was encountered at depths below 1058 metres above mean sea level (masl) in monitoring well MW185 (CH2M 2015a). Siltstone bedrock was encountered from 1054 masl to 1052.5 masl (CH2M 2015a).

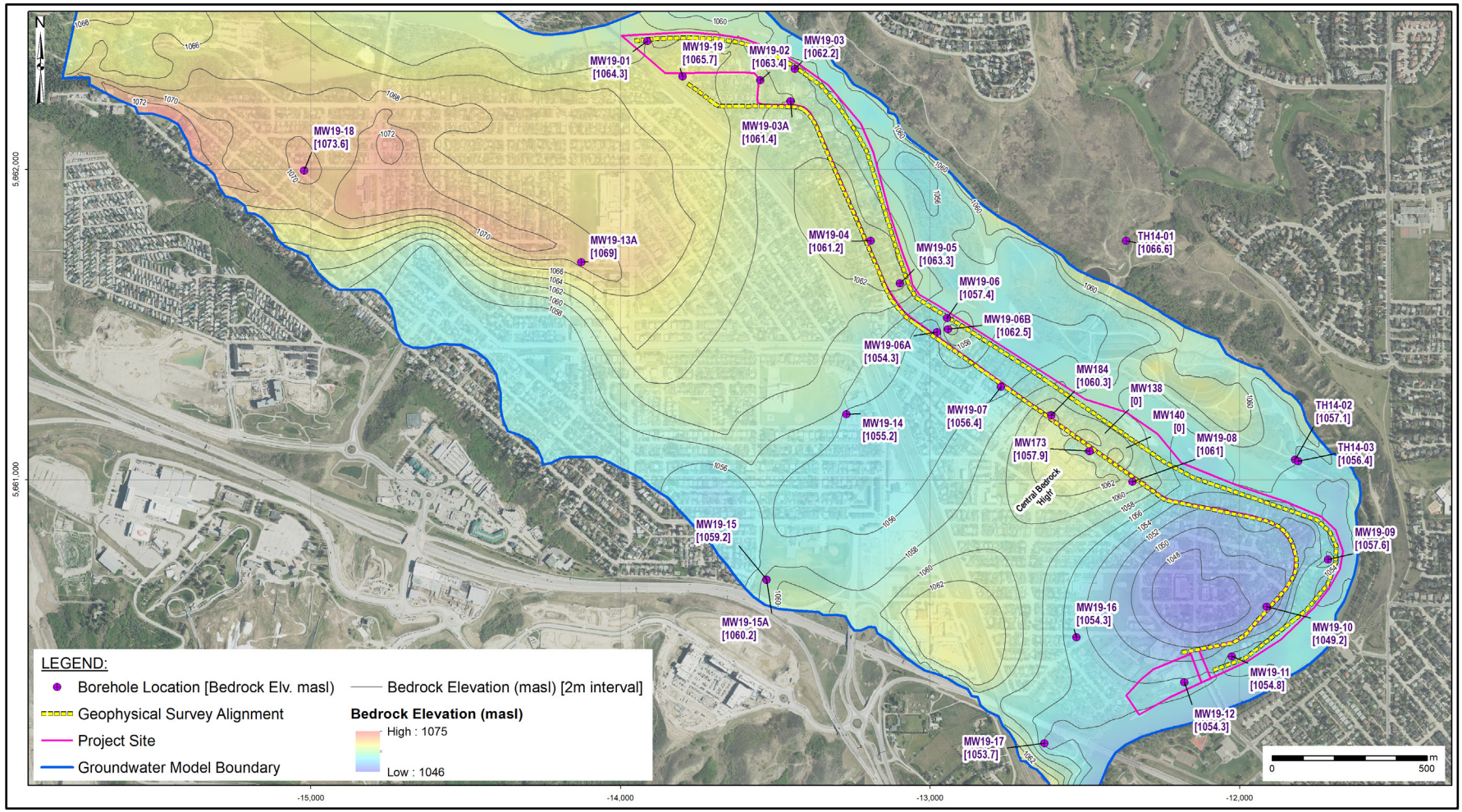
The *Leapfrog™* interpolated bedrock surface contours are shown in Figure 2.4.

2.3.4 Geological Model

The *LeapFrog™ Geo* analysis and visualization program from Seequent Ltd. with the hydrogeology module package was used to create the 3D lithostratigraphic model for input into the 3D groundwater flow model (Section 3).

A synthesis of relevant available background information summarized in Sections 2.3.1 and 2.3.2 supplemented with the 2019 site specific field investigations and the 2019 geophysical investigation (Tetra Tech 2020) was used to create the model. The model combines some adjacent geologic units, considered to have similar hydraulic properties into Hydrostratigraphic Units (HSUs).

Figure 2.4 Interpreted Bedrock Surface Topography



Model Development Process

The *Leapfrog™* model was developed using the following process:

1. Import topography from August 2018 LiDAR DEM (provided by CoC) and reduced the resolution to 10 m (from 20 cm) for faster processing. Topography includes 2013 bathymetry for the Bow River.
2. Import orthophoto from August 2018 (provided by CoC) and reduced its resolution in *TatukGIS* for rapid processing.
3. Import MW19 series (MW19-01 to MW19-19) borehole logs and reinterpret based on Moran's (1986) Surficial Geology Map (Figure 2.2). Model the following key geological surfaces commencing at the top of the sequence and working to the base:
    a. **Topsoil/Silt and Silt Fill**: Includes borehole log descriptions of 'Topsoil', 'SILT' and 'SILT FILL'.
    b. **Topsoil/Clay and Clay Fill**: Includes log descriptions of 'Topsoil', 'CLAY' and 'CLAY FILL'.
    c. **Alluvial Gravel & Sand**: 'GRAVEL' observed within the limits of the Bow River floodplain. Includes many zones of core loss, adjacent to logged gravel layers and assumed to be alluvial gravel and sand.
    d. **Sandy Lacustrine and Till**: Included log descriptions of 'CLAY', 'CLAY TILL', 'SILT' and 'Silty SAND' underlying the Alluvial Gravel and Sand.
    e. **Clayey Lacustrine**: 'CLAY' when seen in areas labeled 'Cc' or 'Uc' on the Moran map.
    f. **Till**: 'CLAY' when seen in areas labeled 'Ut' on the Moran map. The till was reported in WW357688 (Appendix II) with a thickness of approximately 3 m.
    g. **Bedrock**: 'Bedrock' and 'Weathered Bedrock', and 'PF' on the Moran map.
4. Import Figures 3 and 4 from Golder Associates (2016), showing the Alluvial aquifer channel boundaries and bedrock surface elevation contours, respectively. Site investigation details were not able to confirm the surface elevation boundaries; however, borehole logs did indicate that the bedrock surface was not as deep as outlined in the Golder isopach maps.
5. Import the *Surficial Geology of Calgary* map (Moran 1986) into the model and trace relevant outcrop contacts as polylines.
6. Added four boreholes from Alberta Water Wells database to fill in the geology outside of Project Area (388701, 388693, 388791, and 408883). Locations were picked off a map, so coordinates are not exact.
7. Imported the results from geophysical survey completed in October 2019, which included the interpreted top and bottom elevation of the coarse-grained alluvial sediments (gravel and sand unit), and the bedrock surface elevation. The investigation involved Ground Penetrating Radar, Ohm Mapper, and Electrical Resistivity Tomography methods along various sections of the Bow River and Bow Crescent NW. The geophysical survey and report were completed by Tetra Tech (2020). The locations of the two interpolated geophysical profiles are presented in Figure 2.4.

8. Modeled surface contacts as follows:
    a. **Topsoil, Silt and Silt Till**: Bottom contact an Erosion Surface[2] ,set at a constant offset of 0.5 m below topography, for near-continuous cover over entire model domain (i.e., is not tied to borehole contacts).
    b. **Topsoil, Clay and Clay Fill**: Deposit Surface[3] using basal contacts, set using topography as a reference surface, and constrained to area within Golder's Alluvial Aquifer boundary.
    c. **Alluvial Sand & Gravel**: Erosion surface using basal contacts, constrained to area within Golder's Alluvial Aquifer boundary.
    d. **Sandy Lacustrine and Till**: Erosion surface using base contacts, constrained to area within Golder's (2016) Alluvial Aquifer boundary.
    e. **Till**: Bottom contact an Erosion Surface.
    f. **Clayey Lacustrine**: Erosion surface using basal contacts, constrained to the northeast corner of domain (following Moran's [1986] Surficial Geology Map).
    g. **Bedrock**: Deposit surface using upper contacts and following Golder's (2016) bedrock contours at 50 m intervals.

The following limitations, assumptions and simplifications apply to the model development:

- The interpolation algorithm used in the Leapfrog™ model is not ideal for stratigraphic correlation and required considerable manual adjustments to obtain the desired lithological surfaces.
- It was somewhat difficult to fully represent the heterogeneity and variable geometry (thickness and lithological contact elevations) of the relatively thin gravel and sand unit (Alluvial Aquifer) and its connection to the Bow River based on a limited number of borehole logs.
- Assumed 0.5 m of Silty Topsoil/Fill cover across the entire model domain. Assumed Silty Topsoil/Fill is more conservative than Clayey Topsoil/Fill (i.e., more water would be transmitted through a Silty layer compared to a Clayey layer).
- Discontinuous Clayey Topsoil/Fill assumed overlying Alluvial Aquifer, as shown in MW19 borehole logs.
- Did not model relatively thin clay layers within the Alluvial Aquifer for simplicity. Assumed Sandy Lacustrine (dominantly silts, clays and sands) and Till (predominantly Silty Clay Till) would have similar hydraulic properties.

[2] Erosion Surface – a *Leapfrog*™ Term: Erosion contact surfaces are similar to deposit surfaces but can 'cut away' other contact surfaces on the older side of the erosion contact surface.
[3] Deposit Surface – a *Leapfrog*™ Term: Deposit contact surfaces tend to be sheet-like, with the primary lithology on the young side and the contacting/avoided lithologies on the older side. Deposit surfaces do not cut older volumes. A volume defined by a deposit contact surface will, therefore, appear conformably on top of older volumes.

The locations of selected geological cross-sections extracted from the *Leapfrog*™ 3D geology model are presented in Figure 2.5. Figure 2.6 to Figure 2.11 present the geological cross-sections cut across the Project Area. The applicable borehole logs are included in the *Hydrogeological Site Investigation and Groundwater Monitoring Summary* report, Appendix I.

Figure 2.5 Geological Cross-Section and Well Locations

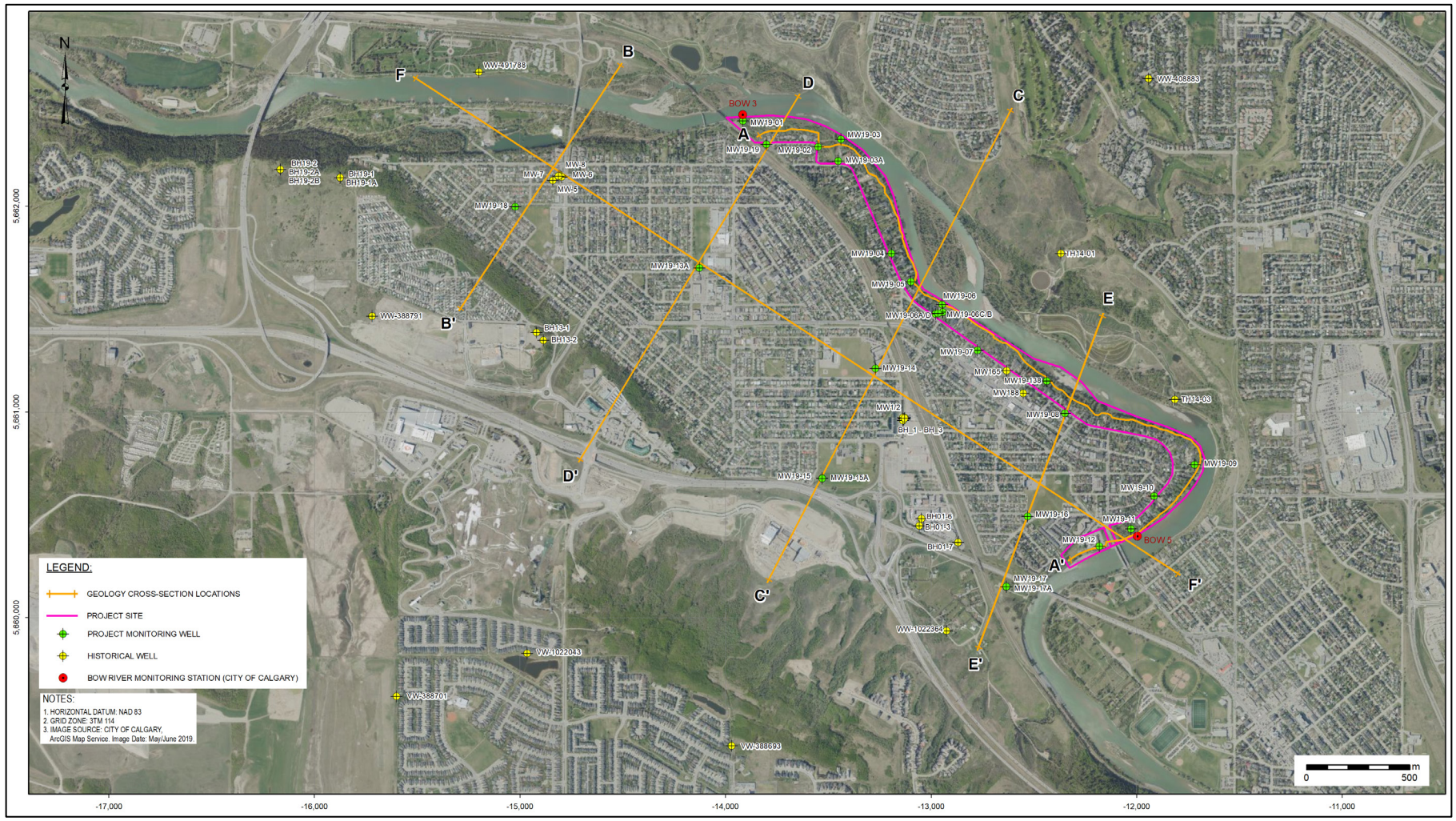
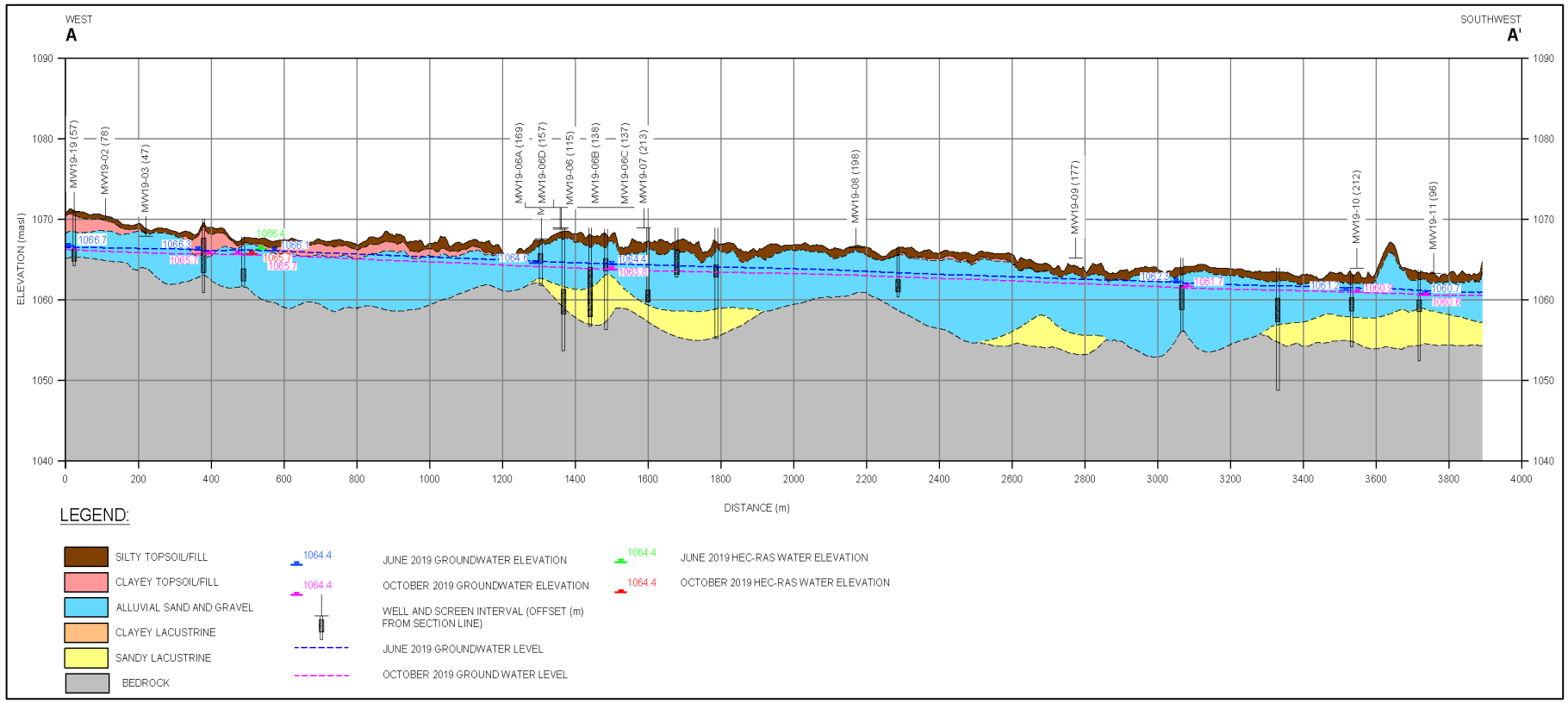
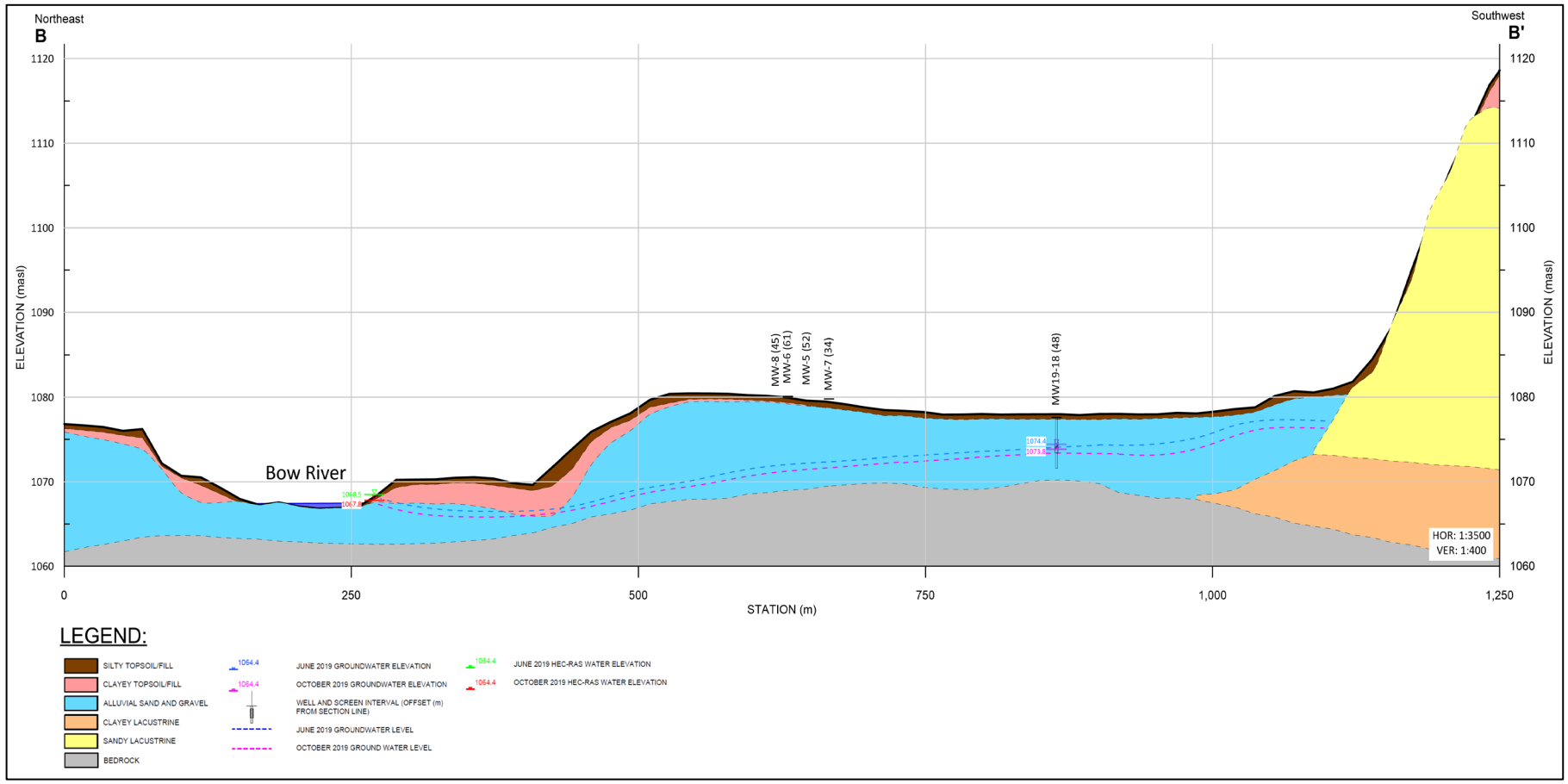


Figure 2.6 Geological Cross-Section A-A'



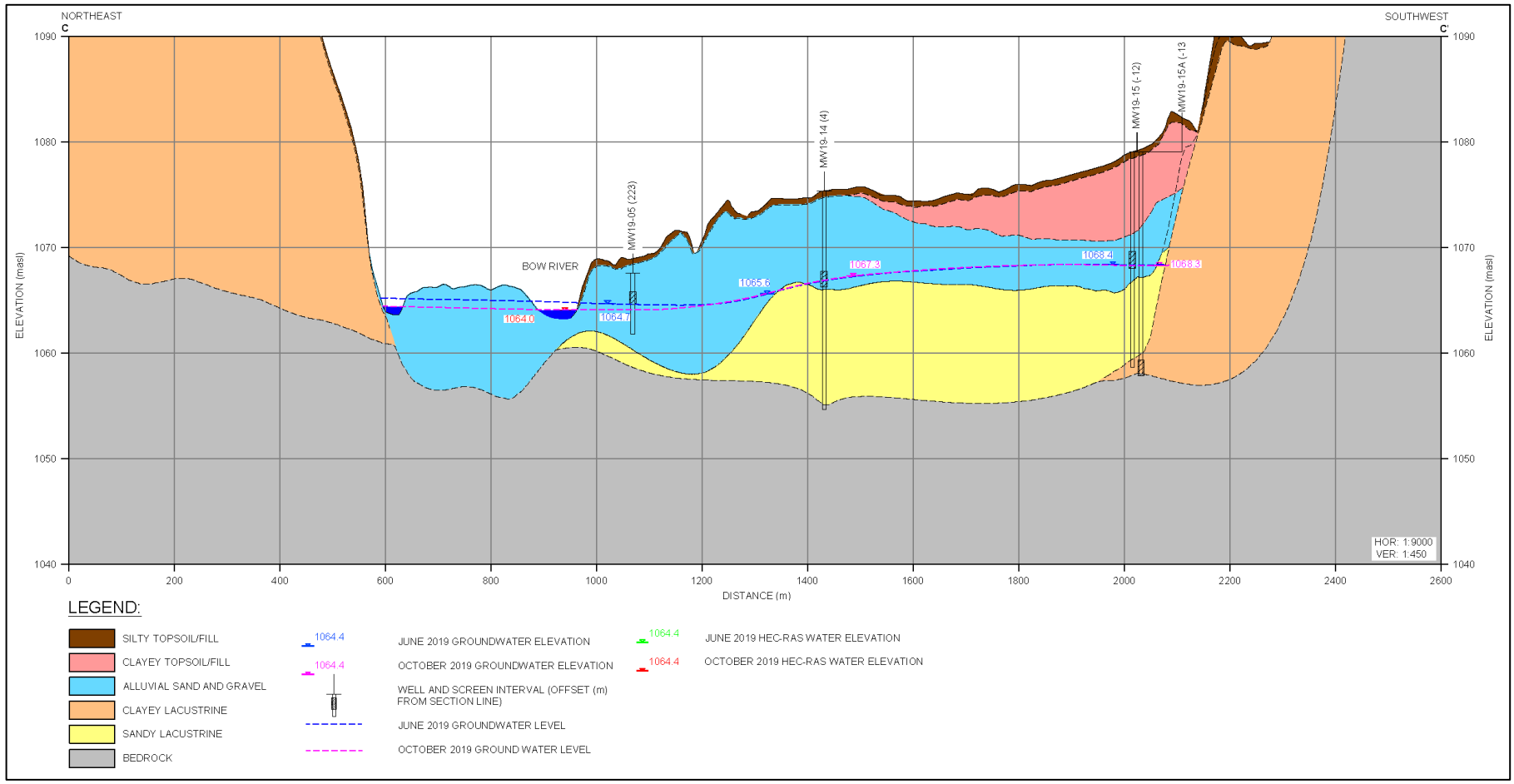
Note: Vertical Exaggeration: x20.

Figure 2.7 Geological Cross-Section B-B'



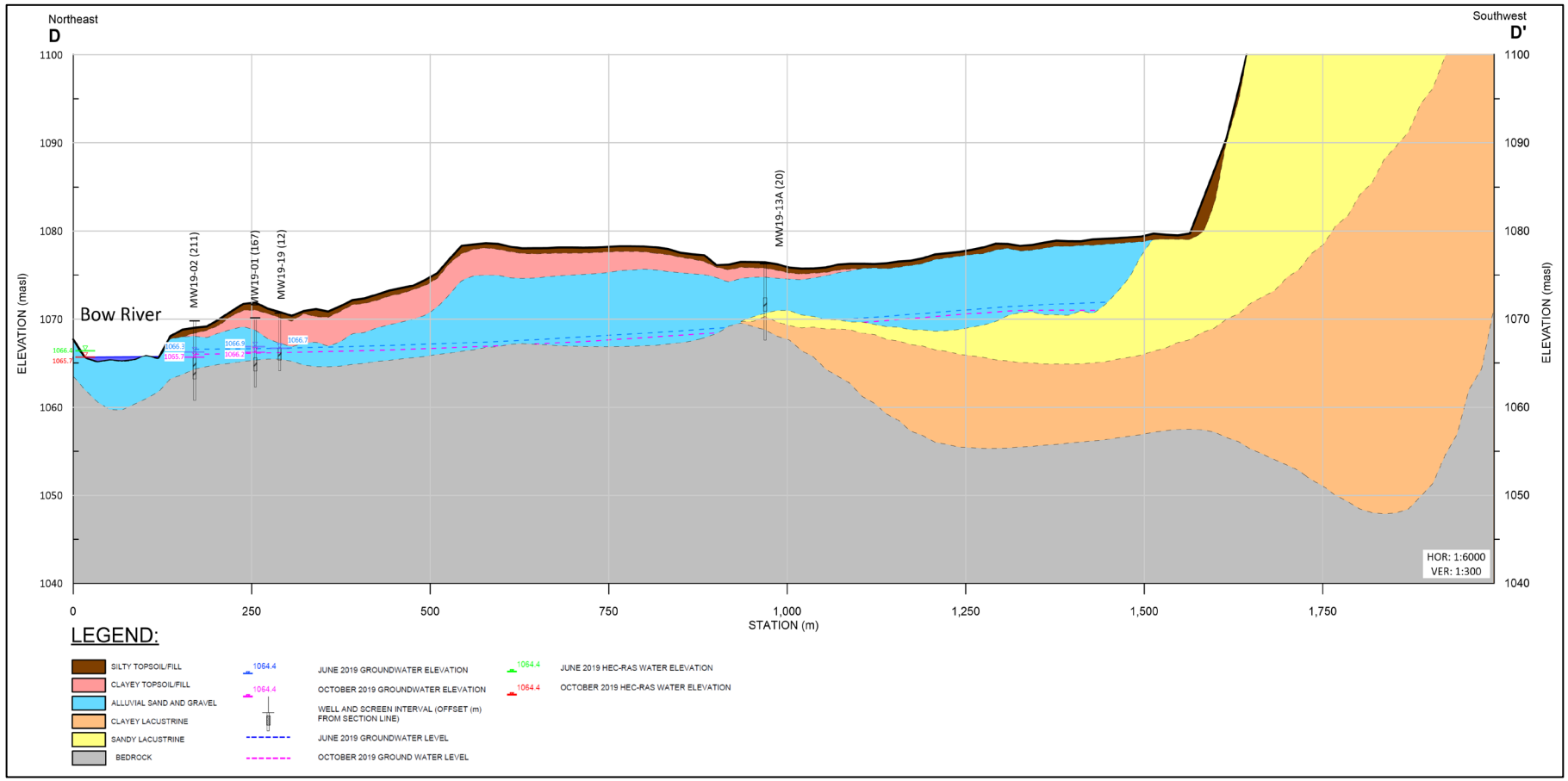
Note: Vertical Exaggeration: x9.

Figure 2.8 Geological Cross-Section C-C'



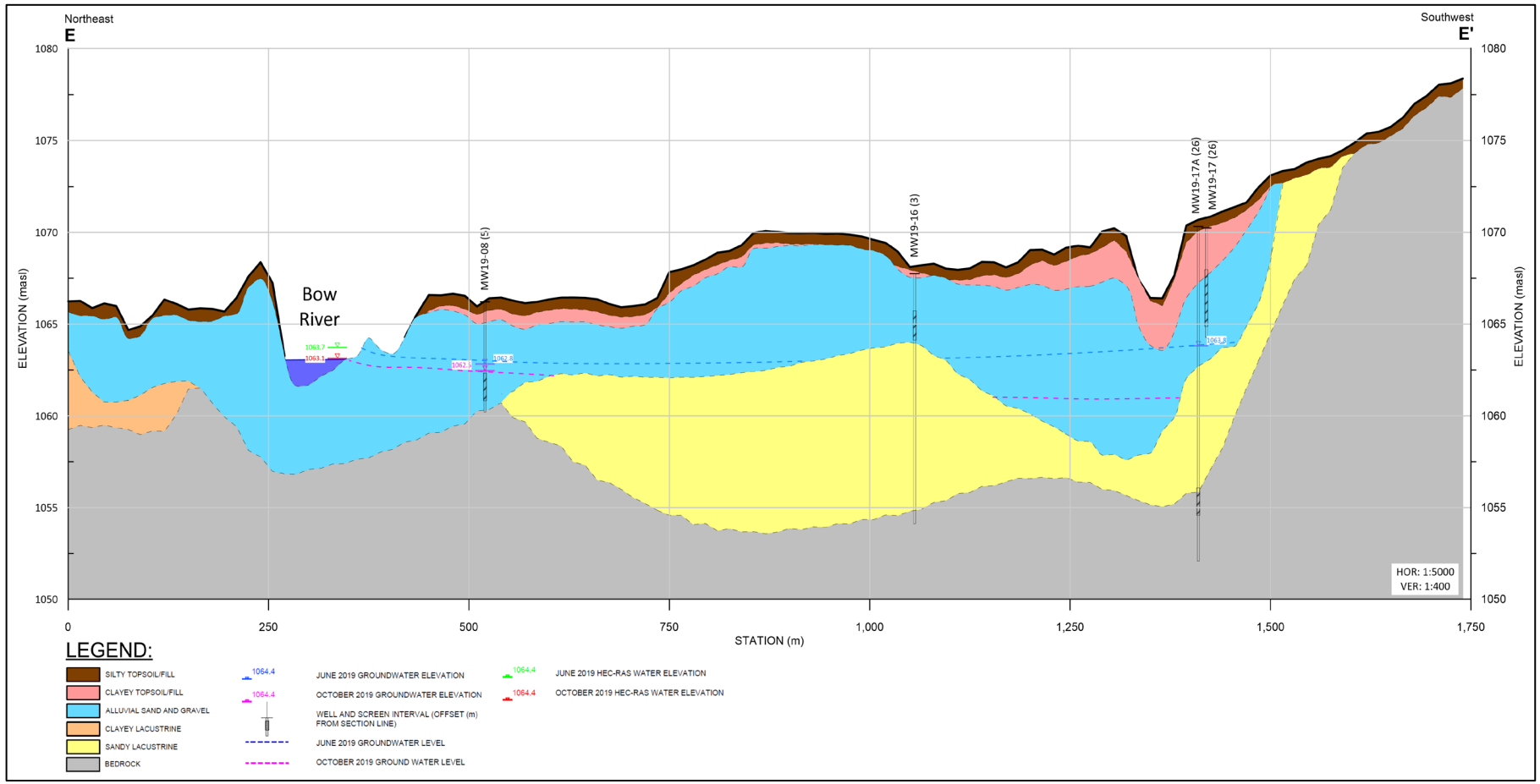
Note: Vertical Exaggeration: x20.

Figure 2.9 Geological Cross-Section D-D'



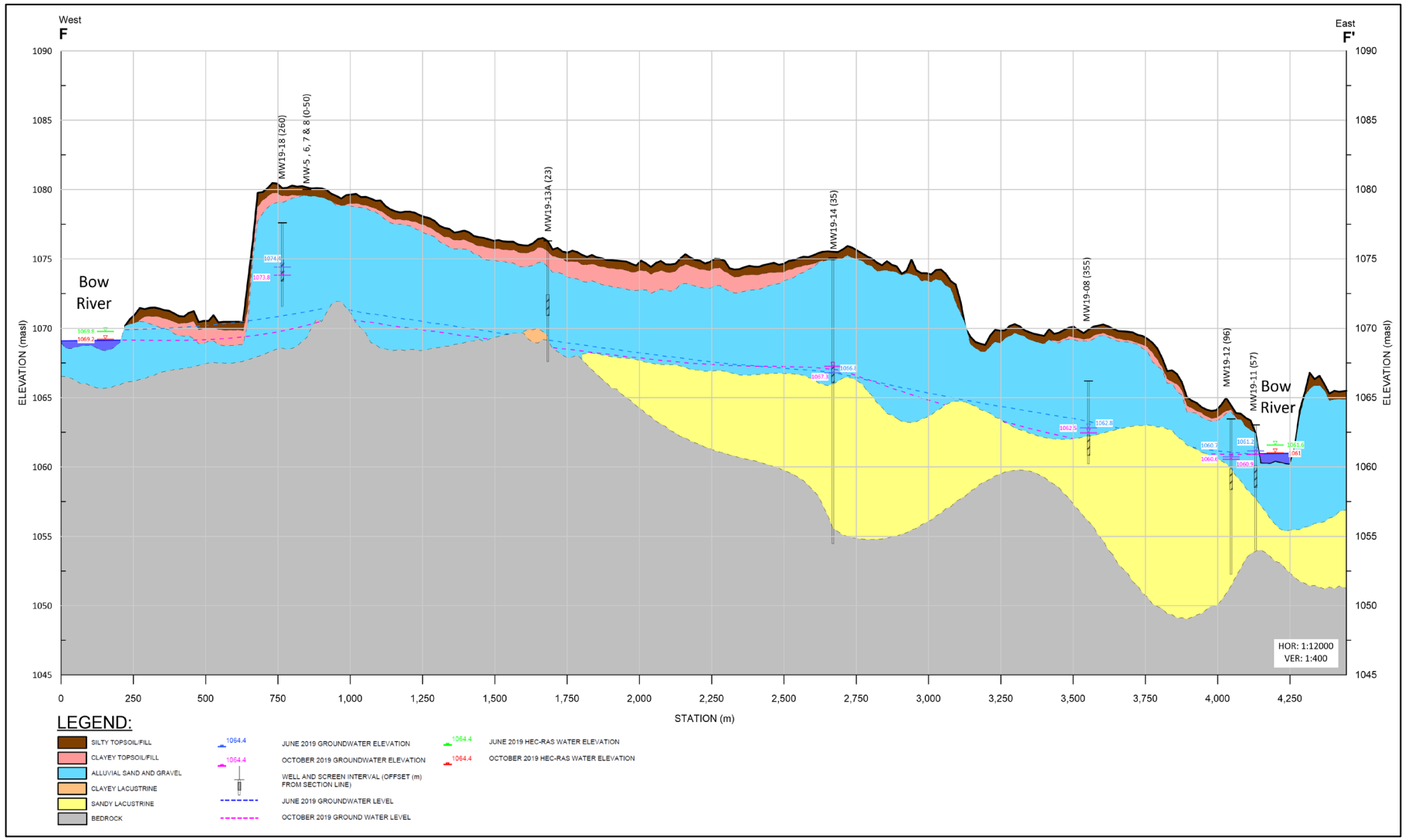
Note: Vertical Exaggeration: x20.

Figure 2.10 Geological Cross-Section E-E'



Note: Vertical Exaggeration: x12.

Figure 2.11 Geological Cross-Section F-F'



Note: Vertical Exaggeration: x30.

2.4 Hydrology

2.4.1 Climatic Water Balance

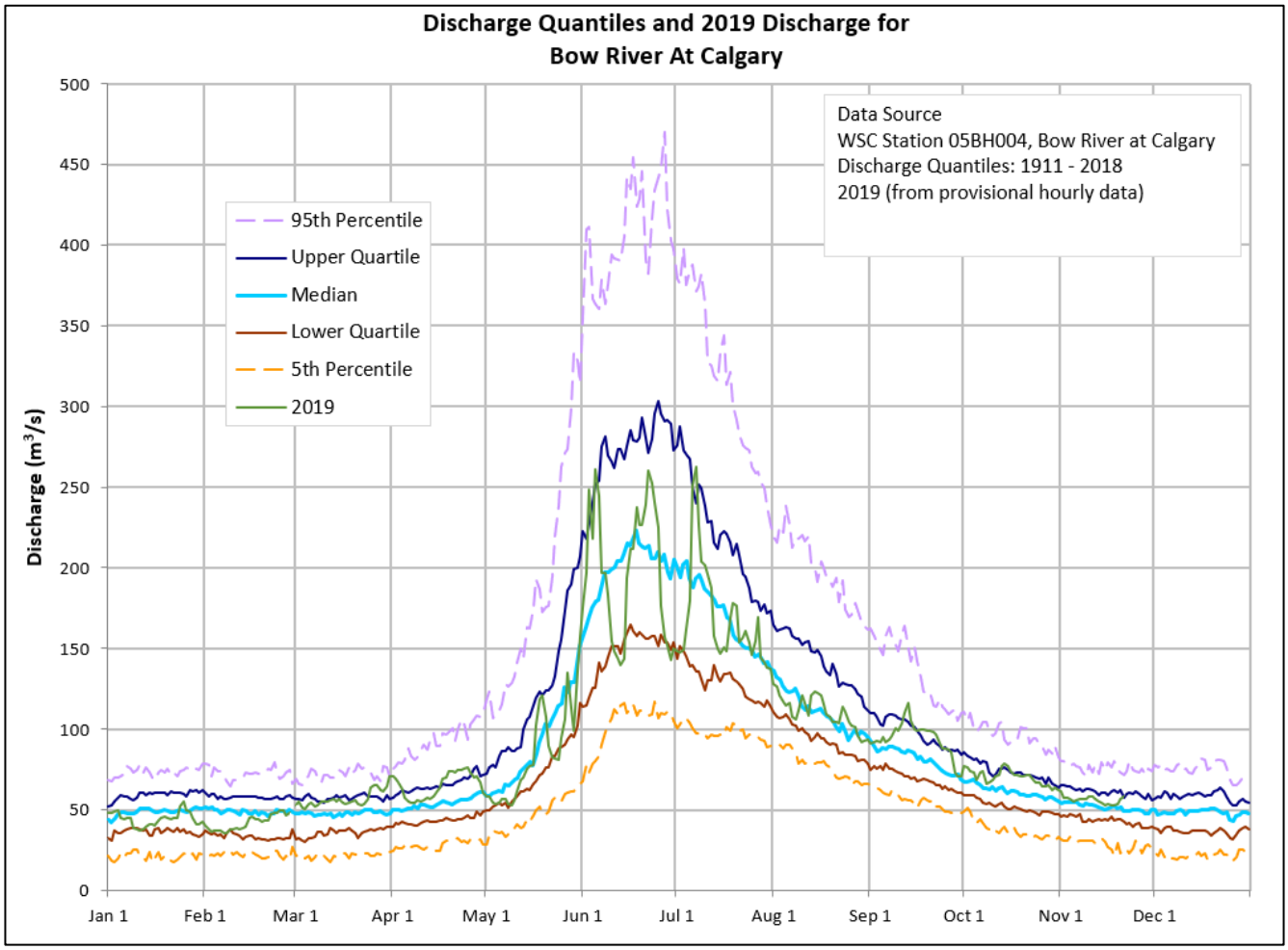
Small soil moisture surpluses (Precipitation – Potential Evapotranspiration) occur only during winter months when snow accumulates. During the freshet in April and May, much of the accumulated snow meltwater runs off before the underlying soil thaws, and hence groundwater recharge during this period is limited. As a result, use of monthly soil reservoir water balances to estimate water surplus, surface runoff and recharge is not possible. Groundwater recharge will typically occur associated with episodic and extended rainfall events, which can occur during the higher rainfall months of May through August. Recharge is anticipated to be greatest where gravel and sand glacial outwash and recent alluvial deposits are at, or near, surface (Meyboom 1961).

