APPENDIX V

Numerical Groundwater Model – Groundwater Flood Mitigation Simulations

Appendix V
Groundwater Flood Mitigation Simulations

TABLE OF CONTENTS

List of Tables

List of Figures

TABLE OF CONTENTS
(continued)

List of Appendices

ACRONYMS FOR GROUNDWATER MITIGATION OPTIONS

FBD	Full Barrier Drain installed along the entire of the Surface Flood Barrier alignment (simulated groundwater flood mitigation measure).
FGC	Full Groundwater Cut-off – cut-off wall installed below the entire SEB and extending to the base of the Alluvial Aquifer (simulated groundwater flood mitigation measure).
FGCD	Full Groundwater Cut-off Deep – cut-off wall installed below the entire SEB and extending to the base of the Competent bedrock (simulated groundwater flood mitigation measure).
SBD	'Split' Barrier Drain installed in the Alluvial Aquifer (simulated groundwater flood mitigation measure).
SEB	Surface Event Barrier or Surface Flood Barrier (simulated surface water flood mitigation measure).
SGC	'Split' Groundwater Cut-off wall installed below the SEB and to base of the Alluvial Aquifer (simulated groundwater flood mitigation measure).
TGC	'Truncated' Groundwater Cut-off wall installed below the SEB and to base of the Alluvial Aquifer (simulated groundwater flood mitigation measure).

V-1 GROUNDWATER FLOOD MITIGATION SIMULATIONS

Predictive transient modelling was undertaken to simulate a range of future impacts from the proposed flood barrier(s) on groundwater levels and groundwater flows in the shallow groundwater system under both 'normal' and 'flood' conditions. The initial simulations evaluated the effect of the proposed Surface Effect Barrier (SEB) on groundwater levels during 'normal' flow and flood events (detailed in Section 5.0 on the main report). Appendix V details additional prediction simulations undertaken to assess the effects of the SEB, together with various groundwater flood mitigation concept designs, including groundwater cut-off walls, interception drains and pumping wells, on groundwater levels during flood events and under 'normal' groundwater flow conditions. The groundwater flood mitigation prediction simulations are summarized in Table V-1.1.

Barrier options with the potential to significantly affect groundwater levels under 'normal' flow conditions (Cases 3 to 6) were simulated under the 2019 conditions and under the 1:200-year Attenuated hydrograph with future upstream flood mitigation (1:200 Attenuated Event). The remaining options were simulated only for the 1:200 Attenuated Event.

V-1.1 Objectives

The objectives of the modelling of groundwater mitigation options included:

- Assess the effect of the proposed SEB with various potential groundwater mitigation measures on the shallow groundwater system designed to either:
  - Eliminate surface flooding; or
  - Maintain groundwater levels at, or below, peak normal levels, as represented by the 2019 Bowness groundwater monitoring data.
- Present the advantages and challenges associated with each option.

Table V-1.1 Flood Barrier and Groundwater Flood Mitigation Simulation Summary

Case	Flood Barrier Combination	Rationale	Conditions Evaluated	Rationale
3	SEB and FGC	Evaluate combined flood protection of SEB + FGC and effects during "normal" flow conditions	2019 Seasonal Conditions	Assess peak groundwater mounding behind FGC
4			1:200 Attenuated Event	Assess flood protection
5	SEB and FGCD	Evaluate effects of deepening cut-off wall	2019 Seasonal Conditions	Assess peak groundwater mounding behind FGCD
6			1:200 Attenuated Event	Assess flood protection
7	SEB and TGC	Evaluate effect of shortening cut-off wall	1:200 Attenuated Event	Assess flood protection
8	SEB and SGC	Evaluate effect of two separate cut-off walls, of shorter aggregate length	1:200 Attenuated Event	Assess flood protection
9	SEB, FGC and SE Drain	To assess peak groundwater mounding behind FGC with supplemental drain, assess flood protection and pumping volumes	2019 Seasonal Conditions	Assess peak groundwater mounding behind FGC + SE Drain
10			1:200 Attenuated Event	Assess flood protection
11	SEB, FGC and 1 PW in SE	To assess peak groundwater mounding behind FGC with pumping wells, assess flood protection and pumping volumes	2019 Seasonal Conditions	Assess peak groundwater mounding behind FGC + PW
12			1:200 Attenuated Event	Assess flood protection
13	SEB and FBD	Evaluate use of full-length groundwater drain for flood protection and pumping volumes	1:200 Attenuated Event	Assess flood protection; no effect anticipated during "normal" seasonal flows
14	SEB and SBD	Evaluate use of two separate drains, of shorter aggregate length, estimate pumping volumes	1:200 Attenuated Event	Assess flood protection
15	SEB and "Barrier" PWs	Evaluate use of pumping wells in place of drain, estimate pumping volumes	1:200 Attenuated Event	Assess flood protection

V-1.2 Simulation Methodology

V-1.2.1 Simulations with Groundwater Cut-Off Wall

The feasibility of a steel sheet pile wall along the river was assessed. A schematic plan and section of the wall is shown in Figure V-1.1. The current alignment is not rectilinear and therefore, the Hydraulic Flow Barrier (HFB) package available in MODFLOW-USG was not used to simulate the groundwater cut-off wall. As an alternative, the wall was simulated as a zone of equivalent hydraulic resistance. The cut-off wall thickness was assumed to be 6 mm, with a bulk permeability of 1×10^{-10} m/s[1]. The wall was simulated across a thickness of 3 m, with an equivalent hydraulic resistance calculated as follows:

$$Ke = \mathrm{Kc}\frac{t_{\mathrm{m}}}{\mathrm{t_s}}$$

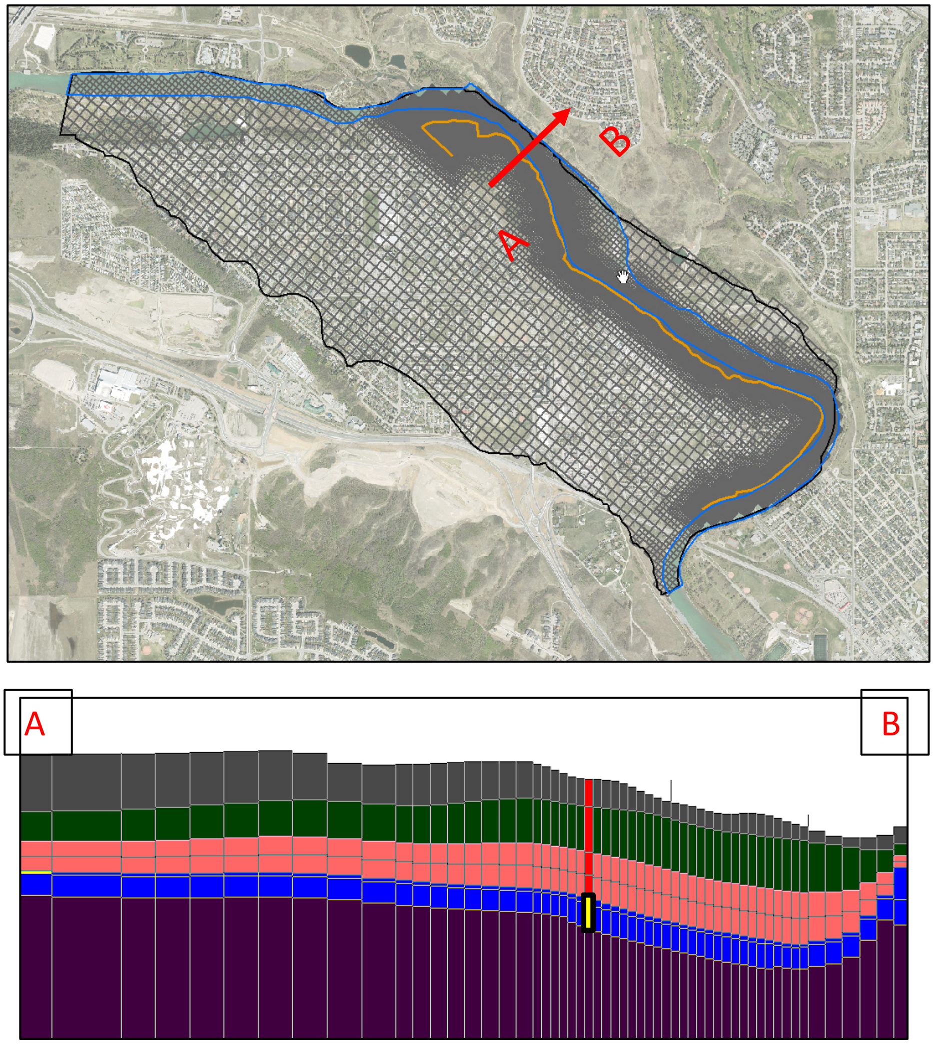
Where:

K_e	=	Equivalent hydraulic conductivity
K_c	=	Cut-off wall hydraulic conductivity
t_m	=	Modelled wall thickness
t_s	=	Sheet pile wall thickness

An effective hydraulic conductivity of 5×10^{-8} m/s was determined for a 3 m wall thickness.