2.4.2 Bow River Flow

Spring and summer snow melt from the Rocky Mountains contributes most of the Bow River discharge, with peak discharges generally occurring during June and minimum flows occurring in January as shown in Figure 2.12. Glacial melt during the summer and fall contributes approximately 2.5% of the total annual river flow and groundwater influences flows during the winter. Approximately 20% of the Bow River annual flow comes from shallow groundwater (KCB 2017).

Descriptions of flood history and flood frequency estimates are presented in KCB (2020) and not repeated here.

Figure 2.12 Bow River at Calgary: Typical Discharge Variability (KCB 2020)



2.5 Hydrostratigraphic Units

The information presented in Section 2.3, together with field hydraulic testing, was used to define the key Hydrostratigraphic Units (HSUs), using individual, or adjacent units as defined in the 3D *Leapfrog*™ geology model. The defined HSUs and estimated hydraulic parameters are summarized in Table 2.3, and graphically displayed in Figure 2.13.

Hydraulic parameters were derived from the following sources:

- Bowness Geotechnical Investigation Report (KCB 2019a);
- Hydrogeological Site Investigation and Groundwater Monitoring Report (Appendix I) and unpublished data from KCB's 2019 field hydrogeological investigation;
- Hydraulic test results from site specific investigation reports from AECOM (2014), CH2M (2015a, 2015b, and 2018), and Golder (2016);

- Site-specific information available from the ESAR database of historical investigation reports;
- Published literature values (Freeze and Cherry 1979, Domenico and Mifflin 1965), where site-specific information is not available;
- Observed vertical flow between units based on a review of the water level monitoring data at nested monitoring wells, existing geologic bedding and textural evaluation from borehole logs.

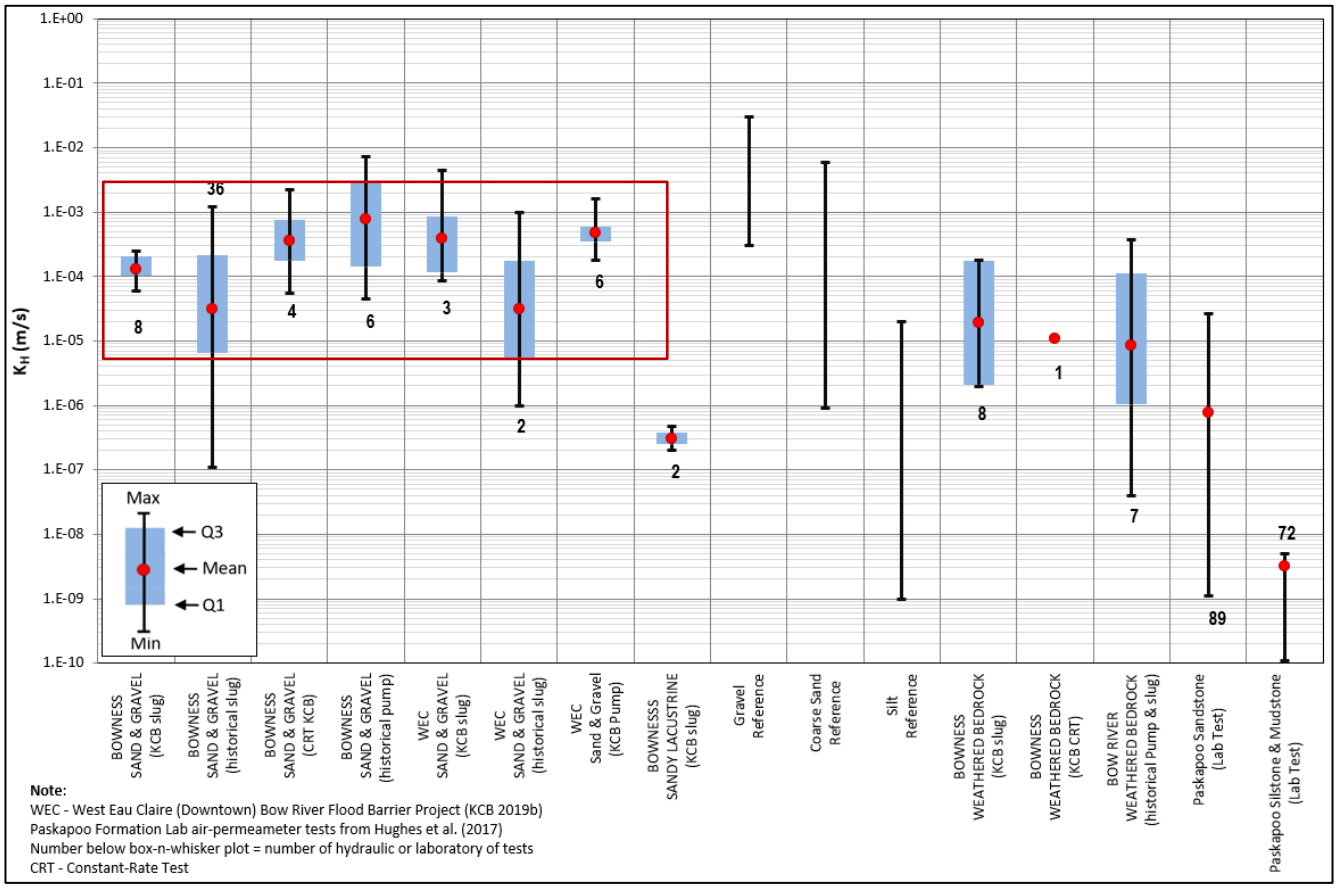
Reported hydraulic conductivity test results for the Paskapoo bedrock in the Calgary area range from 4×10^{-8} m/s to 4×10^{-4} m/s, and most likely represents a combination of the fractured and intact bedrock conditions. As a result, the bedrock unit was subdivided into two HSUs, with a 1 m to 2 m thick weathered bedrock layer assumed to cap the underlying intact bedrock.

Table 2.3 Hydraulic Parameters per Hydrostratigraphic Unit

Hydrostratigraphic Unit (HSU)	Saturated Hydraulic Conductivity			Specific Storage [Ss]# (m^{-1})	Specific Yield [Sy]#
	K_H Range (m/s)	Geometric^ Mean K_H (m/s)	Anisotropy* [K_H/K_V]		
Topsoil, Silt and Clay (aquitard)	$1\times10^{-7} – 1\times10^{-5}$	-	5	1×10^{-5}	0.05
Alluvial Gravel and Sand (aquifer)	$1\times10^{-7} – 7\times10^{-3}$	8×10^{-5}	2	1×10^{-5}	0.05
Sandy Lacustrine and Till	$2\times10^{-7} – 5\times10^{-7}$	-	5	2×10^{-5}	0.05
Clayey Lacustrine	$1\times10^{-8} – 5\times10^{-7}$	-	10	1×10^{-4}	0.03
Weathered/Jointed Bedrock (siltstone, sandstone, and mudstone)	$4\times10^{-8} – 4\times10^{-4}$	1×10^{-5}	5	1×10^{-5}	0.05
Competent Bedrock (siltstone, sandstone, and mudstone)	$4\times10^{-8} – 1\times10^{-7}$	-	10	5×10^{-6}	0.01

Notes: ^ – geometric mean used as initial model parameters.
K_H – Horizontal Hydraulic Conductivity.
K_V – Vertical Hydraulic Conductivity.
* – anisotropy greater than 1 is considered to account for stratification.
# – K_H/K_V, S_Y and S_S values derived from literature for similar materials; Sy for alluvial Gravel and Sand derived from pumping test.

Figure 2.13 Box-Whisker Plot showing Saturated Horizontal Hydraulic Conductivity Values



2.5.1 Topsoil, Silt and Clay

No site-specific hydraulic testing information exists for this unit. This fine-grained uppermost HSU ranges in thickness from 0 m (MW19-07 and MW19-14) to 8.2 m (MW19-15), based on 2019 drilling and is estimated to be of overall moderate permeability. Aquifer parameters have estimated from literature values (Freeze and Cherry 1979). This unit is generally unsaturated but may locally be saturated.

2.5.2 Alluvial Gravel and Sand

The depth of occurrence and thickness of the Alluvial Aquifer is variable across the Project Area, with top depth ranging from 0 mbgs (MW19-07 and MW19-14) to 8.2 m (MW19-15) and bottom depth ranging from 3 mbgs (MW19-05) to 12.2 mbgs (MW19-06A and MW19-15), with thicknesses ranging from 1.1 m (MW19-19) to 11.7 m (MW19-06A) (Figure 2.3). The gravel material was generally described as brown or grey, sandy, with trace clay, silt and cobbles; and moist or wet. At least locally, the unit contains a high content of cobbles and boulders (Figure 2.14). The content of gravel may be over-estimated due to the breaking of larger particles during the drilling process and the inability of the drill sampling method to collect larger particles. The aquifer is generally unconfined (especially

during low flow periods) but may become confined in localized areas during periods of higher river flows, such as was observed in July 2019 at MW19-02, 03, and MW-09.

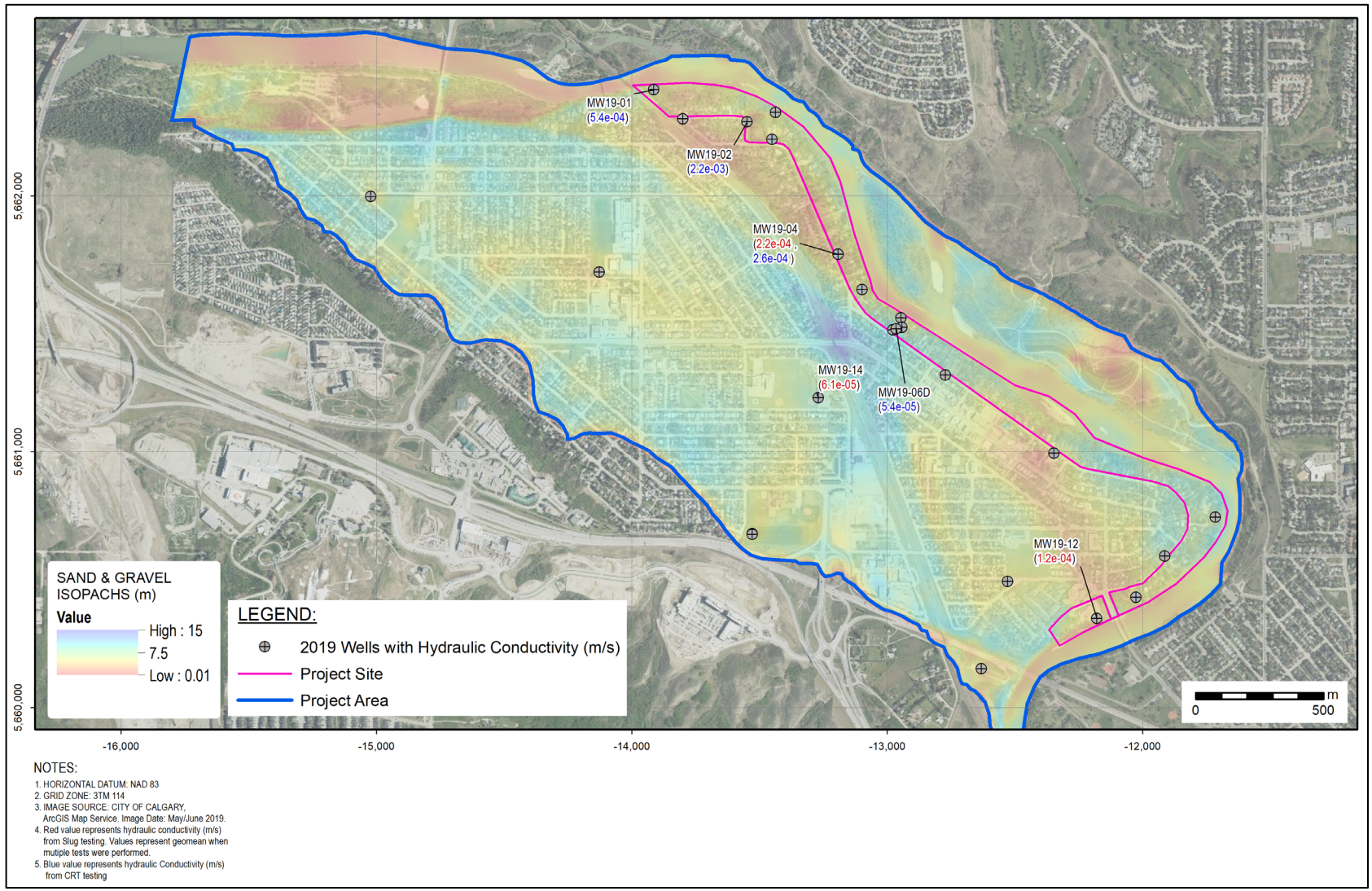
Figure 2.14 Alluvial Gravel and Sand Exposure on Basement Excavation, 6750 Crescent NW



Project well drilling logs indicate that the Alluvial Aquifer generally overlies the weathered/jointed siltstone, mudstone and sandstone of the Upper Paskapoo bedrock adjacent to the Bow River in the northern and north-eastern section of the Project Area (MW19-01, -02, -03, -04, -05, -18, and MW19-19). To the east and southeast (i.e., MW19-06 and downstream), the bedrock is commonly overlain by a relatively thick (1 m to 8 m) clay-rich HSU (e.g., MW19-06, -10, -11, and MW19-16). Where the Alluvial Aquifer is underlain by permeable (sandstone) bedrock, the two units are in direct hydraulic connection, and may form a composite alluvial-bedrock aquifer system, as is interpreted to occur in the region of MW19-02. However, the sandstone permeability is estimated to be at least one order of magnitude lower than the gravel and sand.

Twelve reliable hydraulic tests conducted in the Project Area (Figure 2.15), including constant-rate and recovery tests (4) and falling- and rising-head slug tests (8), indicated saturated horizontal hydraulic conductivity (K_H) values in the range of 5×10^{-5} m/s to 2×10^{-3} m/s, with a geometric mean of 2×10^{-4} m/s. Review of hydraulic conductivities derived from other investigations in the Calgary area shows a range of three orders of magnitude (1×10^{-7} m/s to 7×10^{-3} m/s), indicating the heterogenous nature of the gravel and sand aquifer (Figure 2.13). The limited hydraulic testing undertaken suggests a general increase in permeability within the aquifer towards the Bow River, and potentially an increase with depth within the aquifer. This would appear to a fit a sedimentological model of coarsest sediments deposited at the base of the sequence and at the centre of the channel, where hydraulic energy is greatest.

Figure 2.15 Distribution of Hydraulic Conductivity Results for the Gravel and Sand Aquifer



2.5.3 Sandy Lacustrine Unit and Till

This HSU, combining silty clay till and silt, clay and sand sediments units, ranges in thickness, where it occurs, from 0.5 m (MW19-13) to 8.1 m (MW19-10). Two hydraulic tests completed for this unit provide an average K_H of 3 x 10^{-7} m/s (MW19-17), and overall, this unit is expected to be of low to moderate permeability. Storage parameters have been estimated from literature.

2.5.4 Clayey Lacustrine Unit

This unit was not encountered during the 2019 drilling program but underlies the locations in the southeastern portion of the Project Area and forms the escarpment to the north and south of the Project Area (unit Cc in Figure 2.2). Hydraulic parameters were estimated from literature and it is estimated to be of dominantly low permeability.

2.5.5 Weathered Bedrock

Eight slug tests and one CRT were completed in upper weathered Paskapoo bedrock in the Project Area, which provided a geometric mean hydraulic conductivity of 2 x 10^{-5} m/s. Review of hydraulic conductivities derived from other investigations in the Calgary area shows a range of four orders of magnitude (4 × 10^{-4} m/s to 4 × 10^{-8} m/s), with a geometric mean of 9 × 10^{-6} m/s (7 tests). Storage parameters were estimated from literature values.

2.5.6 Competent Bedrock

No testing data was available for the fresh Paskapoo sandstone and mudstone. Hydraulic data were estimated from literature taking into consideration of the dominance of lower-permeability siltstone and mudstone over higher-permeability sandstone. The geophysical surveys, including Electrical Resistivity Tomography (ERT) and Ground-Penetrating Radar (GPR) were used to help define this surface. The report documenting the geophysical survey (Tetra Tech 2020) is included in Appendix I.

2.6 Groundwater Flow Regime

2.6.1 Monitoring Network

Monitoring well construction and groundwater level data was collected from verified sources within the Project Area and from the ongoing Bowness groundwater monitoring program for the period April to November 2019. Construction details for monitoring wells installed in 2019 by KCB are provided in Table 2.4. Controlling factors on groundwater flow patterns within the Alluvial Aquifer are interpreted as follows, and discussed in the following sections:

- Surface runoff and subsequent recharge from the southern embankment;
- Groundwater flow from underlying units to the southernmost extent of the Alluvial Aquifer;
- Groundwater precipitation and surface runoff recharge to the top of the aquifer, often via topsoil;
- The basal topography of the Alluvial Aquifer;

- The thickness of the Alluvial Aquifer; and
- Bow River levels.

Monitoring well locations are shown in Figure 1.2. Selected wells were instrumented with pressure transducer dataloggers (PTDLs) or level-temperature-conductivity (LTC) dataloggers. Controlling factors on groundwater flow patterns within the Alluvial Aquifer are interpreted as follows, and discussed in the following sections:

- Surface runoff and subsequent recharge from the southern embankment;
- Groundwater flow from underlying units along the southernmost extent of the Alluvial Aquifer;
- Groundwater precipitation and surface runoff recharge to the top of the aquifer, often via topsoil;
- The basal topography of the Alluvial Aquifer;
- The thickness of the Alluvial Aquifer; and
- Bow River levels.

2.6.2 Groundwater Recharge

Precipitation Recharge

The dominant source of flow to the Bow River is spring and summer snowmelt from the Rocky Mountains, approximately 80 km west of Bowness. During peak flow periods, these flows laterally recharge the alluvial gravel and sand units along the river, and bank storage subsequently provides baseflow to the river over the following low flow months.

Estimation of groundwater recharge at Bowness is made more difficult by the presence of significant baseflow to the river originating upstream of the Project Area. Groundwater reporting directly to the river comprises groundwater flows reporting to the upstream end of the Alluvial Aquifer, together with direct precipitation recharge to the top of the aquifer, and seepage from surface runoff along gullies, leakages from stormwater systems, and lawn and garden irrigation. The magnitude of these flows is substantially lower than the Bow River flow during groundwater baseflow-dominated low flow periods. Hence it is difficult to resolve these flows through comparison of Bow River discharge immediately upstream and downstream of the Project Area.

It is difficult to discern water level responses in the Alluvial Aquifer in monitoring wells within the area of the aquifer which displays a direct hydraulic response to significant changes in river level (Bow River Zone of Influence (ZOI)), and rainfall recharge effects are generally masked by water level changes induced by Bow River level fluctuations, as well as by the high transmissivity of the aquifer.

Table 2.4 2019 Borehole/Monitoring Well Installation Details

Borehole ID	Ground Elevation* (masl)	Borehole Depth (m)	Backfill/Installation Details	Screened Material	PTDL or Manual readings*
MW19-01	1070.37	7.9	Screen from 4.6 m to 6.1 m	Gravel and Sand	PTDL
MW19-02	1070.06	9.1	Screen from 4.3 m to 6.7 m	Gravel and Sand	PTDL
MW19-03	1067.85	6.1	Screen from 4.0 m to 5.5 m	Gravel and Sand	PTDL
MW19-03A	1069.02	7.9	Screen from 3.4 m to 6.4 m	Gravel and Sand	PTDL
MW19-04	1067.35	7.9	Screen from 2.4 m to 4.0 m	Gravel and Sand	PTDL
MW19-05	1067.57	5.8	Screen from 1.8 m to 3.0 m	Gravel and Sand	Manual
MW19-06	1068.80	12.5	Screen from 3.7 m to 5.2 m	Gravel and Sand	Manual
MW19-06A	1068.93	15.2	Screen from 7.6 m to 10.7 m	Gravel and Sand	LTC
MW19-06B	1068.94	9.1	Screen from 7.6 m to 9.1 m	Sandstone/Siltstone	LTC
MW19-06C	1068.92	6.1	Screen from 2.7 m to 5.8 m	Gravel and Sand	PTDL
MW19-06D	1068.95	12.2	Screen from 4.9 m to 11.0 m	Gravel and Sand	Manual
MW19-07	1068.93	13.7	Screen from 4.6 m to 6.1 m	Gravel and Sand	PTDL
MW19-08	1066.48	6.1	Screen from 4.0 m to 5.5 m	Gravel and Sand	PTDL
MW19-09	1065.18	9.1	Screen from 3.4 m to 6.4 m	Gravel and Sand	PTDL
MW19-10	1063.95	15.2	Screen from 3.7 m to 6.7 m	Gravel and Sand	LTC
MW19-11	1063.26	9.1	Screen from 3.0 m to 4.6 m	Gravel and Sand	PTDL
MW19-12	1063.71	11.3	Screen from 3.7 m to 5.2 m	Gravel and Sand	PTDL
MW19-13	NR	6.1	Bentonite backfilled, no install		
MW19-13A	1076.58	8.8	Screen from 4.0 m to 5.5 m	Gravel and Sand	Manual
MW19-14	1075.34	20.7	Screen from 7.6 m to 9.1 m	Gravel and Sand	PTDL
MW19-15	1079.04	20.4	Screen from 9.4 m to 11.0 m	Gravel and Sand	PTDL
MW19-15A	1079.05	21.2	Screen from 19.7 to 21.2 m	Siltstone	LTC
MW19-16	1067.99	13.7	Screen from 2.1 to 3.7 m	Gravel and Sand	Manual
MW19-17	1070.54	18.3	Screen from 14.3 to 15.8 m	Silty Lacustrine	PTDL
MW19-17A	1070.53	6.1	Screen from 2.4 to 5.5 m	Gravel and Sand	Manual
MW19-18	1077.85	6.1	Screen from 2.7 to 4.3 m	Gravel and Sand	PTDL
MW19-19	1070.90	6.6	Screen from 4.6 to 6.1 m	Gravel and Sand	Manual

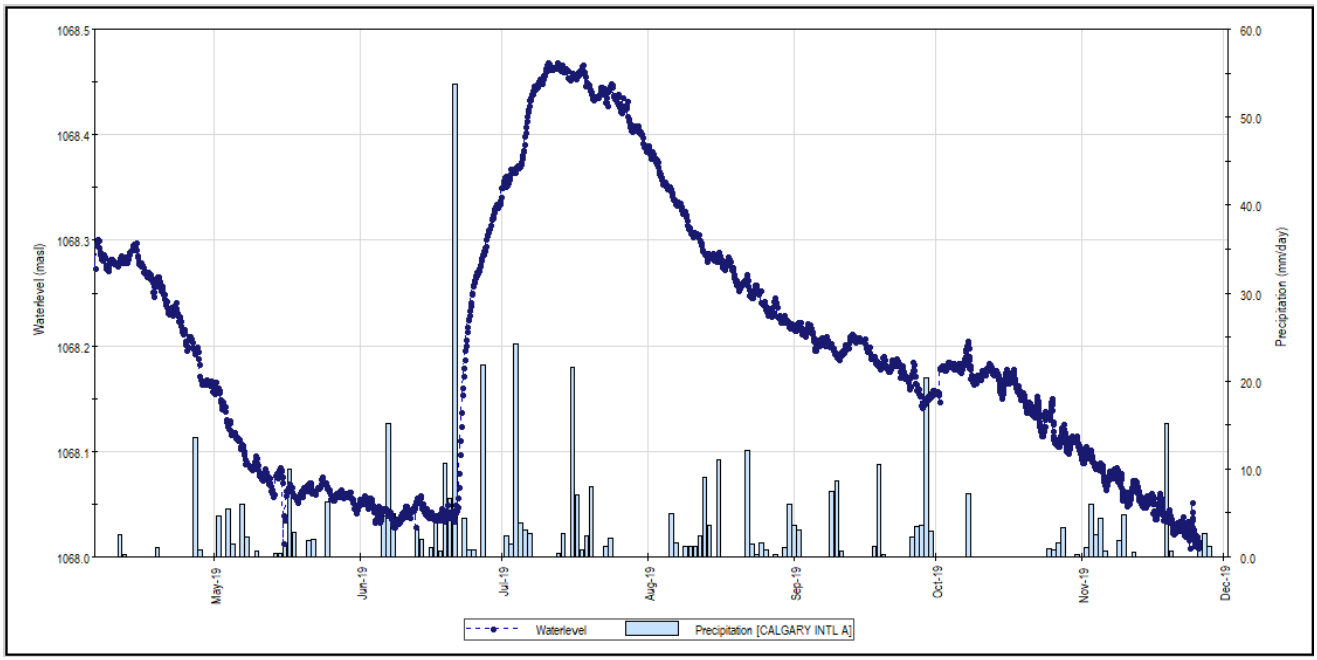
Notes:

* - Current instrumentation as at May 2020.

1. PTDL: Pressure Transducer Datalogger
2. LTC Level, Temperature and Conductivity Datalogger
3. MW19-13 was abandoned at 6.1 m bgs after the rig broke down. The hole was backfilled with bentonite and the replacement well MW19-13A was installed adjacent to MW19-13.

The Bow River flow is also influenced by stormwater runoff following significant rainfall events (e.g., 54 mm on June 21, 2019). However, the piezometric level in bedrock monitoring well MW19-15A, located outside of the Bow River ZOI, shows a clear and sharp response (0.4 m rise) to this and subsequent rainfall events in June 2019 (Figure 2.16). This well may have a strong hydraulic connection with a recharge source at the base of the escarpment along the southern edge of the Project Area. Well MW19-18 (sand and gravel) showed a lesser response to the rain event of June 21, likely due to the unconfined nature and probable higher permeability of the aquifer at this location relative to MW19-15A.

Figure 2.16 Well MW19-15A – Bedrock Piezometric Level Response to Rainfall Recharge



The following information sources were used to estimate recharge to the shallow groundwater system:

- Environment Canada weather station data, Calgary International Airport.
- Impervious surface GIS layer for Calgary, provided by CoC (2019).
- Edmonton-Calgary Groundwater Atlas (Barker et al. 2011).
- *Groundwater Resources of The City of Calgary and Vicinity* (Meyboom 1961).

The mean annual precipitation (MAP) for Calgary is 419 mm (Section 2.2.2), based on data from the Environment Canada weather station at Calgary International Airport. Precipitation recharge estimates are based on the following assumptions:

- Freshet-related recharge is expected to be minimal, due to frozen ground conditions;
- Recharge is highest where permeable sediments (e.g., sand and gravel) occur at or near surface;
- No recharge occurs over the impervious surface areas (estimated to cover approximately 40% of the Project Area); and
- groundwater recharge will be dominated by extended peak rainfall events.

The Project Area was subdivided into groundwater recharge based on HSUs using the MAP and estimates of annual groundwater recharge rates derived by Barker et al. (2011). Barker et al. estimated precipitation recharge rates ranging from 51 mm/year to 75 mm/year, which equates to approximately 18% of MAP. Meyboom (1961) estimated an average annual recharge rate of 52 mm

for the Elbow River basin. There will be significant spatial variability of precipitation recharge rates depending on the ground cover and permeability of the overburden material. Table 2.5 below summarizes the mean annual precipitation recharge rates that were used for initial 3D groundwater flow model setup.

Table 2.5 Precipitation Recharge Rates per HSU

HSU	Recharge Rate (% of MAP)	Mean Annual Groundwater Recharge Rate (mm/year)
Topsoil, Silt and Clay	8.3	35
Topsoil, Silt and Clay – Developed Areas	4.2	17.5
Alluvial Sandy Gravel	16.7	70
Alluvial Sandy Gravel – Developed Areas	8.3	35

Note: MAP: Mean annual precipitation of 419 mm/year.

Seepage Recharge

No significant seepage zones were identified in the Project Area during the background data review and 2019 field surveys. However, seepage zones are most likely to exist along the escarpment ridges to the south and northeast of the Project Area.

Historical groundwater levels measured on the escarpment to the south of the Project Area indicate 'perched' groundwater conditions at levels approximately 30 m to 35 m higher than the Alluvial Aquifer. These areas do not appear to be hydraulically connected to the Alluvial Aquifer but are likely to be a source of springs along the escarpment and recharge to the shallow groundwater system of the Bow River floodplain.

2.6.3 Groundwater Flow Patterns

Sand and Gravel aquifer water level contours for 'typical' seasonal high water conditions (June 15, 2019) and seasonal low water conditions (October 30, 2019) are presented in Figure 2.17 and Figure 2.18, respectively. Historical groundwater level information collected from available datasets were used to inform groundwater levels across the Project Area and provide background information on regional gradients and perched groundwater conditions.

As shown in Figure 2.17 and Figure 2.18, under both 'typical' normal high and low river flow conditions, groundwater flow within the Alluvial Aquifer is generally to the northeast in the western portion of the Project Area, eastwards through the east-central portion of the Project Area and southwards in easternmost section of the Project Area near monitoring wells MW19-09, -10, and -11, where the Bow River bends sharply to the south. The escarpment and upland areas along the southern and western edges of the Project Area, respectively, form a southern boundary to the Alluvial Aquifer.

The inferred basal elevation of the Alluvial Aquifer, drawn from borehole logs and via interpretation of geophysical surveys undertaken, is presented in Figure 2.19. The basal elevation displays a close correspondence with aquifer (saturated) thickness as shown for June 25, 2019 (Figure 2.20) and October 7, 2020 (Figure 2.21). The aquifer saturated thickness varies from dry to 8 m in different

portions of the Project Area, depending on seasonal conditions. There is a noticeable decrease in saturated thickness of the Alluvial Aquifer where the base of the aquifer is elevated (Figure 2.19), such as at MW19-04, MW19-08, and MW19-19. As is expected, the saturated thickness of the sand and gravel unit adjacent to the Bow River showed the greatest increase between October and June 2019, while relatively small changes in the saturated thickness at locations farther inland from the Bow River, where aquifer is relatively thin, show a significant increase in the extent of unsaturated sand and gravel. The sand and gravel unit is unsaturated in the vicinity of wells MW19-13A and MW19-16.

From a comparison of the differences between the June 25, 2019 and October 7, 2019 groundwater level contours for the Alluvial Aquifer, the following is observed:

- Water levels in the aquifer adjacent to the Bow River differ by up to 0.9 m within an area of greatest aquifer thickness and lowest basal elevation within the central area, extending from MW19-05 downstream to MW19-07, possibly due to freshet groundwater 'mounding' directly upstream of the northeast-trending 'central bedrock high' located between MW19-07 and MW19-08. The 2019 seasonal zone of influence (ZOI) between the river and Alluvial Aquifer extends approximately 250 m to 360 m away from the banks of the Bow River.
- Water levels vary by between 0.45 m to 0.95 m within a broad zone within the 'bend' of the Bow River around the Bowness community, extending downstream from the 'central bedrock high' near to the southeastern section of the Bow River (i.e., at monitoring wells MW19-08, MW19-09, MW19-11).
- Along the northern section of the Project Area, the water table declined by approximately 0.8 m (MW19-01) adjacent to the Bow River following the freshet high river flow, while the water level some 140 m inland declined by approximately 0.4 m (MW19-19). At this location, it is inferred that the ZOI extends less than 200 m from the riverbank due to the rapid thinning of the aquifer as shelves up against the local bedrock high (see bedrock elevations in Figure 2.4).
- In the southeastern corner of the Project Area, the Alluvial Aquifer thins as it shelves up against a thick lacustrine silt and clay unit overlying the Upper Paskapoo bedrock that forms the escarpment. The sand and gravel unit is largely unsaturated in this area (wells MW19-15A and MW19-17A).

It must be noted that the groundwater elevation contours compiled for the Alluvial Aquifer only provide a regional and highly generalized representation of the groundwater flow pattern due to the limited number of available monitoring wells in the Project Area, and particularly inland from the Bow River.