[1] The sheetpile thickness was estimated from brochures of commercially available sheet pile products. The estimation of overall wall permeability was undertaken in reference to ArcelorMittal: *Impervious steel sheet pile walls – Design and Practical Approach* (2014). While approximate, it is noted that subsequent simulations are generally insensitive to the permeability value applied, within an approximate range of 1×10^{-8} to 1×10^{-12} m/s.

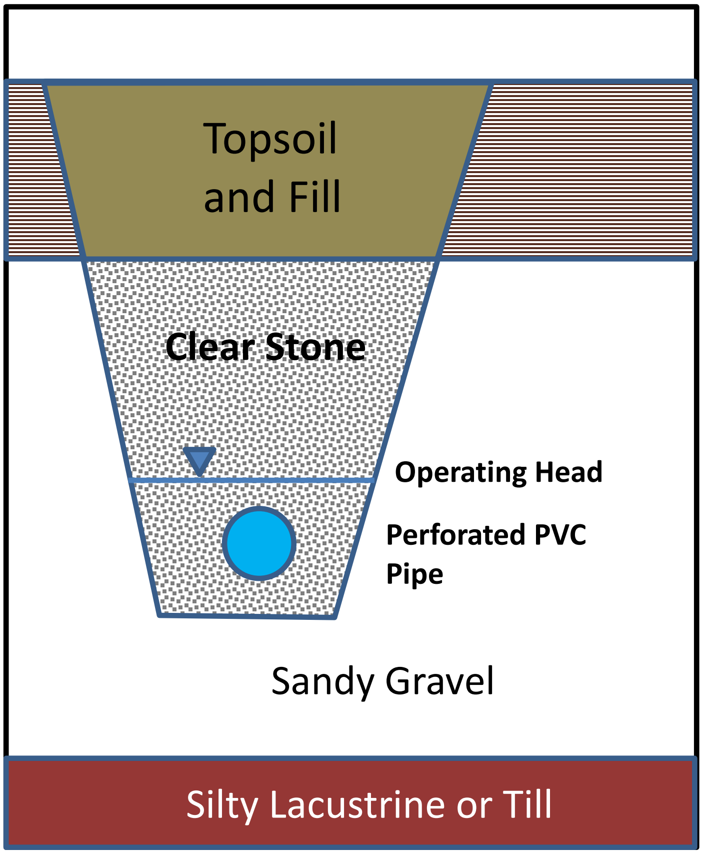
Figure V-1.1 Groundwater Cut-Off Wall Plan and Section



V-1.2.2 Simulations with Groundwater Drains

The use of groundwater drains was assessed, both to complement a groundwater cut-off wall and as a standalone barrier option. A schematic of the drain design is shown in Figure V-1.2.

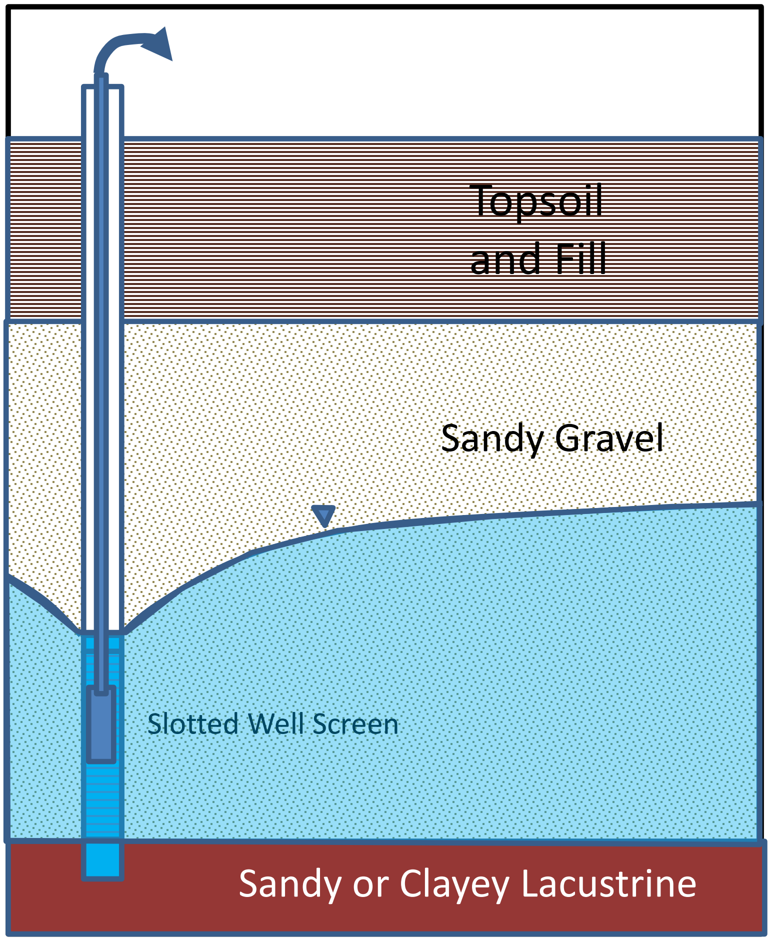
Figure V-1.2 Schematic Drain Design



V-1.2.3 Simulations with Pumping Wells

Pumping wells were also simulated, to fulfill the same role as groundwater drains, with potentially less construction impact. A schematic of a typical pumping well design is shown in Figure V-1.3.

Figure V-1.3 Schematic Pumping Well Design



V-1.3 Surface Event Barrier and Groundwater Mitigation Simulation Results

V-1.3.1 Presentation of Results

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

- Maps showing depth to water table, where water table is less than 2.5 metres below ground surface (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 depth of 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.

V-1.3.2 Cases 3 to 6: Surface Barrier with Full Groundwater Cut-off Wall

The SEB, together with Full Groundwater Cut-off (FGC), extending to the base of the Alluvial Aquifer, a depth estimated to range between 3 mbgs and 8 mbgs, was simulated for both 2019 and the 1:200 Attenuated Event. This simulation was repeated for a barrier extending to the top of 'competent' or unweathered bedrock (FGCD), with depths ranging from about 5 mbgs to 16 mbgs.

Figure V-1.4 presents the peak groundwater level period observed in 2019 (June 25) and shows that under normal flow conditions, the groundwater cut-off wall results in a water level rise in the southeast, due to the 'damming' effect of the wall which reduces the quantity of groundwater discharging to the Bow River. Groundwater discharge is further reduced when the barrier is extended to the top of competent bedrock (Figure V-1.5).

Peak water table increases of approximately 1.0 m and 1.6 m, respectively, are indicated for the two conditions (Figure V1-1 and Figure V1-2, Appendix V1, respectively), while water table decreases up to 0.6 m occur on the northwest end of the alignment.