Figure 2.17 Inferred Water Table, June 25, 2019 ('Typical' High Water Level)

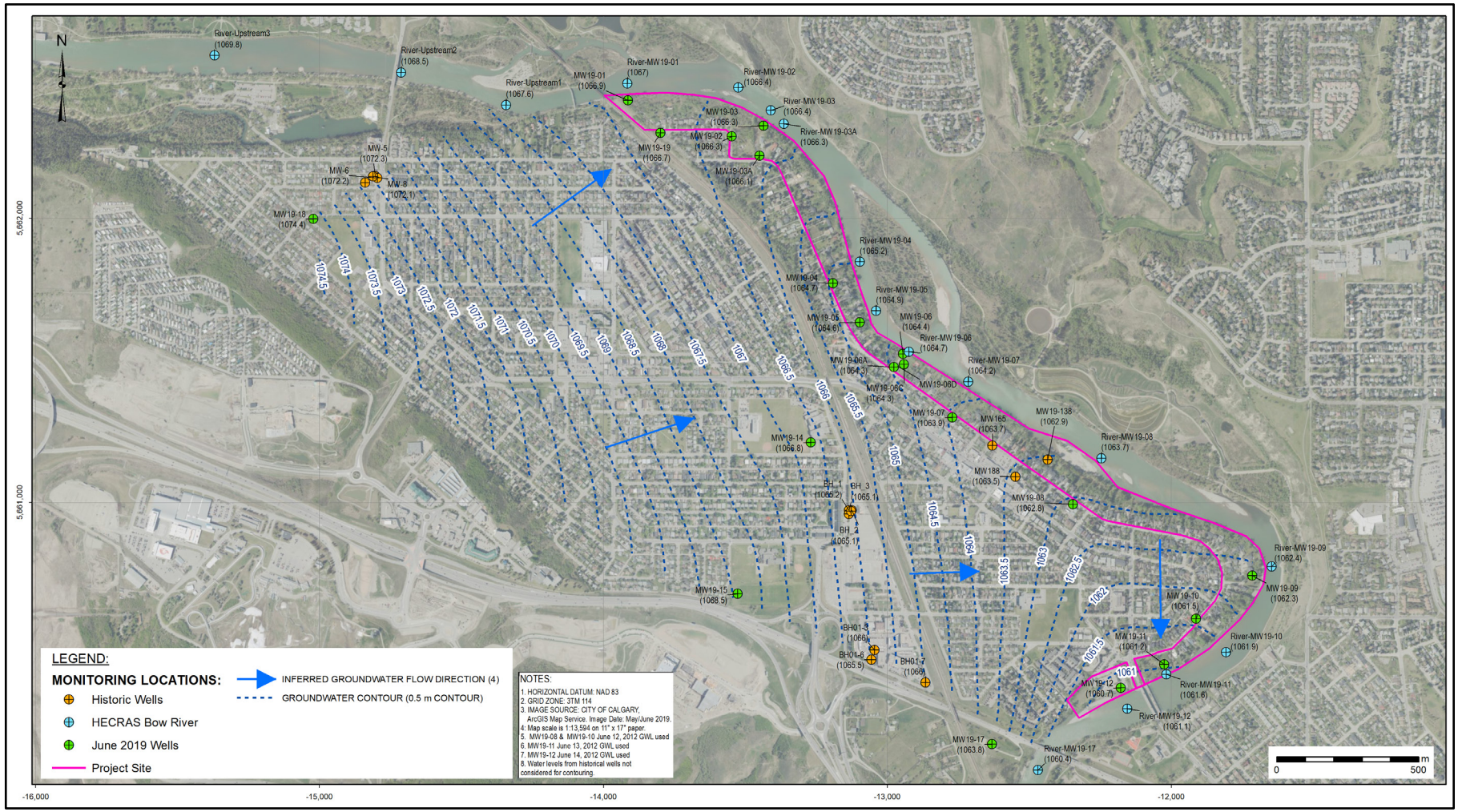


Figure 2.18 Inferred Water Table, October 7, 2019 ('Typical' Low Water Level)

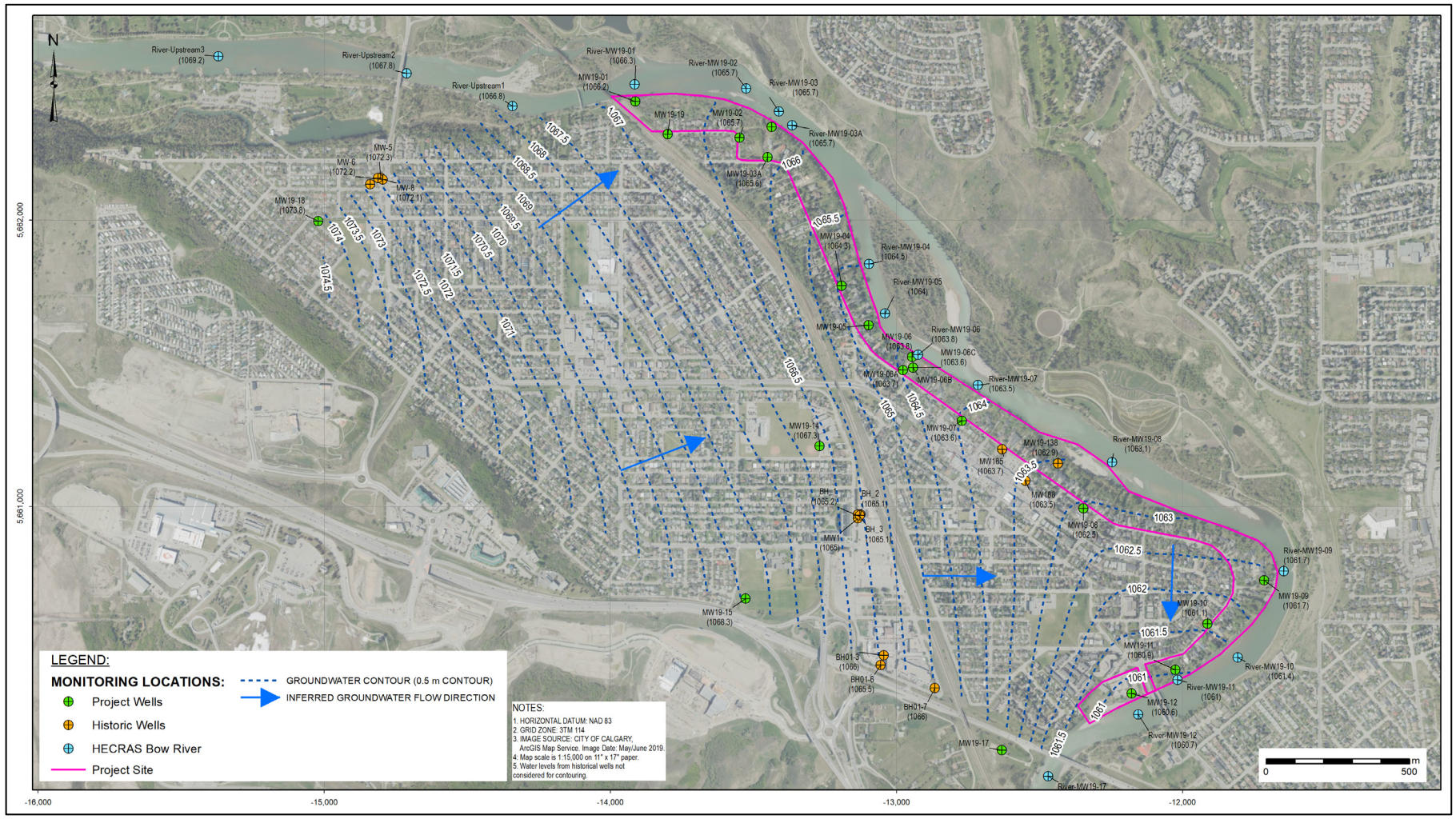


Figure 2.19 Base Elevation of Sand and Gravel Aquifer

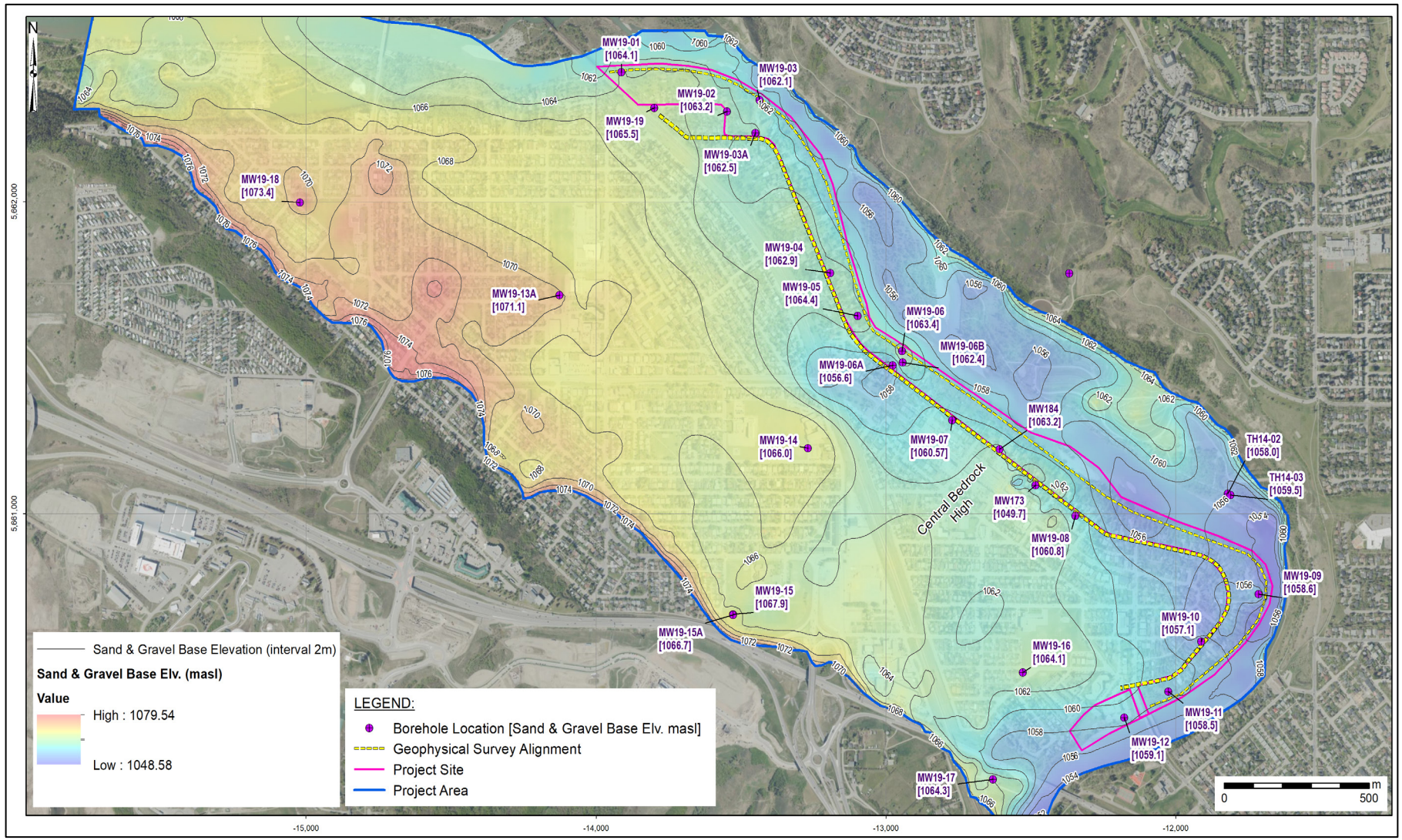


Figure 2.20 Alluvial Aquifer – June 25, 2019 Inferred Saturated Thickness

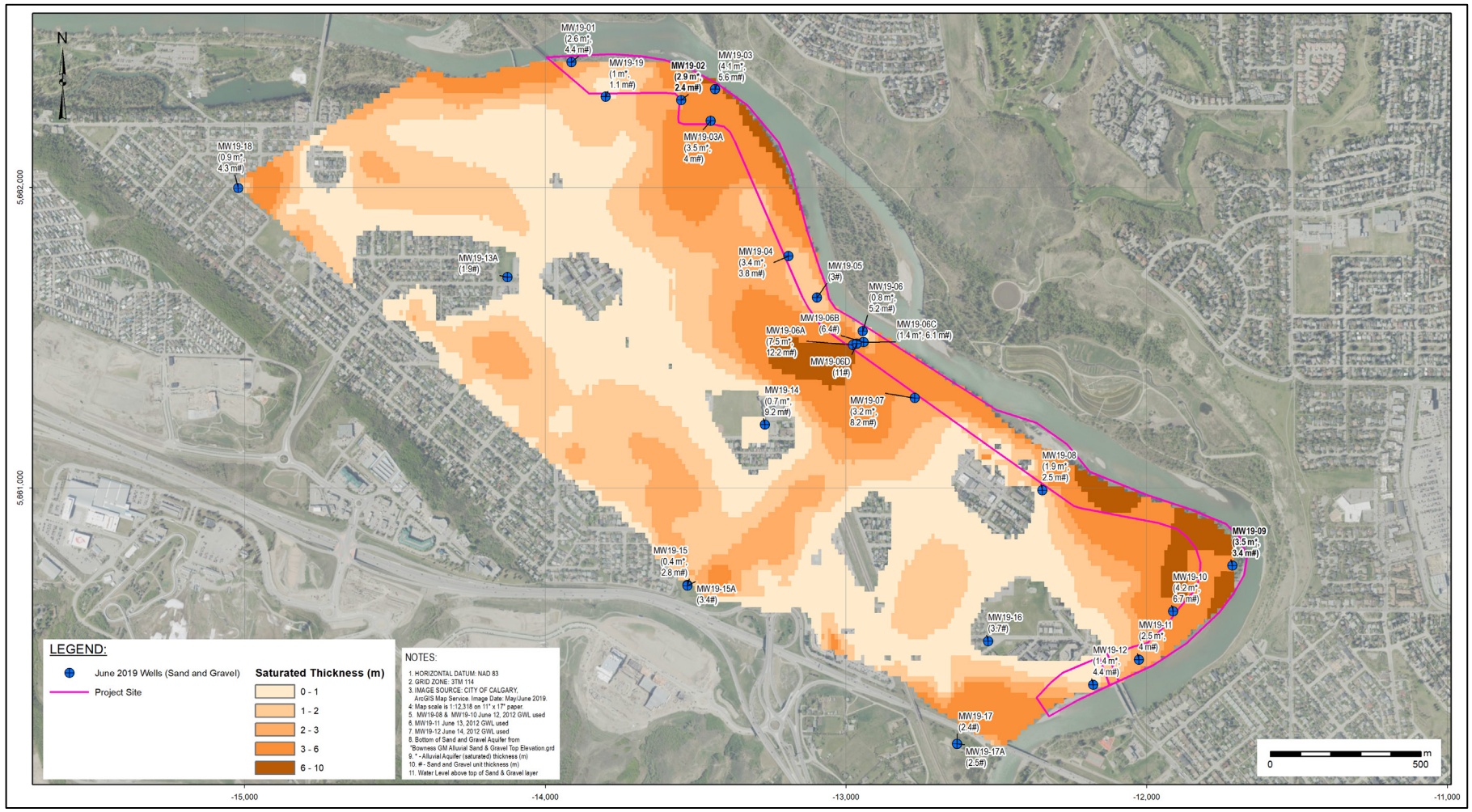
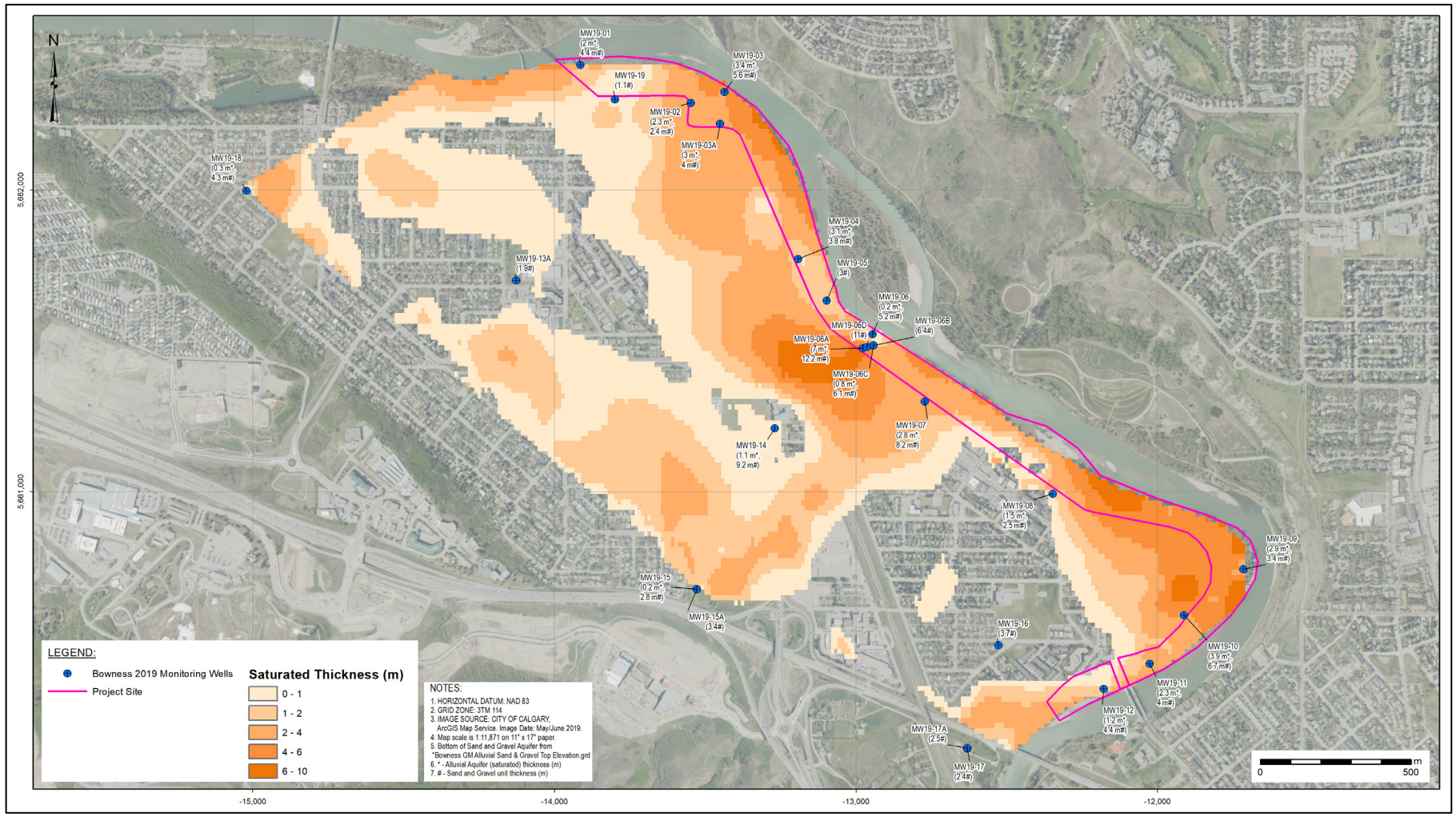


Figure 2.21 Alluvial Aquifer – October 7, 2019 Inferred Saturated Thickness



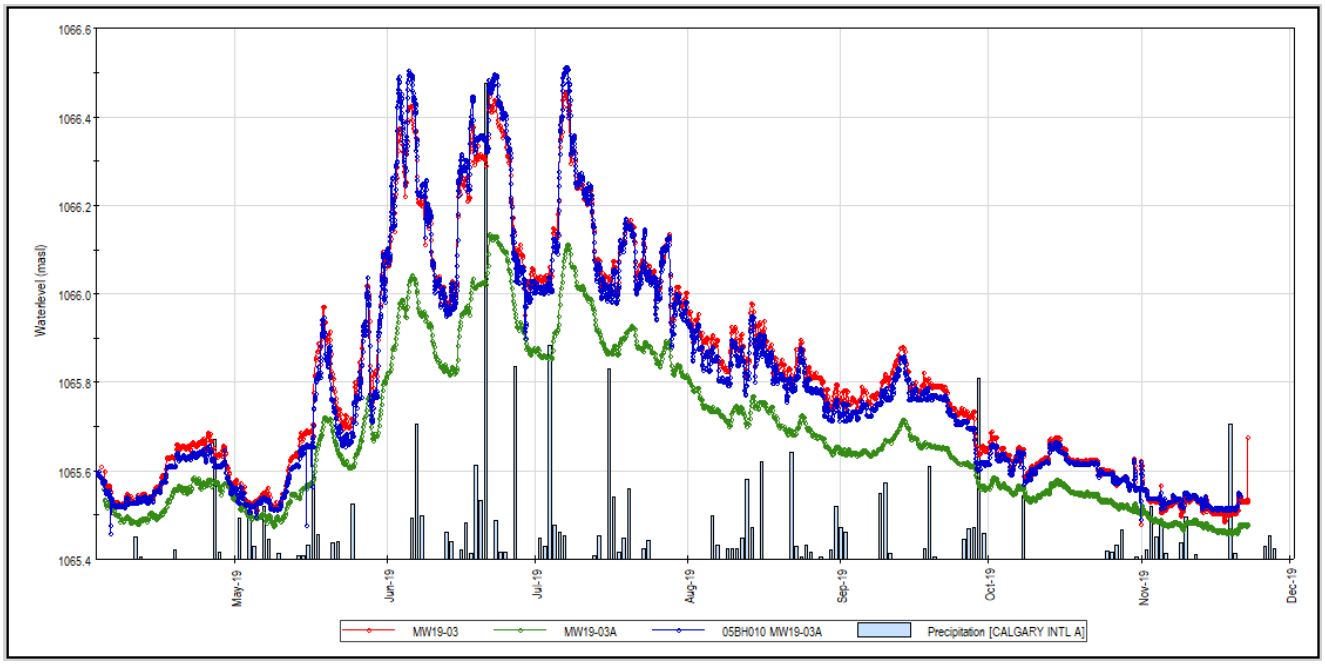
2.6.4 Groundwater-Bow River Interaction

The following sections introduce the water level observations used to conceptualize the interaction between the Bow River and the Alluvial Aquifer.

Wells MW19-03/03A

Monitoring wells MW19-03 and MW-19-03A are screened in the Alluvial Aquifer and are located approximately 20 m and 120 m from the Bow River, respectively (Figure 1.2). The groundwater elevations and fluctuations in well MW19-03 closely mimic that of the HECRAS Bow River station 05BH010 simulated rating curve adjacent MW19-03A (Figure 2.22), indicating the direct hydraulic connection between the two systems. Groundwater water level fluctuations in well MW19-03A also closely match those of the HECRAS simulated hydrograph but show a muted (lower amplitude) response to the river fluctuations. At this location, the Bow River was discharging to the Alluvial Aquifer only from about May through October 2019, based on the monitoring data.

Figure 2.22 Groundwater Elevations in the Alluvial Aquifer at MW19-03/-03A and HECRAS Bow River Levels (05BH010 MW19-03A)



MW19-06 Cluster of Wells

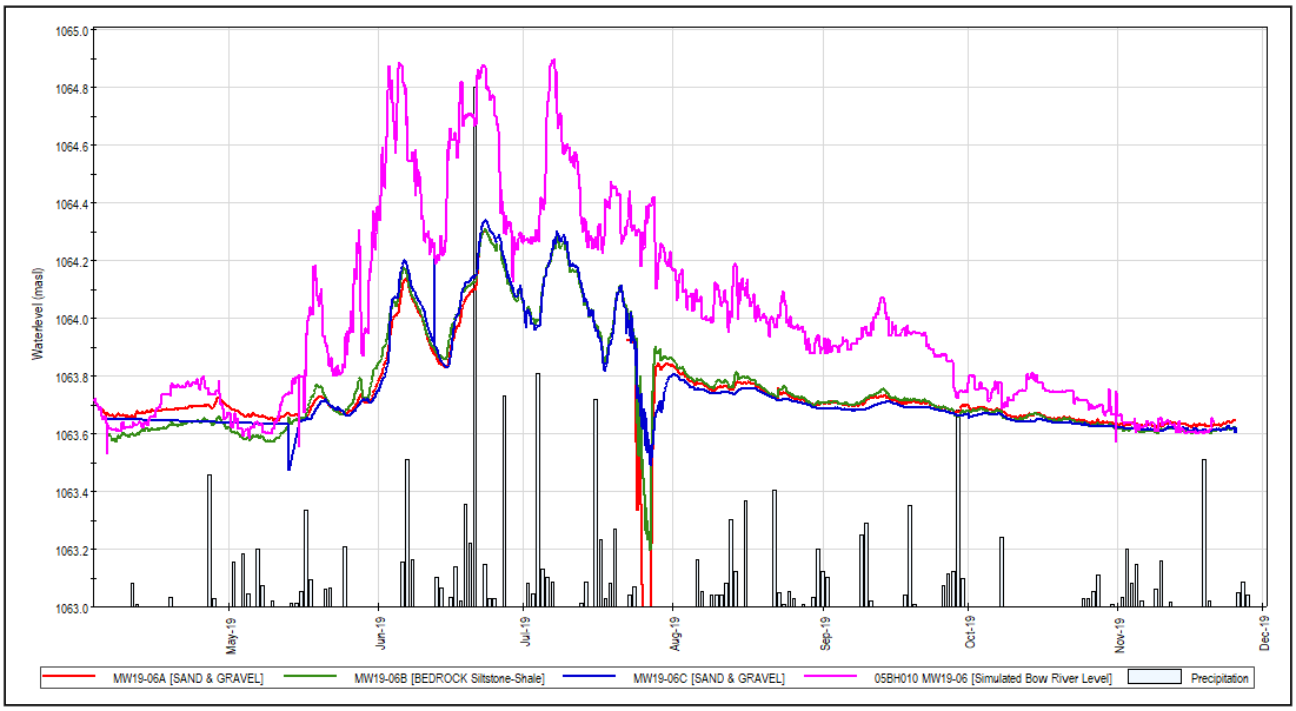
This cluster of monitoring wells includes MW19-06, MW19-06A, MW19-06B, and MW19-06C. Monitoring wells MW19-06 and MW19-06A are located approximately 17 m and 75 m from Bow River, respectively, while nested well pair MW19-06B and MW19-06C are located approximately 50 m from the riverbank (see inset map in Figure 1.2). All the wells are installed in the Alluvial Aquifer apart from MW19-06B, which is installed in siltstone-sandstone bedrock just below the base of the Alluvial Aquifer.

The monitoring data shows that the Bow River was discharging to this lowest section of the Alluvial Aquifer from mid-May to late September 2019. During this period, groundwater levels at the monitoring wells varied between 0.2 m and 0.5 m below that of the river water level (Figure 2.23). The direct hydraulic connection between the two systems is shown by the close correlation between water level fluctuations, limited time lag (less than 24 hours), and magnitude of the water level response. The Alluvial Aquifer, together with underlying bedrock (MW19-06B), is interpreted to discharge to the river during low river flow periods, typically November through April. The low water levels indicated on Figure 2.23 in July 2019 are a result of 50-hour CRT test conducted on nearby pumping well MW19-06D.

Other Wells

A review of monitoring well and river hydrographs for wells located along the river generally indicates that groundwater discharges to the Bow River during lower river flow periods, typically October through May, but also September through June at some locations. Exceptions to this include: MW19-08 and MW19-10, where groundwater levels appear to be slightly below river levels for the entire year. However, the water level difference of a few centimetres may also be attributed to small errors in the HEC-RAS modelling and groundwater survey data. The groundwater level hydrographs for the Project monitoring wells are provided in Appendix I.

Figure 2.23 Groundwater Elevations in the Alluvial Aquifer at MW19-06 Wells and Bow River Levels

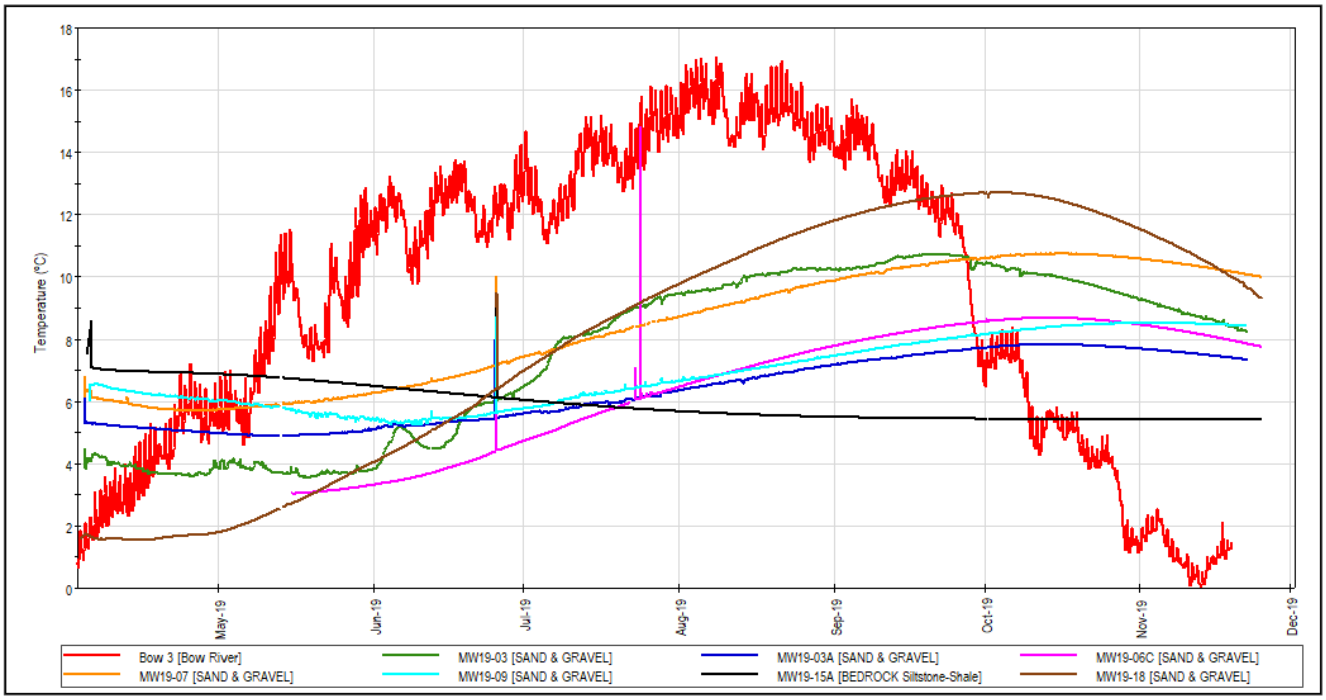


Groundwater Temperature

The water temperatures in the Alluvial Aquifer vary seasonally, with values ranging between 2°C and 7°C from April to June 2019, and gradually increasing to peak temperatures of 7°C to 13°C in late September to November 2019 (Figure 2.24). The observed seasonal trend in groundwater temperature for wells located close to the river is attributed to the gradual mixing with recharging river water, especially during the freshet river flow period, together with the effects of changing air and soil temperature. The groundwater temperature response to changing river temperatures is muted (smoothed) and attenuated depending on the degree of aquifer connectivity to the Bow River and the distance of the monitoring location from the river. Well MW19-03 is 20 m from the riverbank and shows short duration temperature variations associated with specific river flow peaks (e.g., June 6, 2019), while wells MW19-03A (120 m from river), MW19-07 (115 m from river), MW19-06C (50 m from river), and MW19-09 (45 m from river) display long-term seasonal (cyclical) temperature trends.

Well MW15A is screened within the bedrock, well away from the temperature influence of the river, and displays a highly subdued and delayed seasonal response. It is assumed that this reflects the 'natural' seasonal groundwater temperature response related mostly to changing air/soil temperatures and aspect (exposure to solar radiation). Well MW19-18 is a relatively shallow well with a water table close to surface, hence it is particularly sensitive to air temperature changes.

Figure 2.24 Groundwater Temperatures in Alluvial Aquifer and Bedrock vs. Bow River Temperatures



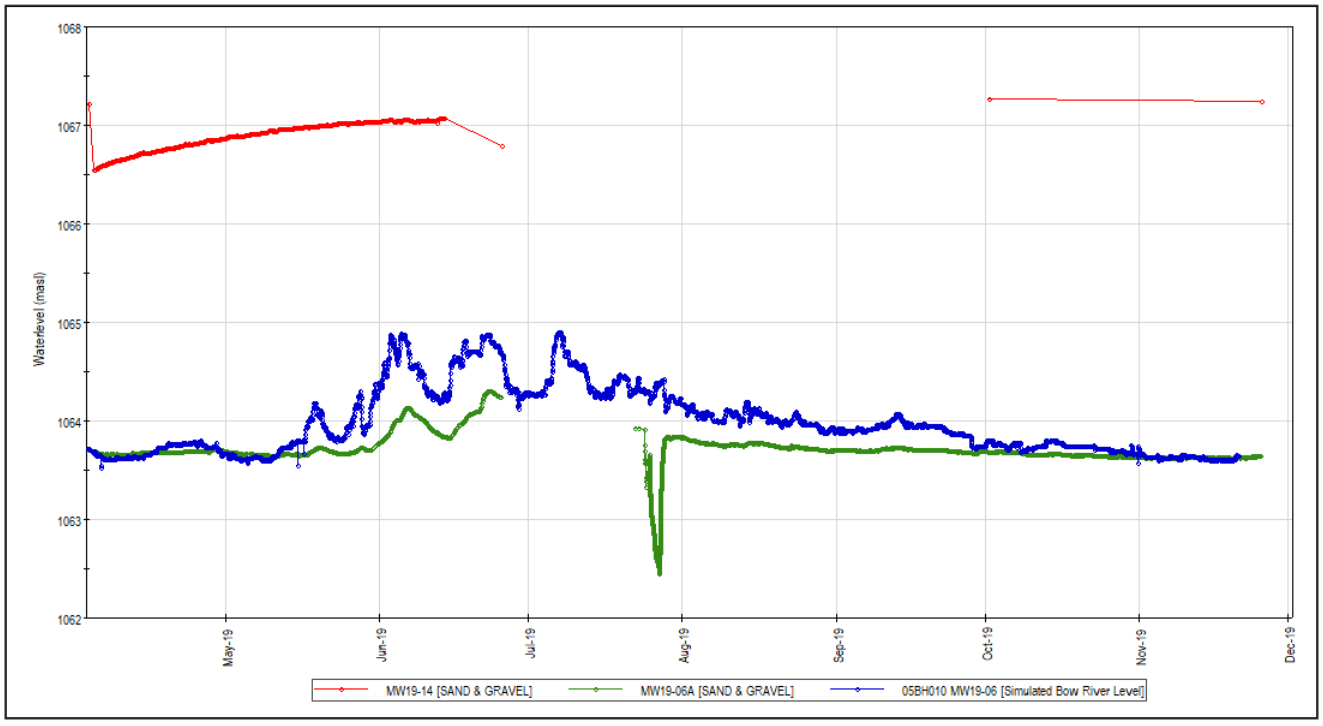
2.6.5 Groundwater Monitoring Outside Bow River Influence

There are a limited number of monitoring wells (MW19-13A, MW19-14, MW19-15/-15A, and MW19-18) installed in the interior of the Project Area, that are not influenced by discharge from the Bow River. The locations of these monitoring wells are indicated in Figure 1.2.

Well MW19-14

Monitoring well MW19-14 is screened across the Alluvial Aquifer and is located approximately 450 m from the Bow River, within the central part of the aquifer (Figure 1.2). The groundwater elevation in the well was about 1067 masl in June 2019, which is approximately 2.8 m and 2.2 m above the June peak levels in the Alluvial Aquifer (MW19-06A) adjacent to the Bow River and the Bow River level, respectively (Figure 2.25). The observed groundwater elevations at MW19-14 shows the well is clearly outside the ZOI of the Bow River, and within a lower-permeability section of the aquifer.

Figure 2.25 Groundwater Elevations in Wells MW19-14 and MW19-06A vs. HEC-RAS Simulated Bow River Levels



Note:

No PTDL installed in MW19-14 after June 2020, manual readings only.

Well MW19-18

Monitoring well MW19-18 is located in the central portion of the Project Area and approximately 500 m southwest of the Bow River (Figure 1.2). The groundwater elevation is approximately 1074 masl (Figure 2.26), approximately 5 m above that of the Bow River. The groundwater gradient in this portion of the Alluvial Aquifer is relatively steep, indicative of lower permeability and limited aquifer thickness, and groundwater flow is consistently towards the Bow River (Figure 2.26). The water levels appear to be influenced by upstream flows and recharge along the escarpment edge.

Figure 2.27 shows a seasonal response of groundwater temperature with seasonal air/soil temperature changes, with water temperature ranging from a low of 2°C in the spring to a high of 12°C in the fall.

Figure 2.26 Monitoring Well MW19-18 - Groundwater Elevations vs. HECRAS Simulated Bow River Levels

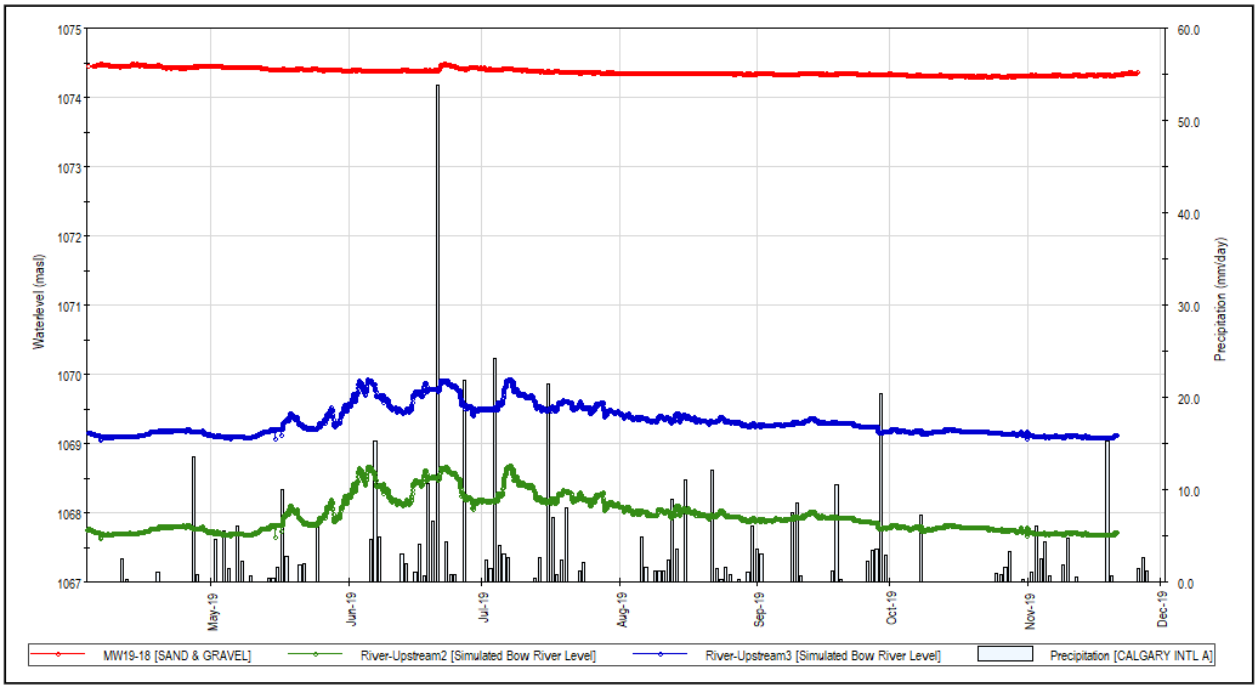
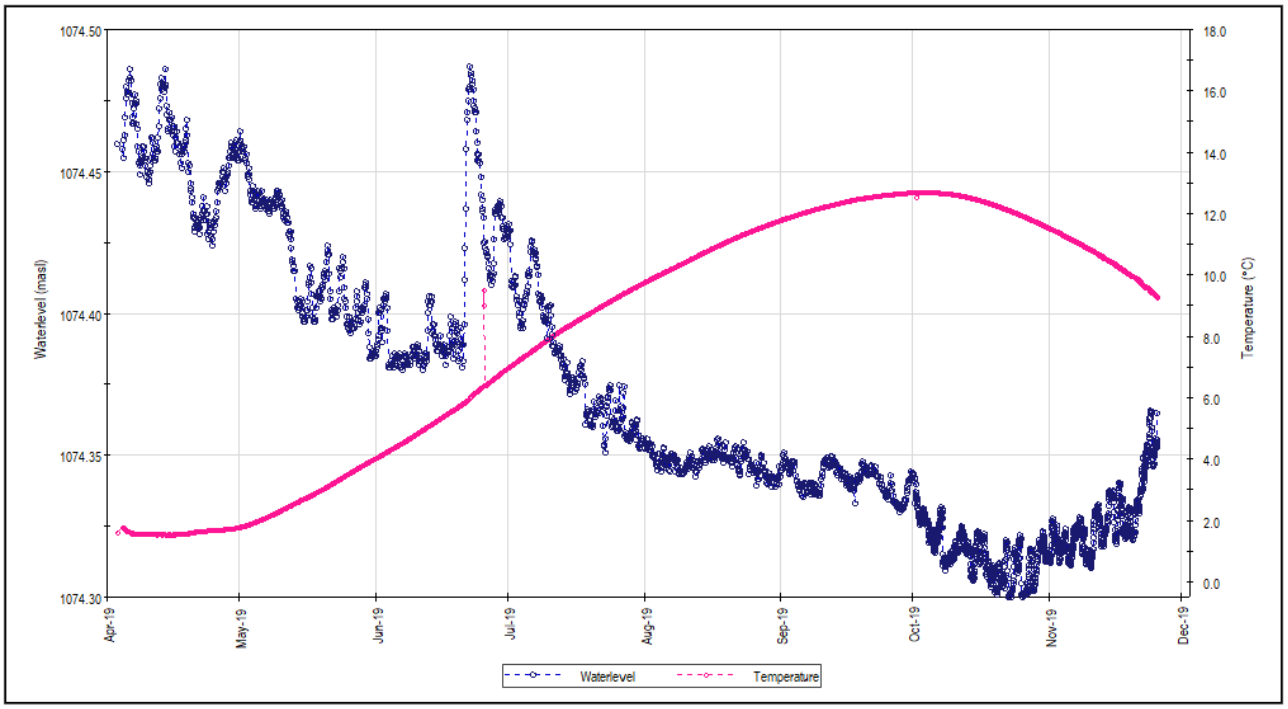


Figure 2.27 Monitoring Well MW19-18 - Groundwater Elevation vs. Temperature



2.6.6 Summary

Based on a review of the groundwater and Bow River hydrographs (measured at Bow 3 and Bow 5, as well as HECRAS simulated river levels) near the 2019 monitoring wells, as well as the inferred water level contours for the Alluvial Aquifer in June 2019 and October 2019, the following main observations are made:

- Groundwater monitoring observations suggest that two flow systems exist within the Project Area; 'Regional' and 'River-influenced' groundwater flows.
- Regional groundwater flow in the Project Area is generally in an easterly to north-easterly direction and sub-parallel to the river at several locations adjacent to the river.
- Groundwater flow is southward in the southeastern section (sharp bend in the Bow River) of the Project Area and is influenced by upstream river water entering the aquifer and then discharging back into the river further downstream, i.e., is a River-influenced flow.
- Water levels in the Alluvial Aquifer adjacent to the Bow River are in direct hydraulic connection with the river and, under typical seasonal river flows, the ZOI of the river on aquifer extends up to about 360 m away from the riverbank.
- Along the northern section of the Project Area, it is inferred that the ZOI extends less than 200 m from the riverbank due to the rapid thinning of the aquifer as it shelves up against a local bedrock high (see bedrock elevations in Figure 2.4).
- The Alluvial Aquifer is generally unconfined, but there are localized areas adjacent to the river where it becomes semi-confined during seasonal high river flows (e.g., MW19-02 and MW19-09 in June 2019).
- Observed local groundwater levels and temperature profiles along the Bow River suggest that the river is generally effluent (discharges) to the Alluvial Aquifer during high river stage periods, with relatively low hydraulic gradients, indicative of relatively high permeability conditions.
- The review of bedrock/till subcrop elevation and saturated thicknesses of the Alluvial Aquifer indicate several zones of elevated bedrock topography which, in many cases, are capped by lower permeability clayey till, which resulted in areas where the Alluvial Aquifer was locally unsaturated during the observed high- (Figure 2.17) and low-river flow (Figure 2.18) periods in 2019. These areas restrict groundwater flow and create preferential flow paths within the aquifer.
- In the southeastern corner of the Project Area, the Alluvial Aquifer thins as it shelves up against the thick silt-clay unit overlying the Paskapoo bedrock which forms the escarpment (Figure 2.19).

2.7 Groundwater and Surface Water Chemistry

Water samples were collected from various project monitoring wells and the Bow River, in April, June, and December 2019 to identify water types and assess interactions between the Alluvial Aquifer and the river. Water samples were analyzed for major ion chemistry (all events) and dissolved metals (April only). Summarized water chemistry results are provided in Appendix I.

Diagnostic plots (Piper, Durov and Stiff diagrams) were used to assess the hydrochemical water types characteristic of the defined HSU's.

The Piper diagram provides a convenient method to classify and compare water types based on the major ionic composition of different water samples. Cation and anion concentrations for each sample are converted to total milliequivalents/litre (meq/L) and plotted as percentages of their respective totals in two triangles. The cation and anion relative percentages in each triangle are then projected into a quadrilateral polygon that describes the water type or hydrochemical facies.

Similar to the Piper diagram, the Durov diagram also provides a visual method to classify and compare water types based on the major ion composition of different water samples. Cation and anion concentrations (meq/L) are plotted as percentages in two ternary (trilinear) graphs which are projected into a central rectangular field that describes the water type or hydrochemical facies. The Durov plot can be extended to graph specific parameters not included in the main Durov plot, i.e., pH, total dissolved solids, dissolved metals etc.

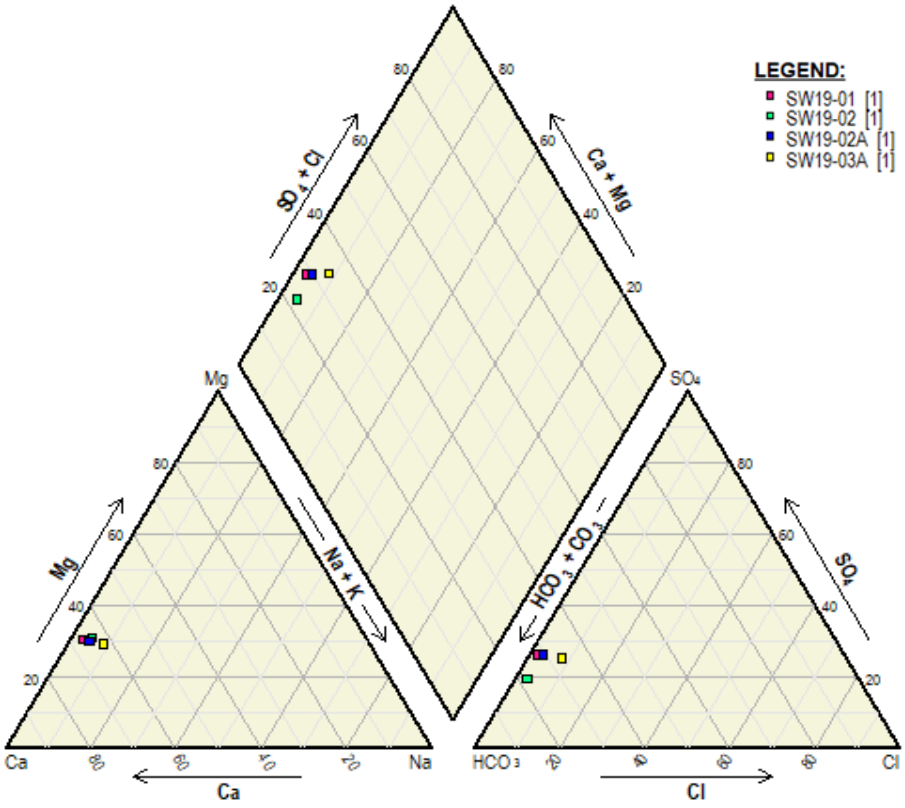
Stiff diagrams can be used for graphical representation of water types. The Stiff diagram is a polygon created from three horizontal axes extended on both sides of a vertical axis. Cations are plotted on the left side of the axis and anions are plotted on the right side, both in meq/L. A greater distance from the central vertical axis represents a larger ionic concentration.

The following sections outline the interpreted results of the major ion chemistry of the analysed water samples.

2.7.1 Surface Water Chemistry

Water samples SW19-02 and SW19-03A were collected upstream of the Project Area (close to MW19-01), and samples SW19-01 (close to MW19-06) and SW19-02A (close to MW19-11) were collected in the middle and downstream of the Project Area, respectively, on the south bank of the Bow River. The samples are all characterized as a calcium-bicarbonate type water (Figure 2.28). The salinity, measured as total dissolved solids (TDS), of the river water varied between 160 mg/L and 220 mg/L. The salinity was lowest (~160 mg/L) during the June 2019 freshet flow period and increased to ~205 mg/L in the December 2019 (low river flow period). Comparison of the upstream and downstream samples taken in December 2019 show a slight increase in salinity between the upstream (SW19-02A) and downstream (SW19-03A) samples of approximately 15 mg/L.

Figure 2.28 Piper Diagram showing 2019 Bow River Water Chemistry



2.7.2 Groundwater Chemistry

Figure 2.29 presents a Piper diagram showing all the 2019 groundwater samples collected from monitoring wells installed in the Alluvial Aquifer and located within the interpreted 2019 seasonal ZOI of the Bow River (estimated at about 250 m to 360 m). Most of the groundwater samples plot in a similar position on the diagram as the surface water samples (Figure 2.28) and can be characterized as calcium-bicarbonate type water. The wells where the groundwater type differs from this water type include MW19-06A to 06C, MW19-07, MW19-11, and MW19-12. These wells all have higher proportions of sodium and chloride compared to the surface water and other groundwater samples.

Figure 2.29 Piper Diagram showing Hydrochemistry of Groundwater Wells within the 2019 Seasonal Bow River ZOI

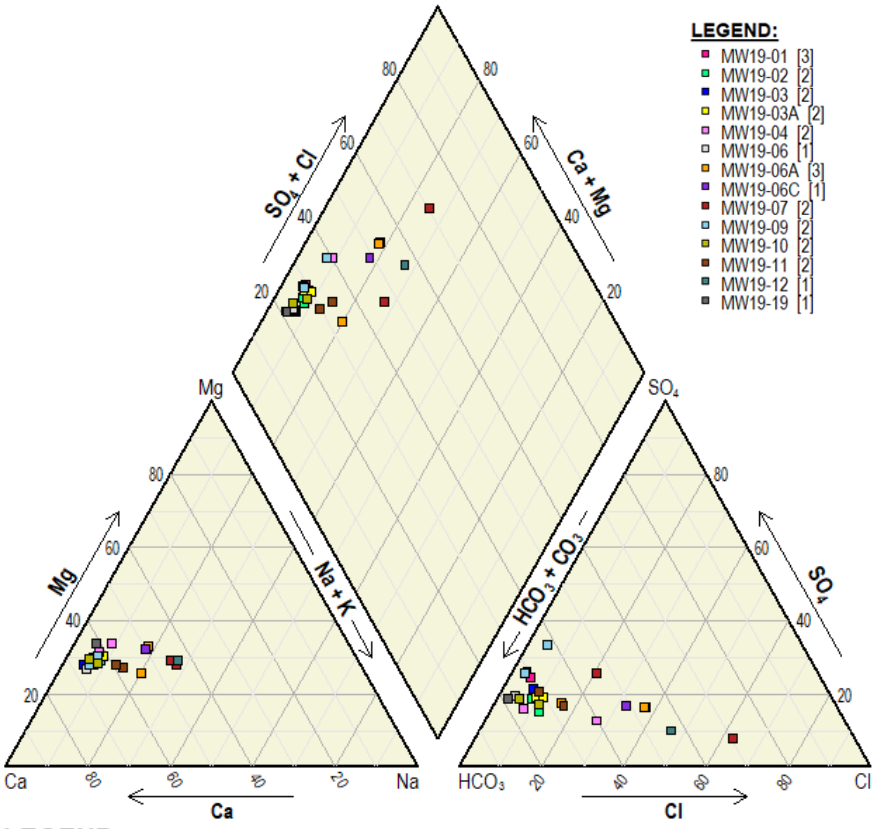
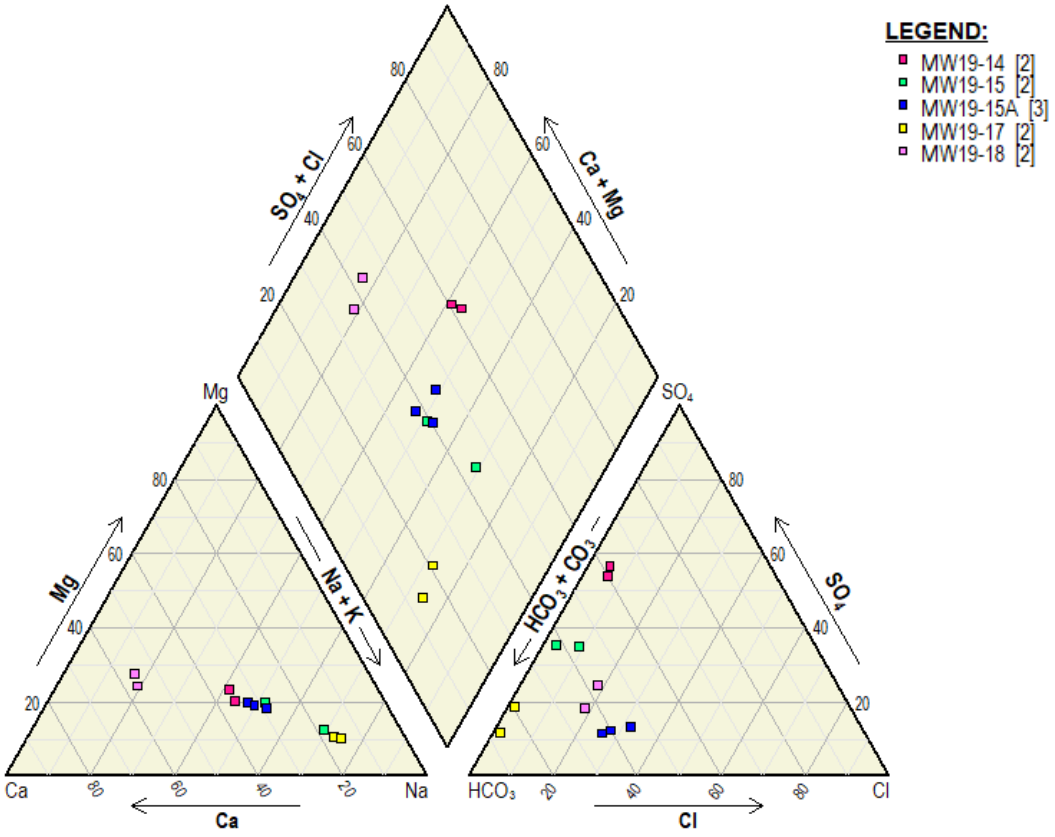


Figure 2.30 presents a Piper diagram for groundwater samples collected from groundwater monitoring wells that are located further inland (>360 m) from the Bow River or not screened in the Alluvial Aquifer. Well MW19-17 is screened in a silt layer separate from the Alluvial Aquifer and MW19-15A is screened in the bedrock. Most of these samples can be described as sodium-calcium-bicarbonate type water.

At the April 2019 sampling event, wells MW19-06A, -06B, and MW19-06C; MW19-19, and MW19-04 had slightly elevated chloride concentrations (>50 mg/L), and during the June 2019 event, the chloride concentrations decreased to below 30 mg/L. MW19-17, MW19-15 and 15A, and MW19-14; deviates from the general groundwater type (calcium-bicarbonate) and has a mixed sodium-calcium-bicarbonate-chloride character (sodium >160 mg/L). The variable sodium-chloride (see also Figure 2.29) observed at some of these monitoring sites may be attributed to contribution from upstream groundwater and potentially from infiltration of run-off from paving and streets containing road salt used during winter. In general, the groundwater salinity is elevated outside of the ZOI with TDS concentrations greater than 500 mg/L, whereas groundwater close to the river are of lower TDS (approximately 200 mg/L to 450 mg/L).

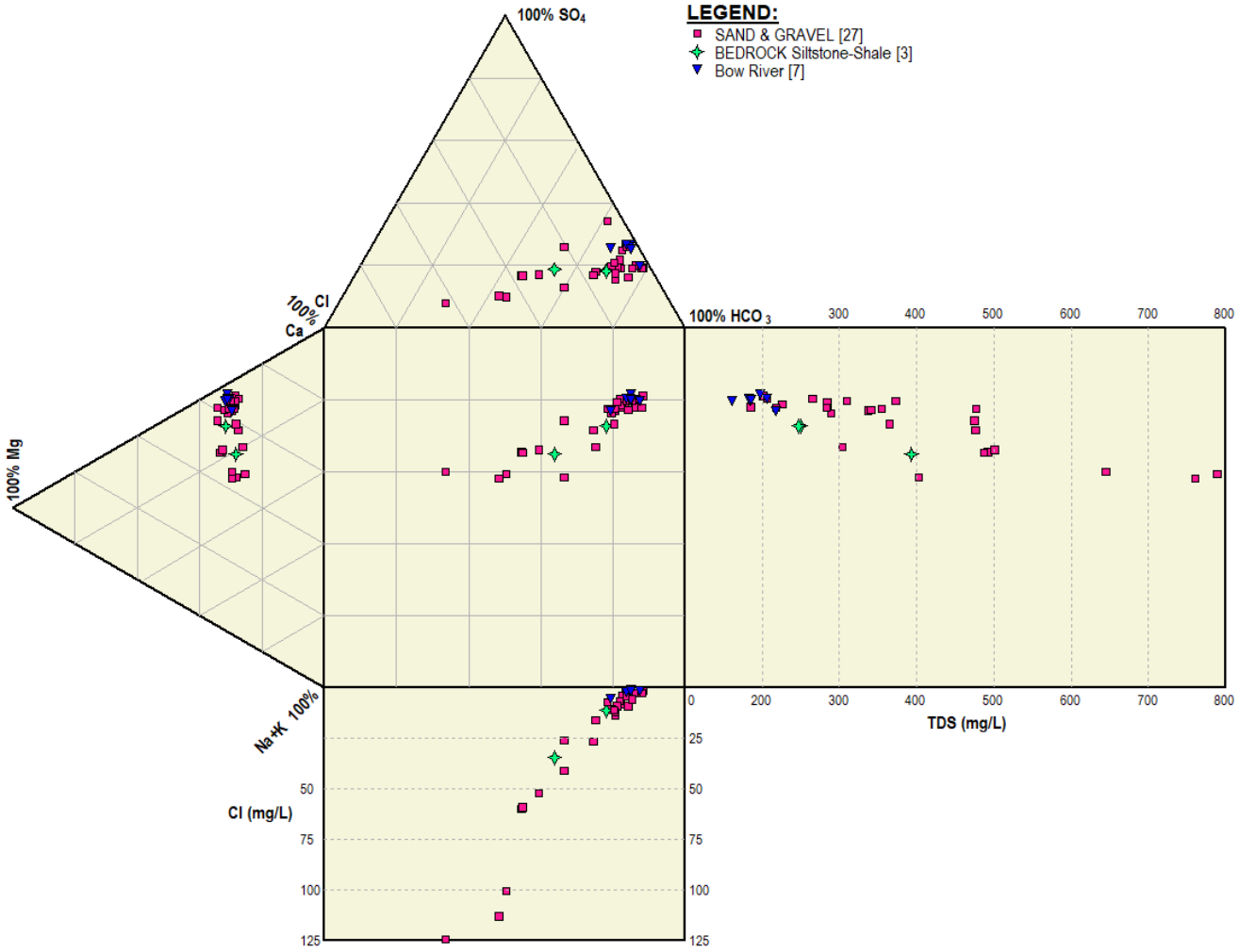
Figure 2.30 Piper Diagram showing Hydrochemistry of the Wells Outside of the 2019 Seasonal Bow River ZOI



Plotting the major ion chemistry for the wells on a Durov diagram confirms the water types identified for the various monitoring sites. Figure 2.31 and Figure 2.32 present Durov diagrams for the monitoring wells located within the 2019 seasonal ZOI and the Bow River water, while Figure 2.34 shows the Durov diagrams for the inland groundwater samples.

The Durov diagrams illustrate the increase in salinity and the shift to sodium (chloride) cation dominance towards the inland monitoring sites. The hydrochemical character of the river water (SW19-01 and SW19-02) is very similar to that observed for the groundwater samples (Figure 2.32) collected in close proximity of the Bow River (e.g., MW19-01, MW19-03, and MW19-06) on the upstream side of the Project Area, reflecting the influence of inland flow and bank storage. In the downstream areas, the groundwater type is still similar to the surface water (SW19-03) but the groundwater has higher salinity than the river water (e.g., MW19-09, MW19-10, and MW19-11), reflecting an increasing component of 'upstream' groundwater.

Figure 2.31 Durov Diagram showing Hydrochemistry of Groundwater Wells within the 2019 Seasonal Bow River ZOI – Grouped per HSU



The Durov diagram for the inland groundwater samples (Figure 2.33) show the clear distinction between groundwater and surface water type. MW19-18 show a calcium-bicarbonate dominance whereas the remainder of the wells tends to be more sodium- bicarbonate. The inland well pair and MW19-15a and MW19-15, can both be typed as sodium-bicarbonate, however the salinity of the sand and gravel aquifer well (MW19-15) is significantly higher (830 mg/L to 930 mg/L) than the TDS (~520 mg/L) of the bedrock well (MW19-15A).

Stiff diagrams were plotted for the groundwater and Bow River water samples collected between April and December 2019 to spatially illustrate the distribution of water types across the Project Area (Figure 2.35). The Stiff diagrams show variation in the major ion chemistry between the shallow groundwater system and the Bow River. The stiff diagrams clearly show the similarity in chemical water types between the river water and the groundwater samples within the ZOI.

Figure 2.32 Durov Diagram showing Hydrochemistry of Groundwater Wells within the 2019 Seasonal Bow River ZOI

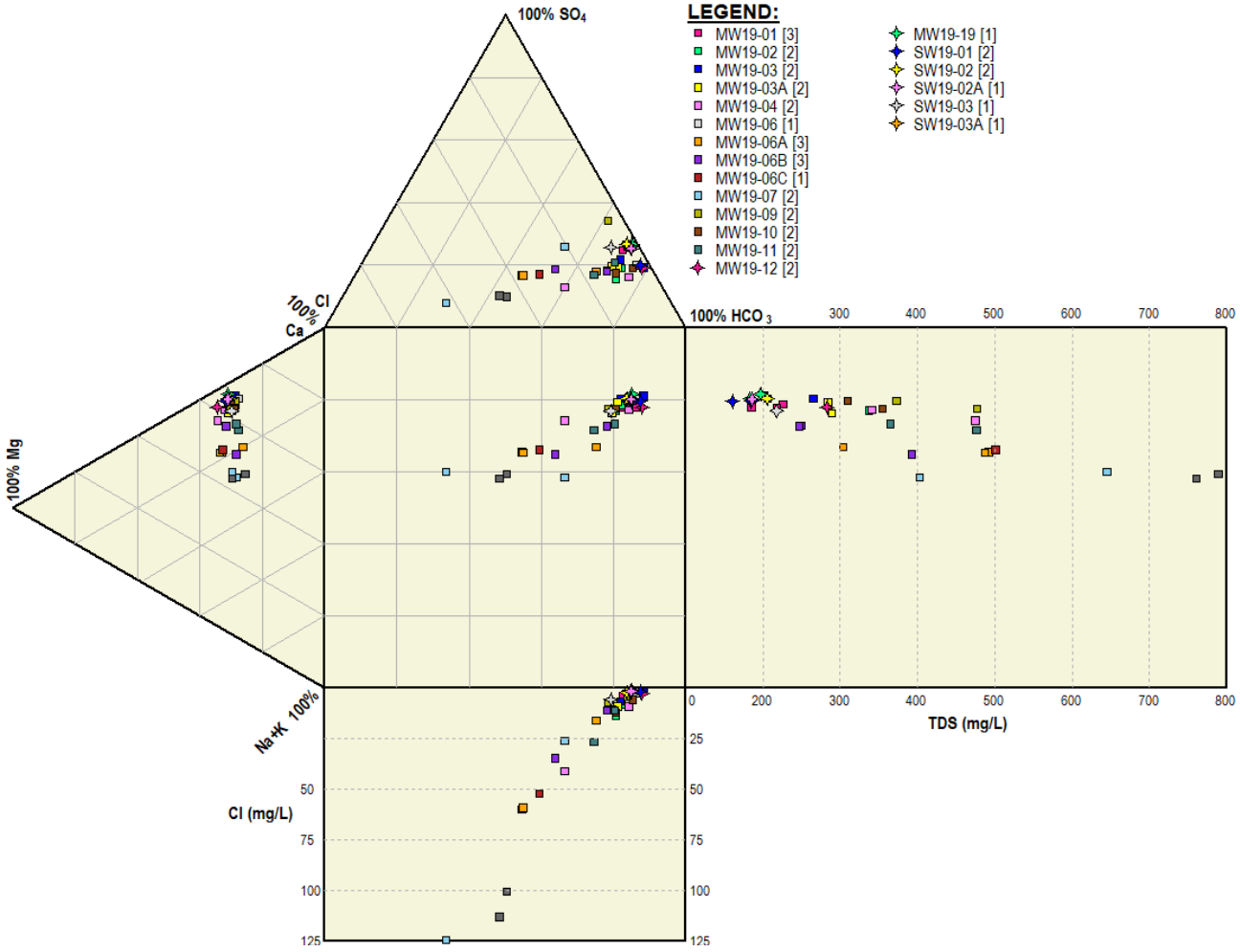


Figure 2.33 Durov Diagram showing Hydrochemistry of Groundwater Wells outside of the 2019 Seasonal Bow River ZOI – Grouped per HSU

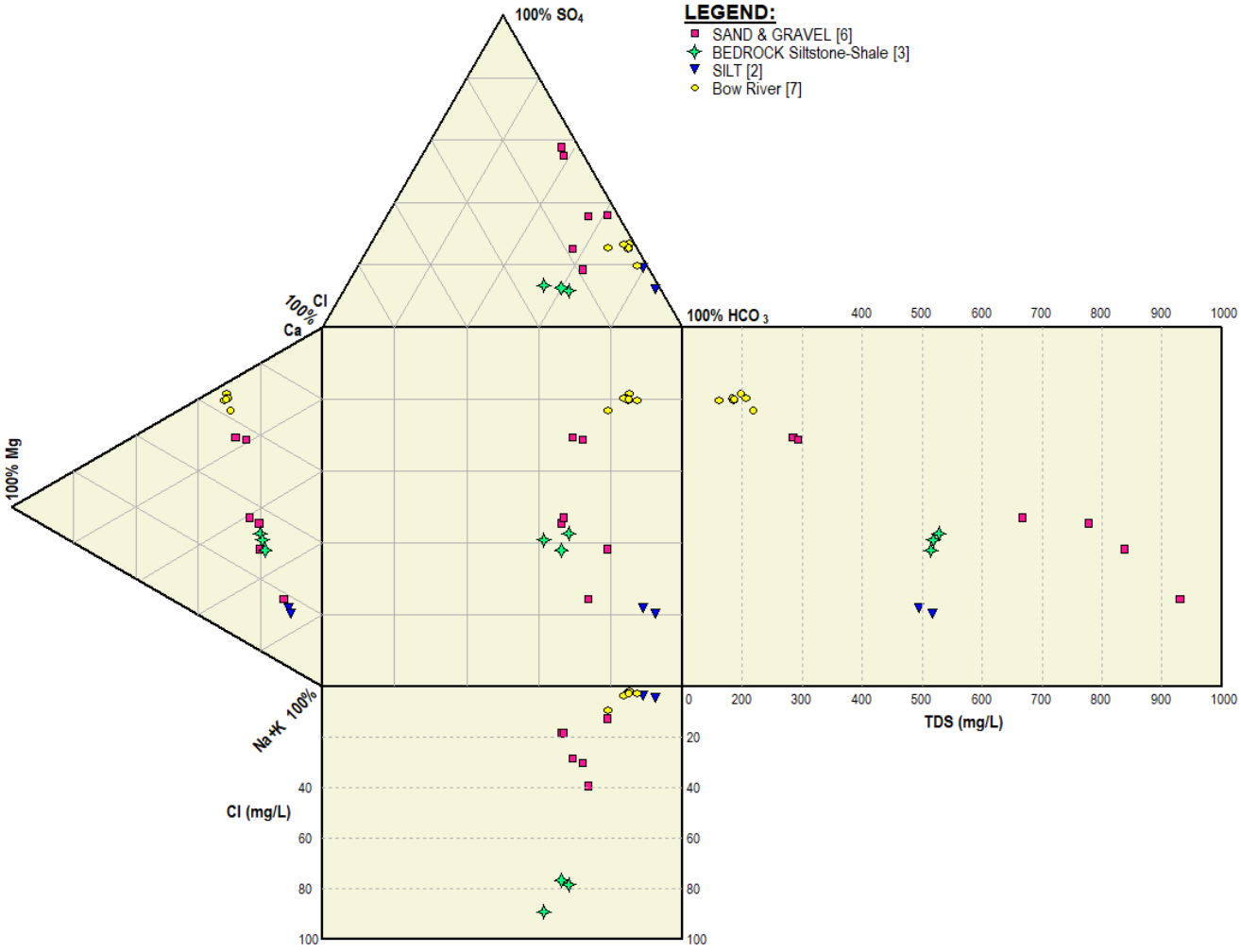


Figure 2.34 Durov Diagram showing Hydrochemistry of Groundwater Wells outside of the 2019 Seasonal Bow River ZOI

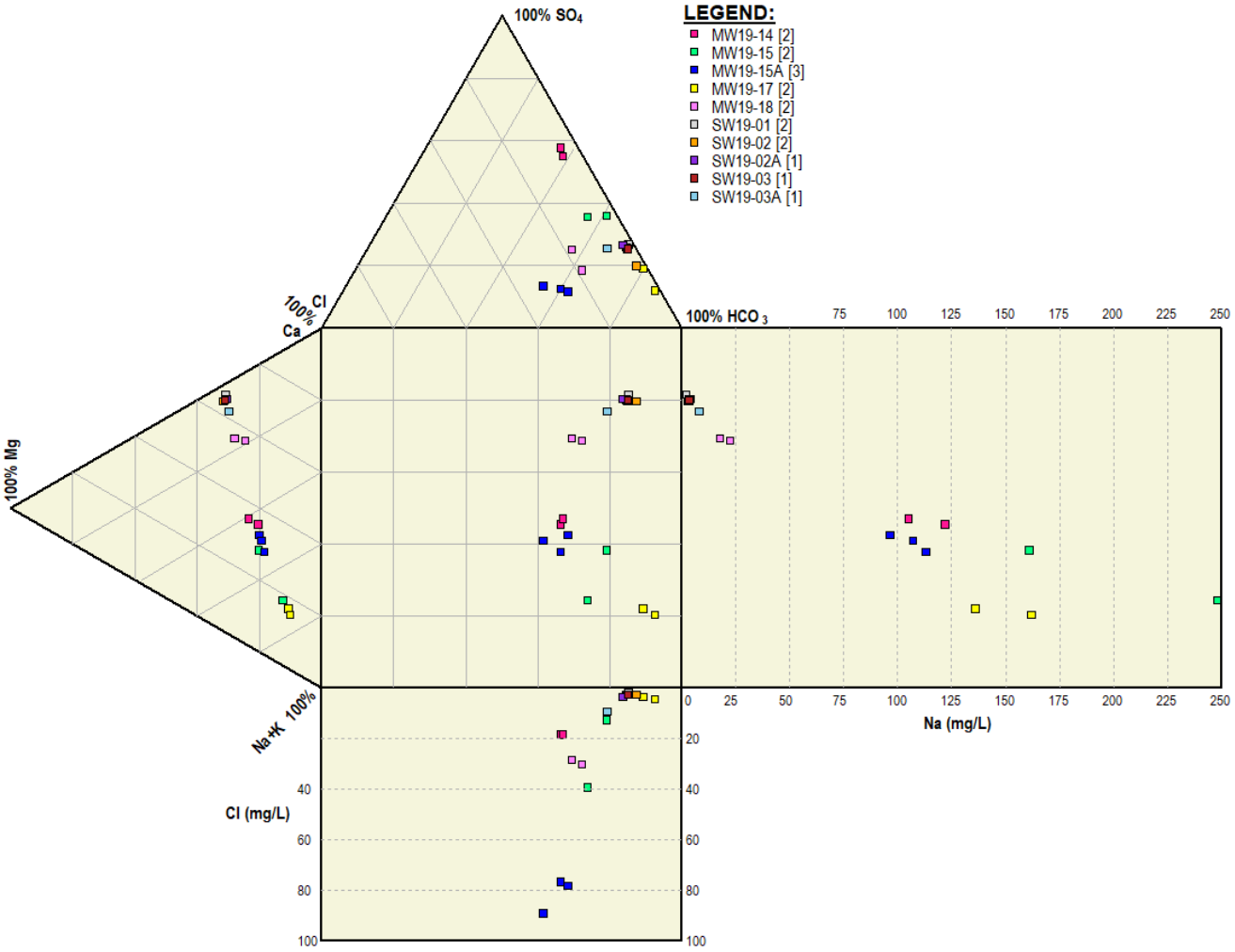
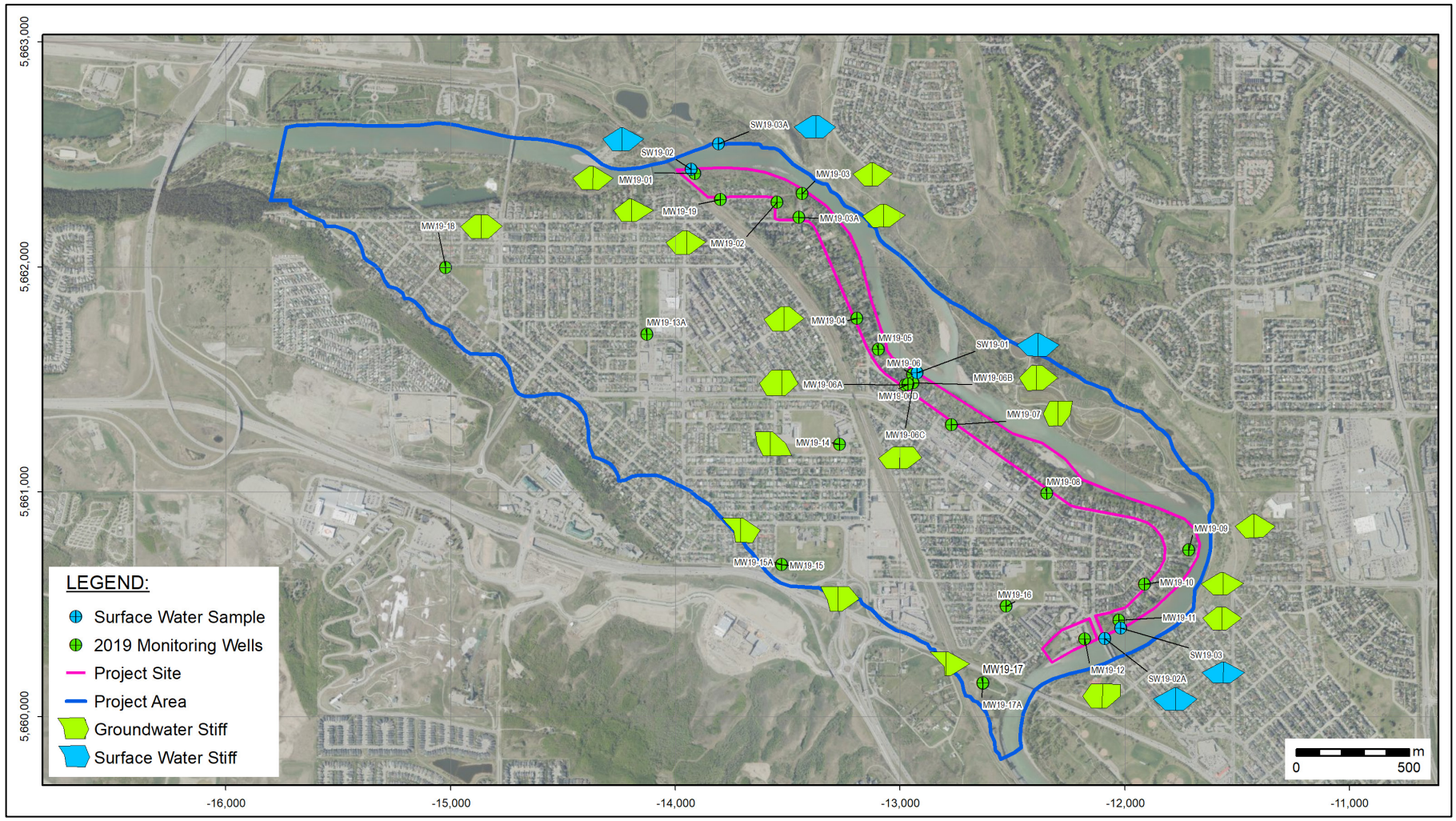


Figure 2.35 Stiff Diagrams showing Spatial Distribution of Groundwater and Surface Water Hydrochemical Types



Note: Wells MW19-06B and MW19-15A are installed in the bedrock, and MW19-17 is installed in Silty lacustrine unit.

2.7.3 Summary

The water chemistry and the hydrochemical diagnostic plots, used for this evaluation, supports the hydrogeological conceptual model by indicating the following:

- A slight increase in the Bow River salinity is observed between the upstream and downstream sampling sites during low river flow conditions, likely indicating that some groundwater baseflow is contributing to the river flow between the monitoring points.
- During high freshet flow periods, the groundwater near the river is very similar in salinity and major ion water type (calcium-bicarbonate) to the Bow River water, indicating inflow to the Alluvial Aquifer from the river.
- Inland groundwater samples exhibit a higher salinity compared to the down gradient groundwater monitoring sites and have a varied hydrochemical type with sodium and bicarbonate as the most abundant ions.
- Hydrochemical interaction between the Alluvial Aquifer and the Bow River is estimated to be limited to areas within 250 m to 360 m from the riverbank.
- Recharge to the shallow aquifer system from surface run-off is likely rapid in areas where the aquifer is not covered by extensive impermeable units, as is evident by the presence of elevated sodium and/or chloride at monitoring well located in these areas (i.e., MW19-07, MW19-17, MW19-06A, and MW19-06B).

3 NUMERICAL GROUNDWATER FLOW MODEL SETUP

Prior to preparation of the numerical groundwater model for Bowness, a Design Basis Memorandum (DBM) was prepared and provided for CoC and third-party review. The DBM is a live document and has been updated as changes were made to the model. The latest version of the DBM is attached in Appendix III.

3.1 Model Construction

The 3D finite-difference, groundwater flow and transport modelling software *Groundwater Vistas Version 7* (ESI 2019) (with MODFLOW-USG code) was used to build the numerical model and analyze the model outputs. The MODFLOW-USG (Unstructured Grid) code is a recent version of the public domain groundwater modelling software MODFLOW that uses a finite volume approach that facilitates the use of triangular, rectangular or other polygon-shaped geometries to discretize the model domain. This allows the user to refine the grid within local areas and provides increased computational efficiency relative to the standard MODFLOW rectilinear grid. It was selected because of its flexibility in grid design to focus resolution along the Bow River, and also due to its computational efficiency, broad usage and acceptance in the industry, and user-friendly interface.

The *Leapfrog*™ geological model was exported directly to the *Groundwater Vistas* package to provide the necessary model hydrogeological surfaces.

ESRI's *ArcGIS Desktop* 10.6.1 was used to visualize, assess, and manipulate model surfaces and geological features for input into the groundwater model as ESRI ASCII raster grids and shapefiles. *ArcGIS* and *ParaView* 5.7.0 were used to visualize and assess model outputs, as well as compile the report figures.

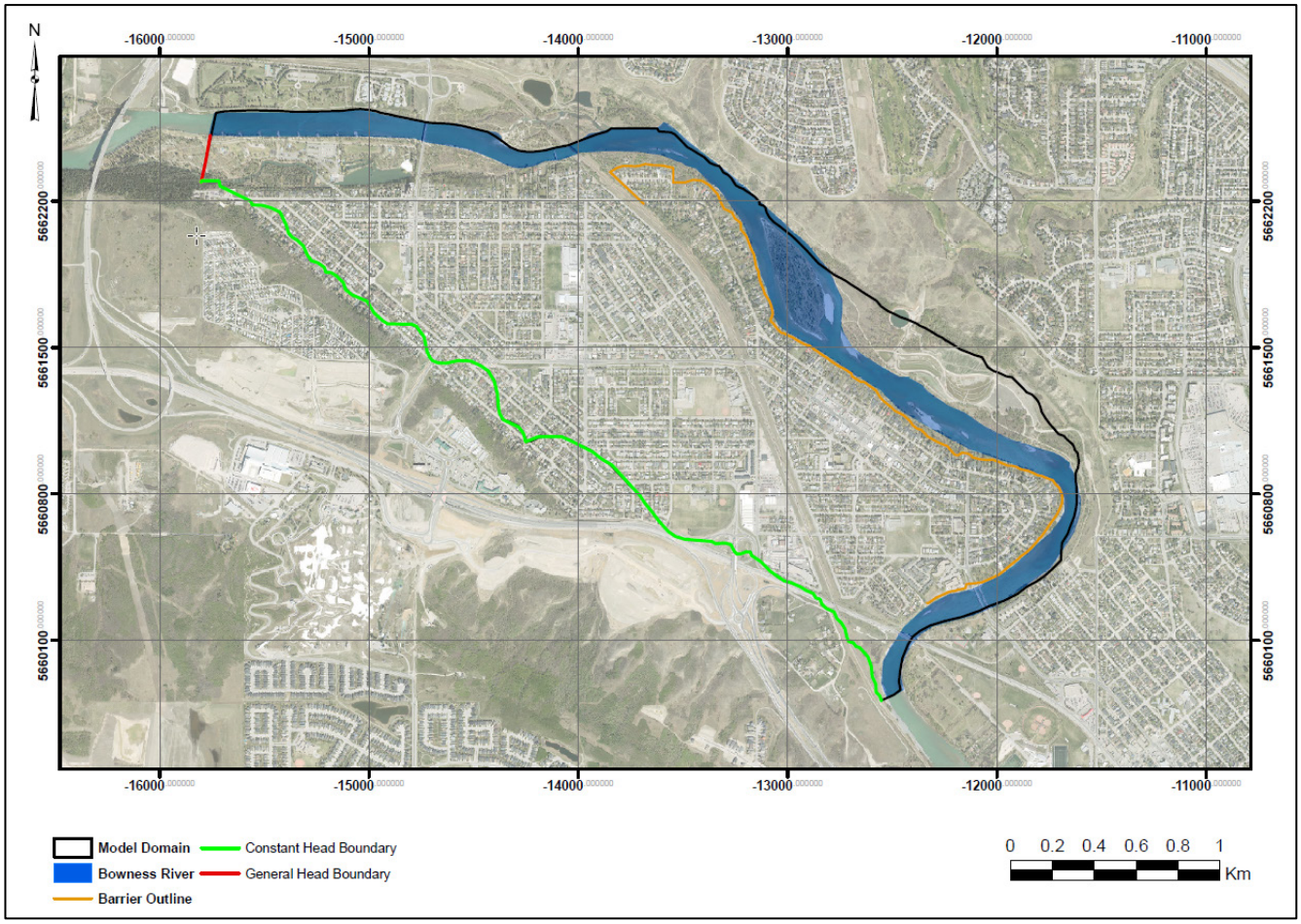
3.1.1 Model Domain

The model domain is shown in Figure 3.1. The model domain was defined based on the Conceptual Hydrogeological Model described in Section 2 and supported by the compiled 3D (*Leapfrog*™ *Geo*) geological model. The areal extent of the model domain is 5,166,213 m^2 (~5.2 km^2) with surface elevations ranging from approximately 1080 masl to 1065 masl and extends to a base elevation of 1035 masl, with an overall height ranging from about 30 m to 45 m. The lateral model limits are summarized below:

- North, northeastern and eastern boundaries include the north shore of the Bow River and parts of the northern riverbank below the northern escarpment;
- Western and southwestern boundaries are defined by the limits of the Alluvial Aquifer which pinches out along the escarpment ridge;
- Southern boundary extents are set along the southern edge of the Alluvial Aquifer; and
- Northwestern boundary marks the upstream model boundary which cuts across the Alluvial Aquifer from the escarpment directly to the Bow River.