Figure V-1.4 Case 3: Depth to Water Table SEB + FGC, June 25, 2019 Condition

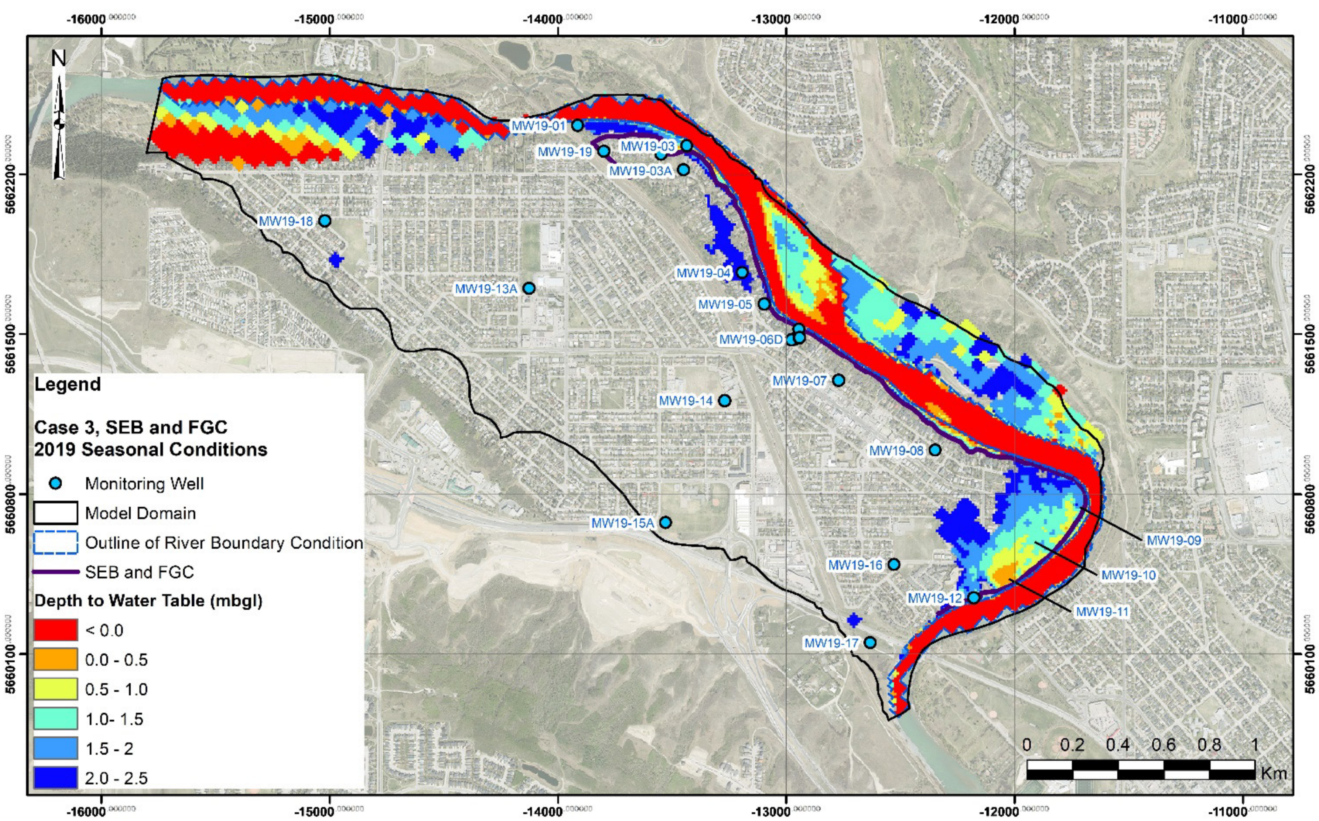
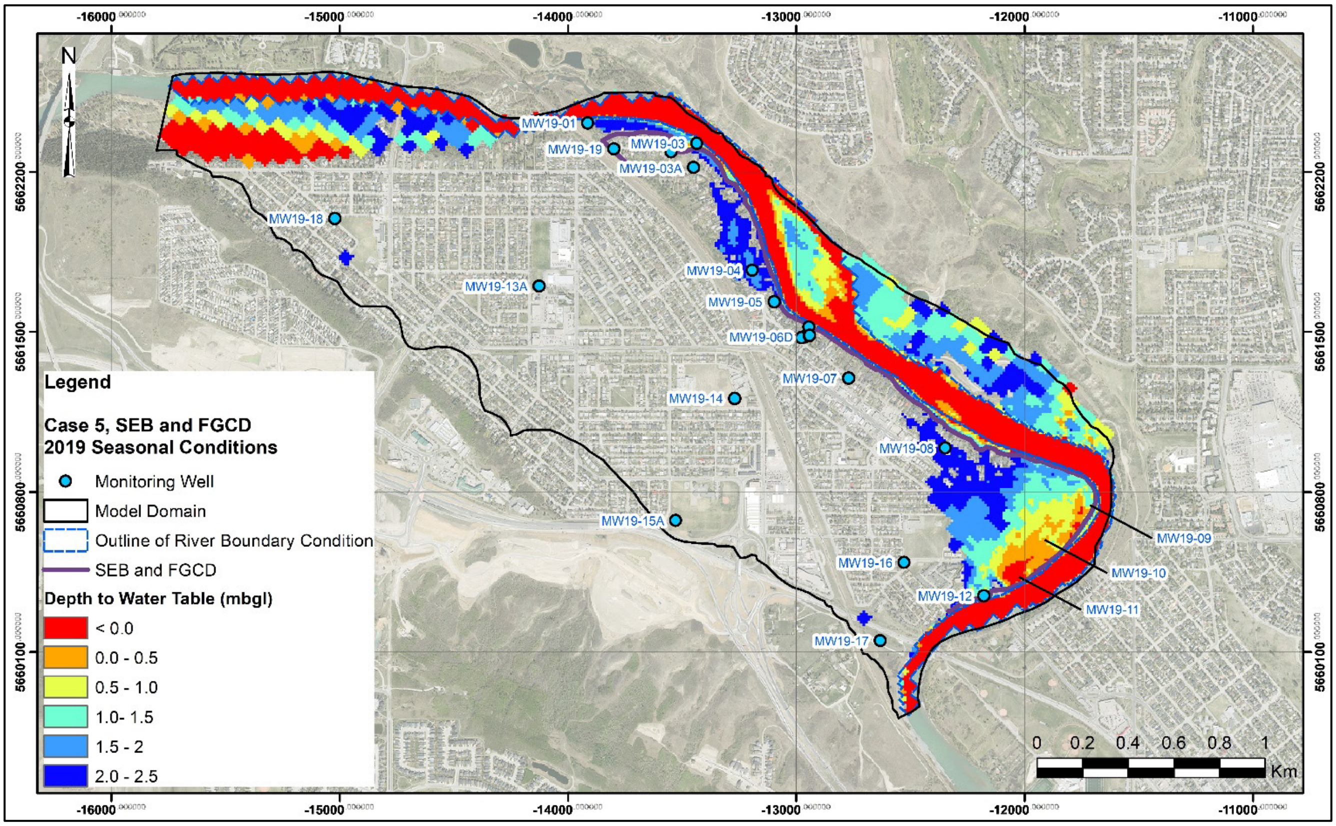


Figure V-1.5 Case 5: Depth to Peak Water Table, SEB + FGCD, June 25, 2019 Condition



Key hydrographs for these simulations are presented in Figure V-1.6, together with the hydrographs without barriers. The hydrographs clearly show the attenuating effect of the groundwater cut-off wall on river-induced groundwater fluctuations for wells on the landward side of the wall (e.g. MW19-02, MW19-06 and MW19-09) and the progressive rise in water table to the southeast. The predicted peak water table at MW19-09 is about 1.3 mbgs. The simulation does not cover an entire year, but it is apparent that the water table would gradually decline from the peak levels in July to a low water table in March or April, although these low levels would be above normal levels without the cut-off wall in place.