The top surface of the model was compiled using the available LIDAR data (CoC 2018), at 0.2 m resolution. The Project Area is generally flat-lying with significant elevation changes along the southern side of the model domain (escarpment); ground elevation ranges from 1080 masl in the west to 1065 masl in the east. The southwestern boundary of the model domain occurs at the base of an ESE-trending escarpment to the south.

Figure 3.1 Numerical Model Domain and Boundary Conditions



3.1.2 Model Discretization

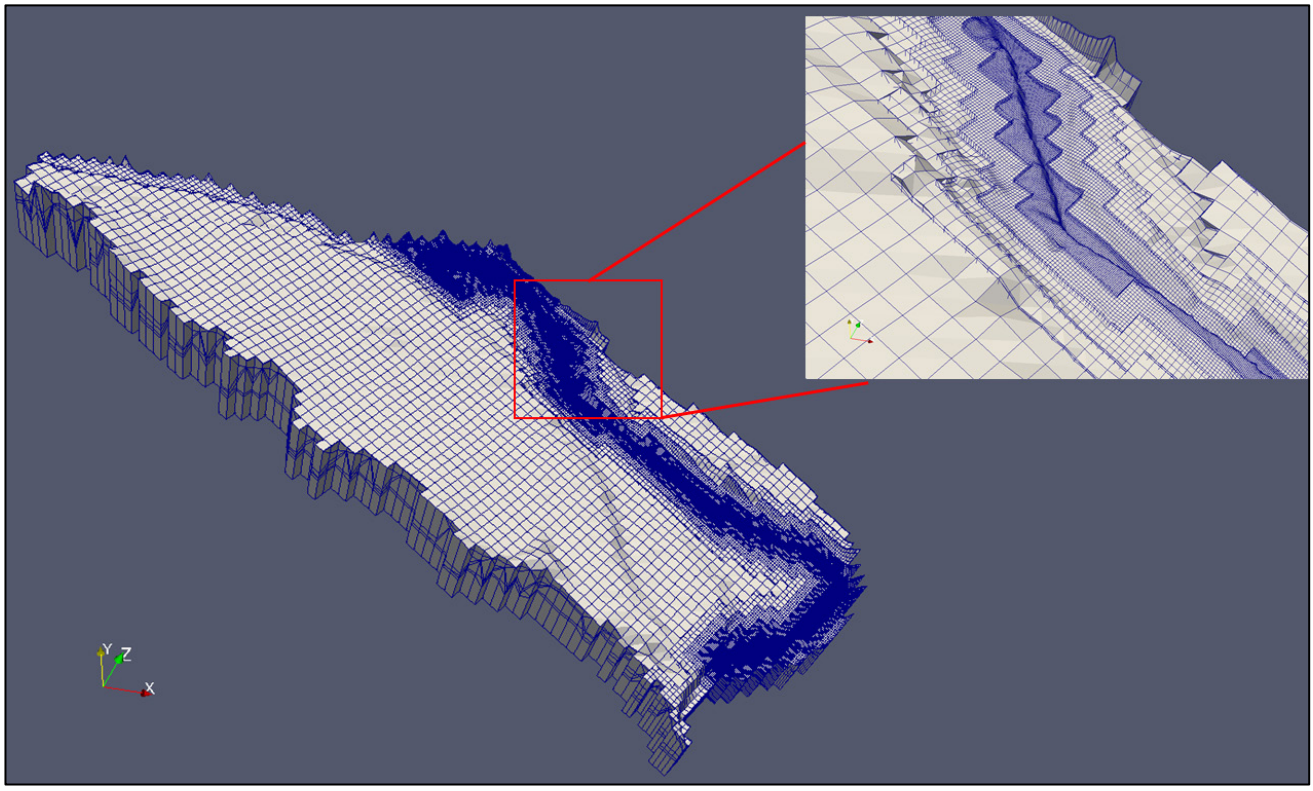
The model domain was discretized into rectangular cells with 93 rows, 38 columns, seven layers, and a total of 406,637 active cells. The 3D numerical model was rotated to align with the top of the model at Azimuth 123°, parallel to the linear section of the Bow River. The model was discretized using the MODFLOW Unstructured Grid (USG) package, to provide maximum discretization in the key areas surrounding the Bow River and the proposed surface water barrier and groundwater cut-off barrier,

while maintaining computation efficiency. The model is separated into the following three mesh density zones:

- High Density Zone – areas along the Bow River boundary extending south from the river to include potential flood barrier alignments along the river (average nodal spacing is 3.1 m).
- Intermediate Density Zone - transition area between the high-density zone and low-density zone (average nodal spacing increase from 6.25 m to 25 m).
- Low Density Zone - extending from the intermediate density zone to the model boundaries along the southern and western edges of the model domain (average nodal spacing is 50 m).

An isometric view of the model is presented in Figure 3.2.

Figure 3.2 Isometric View showing Model Discretization (Vertical Exaggeration is 10)



3.1.3 Boundary Conditions

Model boundary conditions are shown on Figure 3.1, and are described further in the sections below.

Groundwater Recharge

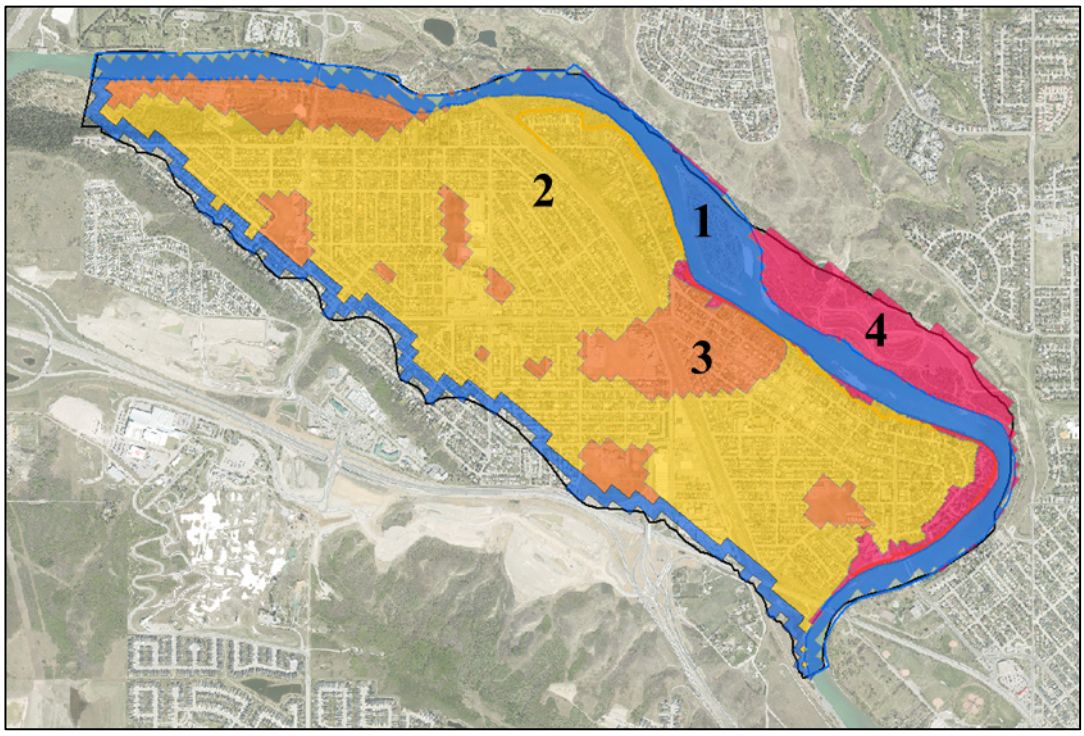
Groundwater recharge was applied to the model as per Table 2.5.

These rates were pro-rated to account for interpreted higher recharge conditions for the 'steady-state' modelling period selected, of May 5 to 9, 2019. Recharge was estimated at a factor of 1.2 times the annual rate, based on a review of Bow River hydrographs and interpretation of the baseflow component.

The steady-state recharge distribution is shown in Figure 3.3 and is summarized as follows:

- Zone 1 (0 mm/yr) was applied on the wetted area of the Bow River and on the southern Constant Head Boundary (CHB) and western General Head Boundary (GHB);
- Zone 2 (17.5 mm/yr) represents zones with the Topsoil, Silt and Clay unit *greater than* 0.5 m thick, and with the presence of impermeable surfaces;
- Zone 3 (35 mm/yr) represents zones with Topsoil, Silt and Clay unit *less than* 0.5 m thick overlying the Alluvial Aquifer in areas of development;
- Zone 4 (70 mm/yr) represents zones with Topsoil, Silt and Clay unit *less than* 0.5 m thick overlying the Alluvial Aquifer in areas of little or no development.

Figure 3.3 Model Recharge Distribution



There have been no significant seepage zones identified in the Project Area during the background data review and field surveys. Seepage zones are most likely to exist along the escarpment ridges to the south and northeast of the Project Area (outside of the model domain).

Shorter-term recharge was allocated for the overall model on the following basis:

$$R_d = (P_d - 10) \times 0.42$$

Where:

R_d = Daily recharge (mm)

P_d = Daily precipitation (mm)

The above formulation provides for an overall average recharge of 42% of daily precipitation depths greater than 10 mm. This overall figure was then distributed pro-rata in accordance with the four recharge zones described above. On this basis, recharge was allocated to more significant rainfall events. For periods of less than one day, the same expression was used, with recharge allocated pro-rata within a given stress period corresponding to days with rainfall.

Constant Head Boundary

The southern boundary (Figure 3.1) was modelled as a CHB, using water level data contoured for the May 5 to 9 steady-state calibration period for the steady-state model and modified according to MW19-18, MW19-15A, and MW19-17 water level data for the May 10 to October 30, 2019 transient model period. Lateral seepage to the Alluvial Aquifer from lacustrine sediments and bedrock at the southern margin of the model domain were effectively simulated using boundary conditions (e.g., elevated hydraulic heads). The boundary was applied to all layers, with no induced vertical gradients.

General Head Boundary

A General Head Boundary (GHB) was applied at the western end of the model domain (Figure 3.1), to reduce the potential for a strong, artificial interaction between the Specified Head and Bow River boundaries, and to assist in modelling flow parallel to the river within the thin floodplain at this location. The model boundary values were determined through review of water level data for wells MW19-01 and MW19-19 and with reference to upstream river levels. The conductance and distance to Constant Head terms were reviewed to ensure the boundary handled flux appropriately. The boundary was applied to all layers, with no induced vertical gradients.

No-Flow Boundaries

The model base, at 1035 masl, was assigned as a no-flow boundary.

Bow River Boundary

The groundwater-Bow River interaction was simulated using the MODFLOW River package, a head-dependent flux boundary.

The existing 2D HEC-RAS model was used to simulate Bow River stage hydrographs for January to November 2019 along the Bow River at 13 locations adjacent to selected monitoring well locations and four locations upstream of the proposed groundwater flood barrier alignment (KCB 2020). Three additional river stage hydrographs were prepared for locations within the model domain and

upstream of the flood barrier alignment. These data were adjusted downward slightly to better correspond to actual river measurements, with an elevation adjustment of -0.05 m at 05BH010 MW19-01 to -0.19 m and 05BH010 MW19-17. River stage data were averaged over 63 selected stress periods, ranging from one to 13 days' length for the transient modelling period of May 9 through October 30, 2019. Data were interpolated between HEC-RAS control points and extrapolated upstream and downstream locations as required. The 2019 river stage elevation hydrograph for the HEC-RAS control points, together with the simulated boundary condition, are shown in Figure 3.4.

A short-term detailed transient model was developed for the period July 4, 2019 0:00 to July 8 1:00, a period of 97 hours, to assess the model response to shorter-term changes in river stage over a period of relatively rapid water level increase. The longer-term transient model outputs for July 4, 2019 0:00 were used as the starting heads for this model. The river stage data and the river boundary condition are presented in Figure 3.5.

The following Bow River information sources were used:

- Logger data from two installations (CP Rail Bridge (BOW 3) and Hextall Bridge (BOW 5)) provided by CoC from their river monitoring program (Figure 1.2).
- KCB HEC-RAS model (KCB 2020) used for rating-curve analysis and estimate of river stage levels.

Ice damming effects are not being considered as the peak period of flooding occurs in June, and the river typically is free from ice by April. The potential for elevated river levels due to ice jams in Bowness has been greatly reduced within the construction and operation of the Bearspaw Dam.

For simplicity, the river boundary was modelled with an averaged base elevation, as opposed to detailed river bathymetry or thalweg elevation applied across the full width of the river. This data was drawn from river bathymetric cross-sections.

The riverbed material has been observed to be relatively coarse and was assigned a thickness of 0.5 m and relatively high vertical hydraulic conductivity (K_v), of 1×10^{-5} m/s for the purposes of calculating riverbed conductance.

There are no known significant surface water discharges to the Bow River upstream and within Bowness area. Cantafio and Ryan (2014) indicated that stormwater contributions to baseflow of the Bow River within the Calgary area are relatively small.

Figure 3.4 'Observed' and Simulated Bow River 2019 Long-Term Transient Boundary Condition for Control Point MW19-03

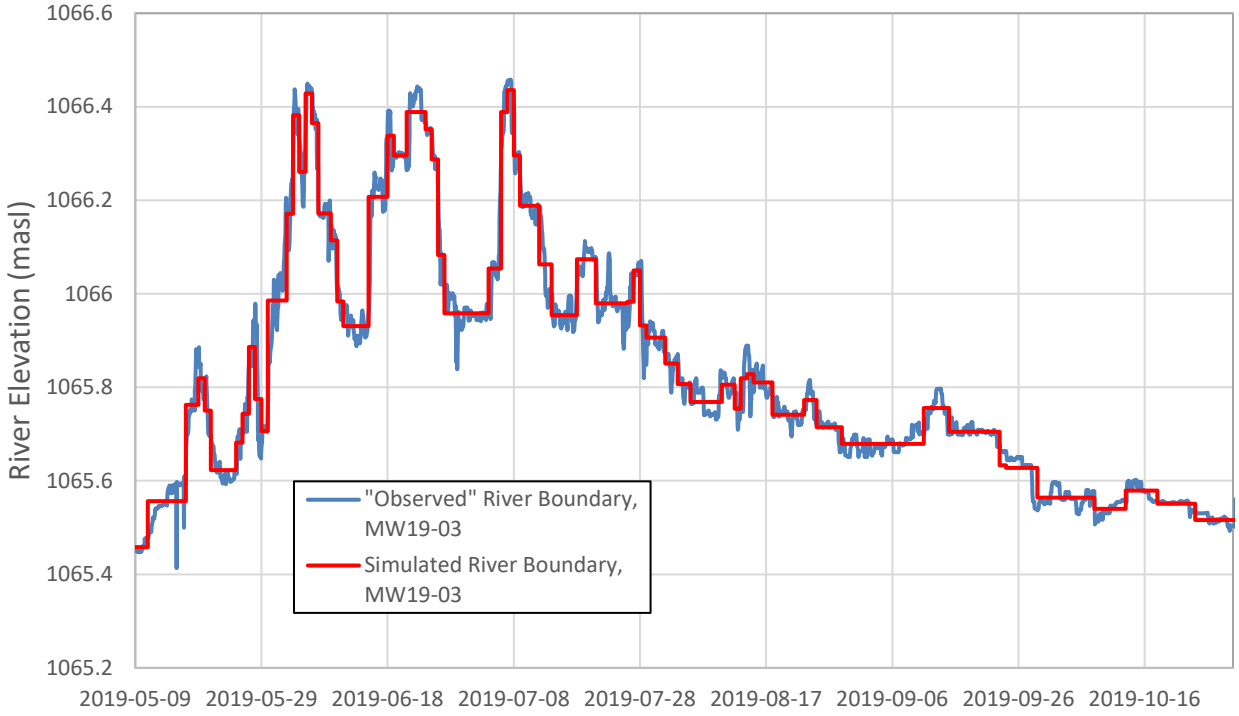
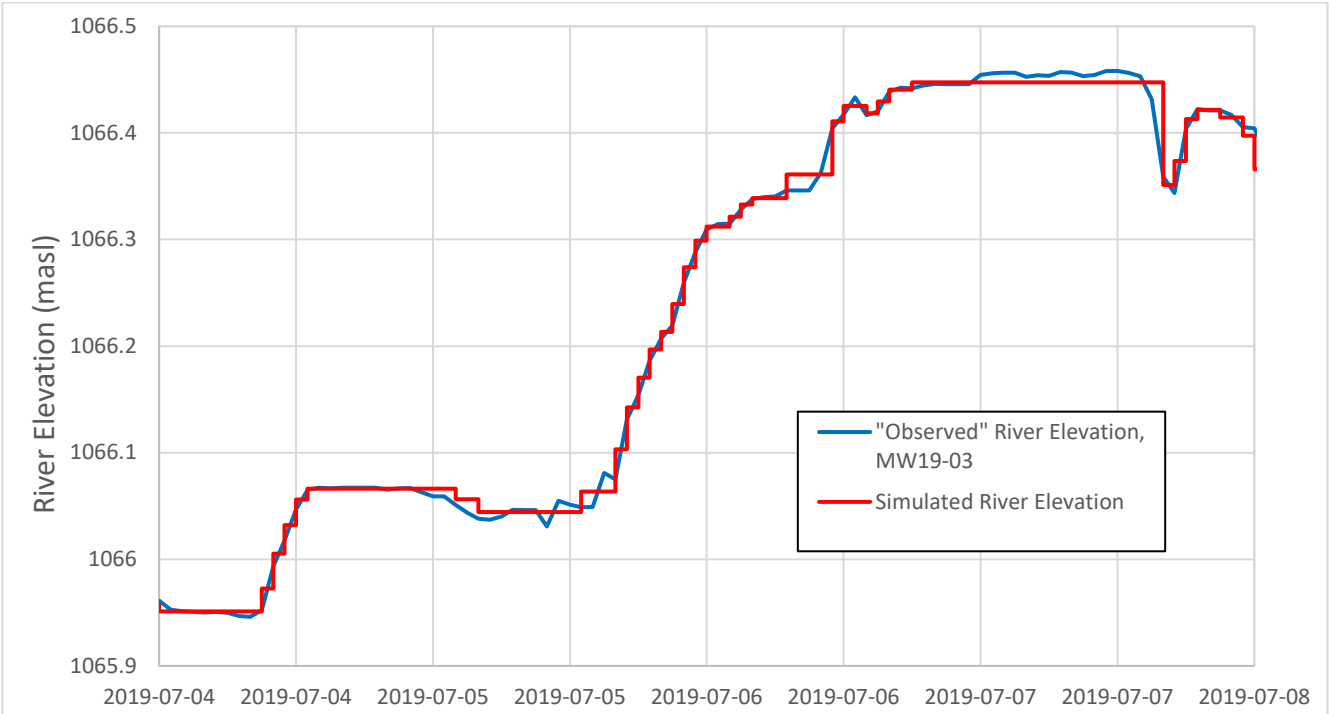


Figure 3.5 'Observed' and Simulated Bow River 2019 Short-Term Transient Boundary Condition for Control Point MW19-03



Evapotranspiration

Evapotranspiration was not explicitly modelled in the model: significant surface groundwater discharges were not observed within the model domain and groundwater recharge implicitly considers water losses to evaporation and transpiration.

3.1.4 Hydrostratigraphic Units and Initial Parameterization

The lithostratigraphic units compiled in the 3D geology model were categorized into key HSUs based on their hydrogeological significance. The *Leapfrog*™ geological units, equivalent HSUs, hydrogeologic roles and model layers are summarized in Table 3.1, listed in stratigraphic order. The Alluvial Aquifer was discretized into three layers to simulate flow within this relatively thin and irregular unit, and allow for model flexibility to assess relatively small scale water level fluctuations. The additional layers were intended to offer flexibility within the model and to provide sufficient resolution in the vertical plane to model the flood barrier and seepage cut-off barrier(s).

Table 3.1 Model Hydrostratigraphic Units

Leapfrog™ Geological Unit	Hydrostratigraphic Unit (HSU)	Hydrogeological Role	Saturated Thickness (m)	Layer
Topsoil, Silt and Silt Fill	Topsoil, Silt and Clay	aquitard	unsaturated to 1	1
Topsoil, Clay and Clay Fill				
Alluvial Gravel and Sand	Gravel and Sand	aquifer	unsaturated to 6	2 (50% thickness), 3 & 4 (25% thickness each)
Sandy Lacustrine and Till	Sandy Lacustrine and Till	aquitard	0 to 14	5
Sandy and Clayey Lacustrine	Sandy and Clayey Lacustrine	aquitard	0 to 11	5
Clayey Lacustrine	Clayey Lacustrine	aquitard	0 to 3	5
Weathered Bedrock	Weathered Bedrock	aquifer	1.5	5,6
Bedrock - Siltstone and Sandstone	Bedrock	aquitard	fully saturated	7

The initial bulk hydraulic conductivity values assigned to the model HSUs are presented in Table 3.2; these were derived from the data summarized in Section 2.5. Where specific testing data were not available, published literature values were used as a reference. Estimation of vertical anisotropy in hydraulic conductivity was based on a review of piezometric database, existing geologic bedding, and vertical textural evaluation. Storage parameters were estimated based on hydraulic testing, grain size analyses and with reference to literature values.

Where field testing data were available, values intermediate to the geometric mean and arithmetic mean of hydraulic conductivity for each HSU were used as initial inputs for those HSU layers.

The Alluvial Aquifer is highly heterogeneous; key areas near the Bow River may locally consist of gravelly cobbles, some sand and boulders, trace silt as shown on photographic documentation of excavations (Figure 2.14). The high proportion of large particle sizes with a sandy matrix suggests a

relatively low porosity and specific yield for a sandy gravel, since the large particles are estimated to have a specific yield typically less than 1%.

The hydraulic test results include approximately 23 tests at eight locations. A spatial plot of available hydraulic conductivity data is provided in Figure 4.8 and was used as the basis for assigning initial values. In general, it was interpreted that hydraulic conductivity generally increases towards the Bow River.

Table 3.2 Initial Model Hydraulic Parameters per Hydrostratigraphic Unit

Hydrostratigraphic Unit (HSU)	Saturated Hydraulic Conductivity					Specific Storage [Ss]# (m^{-1})	Specific Yield [Sy]#	Layer Properties
	K_h Tested Range (m/s)	Geometric ^ Mean K_h (m/s)	Arithmetic Mean K_h (m/s)	Initial K_h (m/s)	Anisotropy * [K_h/K_v]			
Topsoil & Clay/ Clay Fill	-	-	-	1×10^{-6}	5	1×10^{-5}	0.05	**Layer 1:** $K_h = 1\times10^{-6}$ m/s, $K_z = 2\times10^{-7}$ m/s
Silt Topsoil/Fill	-	-	-	1×10^{-6}	5	1×10^{-5}	0.1	$S_s = 1\times10^{-5}$, $S_y = 0.1$
Alluvial Gravel & Sand	$1\times10^{-7} – 7\times10^{-3}$	8×10^{-5}	5×10^{-4}	$5\times10^{-6} – 1\times10^{-3}$	2	1×10^{-5}	0.05 – 0.20	**Layers 2 – 4**
Sandy Lacustrine &Till	5×10^{-7}	-	-	1×10^{-6}	5	2×10^{-5}	0.05	**Layer 5:** *Clayey Lacustrine* – as per Clayey Lacustrine *Sandy Lacustrine* – as per Sandy Lacustrine *Both* –$K_h = 1\times10^{-7}$ m/s; $K_z = 1\times10^{-8}$ m/s $Ss = 5\times10^{-5}$; Sy = 0.04
Clayey Lacustrine	-	-	-	1×10^{-8}	10	1×10^{-4}	0.03	
Weathered Siltstone, Mudstone & Sandstone	$4\times10^{-8} – 4\times10^{-4}$	1×10^{-5}	9×10^{-5}	-	5	1×10^{-5}	0.05	**Layer 6**: as per geometric mean and other parameters; used 1.5 m thickness
Competent Siltstone & Sandstone	-	-	-	-	10	5×10^{-6}	0.01	**Layer 7**: as per geometric mean and other parameters

Note: ^ Value intermediate to arithmetic means to be used as initial model parameters.
K_H – Horizontal Hydraulic Conductivity,
K_V – Vertical Hydraulic Conductivity.
n/a -data not available.
* – anisotropy greater than 1 is considered to account for stratification. K_H/K_V, S_Y and S_S values derived from literature for similar materials

Published literature value ranges were used to assign an initial hydraulic conductivity value for those HSUs without site-specific data. Reported results for competent bedrock layer ranged from 4×10^{-8} m/s to 4×10^{-4} m/s and most likely represented a combination of the weathered and competent bedrock conditions. As a result, these layers were separated and a 1.5 m thick weathered layer was assumed to exist overlying the competent bedrock layer, based on review of drill logs. The mudstone and siltstone is anticipated to be of low permeability[4], while lenticular sandstone layers typically have a permeability in the range of 1 to 3×10^{-5} m/s (Meyboom 1961). During the 2019 drilling, sandstone was encountered in one of 23 holes drilled to bedrock.

3.1.5 Initial Heads

The model ground surface was used to initialize the starting groundwater head for the steady-state model. After the steady-state model provided satisfactory calibration results, the output heads from the steady-state simulation were used as the starting heads to initialize the transient calibration model. Similarly, the output heads for the long-term transient calibration model for the appropriate day were used to initialize the short-term calibration model.

[4] Hydraulic conductivity: Very Low: $< 1 \times 10^{-9}$ m/s; Low: 1×10^{-9} m/s to 1×10^{-7} m/s; Moderate: 1×10^{-7} m/s to 1×10^{-5} m/s; High: 1×10^{-5} m/s to 1×10^{-3} m/s; Very High: $> 1 \times 10^{-3}$ m/s

4 MODEL CALIBRATION, SENSITIVITY ANALYSIS AND VERIFICATION

4.1 Calibration Methodology

4.1.1 Approach

The groundwater calibration process consists of the gradual adjustment of model input parameters until a good correlation exists between the calculated and observed piezometric heads and the calculated and observed flows (e.g., groundwater baseflow to streams or rivers) is achieved.

Calibration was undertaken for three separate periods where detailed monitoring data was available:

- Steady state[5] (Baseline) calibration was completed using the May 5 to 8, 2019 period, a period of relatively stable river levels preceding increases in river stage due to freshet river flows;
- Long-term transient calibration was undertaken for the 175-day period from May 9 to October 30, 2019, with stress periods ranging from one to 13 days; and
- Short-term transient calibration was undertaken for the 97-hour period from July 4, 2020 0:00 to July 8 1:00, a period of rapid rise, then fall, of Bow River levels, with stress periods ranging from one to two hours.

Calibration was undertaken over stress periods ranging in length from one hour to 13 days to ensure the calibration addressed the hydraulic interaction between the Bow River and the Alluvial Aquifer. This required averaging of the HEC-RAS river elevations (at hourly intervals) for each stress period to set the boundary conditions and averaging of PTDL water level elevations in the same manner.

Transient model calibration results were reviewed for both high and low river level conditions to ensure overall calibration was appropriate for both these seasonal conditions, in consideration of the model use as a predictive tool for both ‘normal’ and flood river level conditions.

The results were analyzed quantitatively and qualitatively by evaluating the data statistics (variance, mean, residuals, and head gradients), matching simulated and observed hydrographs in monitoring wells, and visual comparison of the simulated to the observed groundwater flow patterns. Greatest emphasis was placed on obtaining a reasonable calibration to the high river levels, given the need to simulate flood events.

The steady-state calibration was undertaken by manually changing the following parameters within discreet units or areas to match observed groundwater levels:

- Recharge;
- Hydraulic conductivity; and
- Riverbed conductance.

[5] A steady-state simulation effectively simulates the groundwater conditions where boundary conditions are unchanging, or in steady-state. In practice, the boundary conditions are never “unchanging”, however are sufficiently stable to make this simplification while providing a reasonable result.

The transient calibrations utilized changes in the above parameters as well as the unconfined storage parameter of specific yield.

To a large extent, calibration was undertaken through the modification of horizontal and vertical hydraulic conductivity throughout a given HSU, or within a sub-area of that unit. Emphasis was placed on achieving a good calibration in the key area (ZOI) of hydraulic interaction between the Bow River and the Alluvial Aquifer.

Recharge was modified on a proportional basis, according to the textural variations in surface soil, as documented in Section 2.6.2. In this manner, the calibration process was simplified while still providing results considered to be representative of the field conditions.

4.1.2 Head Targets and Calibration Criteria

Groundwater level data recorded by dataloggers at 10 monitoring wells was available on a continual basis (measurements at hourly intervals) for the long-term calibration period (May 5 to October 30, 2019), while shorter-term datalogger data was available for four monitoring wells. Periodic manual water level data was available for an additional five monitoring wells.

Calibration data was not available for all of these wells for the short-term calibration model (Section 4.3.2).

Residual errors were calculated for all piezometers for all stress periods in the simulations. In this context, the residual error is the *simulated* piezometric (groundwater level) elevation, or head, minus the *observed* piezometric elevation, or head at a given observation point at a given time.

Model calibration was assessed in terms of the following statistics:

1. Maximum Residual Error: The highest residual error among the various observation points for a given time, determined as the final value for the steady-state simulations and herein presented as the average residual value for all time steps[6] for the transient simulations. This provides a measure of the worst geographic areas of calibration in the model.
2. Minimum Residual Error: The lowest residual error. This also provides a measure of the worst geographic areas of calibration in the model.
3. Absolute Mean Residual Error: The mean of the absolute value of each residual error. This provides a measure of the "scatter" of data points around the central tendency.
4. Residual Mean: The arithmetic mean of the residual errors. This provides a mean of assessing whether the simulation is providing overall values that are too high or too low, relative to the observed groundwater elevations.

[6] Piezometric heads, or water levels, and water balance calculations are undertaken for each specified time step, or time period within the simulation. In the simulations undertaken for this study, time step length ranged from 1 hour to 13 days.

5. Scaled Residual Mean: The residual mean as a proportion of the range in observed piezometric elevations, expressed as a percent. This is useful as it allows comparison of "goodness of fit" between different datasets or models.
6. R^2: The coefficient of determination is the proportion of the variance in the dependent variable that is predicted from the independent variable. In the current context, this is a measure of how well the simulated piezometric elevations match the observed piezometric elevations.
7. Root Mean Square Error (RMSE): The square root of the sum of the square of all residual errors divided by the number of errors. This is a frequently used means for assessing the difference values predicted by a model and those values observed (in this case in the field).
8. Normalized Root Mean Square Error: RMSE divided by the range in observed piezometric elevations or heads, expressed as a percent. This error facilitates the comparison of datasets or models at different scales. This is the most quoted statistic when evaluating a groundwater model calibration of piezometric elevations.

4.1.3 Flow Targets

In view of the difficulties of assessing baseflow to the reach of the Bow River bordering the Project Area, as noted in Section 2.6.2, calibration to flow targets was not possible. However, groundwater discharge volumes simulated as discharging to the Bow River were reviewed in general terms for reasonableness and to confirm an overall fit with the conceptual model.

4.2 Steady-State Calibration

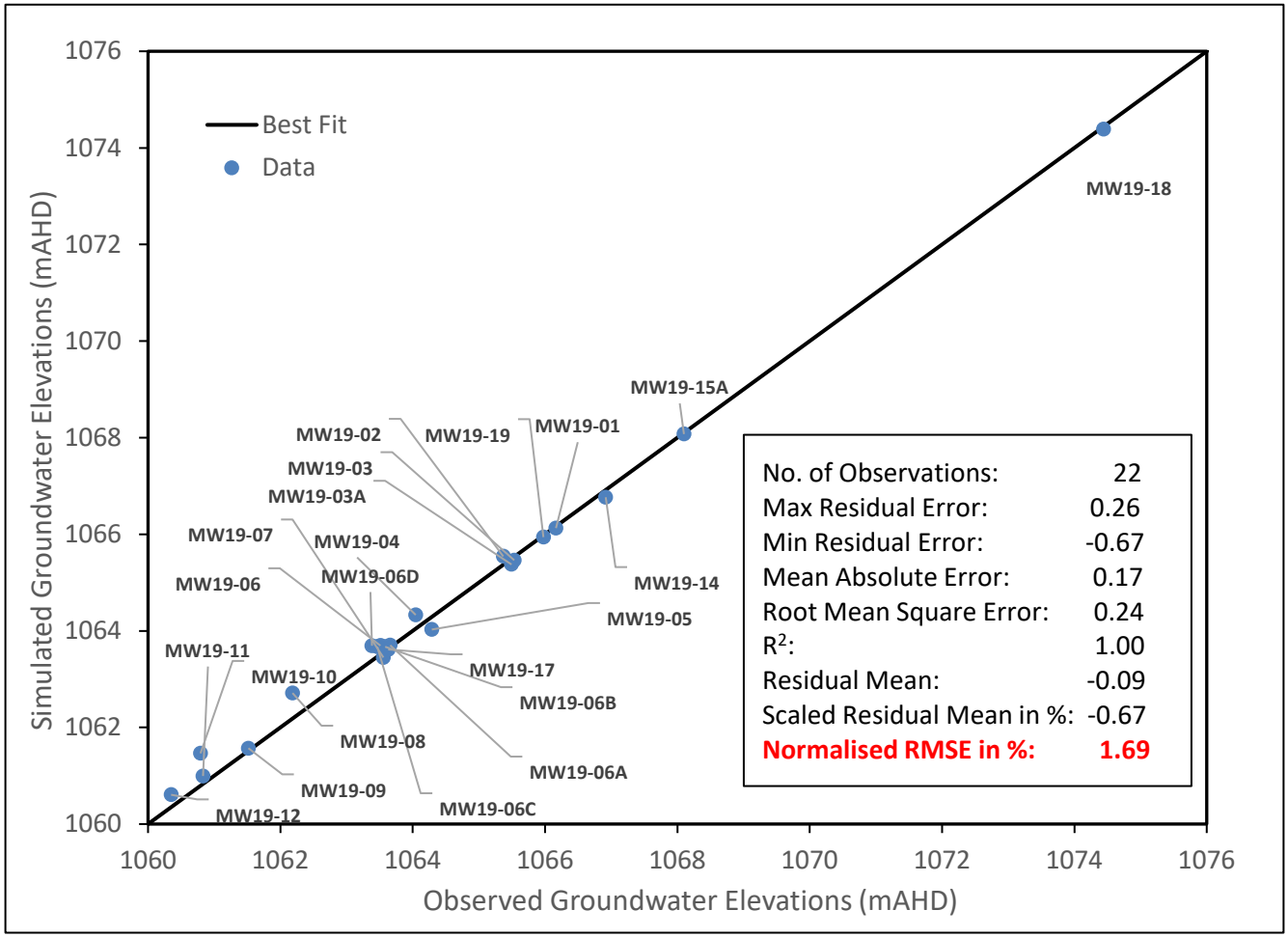
Table 4.1 shows the overall water balance of the steady-state calibration model. The water balance error is the difference between total predicted inflow and total predicted outflow of the simulation domain, and an extremely small value of -0.0009% indicates the model is well balanced in terms of water inputs and outputs. A water balance error of less than 1% is normally considered appropriate (Barnett et al. 2012). The water balance indicates an average precipitation recharge of about 304 m^3/day for the model domain, or about 3.5 L/s. Net discharge to the Bow River is about 4,031 m^3/day, or 47 L/s.

Figure 4.1 presents the observed versus simulated groundwater elevations. The residual mean is -0.04 m, which indicates the calculated piezometric elevations are, on average, 4 cm higher than the field-observed piezometric elevations. The piezometers installed close to the river (MW19-01 through MW19-12) were, on average, 7 cm higher than observed values, while the inland piezometers (MW19-14 through MW19-19) were 6 cm lower than observed on average.