Figure V-1.6 Cases 3 and 5: Key Hydrographs, SEB + FGC/FGCD, 2019

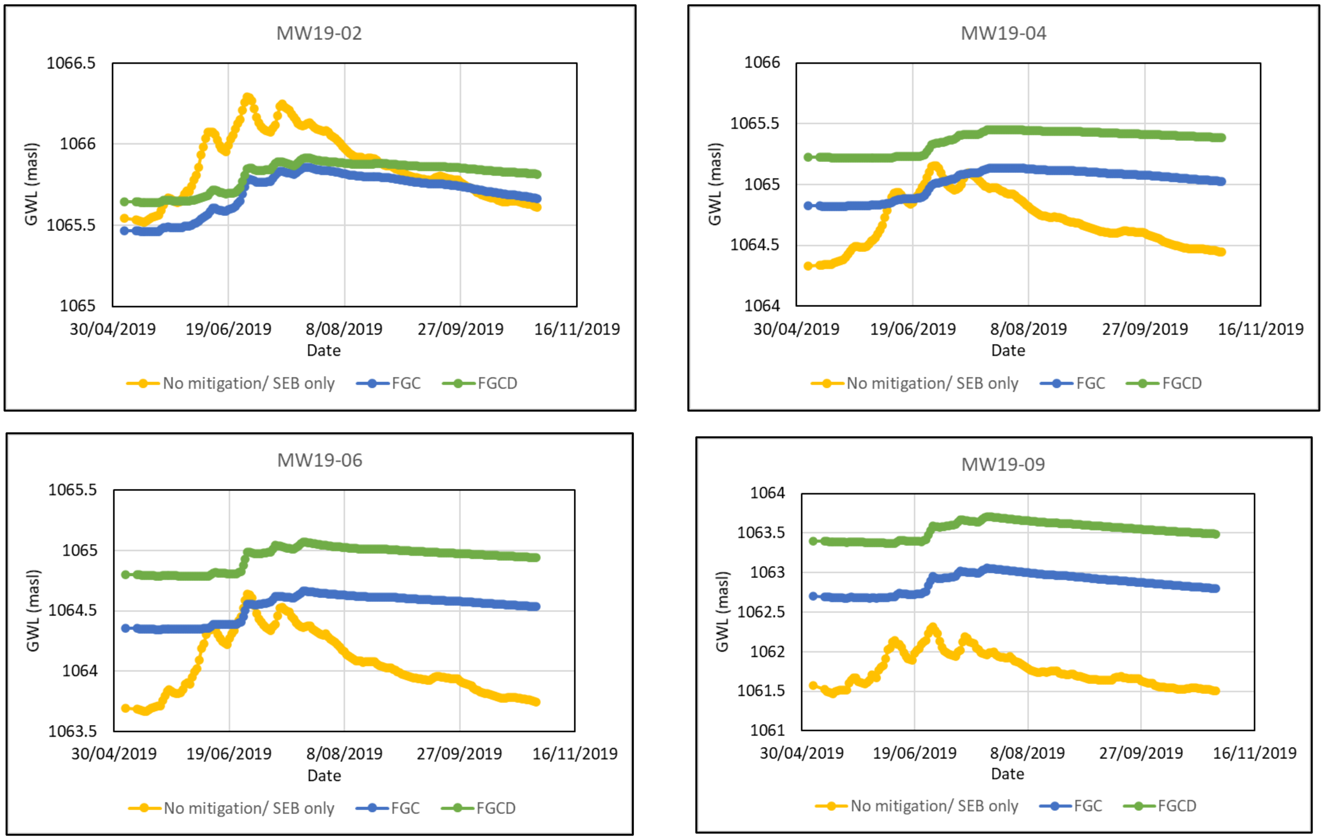
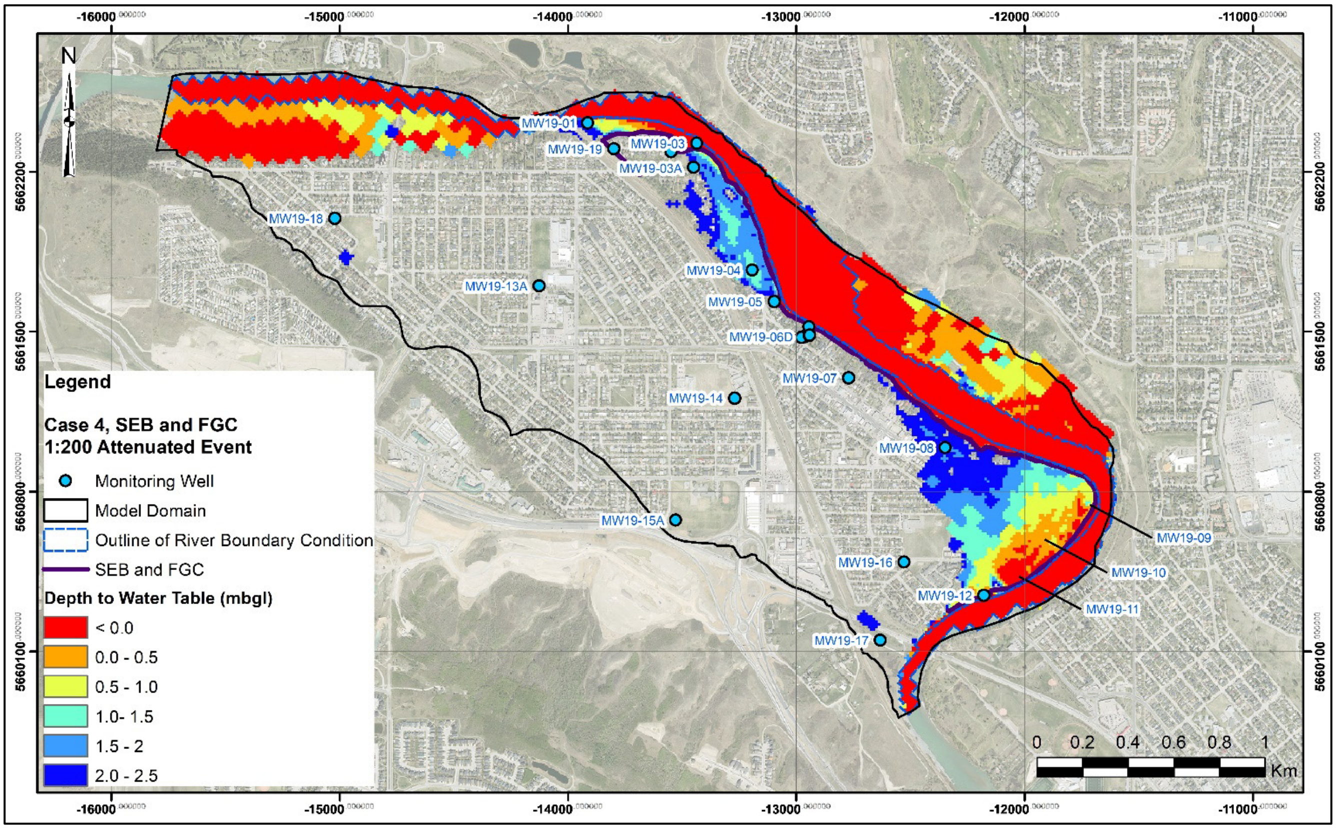


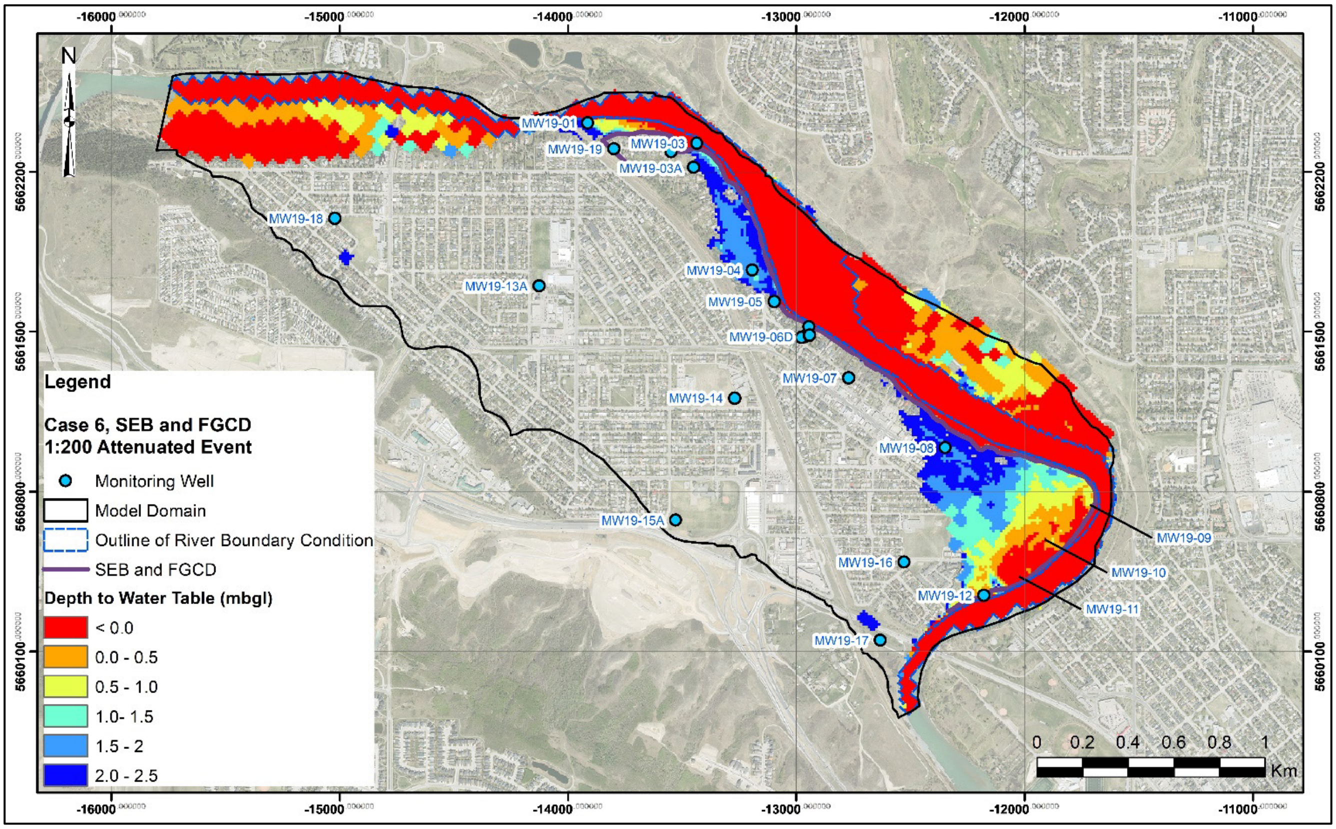
Figure V-1.7 and Figure V-1.8 present depth to peak water table during the 1:200 Attenuated Event for the Case 4 (FGC) and Case 6 (FGCD) options, respectively. These simulations incorporate the antecedent elevated water table resulting from the “damming” of normal seasonal flows.

Figure V-1.7 Case 4: Depth to Peak Water Table, SEB + FGC, 1:200 Attenuated Event



On this basis, it is apparent that installation of a 'full' groundwater cut-off wall along the entire alignment would be unproductive without some form of mitigation such as truncating the cut-off to allow groundwater flow back to the river or incorporating drains and/or pumping wells behind the cut-off wall to lower groundwater levels.

Figure V-1.8 Case 6: Depth to Peak Water Table, SEB + FGCD, 1:200 Attenuated Event



V-1.3.3 Cases 7 and 8: Alternative Groundwater Cut-off Alignments

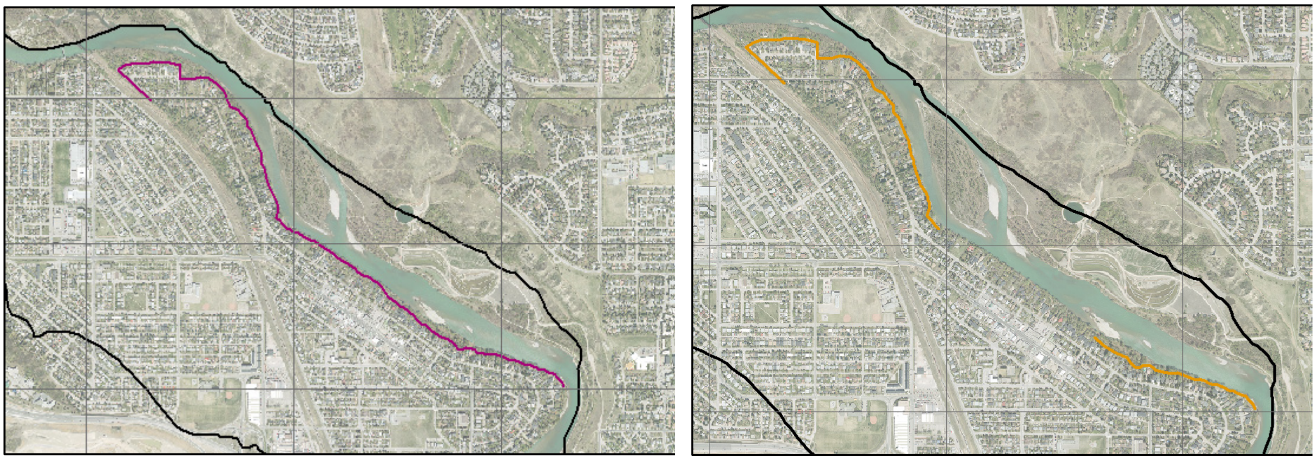
Simulations were subsequently undertaken for a 3 km long, 3 m to 8 m deep 'Truncated' groundwater cut-off (TGC) wall and a 3 m to 7 m deep 'Split' groundwater cut-off (SGC) wall, with an aggregate length of 1.8 km, to provide protection to those areas most sensitive to groundwater flooding and to mitigate some of the groundwater 'damming' affect under 'normal' groundwater flow conditions. The locations of these cut-off wall options are shown in Figure V-1.9.

These cut-off wall alignment options were evaluated for depth extent to the base of the Alluvial Aquifer only. Both alignment options provide a reduction in the areas of predicted surface inundation resulting from water table rise and also areas with water table < 2.5 mbgs during the 1:200 Attenuated Event, as shown in Figure V-1.10 and Figure V-1.11. The TGC provides the highest-level flood protection, while the SGC is the lower cost/ disturbance option,.

The TGC provides a good improvement in performance, almost eliminating surface flooding while lowering peak flood water table levels by up to about 1.2 m.

The SGC also results in effectively no surface flooding, while resulting in a lesser lowering of groundwater level of up to about 1 m in the northwest and southeast ends of the alignment.

Figure V-1.9 (a) 'Truncated' Groundwater Cut-off and (b) 'Split' Groundwater Cut-off Wall Extents



Key hydrographs for all cut-off wall options with reference to the SEB alone, and showing ground elevation, river level, and the peak 2019 water table are provided in Figure V-1.12. Remaining hydrographs are contained in Figure V1-7, Appendix V1.

Figure V-1.10 Case 7: Depth to Peak Water Table, SEB + TGC, 1:200 Attenuated Event

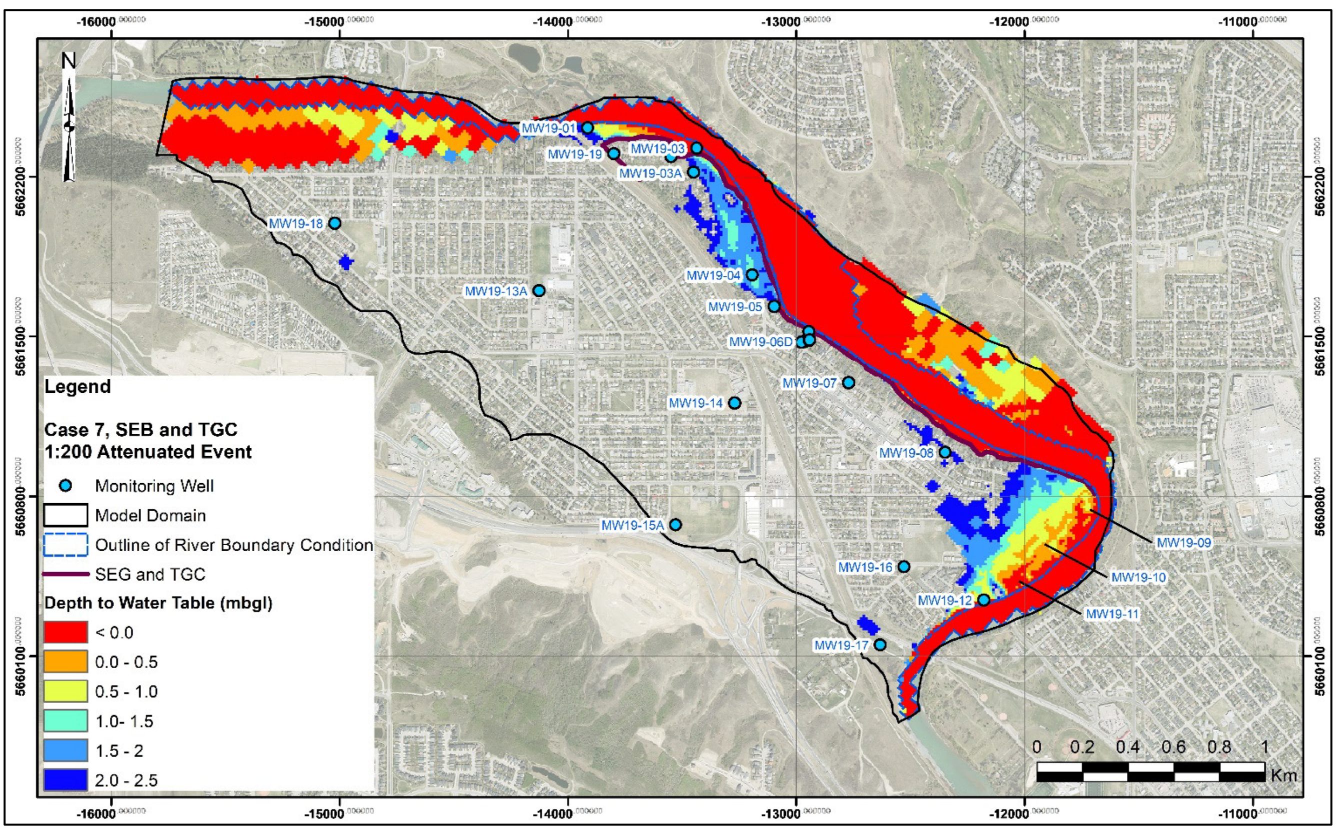


Figure V-1.11 Case 8: Depth to Peak Water Table, SEB + SGC, 1:200 Attenuated Event