Table 4.1 Steady-State Water Balance (Calib 34)

Component	Input (m^3/day)	Output (m^3/day)
Constant Head Boundary	3733	5.3
General Head Boundary	1.0	1.3
River Boundary	1044	5075
Recharge	304	0
Total	5081	5081
% Discrepancy	-0.0045	

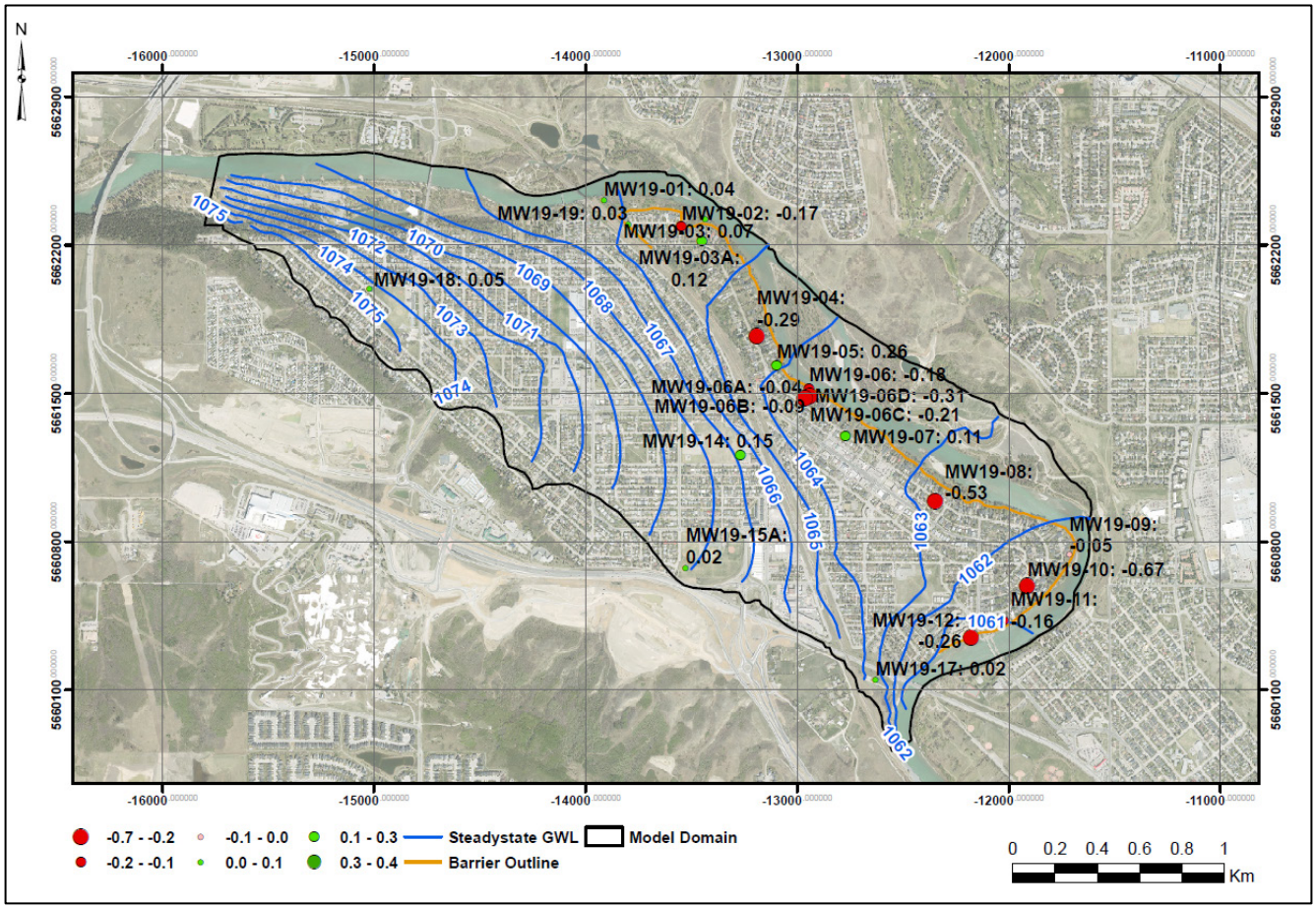
Figure 4.1 Steady-State Calculated vs. Observed Heads (Calib 34)



A Normalized Root Mean Square Error (NRMSE) value of 1.69% was obtained; a value less than 5% is frequently considered to represent a satisfactory fit (Barnett et al .2012) when the model adheres to a rigorously considered and reviewed conceptual model. The scatter undoubtedly reflects local variability in the distribution of recharge, variability in the distribution and anisotropy of hydraulic conductivity, variability in actual versus simulated boundary conditions, and potentially small errors in the river elevation and field piezometric elevation data.

The residual map shows the difference between the observed and simulated piezometric elevations (Figure 4.2), and a negative residual indicates the simulated elevation lies above the observed elevation. The figure shows that the groundwater elevation is generally well simulated by the steady-state model, with a maximum absolute residual error of 67 cm (at MW19-10). Most absolute residual errors (19) are in the range of 3 to 31 cm, with only two outside this range.

Figure 4.2 Steady-State Calibration Residual Error – Piezometric Elevation



4.3 Transient Calibration

4.3.1 Long-Term Calibration

Table 4.2 and Table 4.3 list the overall water balance for high and low river levels, respectively for the long-term transient calibration results over the May 9 to October 30, 2019 monitoring period.

Table 4.2 Long-Term Transient Water Balance: High River Level (June 25, 2019 – Calib 34)

Component	Input (m^3/day)	Output (m^3/day)
Storage	1605.9	1162.9
Constant Head Boundary	3797.0	4.0
General Head Boundary	0.78	1.5
River Boundary	763.2	4998.5
Total	6166.8	6166.9
Discrepancy %	-0.002	

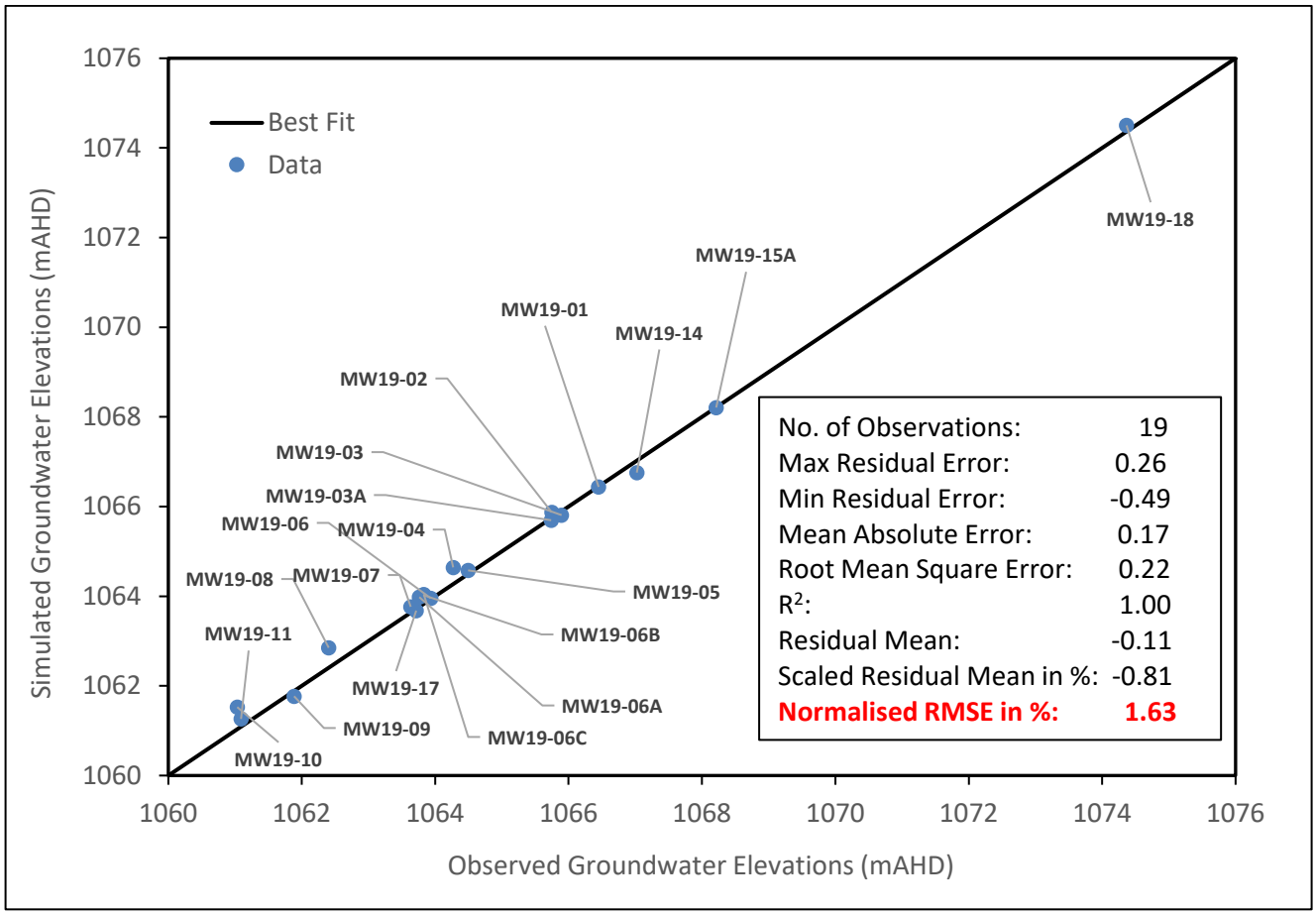
Table 4.3 Long-Term Transient Water Balance: Low River Level (October 1, 2019 – Calib 34)

Component	Input (m^3/day)	Output (m^3/day)
Storage	746.5	8.7
Constant Head Boundary	4794.4	7.0
General Head Boundary	1.0	1.3
River Boundary	605.1	6130.0
Total	6147.0	6147.0
Discrepancy %	-0.001	

The model water balance errors are between 0.001% and 0.002%, indicating the balance between water inputs and outputs is appropriate. At low river level (October 1, 2019), net discharge to the river is about 5525 m^3/day (64 L/s), despite the relatively dry conditions, due to an increased hydraulic gradient due to the low river level.

Figure 4.3 presents the observed versus simulated piezometric groundwater elevations for the average groundwater elevation of the entire transient calibration period. Plots for the high river level (June 25) and low river level (October 1) are presented in Figures IV-1 and IV-2, Appendix IV. The NRMSE for these three periods are 1.63%, 2.22%, and 1.56%, respectively, all within an acceptable range.

Figure 4.3 Long-Term Transient Final Calculated vs. Observed Head Averaged over all Time Steps (Calib 34)



A calibration residual map for the average of the entire simulation is shown in Figure 4.4.

Calibration residual maps for the high river and low river conditions are presented in Figure IV-3 and Figure IV-4, Appendix IV, respectively. The results show that, on average, the transient calibration model slightly overestimates the groundwater levels, with a residual mean of -11 cm, or with simulated heads higher than observed heads. The average residual map indicates the maximum overestimation is 0.49 m at MW19-10. The high river level period shows the maximum residual error of -0.62 m with an average of -0.17 m as a result of the overestimation of MW19-04, -05, -06, and MW19-07.

After the calibration was achieved, the hydraulic properties of HSUs were confirmed and used for further prediction simulations. The final hydraulic property distributions of the Alluvial Aquifer unit are shown in Figure 4.8 and the distribution shows a good match with test values.

Key hydrographs are presented in Figure 4.5, and include river elevation, observed and simulated water table elevations. The remaining hydrographs are presented in Figure IV-5, Appendix IV.

Figure 4.4 Long-Term Transient Average Residual Heads

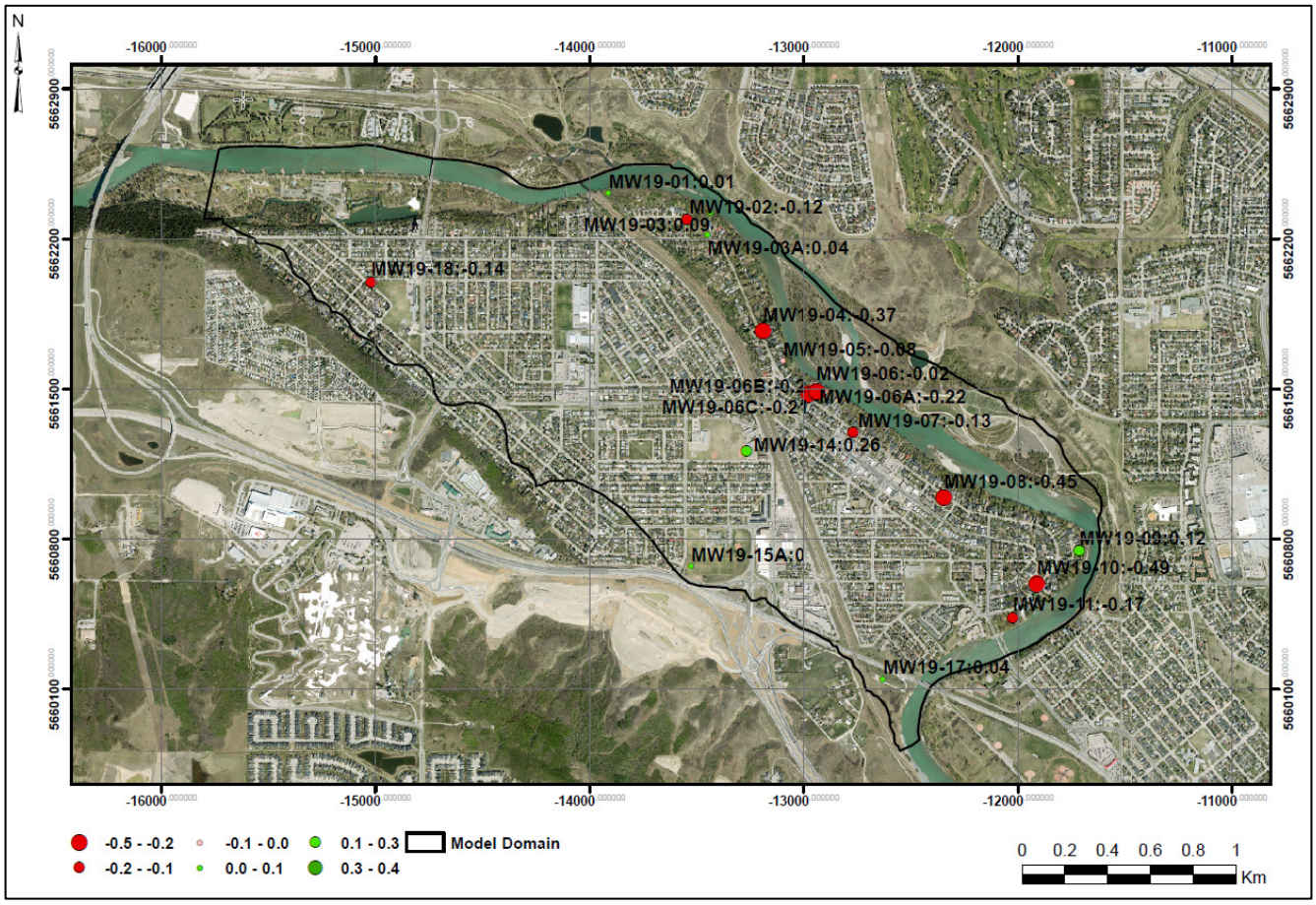
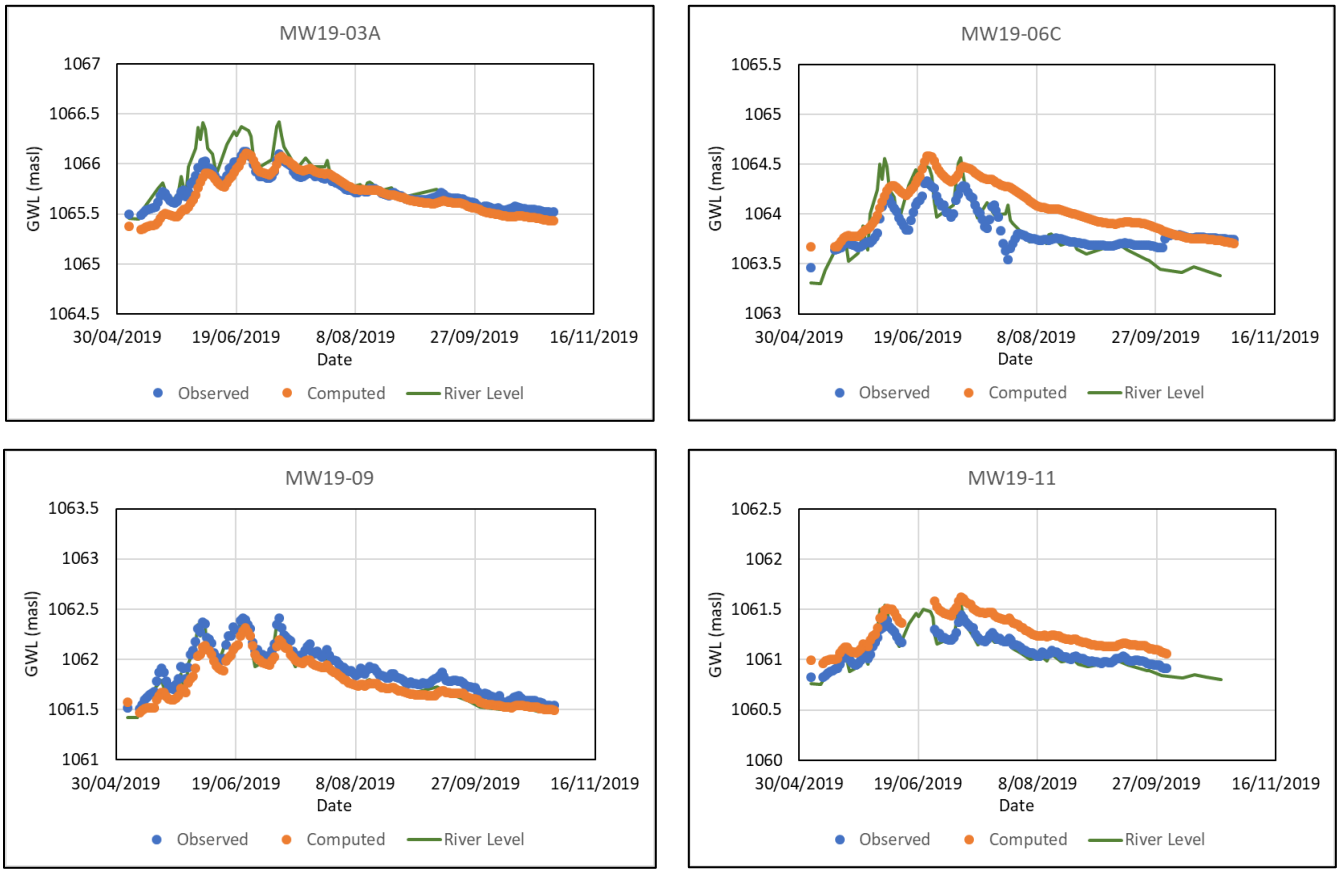


Figure 4.5 Key Hydrographs, Long-Term Transient Calibration



4.3.2 Short-Term Calibration

To test the numerical model's performance over shorter stress periods and to assess the response to short-term changes in river level and recharge, a short-term calibration model was created. Figure 4.6 shows the short-term calibration period, which represents a short-term rise in river level associated with a rainfall event.

Table 4.4 lists the overall water balance for the high river level (July 6 18:00 to July 7 16:00).

Figure 4.6 Short-Term Calibration Period

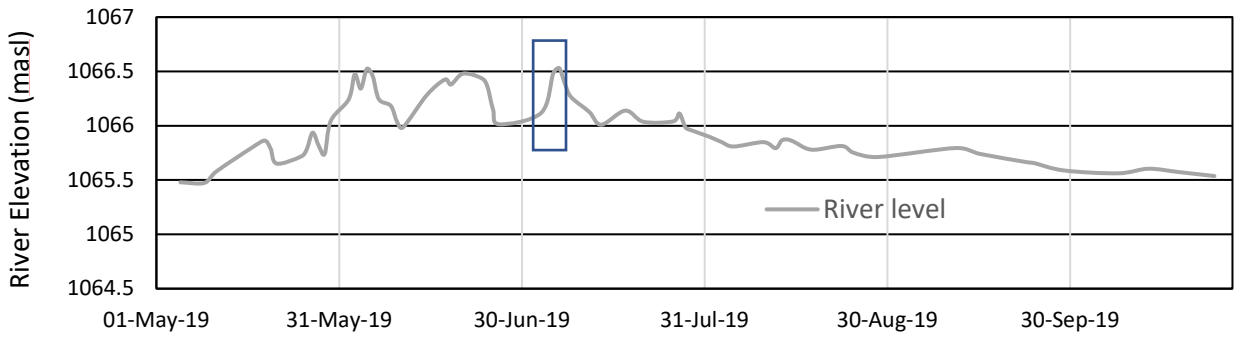


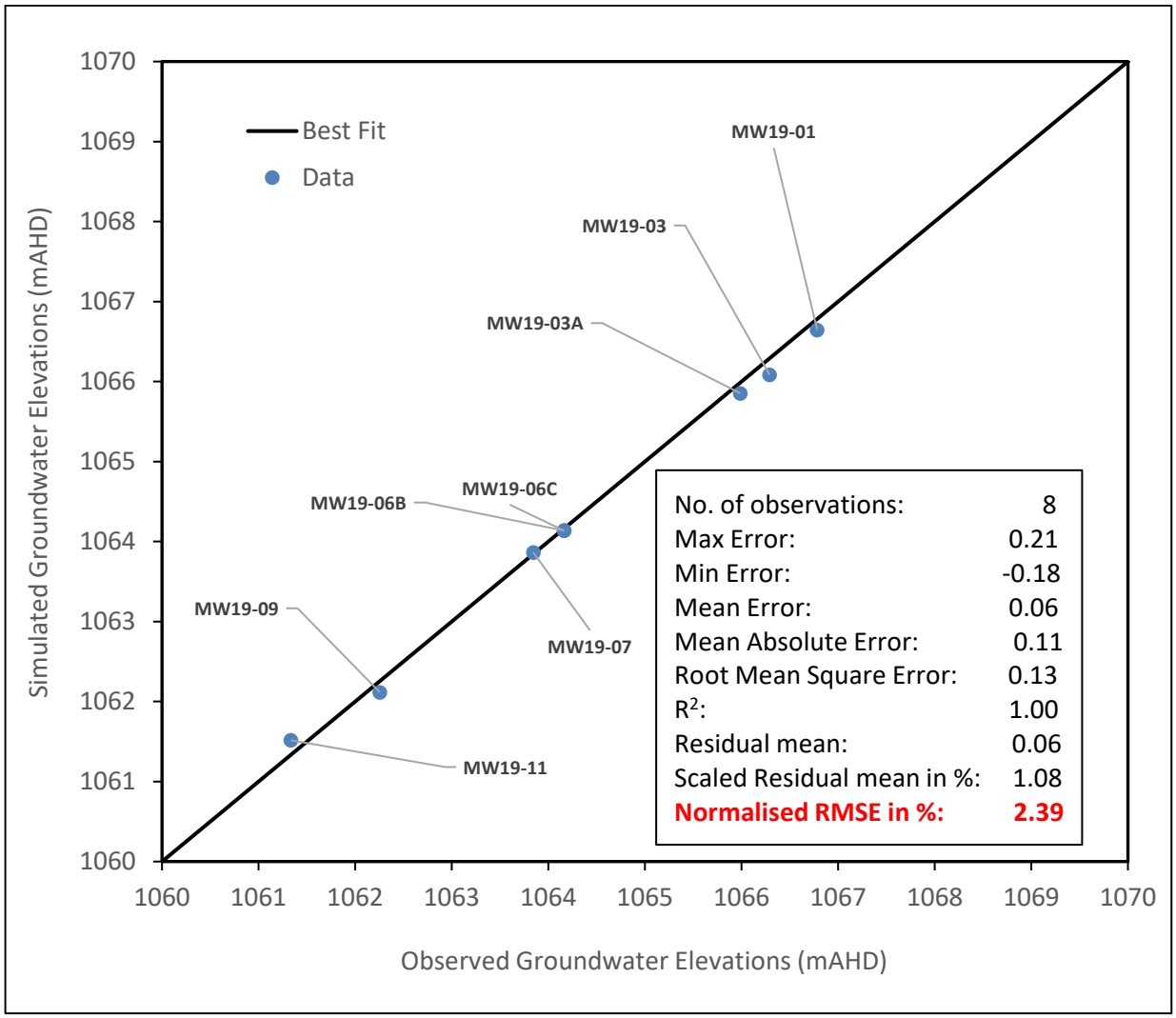
Table 4.4 Short-Term Transient Water Balance, High River Level (Calib 8)

Component	Input (m^3/day)	Output (m^3/day)
Storage	42.2	5105
Constant Head Boundary	3583	0.7
General Head Boundary	0.8	1.4
River Boundary	4899	3418
Total	8525	8525
Discrepancy %	-0.002	

The water balance error over all time steps is 0.002%, indicating the balance between water inputs and outputs is appropriate. At high river level, net flow is from the river inland, 1481 m^3/day (17 L/s), due to the high river stage. Figure 4.7 presents the observed versus simulated piezometric groundwater elevations for all stress periods within the short-term transient calibration period. The NRMSE is 2.4%, within an acceptable range. Short-term hydrographs are presented in Figure IV-6, Appendix IV. Only monitoring wells with equipped with transducers/ dataloggers, which provided frequent groundwater level readings, are presented.

Plots of saturated aquifer thickness for high river (June 25, 2019) and low river (October 1, 2019) flow conditions are presented in Figure IV-7 and Figure IV-8, Appendix IV, respectively. These may be compared from the saturated thickness maps based on field monitoring data in Figure 2.20 and Figure 2.21, respectively.

Figure 4.7 Average Short-Term Transient Calculated vs. Observed Head (July 4 to 8, 2019 – Short Cal8)



4.3.3 'Base Case' Model Calibrated Parameters

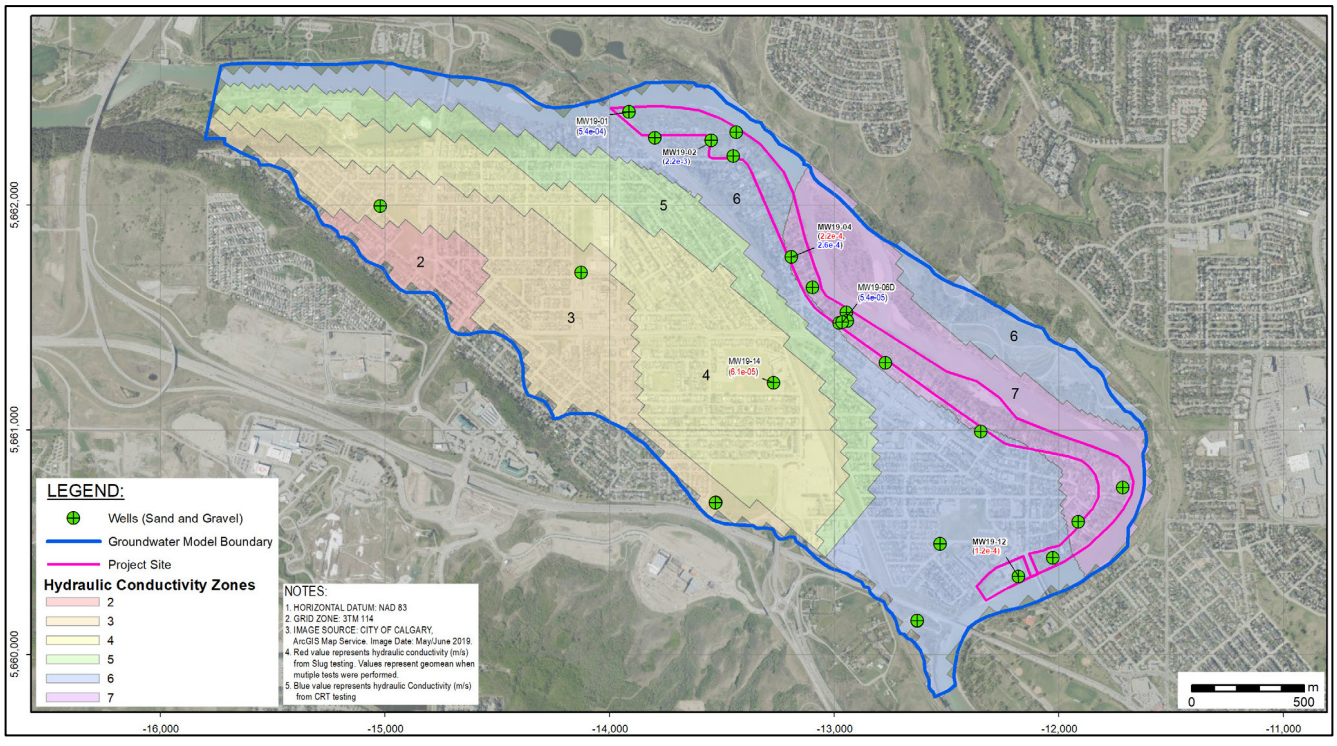
The final calibrated 'Base Case' model hydraulic parameters are presented in Table 4.5. Figure 4.8 shows the final calibrated K_h distribution for the Alluvial Aquifer. The K_h of the aquifer is interpreted to increase towards the Bow River and with depth in the aquifer in the portions of the aquifer adjacent to the river.

Table 4.5 Calibrated Model Hydraulic Parameters

Layer	AQ Zone	Description	Kh (m/s)	Anisotropy (Kh/Kv)	Ss (m^{-1})	Sy (%)
1	1	Clayey & Silty Topsoil	1×10^{-6}	5	1×10^{-5}	10
2 & 3 & 4	2	Alluvial Sand & Gravel	5×10^{-6}	2	1×10^{-5}	5
	3		1×10^{-5}	2	1×10^{-5}	6
	4		1×10^{-5}	2	1×10^{-5}	7
	5		2×10^{-5}	2	1×10^{-5}	8
	6		From L2 to L4: 2×10^{-6} - 1×10^{-3}	2	1×10^{-5}	From L2 to L4: 5-10
	7		From L2 to L4: 5×10^{-4} - 2×10^{-3}	2	1×10^{-5}	From L2 to L4: 10-20
5	8	Sandy Lacustrine	1×10^{-6}	5	2×10^{-5}	5
	9	Clayey Lacustrine	1×10^{-8}	10	1×10^{-4}	3
	10	Sandy & Clayey Lacustrine	1×10^{-7}	10	5×10^{-5}	4
5 & 6	11	Weathered Bedrock	5×10^{-6}	5	1×10^{-5}	5
7	12	Competent Bedrock	5×10^{-7}	10	5×10^{-6}	1
1 & 2 & 3 & 4	13	Barrier & cut off wall	1×10^{-10}	1	1×10^{-5}	1

Note: River conductance parameters: Thickness (b) = 0.5 m K = 1×10^{-5} m/s

Figure 4.8 Gravel and Sand Final Calibrated K_H Distribution



4.4 Sensitivity Analysis

4.4.1 Methodology

Sensitivity analyses were undertaken on the calibrated steady-state, long-term, and short-term transient models to investigate the model's sensitivity to HSU hydraulic properties, precipitation recharge, and hydraulic conductance of the Bow Riverbed. In undertaking the analysis, single parameters were changed and the effect of the change on the model NRMSE was reviewed. Parameters were varied by up to two order of magnitude (factor of 100).

4.4.2 Results

The results of sensitivity analyses completed are presented in Table 4.6.

Table 4.6 Summary of Sensitivity Analyses

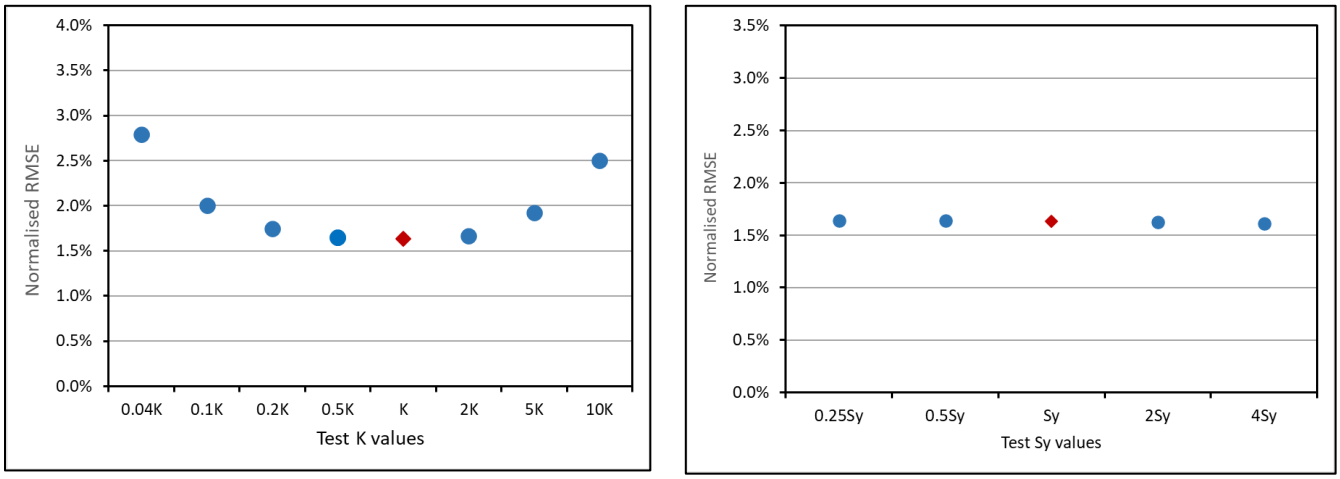
Model	Parameter	Zone	Change	NRMSE (%)
Long-Term Transient	All	All	Base Case	1.63 (Average) 2.22 (High River) 1.56 (Low River)
	K_h	6 & 7 (Gravel and Sand)	0.04 K_h	2.79 (Average)
			0.1 K_h	2.00 (Average)
			0.2 K_h	1.75 (Average)
			0.5 K_h	1.65 (Average)
			2 K_h	1.67 (Average)
			5 K_h	1.92 (Average)
			10 K_h	2.50 (Average)
	Sy	6 & 7 (Gravel and Sand)	0.25 S_y	1.64 (Average)
			0.5 Sy	1.64 (Average)
			2 Sy	1.63 (Average)
			4 Sy	1.61 (Average)
	K (both K_h and K_v)	8 (Sandy Lacustrine)	0.01 K	2.79 (Average)
Short-Term Transient	All	All	Base Case	2.39 (Average)
	Bow Riverbed Conductance	N/A	5 C	2.38 (Average)

Figure 4.9 shows graphically the sensitivity results for K and Sy of the Alluvial Aquifer.

The data show that the model calibration is moderately sensitive to the K_h of the portion of the Alluvial Aquifer within approximately 100 m and 500 m from the south bank. Similar calibrations are obtained for a range of K values within a factor of 4.

The model is relatively insensitive to Sy across the range of values tested, up to four times less and four times greater than the value used in the model.

Figure 4.9 Model Calibration Sensitivity to K and S_y



The model is somewhat sensitive to the K of the underlying Sandy Lacustrine unit. The value used in the calibrated model (K_h = 1 x 10^{-6} m/s) is near the upper range limit for this unit. A poorer calibration (measured as NRMSE) was obtained when the K value is increased or decreased by more than two orders of magnitude.

Alternative model calibrations were undertaken with recharge values 50% less and 50% greater than the recharge used in the calibrated model. Increases/decreases were proportional across the various recharge zones. The 'inland' monitoring wells (MW19-14 to 18) are sensitive to changes in recharge, while the monitoring wells installed adjacent to the river (MW19-01 to MW19-12 and MW19-19) are relatively insensitive to changes in recharge. The mean residual error for a 2x *increase* in recharge and a 5x *increase* in K, was -0.10 m for the wells near the river and -0.59 m for the inland wells, with an overall NRMSE of 3.5%. The mean residual error for a 2x de*crease* in recharge and a 5x *decrease* in K, was -0.07 m for the 'river' wells and 0.10 m for the inland wells, with an overall NRMSE of 1.45%, so this calibration represents a good alternative calibration, although it does not match aquifer peak fluctuations as well as the calibrated model.

4.5 Model Verification

4.5.1 2005 Bow River Flood Simulation

To provide verification of the model calibration, the calibrated model was used as the basis for simulating the groundwater system response to the 2005 Bow River flood event, which occurred between June 17 and June 21, 2005, with peak flood water level on June 19. Modelled river levels corresponding to each of the monitoring wells close to the river are presented in Figure 4.10.

This flood event was used for verification because flooding was largely driven by inland groundwater flow, as there was little overbank flooding in Bowness, apart from the park area on the northwest edge of the Project Area (Figure 4.11).