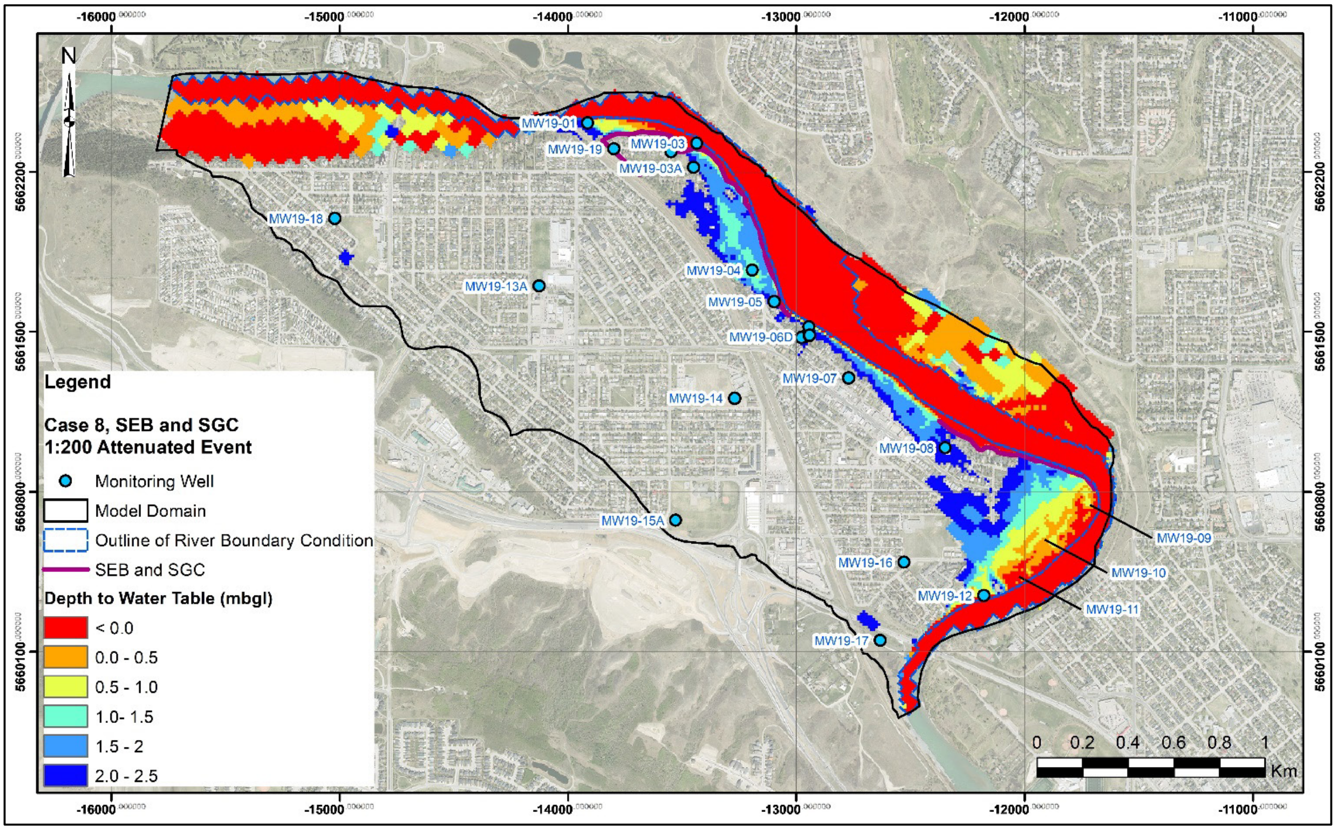
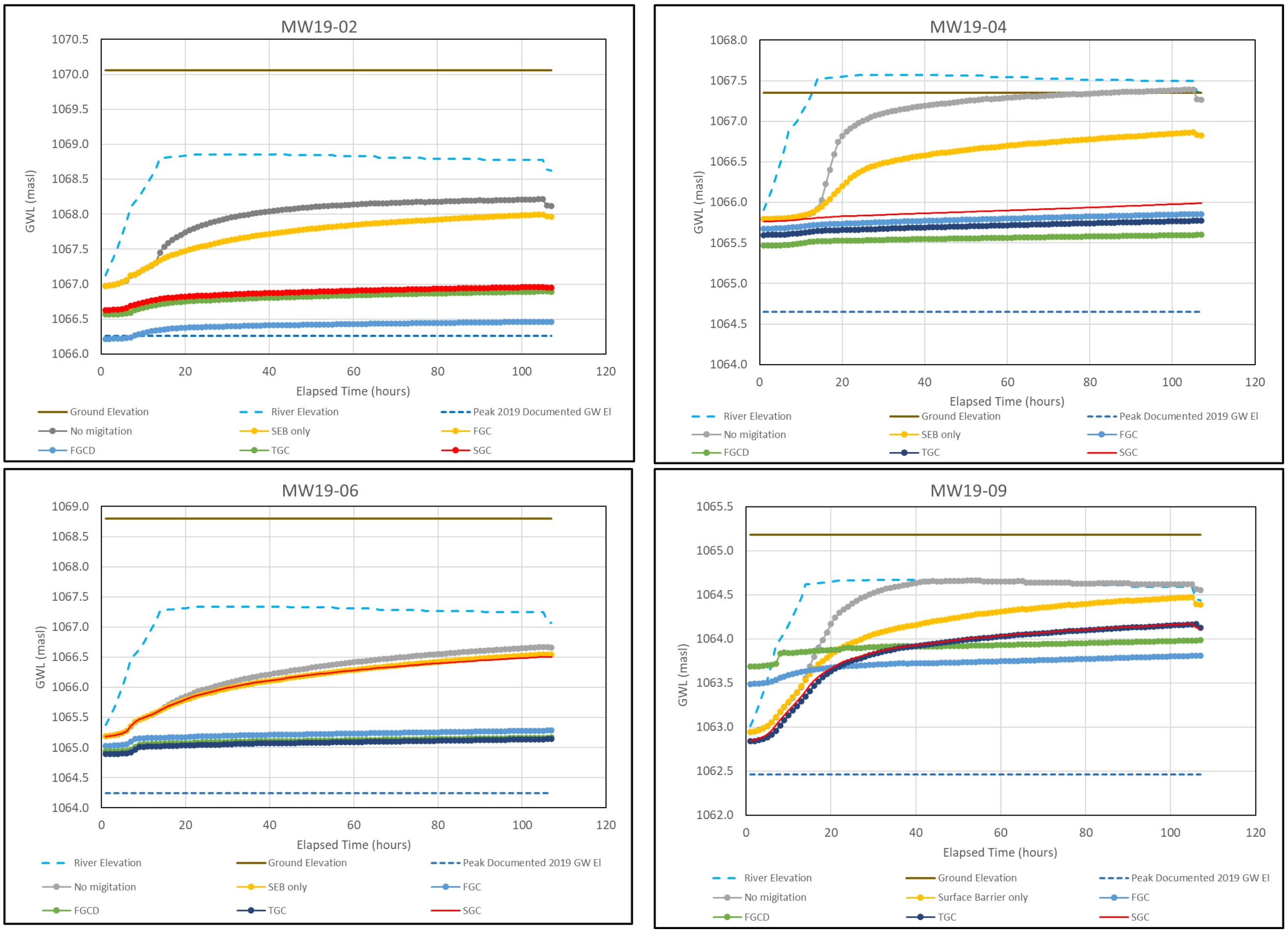


Figure V-1.12 Key Hydrographs, Groundwater Cut-off Options, 1:200 Attenuated Event



V-1.3.4 Cases 9 and 10: Groundwater Cut-off Wall with Drain

To compensate for the 'damming' effect that the cut-off wall has on groundwater flow to the Bow River, and particularly at the southeast end of the barrier alignment, a simulation was run with a groundwater interception or 'French' drain placed in the southeastern end of the alignment (Southeast Drain) on the inside (inland or west side) of the flood barrier.

The Southeast Drain design specifications are as follows:

Length:	800 m	
Installation Depth:	3 mbgs to 4 mbgs	
Drain Head Elevation:	NE end:	(Sim 1) 1062.3 metres above means sea level (masl) (Sim 2) 1062.8 masl
	SW end:	(Sim 1) 1061.4 masl (Sim 2) 1061.9 masl
Drain Conductance:	Equivalent to highest Sandy Gravel hydraulic conductivity	

As indicated above, the SE Drain was simulated for the 2019 Conditions for two differing operating levels and with the FGC in place.

Figure V-1.13 shows the drain location and areas where the water table is < 2.5 mbgs for both drain operating head conditions. The lower drain operating level (Sim 1) maintains peak water table levels below the 'normal' groundwater peaks, while the upper drain operating level (Sim 2) maintains peak water levels at or slightly above the 'normal' peak levels.

The drains would serve to reduce the water table elevation to, or below, pre-groundwater cut-off wall levels during 'normal' river flow periods and would typically only be operated for two months of the year. The lower drain operating level (Sim 1), however, requires relatively higher pumping rates during high river periods (typically 2 L/s to 6 L/s), as shown in Figure V-1.14, with higher flows passing below the cut-off wall from the river. The higher operating level (Sim 2) typically requires pumping at rates of between 1 L/s and 4 L/s during the summer months. Hydrographs for this option are presented in Figure V1-8, Appendix V1.

Figure V-1.13 Case 9: Depth to Peak Water Table, w/wo SEB + FGC + SE Drain, Simulation 1 (Lower Drain Elevation), June 25, 2019

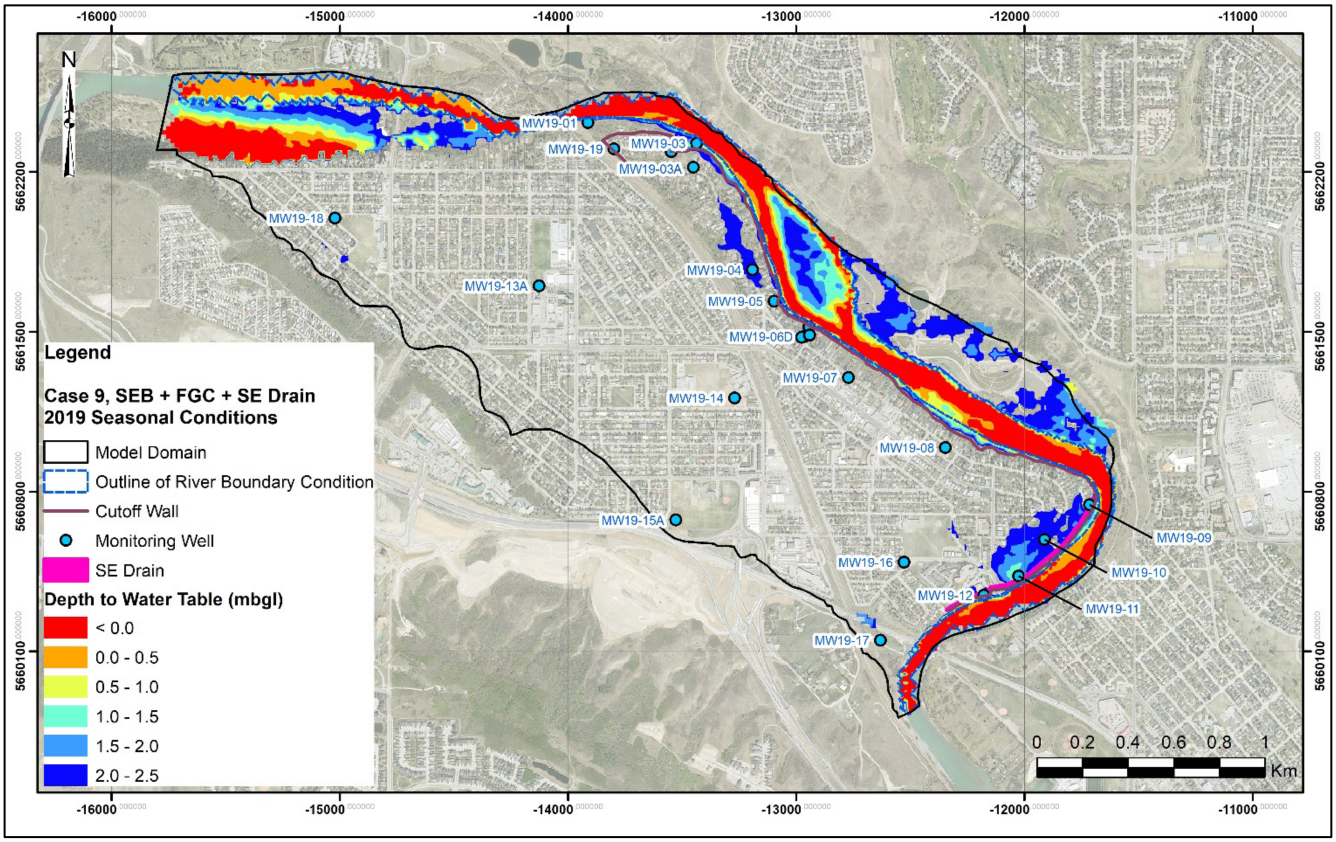
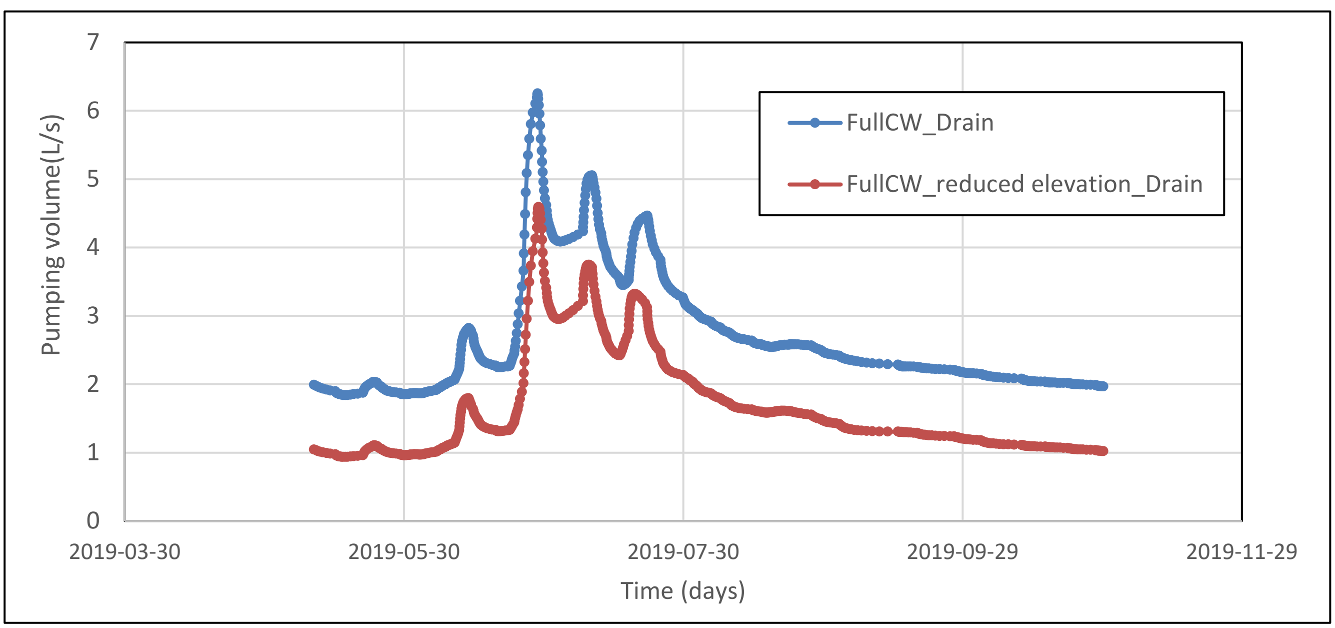
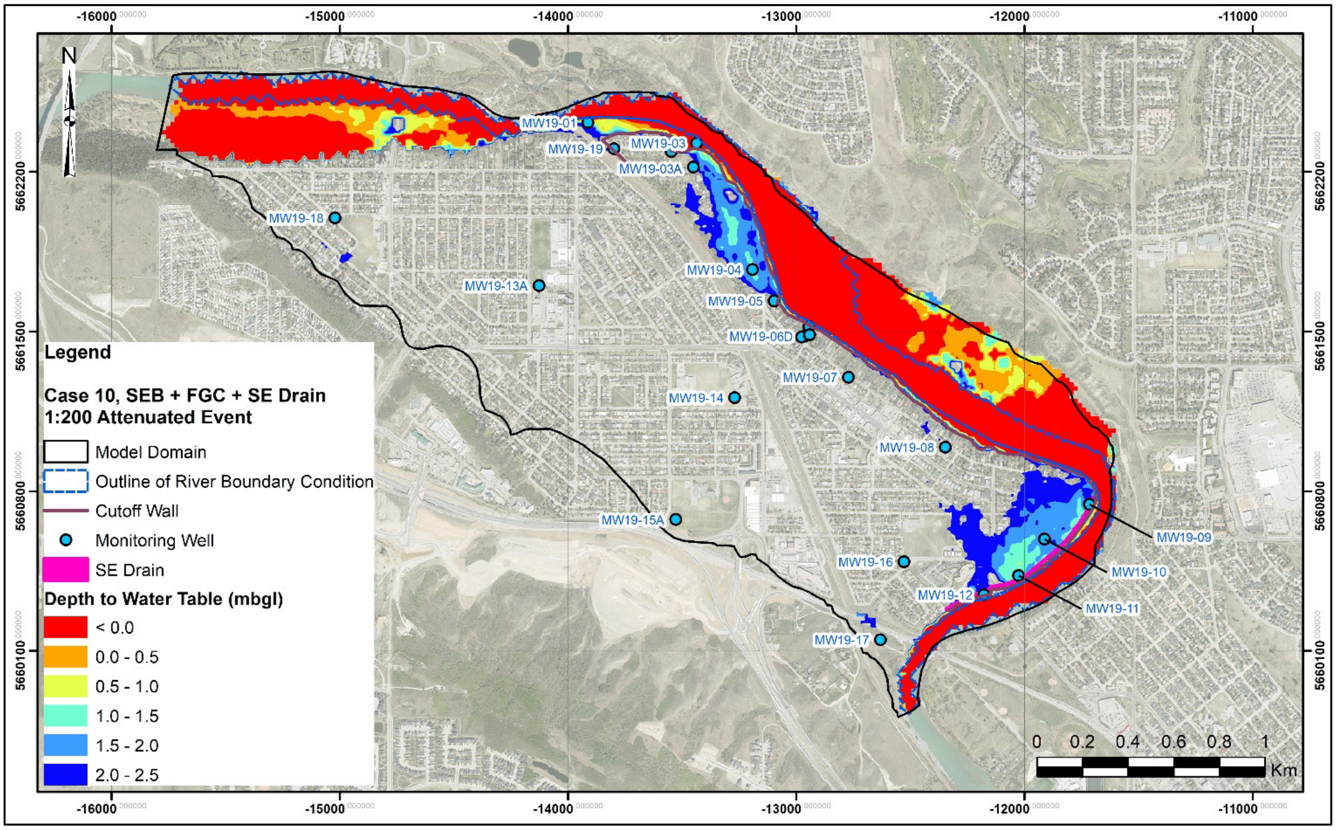