Figure 4.10 2005 Flood Hourly River Levels

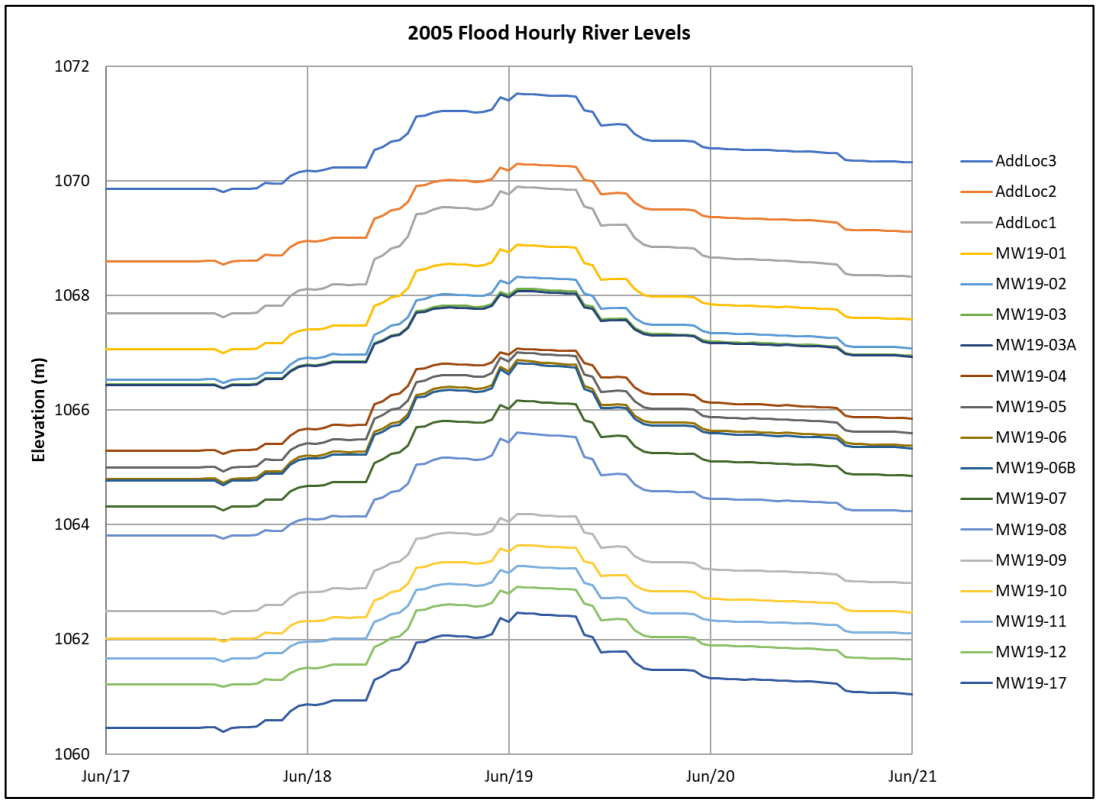
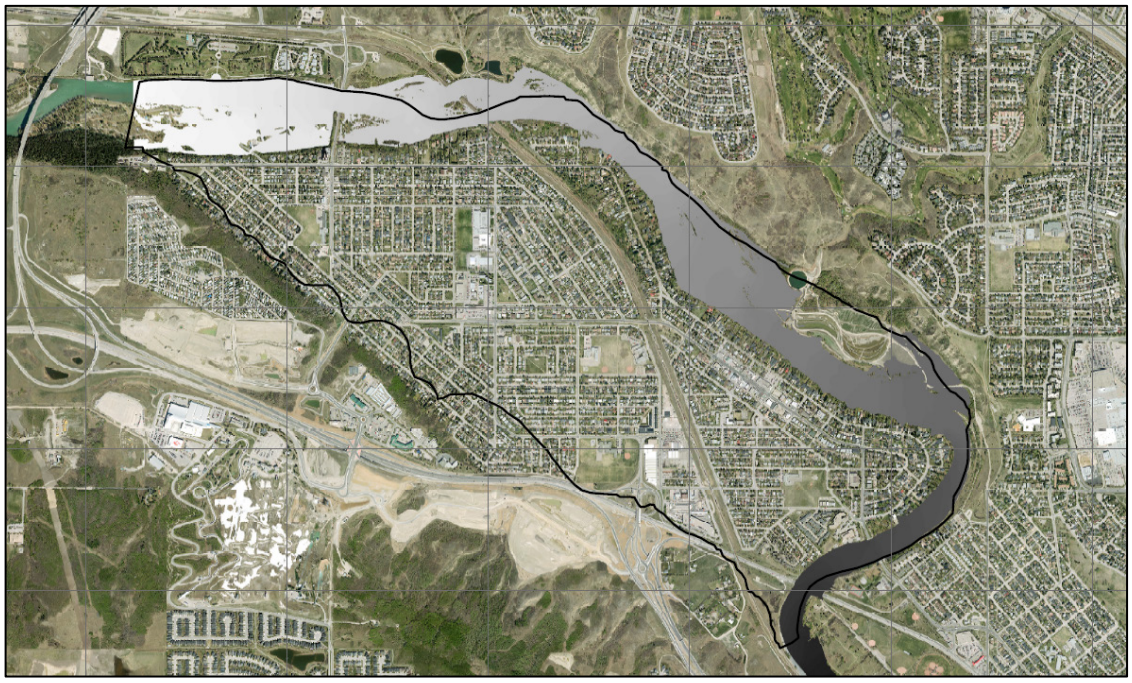


Figure 4.11 Peak Water Table and Areas of Groundwater-Induced Surface Flooding, 2005 Flood

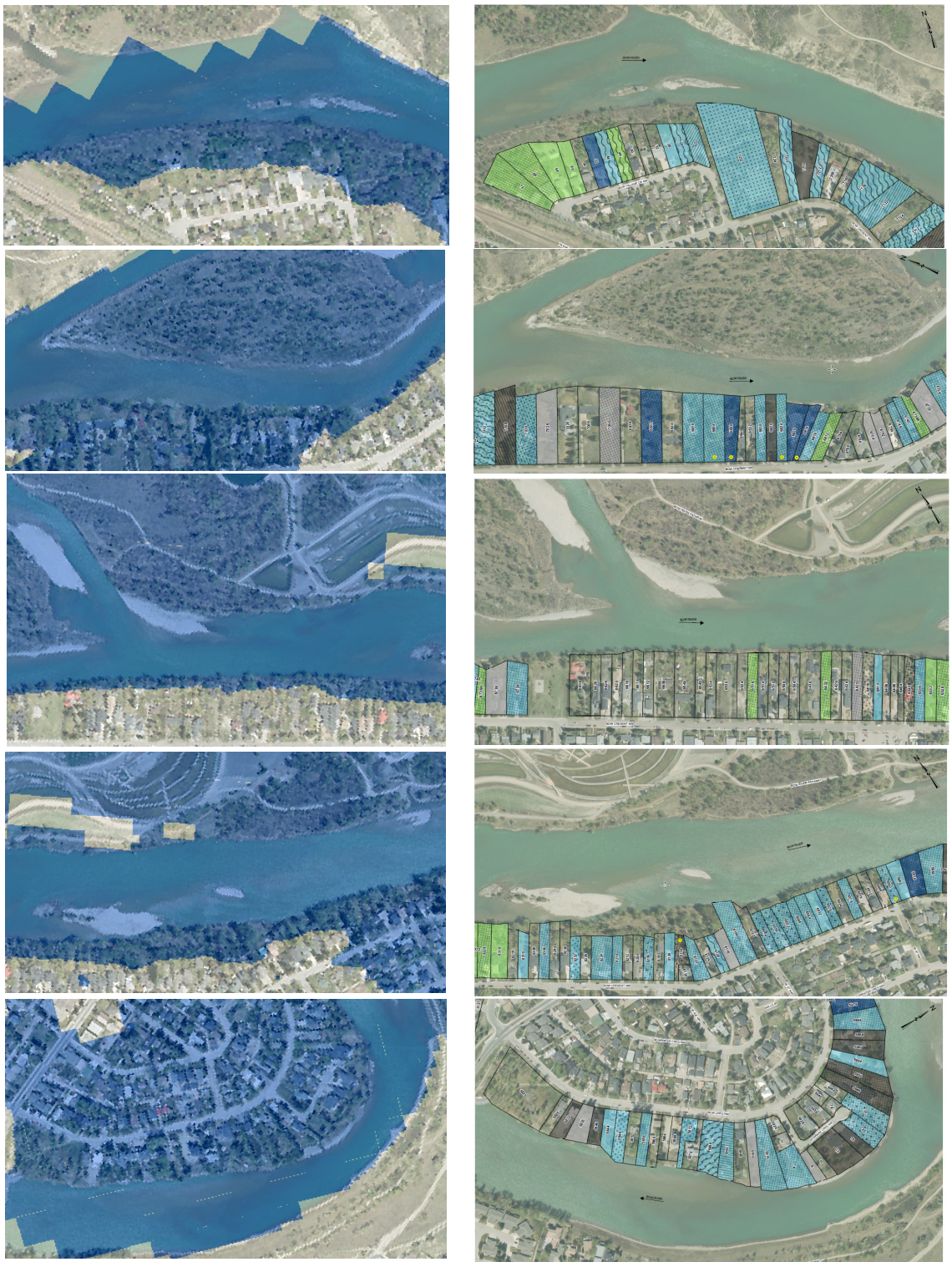


To undertake the simulation, the early part of the flood was simulated, extending from June 17 at 10:00 am through June 19 at 1:00 am, a period of 49 hours. The river levels were averaged for each stress period, which ranged from one to two hours in duration, and input into the model as river boundary conditions. Starting heads were determined by use of an initial steady-state period corresponding to the early period of relatively stable river level, albeit about 1.5 m higher than the peak river levels observed during 2019. Other boundary conditions were set as per 2019 high river level conditions and observed rainfall was converted to recharge using the equation documented in Section 3.1.3.

As no piezometric data was available for Bowness during the 2005 flood, 'verification' was undertaken by comparison of the model results to anecdotal reports of basement flooding collected by the CoC. Lots with a dark blue fill reported basement flooding in 2005, while lots with a light blue fill reported flooding in 2013.

These plots are compared with the modelling results on the left-hand side. Dark blue shaded areas indicate where the peak flood water table level is < 2.5 m below ground surface, hence represent the potential for flooding of a standard basement, extending eight feet below ground. The results appear to demonstrate a basic correlation between model outputs and reported basement flooding at Bowness.

Figure 4.12 (a) Modelled Zones with Potential for Basement Flooding, Moving Downriver vs. (b) Anecdotal Reports of 2005 Basement Flooding



5 MODEL PREDICTIONS

5.1 Surface Event Barrier Simulations

The calibrated transient model (long-term and short-term models have the same calibrated parameter values) was used as the base for all predictive model runs. Predictive transient modelling was undertaken to simulate a range of future impacts from the proposed SEB on groundwater levels and groundwater fluxes in the shallow groundwater system under both 'normal' and 'flood' conditions. Simulation of flood conditions with the SEB utilized the same 1:200 hydrograph as for simulation without the SEB as KCB (2020) determined the SEB would have only a slight effect on the flood hydrograph. The simulations evaluated the effect of the proposed SEB on groundwater levels during flood events only, as it is assumed that the SEB would have negligible influence during normal river/ groundwater flow conditions. Table 5.1 presents the simulations undertaken for the SEB.

Table 5.1 Barrier Simulation Summary

Case	Flood Barrier Combination	Rationale	Conditions Evaluated	Rationale
1	No Barrier	Baseline assessment	1:200 Attenuated Event	Baseline assessment
2	SEB only	Assess SEB effect on groundwater levels during flood	1:200 Attenuated Event	No effect anticipated during "normal" seasonal flow

Various groundwater flood mitigation concept designs were also simulated and are provided in Appendix V. These groundwater mitigation simulations all included the SEB and were developed in sequence, in response to the findings of the previous simulations.

5.2 Simulation Methodology

5.2.1 General Approach

The focus of the prediction simulations undertaken has been to evaluate all flood mitigation measures in terms of:

- Effect on 'normal' peak groundwater levels (i.e., normal seasonal water table fluctuations), through comparison to average and peak 2019 levels; and
- Effect on 'flood' groundwater levels relative to performance without any flood mitigation measures, utilizing the 1:200 return period 'Attenuated' river levels, described in Section 5.2.2.

Performance was evaluated in terms of deviation from 'normal' and 'flood without mitigation' conditions and in terms of areas with a peak water table < 2.5 m below ground. This depth was selected as representative of the depth below ground of a 'standard' basement. With water table rises above this level, some potential for basement flooding may exist, although the actual risk will vary significantly on a case-by-case basis, in view of actual depths of basement floor slabs, installed

drainage works such as sump pumps, presence of walk-out doors, etc. It should be noted that the water table frequently lies less than 2.5 mbgs in selected areas of the Project Area, notably in the southeastern end of the Bowness community adjacent to the river.

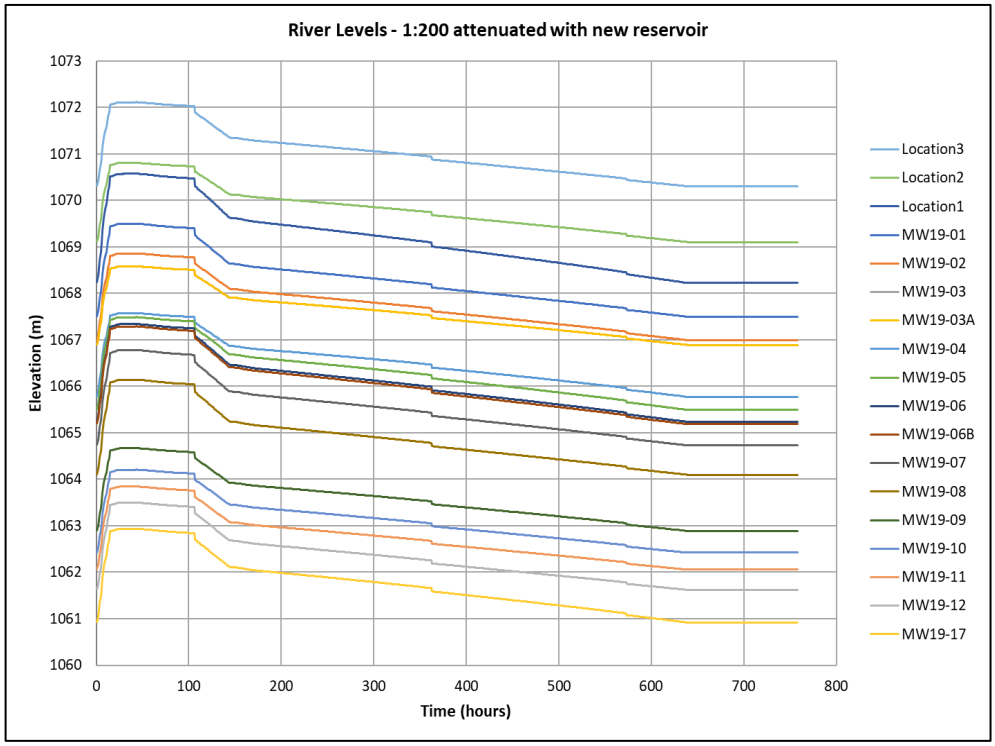
Although 2019 had lower freshet flows than an average year (refer Figure 2.12), annual precipitation (526 mm total precipitation at Calgary International Airport) exceeded the MAP, hence 2019 was considered to be sufficiently similar to an average year in terms of rainfall and river conditions to permit its use to evaluate average or 'normal' climatic and hydrological conditions.

5.2.2 Bow River 1:200-year Attenuated Hydrograph with Future Upstream Mitigation

KCB (2020) presents the development of the HEC-RAS modelled 1:200-year Attenuated Hydrograph with Future Upstream Mitigation (1:200 Attenuated Event).

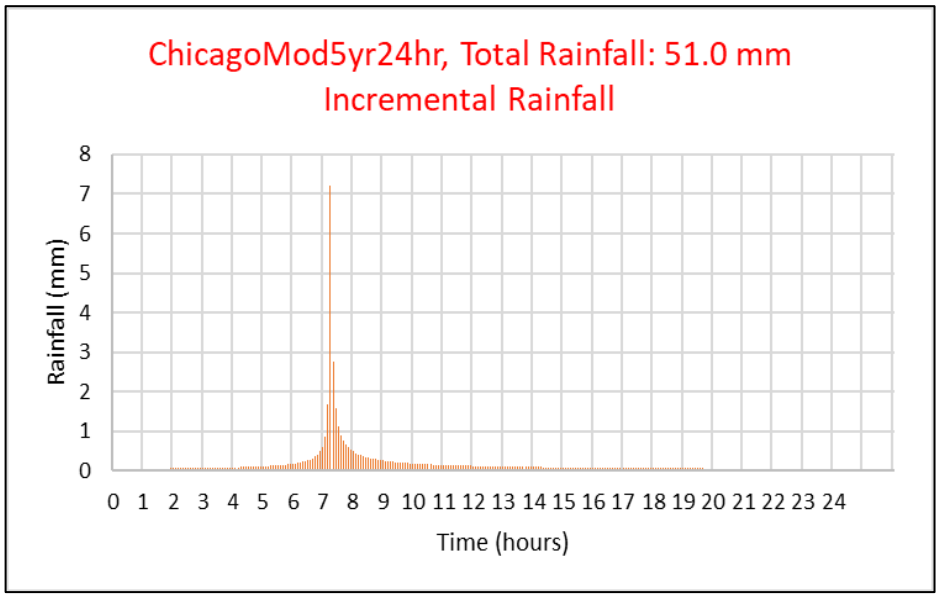
These data were used to establish transient Bow River boundary conditions along the Bow River reach within the numerical model (Figure 5.1). To undertake the prediction simulations, the early part of the flood was simulated, for a period of 107 hours, with stress period lengths of one to 15 hours. Stress periods of longer duration represented periods of relatively stable river level. The HEC-RAS river level data were averaged for each stress period and input as river boundary conditions. Starting heads were determined by use of an initial steady-state period corresponding to the beginning water level, albeit about 1.5 m higher than the peak river levels observed during 2019. Other boundary conditions were set as per equivalent 2019 'high river' level conditions.

Figure 5.1 Bow River Levels at Bowness: 1:200-year Attenuated Event Hydrograph



As the flood event was considered likely to occur coincident with significant local rainfall, a 1:5 year 24-hour duration rainfall event was simulated at the start of the flooding event as shown in Figure 5.2. This event was chosen in consideration that flood events are normally driven by coincident Rocky Mountain snowmelt and rainfall events. CoC normally uses 1:5 year 24-duration events as the basis for design. Rainfall was apportioned pro-rata to the stress periods, as per the hourly records provided, and was converted to recharge using the equation documented in Section 3.1.3.

Figure 5.2 1:5 Year 24-hour Duration Rainfall Event



5.2.3 Flood Events without Mitigation

Simulation of the 1:200-year flood event without the surface barrier or any groundwater mitigation, was undertaken to simulate the effects of both overbank flooding and groundwater flow inland. Overbank flooding was simulated by activating temporary River boundaries within areas below the peak flood level, as per Figure 5.3. and the area of overbank flooding as shown in Figure 5.4.

Figure 5.3 Period of Simulated Overbank Flooding, 1:200 Attenuated Event

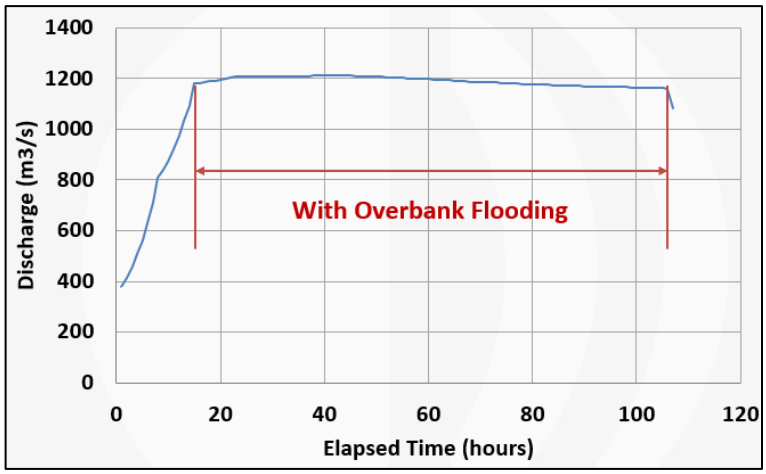
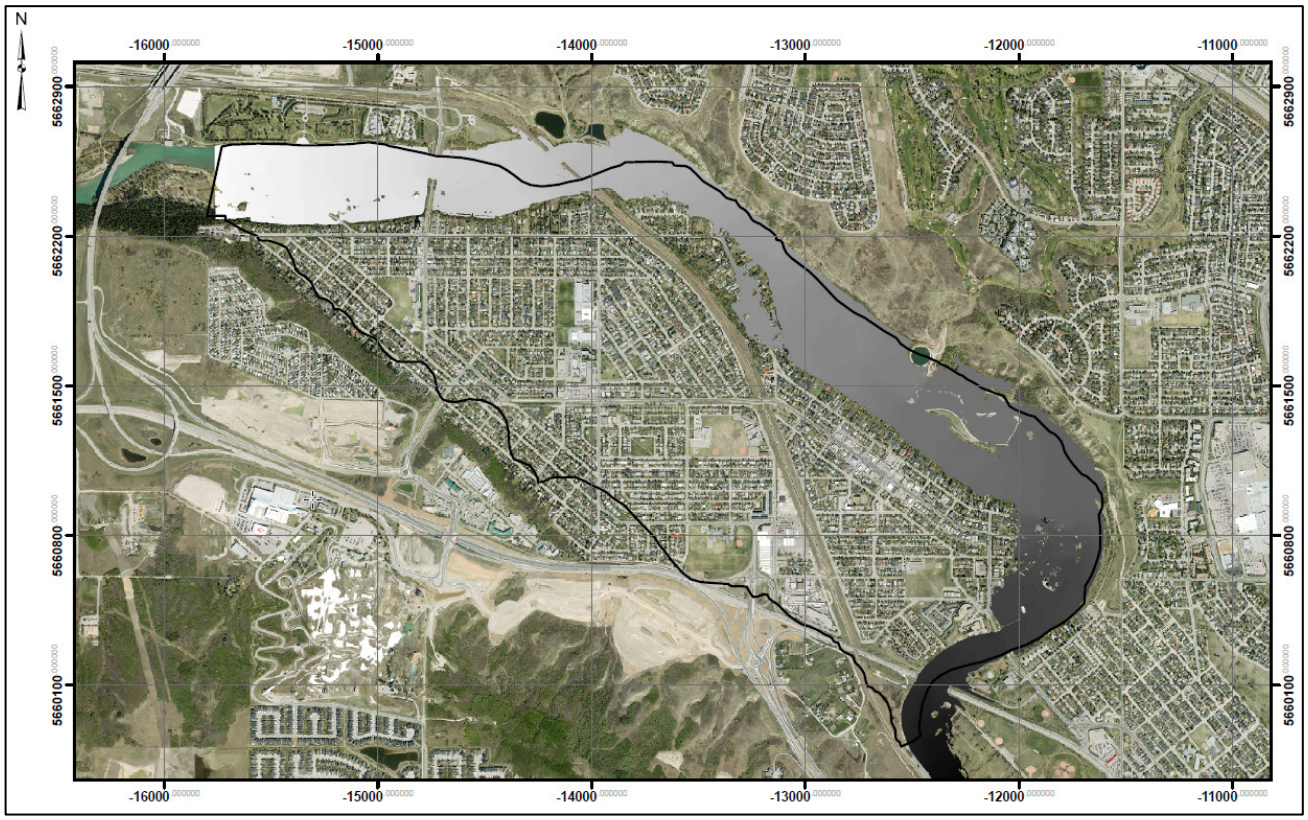


Figure 5.4 Area of Surface Inundation, 1:200-year Attenuated Event



5.2.4 Simulations with Surface Flood barrier

The proposed surface flood barrier design is discussed in KCB (2020). Simulation of the effects of the flood barrier was undertaken simply by not applying the temporary River boundaries described in Section 5.2.3.

5.2.5 Presentation of Results

All flood mitigation option simulation results are been presented with the following graphic outputs:

- Maps showing depth to water table, where water table is less than 2.5 mbgs, and showing zones of groundwater-induced surface inundation; and
- Groundwater hydrographs for all observation points; hydrographs for those wells distant from the river are not presented for the predictive runs, as these wells are generally unaffected by the simulated barrier options.

Where consecutive simulations display design modifications (for example a groundwater cut-off wall), maps illustrating the peak piezometric level changes between simulations are presented. These include both positive (piezometric level increase) and negative (piezometric level decrease) contours between simulations.

These latter maps are also utilised to illustrate peak piezometric level increase or decreases relative to 'normal' seasonal peak levels, as represented by the observed peak levels for 2019.

5.3 Surface Event Barrier Simulation Results

Figure 5.5 presents groundwater-induced surface flooding[7] (depth water table less than 0 m) and depth to water table, where water table is less than 2.5 mbgs, without the SEB (Case 1) for the inferred peak groundwater level of the 1:200 Attenuated Event. These groundwater levels are a manifestation of water which has flowed inland through the subsurface as a result of high river levels, groundwater flow from topographically-higher areas and downward infiltration from overbank flooding.

Figure 5.6 presents the same condition with the SEB in place (Case 2). Within the zone of the barrier alignment, the areas of surface flooding are substantially reduced, with only small remnant zones in areas substantially flooded without the barrier in the northwest and southeast ends of the alignment. By contrast, there is only a small difference in areas with water table <2.5 mbgs between the two cases.

The effect of the barrier is apparent on key monitoring wells located inside (land side) the SEB, as shown in Figure 5.7.

[7] The area of surface inundation may well be greater than indicated as a result of ponded precipitation and runoff from topographically elevated areas; these processes are not represented in the model.

A substantial piezometric level reduction is obtained at MW19-04 in the central portion of the alignment as shown in Figure 5.7, while the reduction at MW19-06 is minimal. The surface barrier provides a noticeable piezometric level reduction at MW19-09, 10 and 11 on the southeast end of the alignment.

Figure 5.8 shows the best estimate peak groundwater level reduction with the SEB. Greatest reduction is predicted for northwest Bowness, with lesser reductions predicted for southeast Bowness and virtually no change in water table predicted between these two areas.

Figure 5.5 Case 1: Depth to Peak Water Table without SEB, 1:200 Attenuated Event

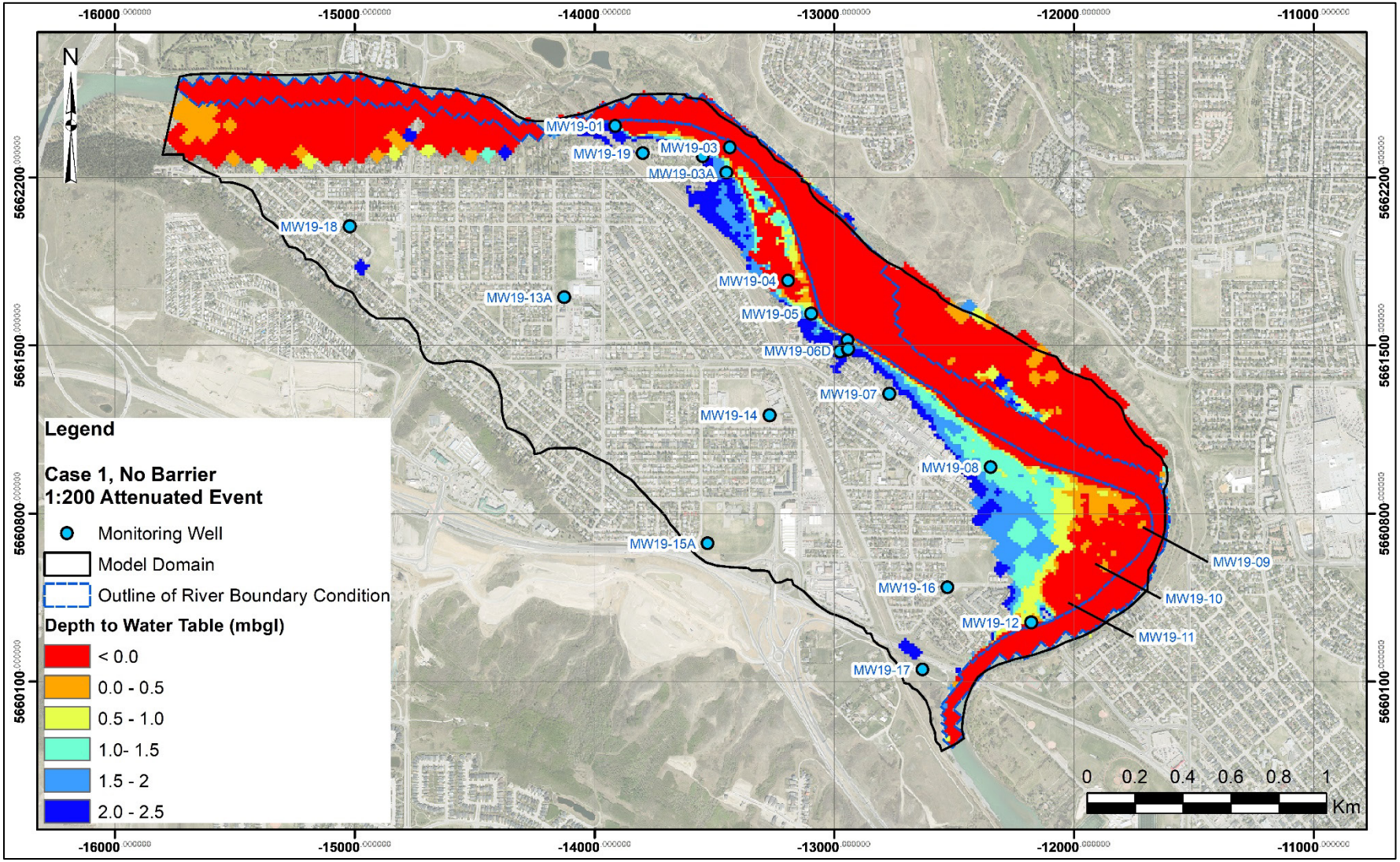


Figure 5.6 Case 2: Depth to Peak Water Table with SEB, 1:200 Attenuated Event

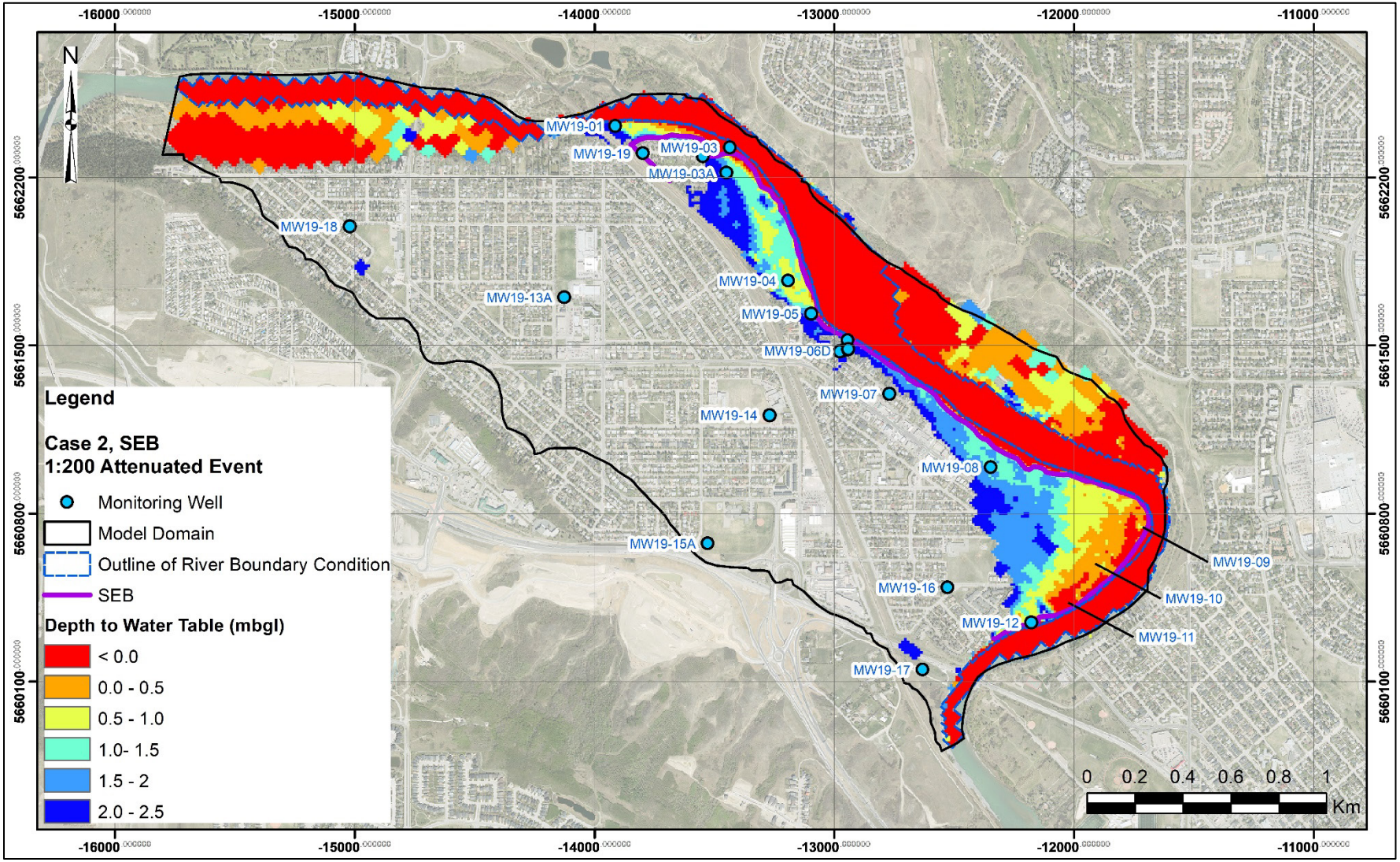
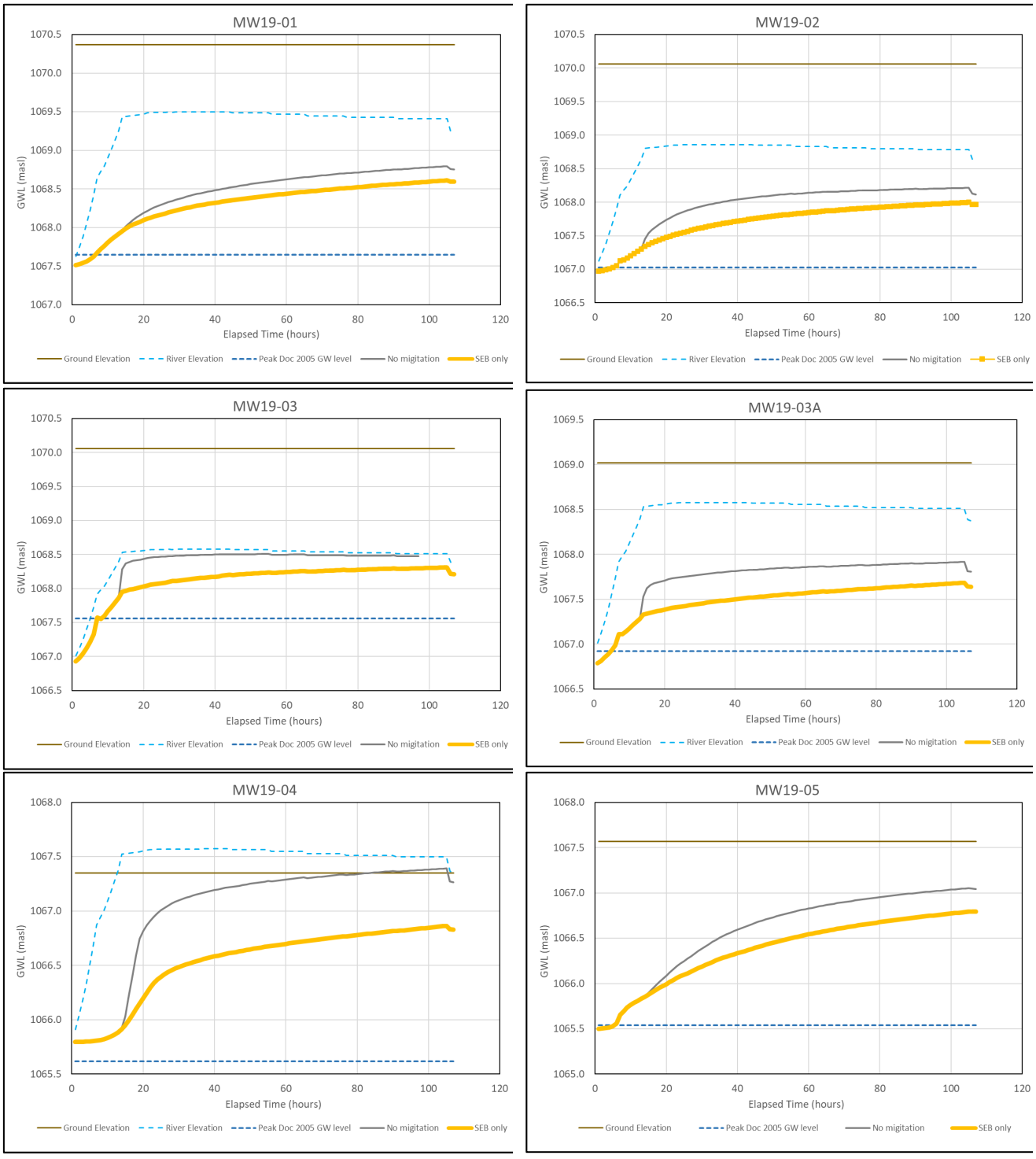
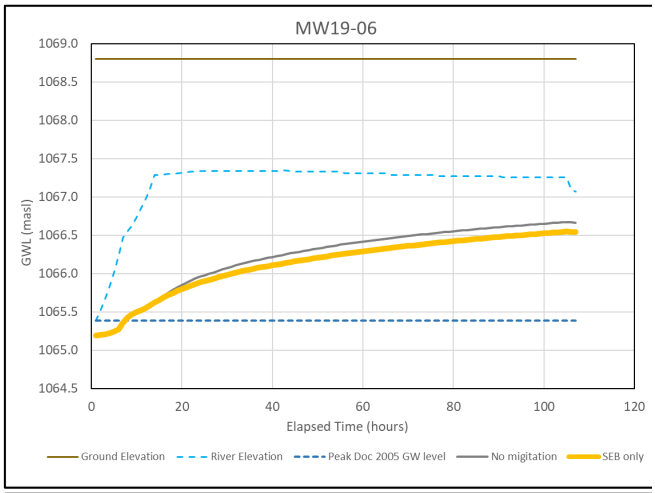
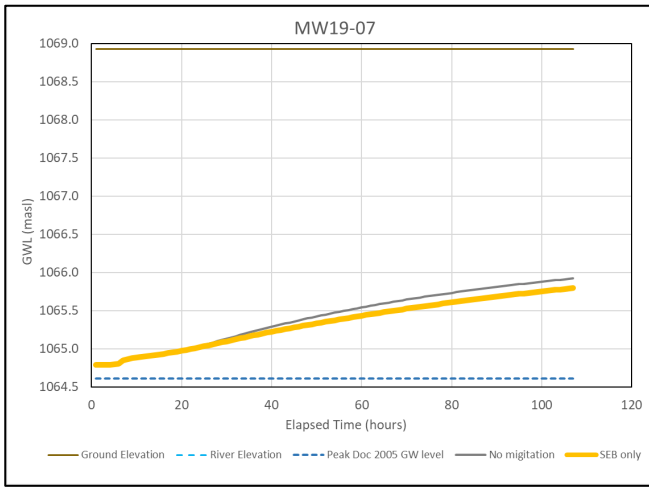
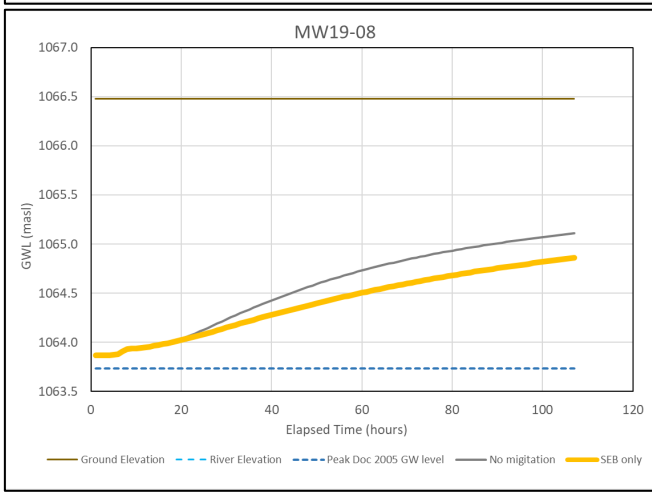


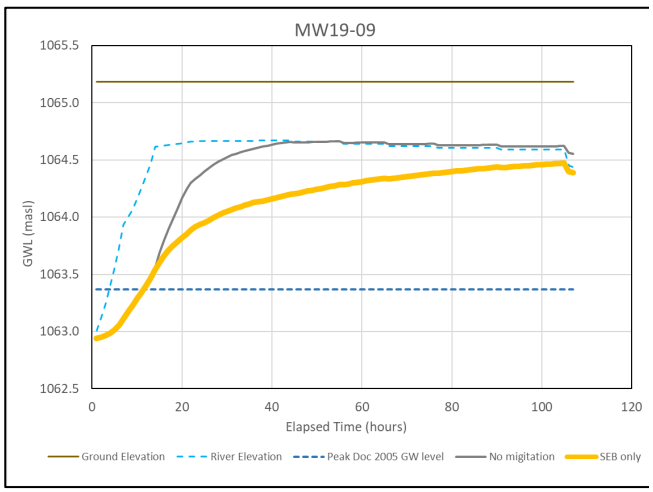
Figure 5.7 Cases 1 and 2: Hydrographs, with/without SEB, 1:200 Attenuated Event

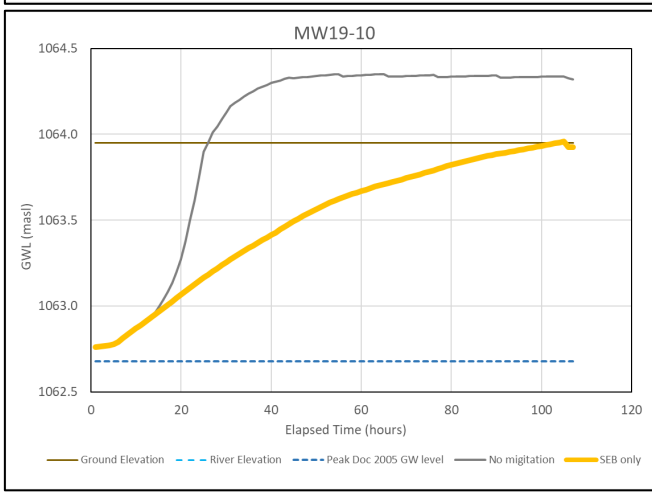



MW19-06
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only


MW19-07
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only


MW19-08
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only


MW19-09
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only


MW19-10
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only

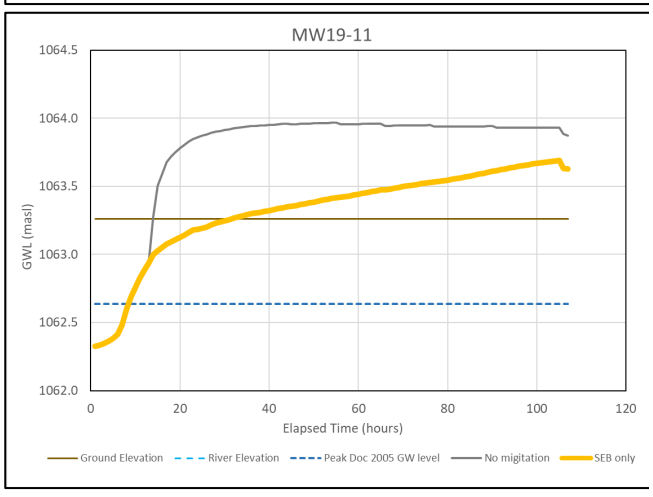
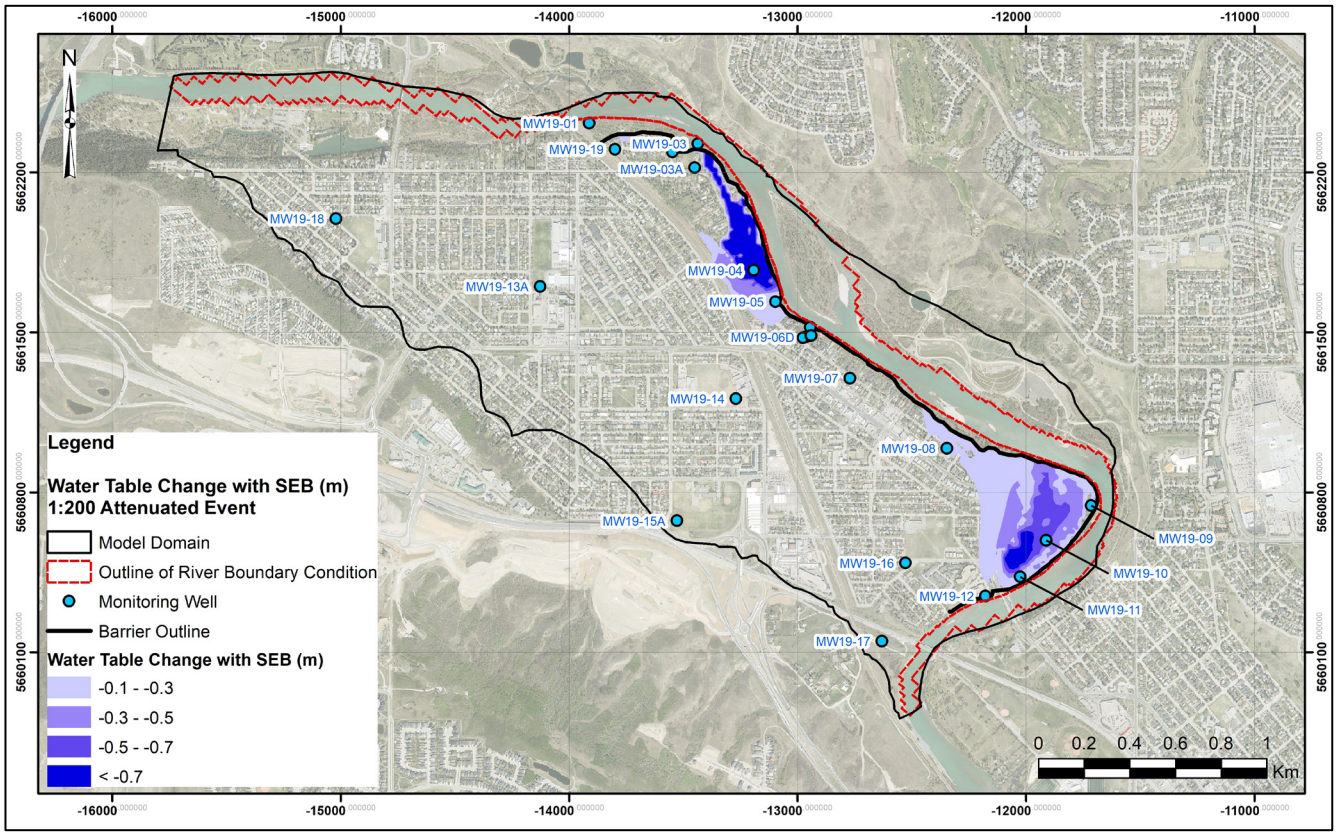

MW19-11
GWL (masl)
Elapsed Time (hours)
Ground Elevation
River Elevation
Peak Doc 2005 GW level
No migitation
SEB only

Figure 5.8 Peak Water Table Reduction With SEB, 1:200 Attenuated Event



5.4 Groundwater Barrier Options

The model was then used to assess the effectiveness of various groundwater barrier options in controlling groundwater levels during flood events and their compatibility with the normal groundwater flow system. The barrier options were evaluated over a proposed 3900 m long alignment directly adjacent to the Bow River on the south bank for the full alignment and for two sections of shorter aggregate length, with a central gap, where groundwater-induced flooding has not been observed to date. The results of these simulations are detailed in Appendix V of this report.

6 MODEL UNCERTAINTY AND LIMITATIONS

6.1 Uncertainty Analysis

6.1.1 Methodology

In order to address residual uncertainty in the model predictions, sensitivity analyses were undertaken to assess which input parameters are most likely to affect model calibration and outputs, as described in Section 4.4. Alternative calibrations were then undertaken by varying key parameters to obtain a model calibration that matched the calibration criteria in a manner similar to the 'Base Case' calibrated model. These alternative calibrations (listed in Table 6.1) were then utilised to re-run key predictive simulations as a means of evaluating the robustness of those prediction results.

Table 6.1 Summary of Uncertainty Analyses

Model	Parameter	Zone	Change	NRMSE (%)
Long-Term Transient Calib34 Modified	K_h and Recharge (R)	6 & 7 (K_h) Recharge (all)	5K_h and 2R	4.1 (Average)
		6 & 7 (K_h) Recharge (all)	0.2K_h and 0.5R	2.1 (Average)
Short-Term Transient Calib34 Modified	K_h and Recharge (R)	6 & 7 (K_h) Recharge (all)	0.2K_h and 0.5R	2.7 (Average)
		6 & 7 (K_h) Recharge (all)	5K_h and 2R	4.4 (Average)

Note: NRMSE for calibrated 'Base Case' calibration model is 1.6%.

6.1.2 Alternative Calibration 1

The 'Base Case' calibrated model was re-calibrated through a *reduction* in K_h and K_v by a factor of 5 for Alluvial Aquifer zones 6 and 7. Recharge was also decreased across the entire model by a factor of 2. Calibration plots for the average of all time steps for both the long-term and short-term models are presented in Figure 6.1 and Figure 6.2, respectively.

Figure 6.1 Long-Term Transient Final Calculated vs. Observed Head Averaged over all Time Steps, Alternative Calibration 1

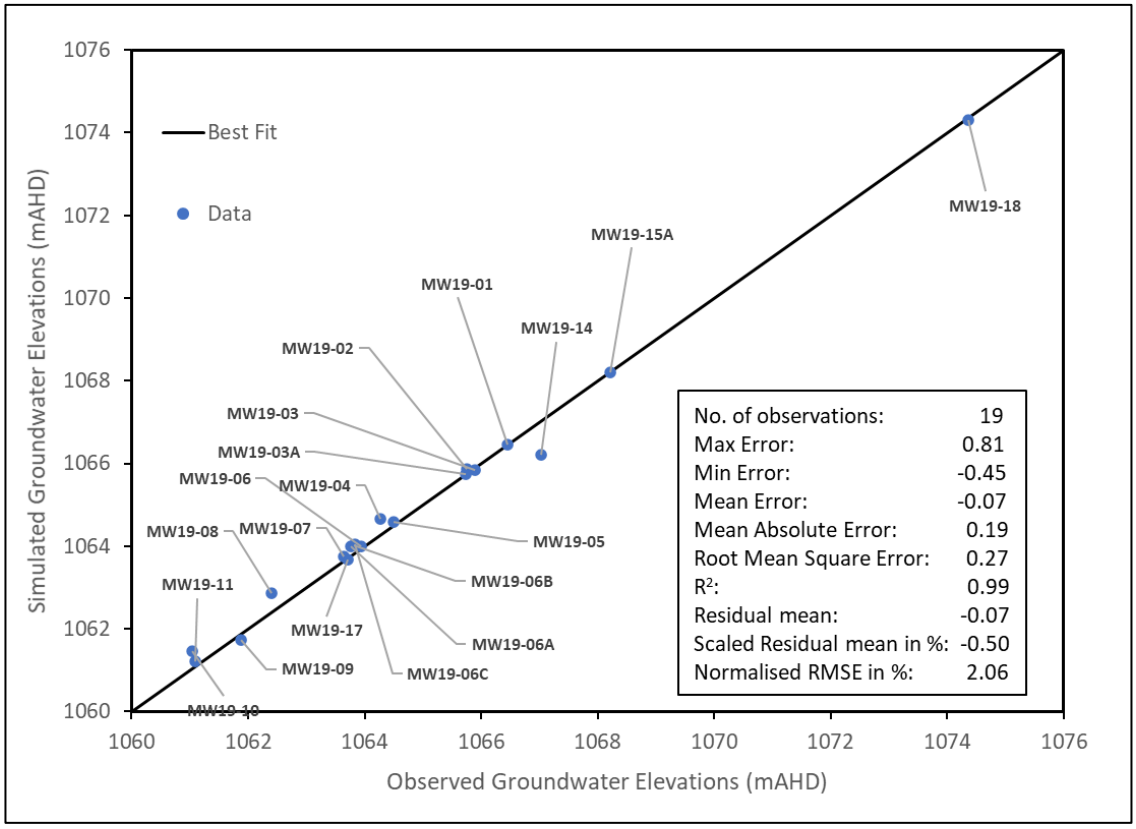
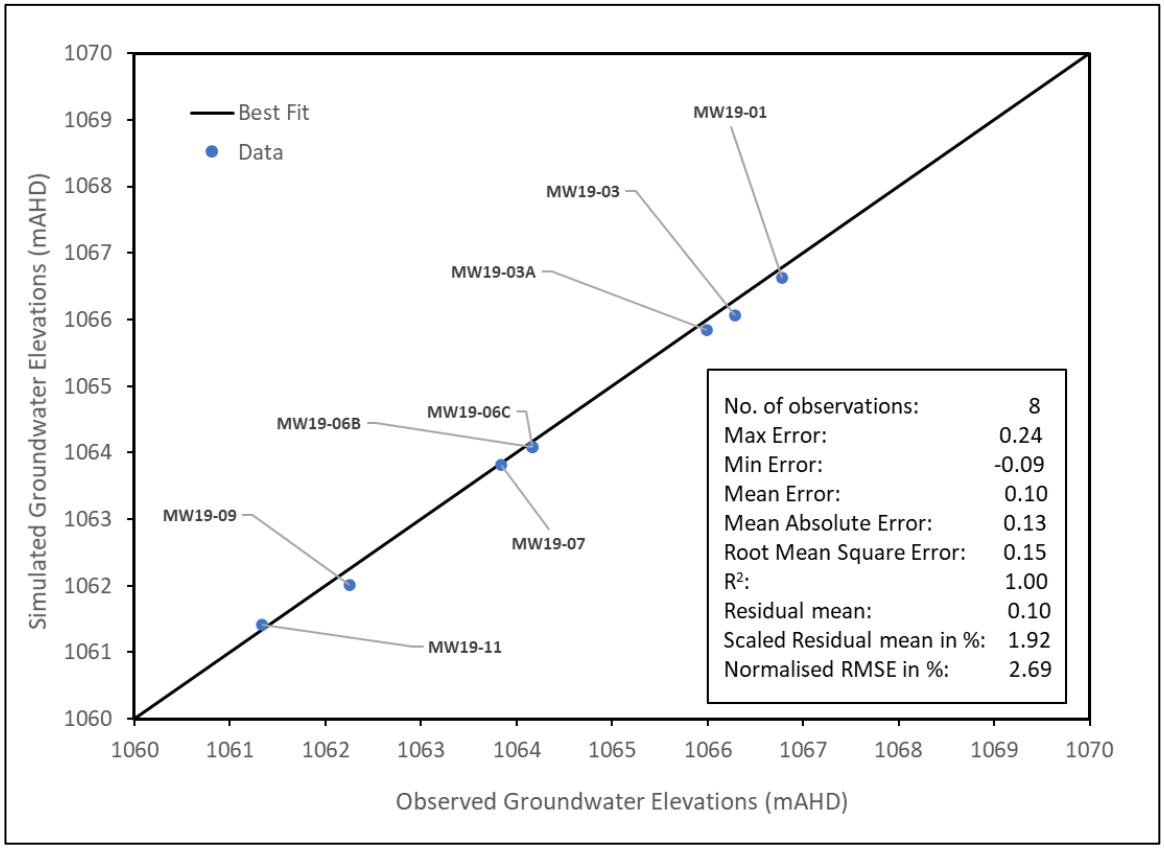
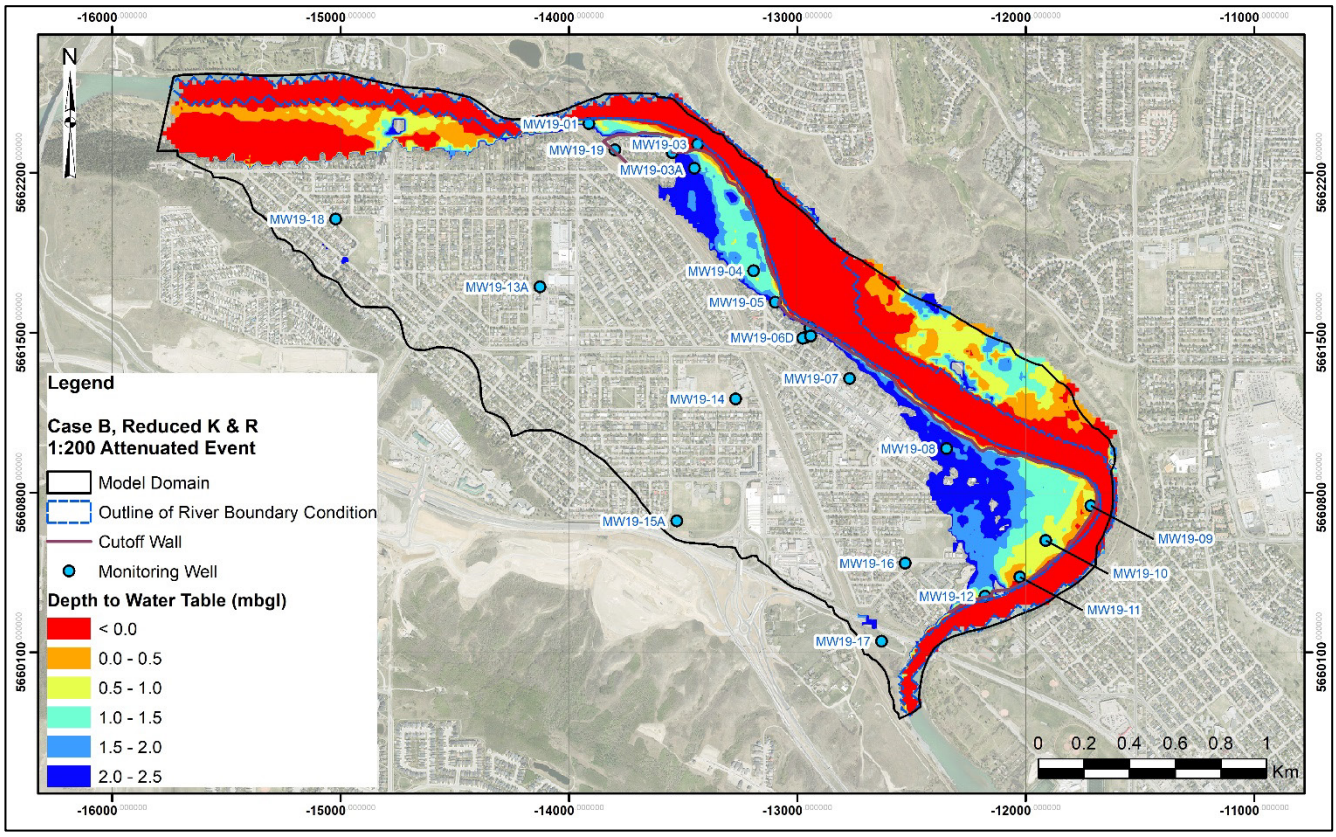


Figure 6.2 Short-Term Transient Final Calculated vs. Observed Head Averaged over all Time Steps, Alternative Calibration 1



The alternative model was then used to re-simulate Case 1 and 2 (with/without the SEB) for the 1:200-year Attenuated Event. Figure 6.3 shows the results of Case 2 for the reduced K/recharge calibration and may be compared to Figure 5.6. As expected, groundwater-related flooding is reduced with the lower Alluvial Aquifer near-river K and lower recharge, with potential for significant flooding largely near-river in southeast Bowness.

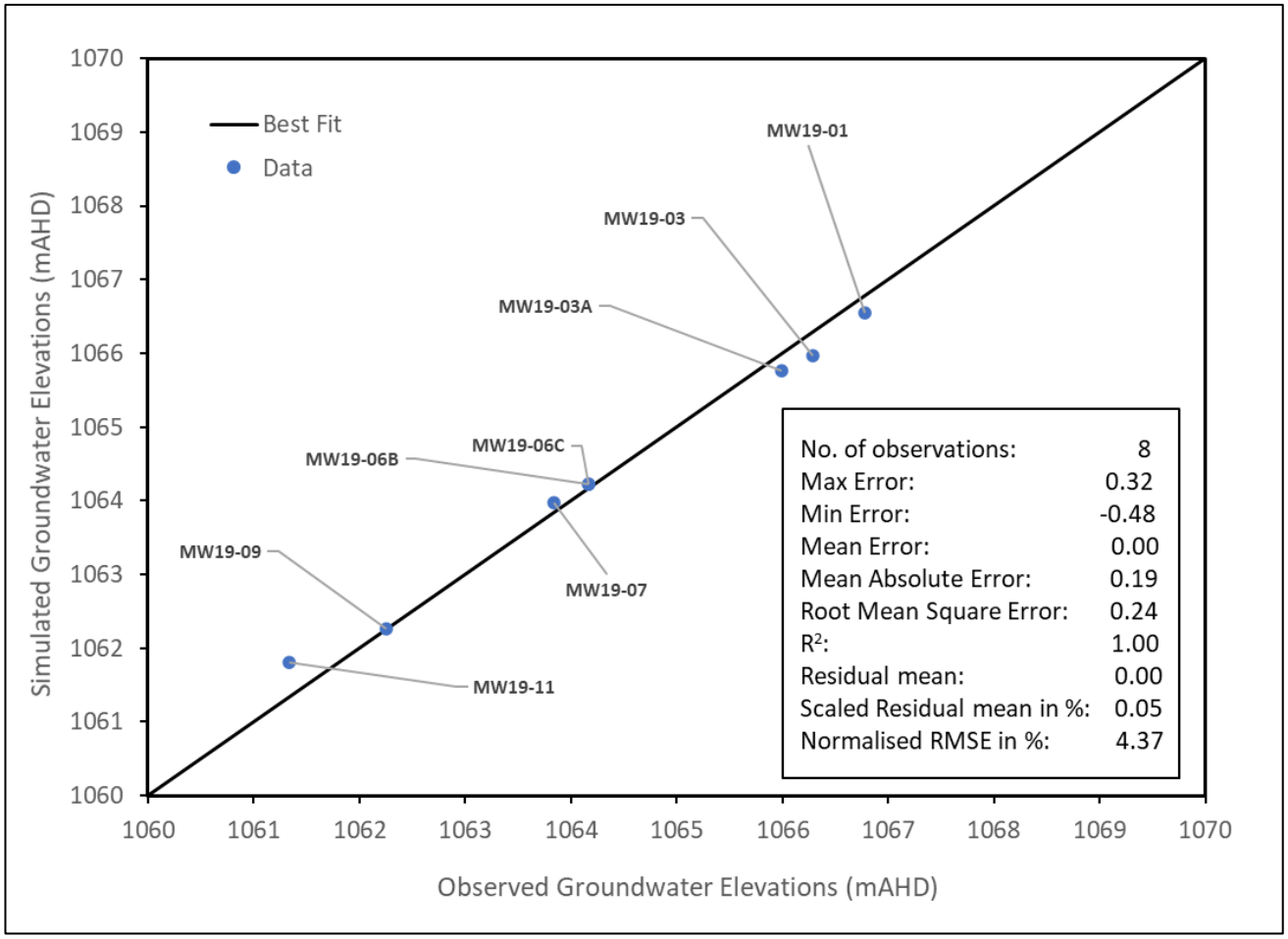
Figure 6.3 Case 2A – Depth to Peak Water Table with SEB, 1:200-year Attenuated Flood Event, K = 0.2 K_{cal}, R = 0.5R_{cal}



6.1.3 Alternative Calibration 2

The 'Base Case' calibrated model was re-calibrated through an *increase* in K_h and K_v by a factor of 5 for key Alluvial Aquifer zones 6 and 7. Recharge was also increased across the entire model by a factor of 2. The calibration plot for the average of all time steps for the short-term model is presented in Figure 6.4.

Figure 6.4 Short-Term Transient Final Calculated vs. Observed Head Averaged over all Time Steps, Alternative Calibration 2



Although the NRMSE error was high relative to the “best estimate” case, and hence a poorer calibration.

The alternative model was then used to re-simulate Case 1 and 2 (with/without the SEB) for the 1:200-year Attenuated Event.

Figure 6.5 Case 2A - Depth to Peak Water Table *without* SEB, 1:200-year Attenuated Flood Event, K = $5K_{cal}$, R = $2R_{cal}$

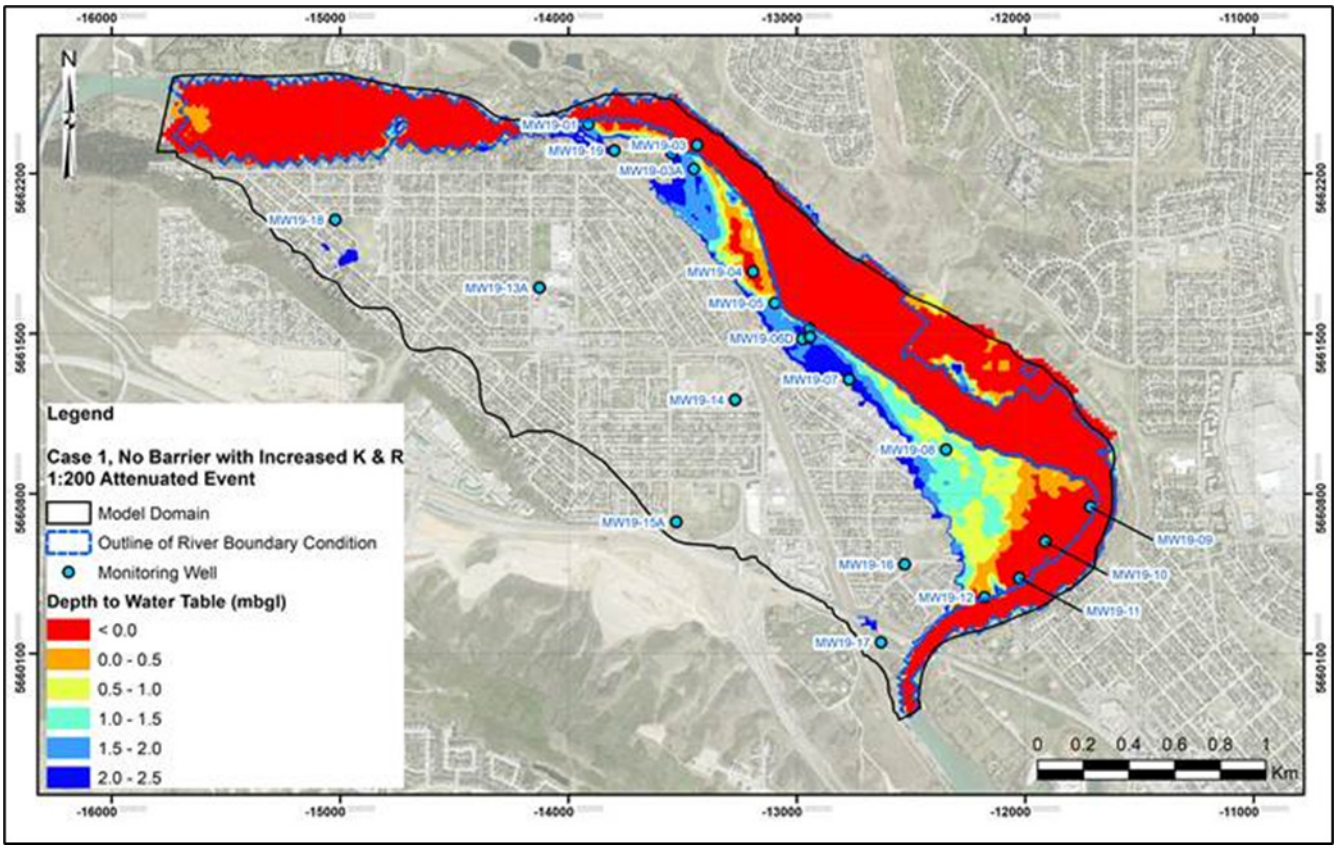
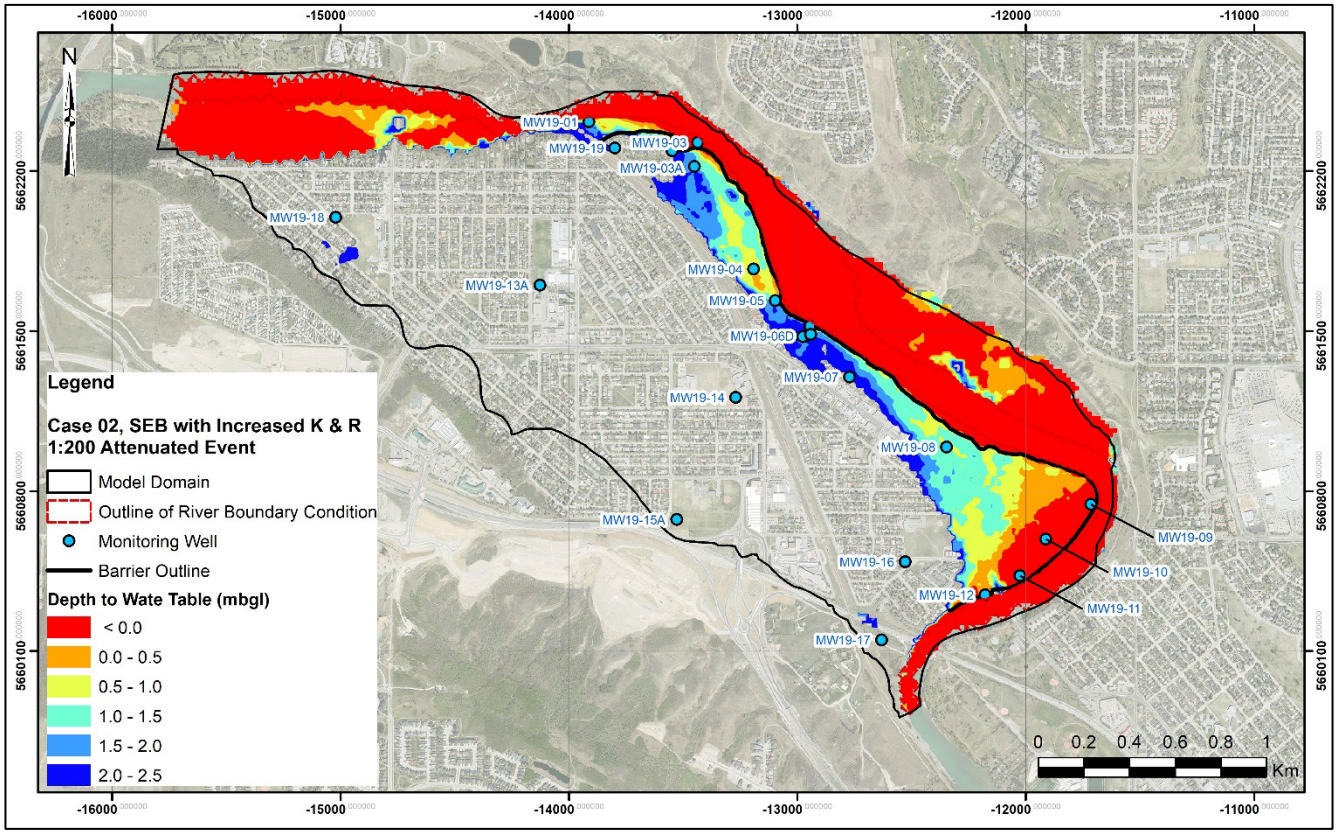


Figure 6.5 shows the increase extent of groundwater flooding and groundwater-induced surface flooding associated with the higher K/ recharge conditions.

Figure 6.6 shows the results of Case 2 for the reduced K/recharge calibration and may be compared to Figure 5.6. As expected, groundwater-related flooding is increased with the higher Alluvial Aquifer near-river K and higher recharge. The overall area with groundwater <2.5 m below ground is not significantly changed from the low K/recharge case, however, however water table is typically on the order of about 0.5 to 1 m higher. As with the other cases, the potential for groundwater flooding is greatest in southeast Bowness, with groundwater-induced flooding over a larger area relative to the "best estimate" simulation (Figure 5.6).

The results for Cases 2A and 3A display a general correspondence with those of Cases 2 and 3, as shown in Figure 5.6 and Figure V-1.4, Appendix V.

Figure 6.6 Case 2B – Depth to Peak Water Table *with* SEB, 1:200-year Attenuated Flood Event, K = 5K_{cal}, R = 2R_{cal}



While not exhaustive, the re-run of key predictive simulations with alternative models has served to reduce uncertainty in the viability assessment of the key groundwater flooding mitigation measures.

6.2 Sources of Remaining Uncertainty

6.2.1 Hydrological Modelling

There remains some uncertainty in modelled river levels as a result of measurement error, model error, and differences in the simulated and actual river characteristics. Although this error is thought to be small, given the strong hydraulic connection between the river and the Alluvial Aquifer, small errors can affect the interpretation. Similarly, small changes (<8 cm) in 1:200 Attenuated Flood river levels may occur with the SEB in place, and these have not been modelled.

6.2.2 Hydrogeological Characterisation

There remains some uncertainty in the representation of the variable geometry (thickness and contact elevations) of the relatively thin gravel and sand unit, and its connection to the Bowness River based on a limited number of borehole logs. Drilling of five boreholes in the relatively small Bowness Park area (MW19-06, 06A, 06B, 06C, and 06D), where the Alluvial Aquifer thickness varies from 4.9 m

to 11.7 m, demonstrates that there is potential for significant variability in the Alluvial Aquifer thickness over short (<60 m) distances.

Under normal flow conditions, the saturated thickness of the aquifer is highly variable and water levels are estimated over a short period of time from a limited number of wells. The simulated fluxes and flow paths may be significantly influenced by these uncertainties, especially during seasonal low groundwater conditions.

The interpolation technique used in the *Leapfrog*™ geology model is not always ideal for stratigraphic correlation and requires considerable manual intervention to obtain desired geological surfaces.

6.2.3 Model Simplifications and Non-Uniqueness of Calibration

There remains some uncertainty related to the modelling process as follows:

- In order to maximize computational efficiency and model stability, without significantly affecting the model function, adjacent geological units with similar hydraulic characteristics were combined, thus simplifying the hydrogeological system.
- The model does not explicitly quantify changes to baseflow due to drainage features that may exist within the model domain.
- The model does not explicitly consider effects of basements, sumps, dewatering work, or underground infrastructure, on the groundwater flow hydraulics, and is hence likely to estimate recharge and conductivity values lower than 'natural' conditions.
- The model assumes only net rainfall recharge and that there is only limited evapotranspiration.
- The model does not consider alterations in hydraulic conductivity associated with seasonal ground freezing, or compaction due to loading.

6.3 Summary

Some model uncertainty remains with respect to the characterization of the hydrological and hydrogeological flow regimes at Bowness. In addition, some uncertainty resides in the numerical model simulation of these regimes. However, it is considered that the understanding of the key hydraulic interaction between the Bow River and the Alluvial Aquifer, responsible for past basement flooding events at Bowness, is reasonably well-understood and satisfactorily simulated by the numerical model, in consideration of the objectives of the modelling.

It is therefore considered that the basic findings of this study are robust and *unlikely to change* significantly with more detailed studies in light of the remaining uncertainties listed in 6.2.1, 6.2.2 and 6.2.3. Future studies should focus on defining the design objective, assessing the cost-benefits of key options to meet that objective and selection of a design alternative to take forward.

7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

Klohn Crippen Berger Ltd. (KCB) has undertaken a hydrogeological study of the community of Bowness to support CoC's Flood Mitigation Measures Assessment. The investigation included multi-method geophysical surveying, borehole drilling, monitoring well installation, hydraulic testing, piezometric monitoring, and groundwater sampling. The compilation and analysis of this data and other relevant data were used to develop a conceptual hydrogeological model for the Bowness Project Area, including a strong understanding of the interaction between the shallow groundwater system and the Bow River and the development of a 3D geological model.

The *Leapfrog*™ geological model was used as the basis for construction of a 3D groundwater flow model using the *MODFLOW USG* program with a *Groundwater Vistas* pre- and post-processor. The objectives of the modelling were to:

- Assess the effect of the proposed Surface Event Barrier[8] (SEB) on the shallow groundwater system;
- Assess the effect of the proposed SEB with various potential groundwater mitigation measures on the shallow groundwater system;
- Predict the extent, magnitude, and timing of surface flooding due to groundwater level rises associated with specific Bow River flood events and various flood mitigation options; and
- Review potential groundwater mitigation options, and present advantages and challenges associated with each option.

Numerical groundwater modelling was undertaken in general accordance with the guidelines presented in *Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities* (Wels et al. 2012). Numerical model calibration was undertaken using piezometric data collected during the 2019 groundwater monitoring program and river level monitoring data provided by CoC, and HEC-RAS modelling of river levels (KCB 2020). The groundwater model was calibrated using two separate conditions: an approximate six-month 'long-term' transient model covering the period of greatest river level fluctuation for 2019, and a 'short-term' model of four-day duration to evaluate model calibration performance associated with shorter-term changes in the river level.

A good calibration with an average Normalized Root Mean Square Error of 1.6% and 2.4% were obtained for the long and short calibrations, respectively. The model was then verified against the 2005 Bow River flood event by comparison of areas of high groundwater table (< 2.5 m below ground surface) with anecdotal information gathered regarding basement flooding. The verification showed general correspondence between areas of simulated high groundwater tables and properties where basement flooding was reported.

[8] Nominated term for surface flood barrier

The model was then used to assess the effectiveness of various groundwater barrier options in controlling groundwater levels during flood events and their compatibility with the normal groundwater flow system. The barrier options were evaluated over a proposed 3900 m long alignment directly adjacent to the Bow River on the south bank for the full alignment and for two sections of shorter aggregate length, with a central gap, where groundwater-induced flooding has not been observed to date.

The 1:200 Attenuated flood hydrograph with Future Upstream mitigation (1:200 Attenuated Event) was used as the basis for assessment of barrier performance. Bow River levels and areas of surface inundation resulting from overbank flow during this event were modelled previously (KCB 2020).

7.2 Conclusions

1. The Bowness community is underlain by between about 1 m to 21 m of stratified glacial and postglacial sediments, consisting of from the top down, topsoil, silty and clayey fill, alluvial gravel and sand deposits, fine glaciolacustrine sediments, and silty to clayey glacial till. These sediments overly Tertiary-aged Paskapoo Formation bedrock, comprising mostly siltstone and mudstone, with occasional sandstone beds.
2. The alluvial gravel and sand (Alluvial Aquifer), which also contains appreciable coarser material, including cobbles, is laterally bounded by escarpments formed in the fine-grained lacustrine sediments on the northern and southern margins of the Bow River valley. This unit forms a moderately to highly permeable aquifer with horizontal hydraulic conductivities estimated to range between about 5×10^{-6} and 2×10^{-3} m/s, and permeability within the aquifer tends to increase with proximity to the Bow River. The gravel and sand ranges in thickness from about 1 m to 12 m in the Bowness area, based on drilling and geophysical data. The Alluvial Aquifer is mostly unconfined, although portions of the aquifer may become confined by the overlying fine sediments during high water table periods.
3. The aquifer displays a strong hydraulic connection with the Bow River, and past experience, notably the 2005 Flood Event, has shown that high Bow River levels can result in basement flooding through the raising of groundwater levels alone. During the significant flood events, groundwater levels may rise due to three mechanisms: (1) Rainfall and surface runoff recharge; (2) Surface inundation from overbank flow; and (3) High groundwater levels driven by high Bow River levels causing river water to enter the Alluvial Aquifer.
4. Groundwater flow below Bowness is dominated by the Alluvial Aquifer, and flow is generally northward from the southern escarpment towards the Bow River in the westernmost portion of Bowness, and northeastward to eastward in the eastern half of Bowness. Piezometric and groundwater chemistry data indicate a high degree of mixing of groundwater and river water within a distance of up to 360 m of the river, and river water enters the Alluvial Aquifer during high flow periods, and even during normal flow periods within portions of the aquifer proximal to the river, including the point bar on the northeastern end of Bowness.

5. Simulation of the Surface Event Barrier (SEB) indicates that the proposed SEB will not result in higher water tables during flood events and will marginally reduce water table levels in areas close to the river within northwestern and southeastern Bowness.
6. Alternative model calibrations were then used as the basis for re-simulation of the key flood mitigation options. These alternative calibrations were undertaken by obtaining good calibrations using differing combinations of key model input parameters, notably hydraulic conductivity and groundwater recharge. The conclusions drawn from these simulations were similar to those provided by the 'Base Case' best calibration, although varying in magnitude. All simulations indicate water table levels will decline slightly in northwestern and southeastern Bowness with the SEB, and will be unchanged elsewhere, hence the predictions listed above are considered to be robust.

7.3 Recommendations

To meet a design objective of eliminating surface inundation during significant flood events, KCB recommends further investigation of those areas identified as potentially susceptible to groundwater-induced flooding with the SEB in place, within the northwestern and southeastern extents of the proposed barrier alignment. This would include:

- Continue monitoring groundwater levels and water chemistry at select wells within monitoring network. Install pressure transducer/dataloggers in those monitoring wells not instrumented during 2019, which are not dry for significant periods of the year.
- Install, develop and hydraulically test (slug and constant-head tests) three test pumping wells, each screened across the Alluvial Aquifer, one between existing wells MW19-03 and MW19-04, a second between MW19-08 and MW19-09 and a third between MW19-09 and MW19-10.
- Compile and analyse this data and use as input to the next design phase.

Should the City of Calgary wish to proceed with a detailed assessment of groundwater mitigation options, a more extensive field investigation program is advocated, and is presented in Appendix V of this report.

8 CLOSING

This report is an instrument of service of Klohn Crippen Berger Ltd. (KCB). The report has been prepared for the exclusive use of The City of Calgary (Client) for the specific application to the Bowness Flood Control Barriers project, and it may not be relied upon by any other party without KCB's written consent. KCB has prepared this report in a manner consistent with the level of care, skill, and diligence ordinarily provided by members of the same profession for projects of a similar nature at the time and place the services were rendered. KCB makes no warranty, express or implied.

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