Figure V-1.14 Case 9: Drain Pumping Rates, SEB + FGC + SE Drain, 2019 Conditions



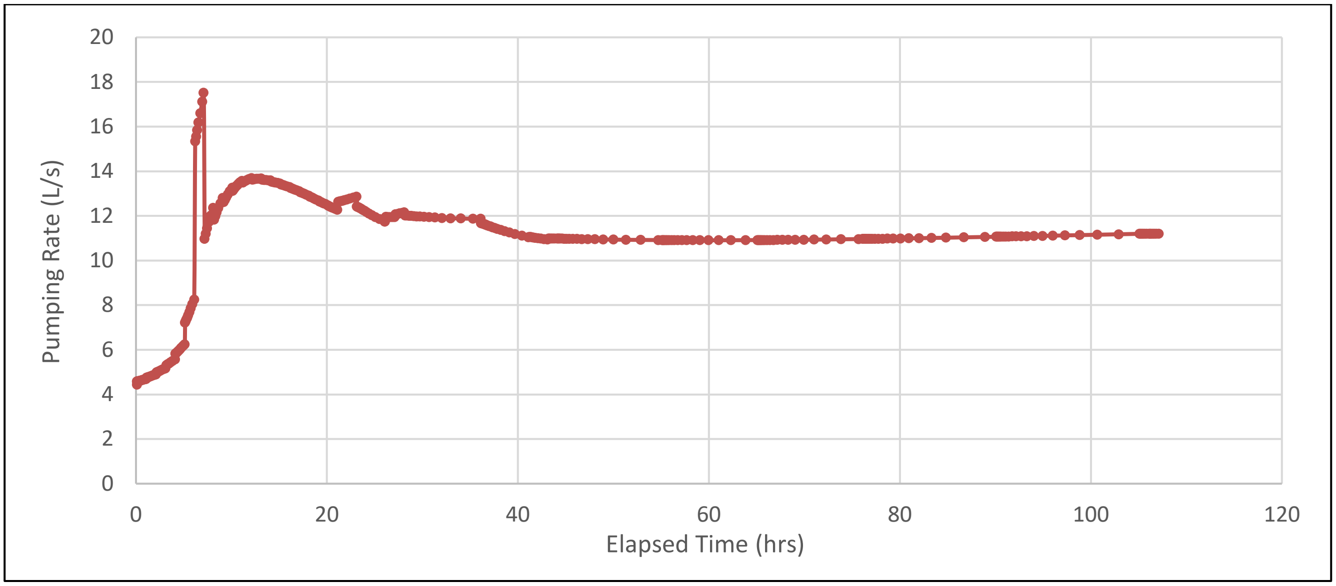
The drains would also be utilized to remove any excess river flows passing under the groundwater cut-off wall during flood periods. Figure V-1.15 shows depth to peak water table for the lower operating level during the 1:200 Attenuated Event. The deeper operating head scenario results in areas of water table lower than normal peak seasonal levels.

Figure V-1.15 Case 10: Depth to Peak Water Table, SEB + FGC + SE Drain, Simulation 1 (Lower Drain Elevation), 1:200 Attenuated Event



Predicted drain pumping rates for both drain operating levels are shown in Figure V-1.16.

Figure V-1.16 Case 10: Drain Pumped Flows, SEB + FGC + SE Drain, 1:200 Attenuated Event



V-1.3.5 Cases 11 and 12: Groundwater Cut-off Wall with Pumping Well

A second alternative was evaluated for reducing high water tables in the key southeast area of the flood barrier alignment through the periodic water extraction from a single shallow pumping well installed in the Alluvial Aquifer. In practice, a backup pumping well would also be utilized. These wells would essentially serve the same function as the Southeast Drain and may be potentially less invasive from a construction standpoint. A single pumping well was simulated as summarized in Table V-1.2, with its location shown in Figure V-1.17. The well was simulated as pumping at 2 L/s during high water conditions in 2019 and during the 1:200 Attenuated Event.

Table V-1.2 Notional Pumping Well Construction Details

Easting	Northing	Surface Elevation (masl)	Top Gravel and Sand (masl)	Bottom Gravel and Sand		Gravel and Sand Thickness (m)	Pumping Rate (L/s)
				masl	mbgs		
-12047.7	5660432	1063.1	1062.4	1058.7	4.4	3.7	2.0

Note: The well was simulated with screened interval extending to depths between 2.6 and 4.4 mbgs.

Figure V-1.17 shows depth to water table for the SEB plus FGC plus 1 pumping well for June 25, 2019. The simulations indicate that the well is effective in maintaining peak water levels at or below the normal seasonal peak levels. Figure V-1.18 shows the FGC and well maintain the water table less than one metre above the peak 2019 water table during the 1:200 Attenuated Event. A better drawdown performance during the 1:200 Attenuated Event may be obtained by increasing the pumping rate to match the 2019 peak water table, and by placing the well further north.

Key hydrographs for cut-off wall and drain or pumping well scenarios are presented in Figure V-1.19. Remaining hydrographs are presented in Figure V1-8, Appendix V1.

Figure V-1.17 Case 11: Depth to Peak Water Table, SEB + FGC + 1 Pumping Well, June 25, 2019

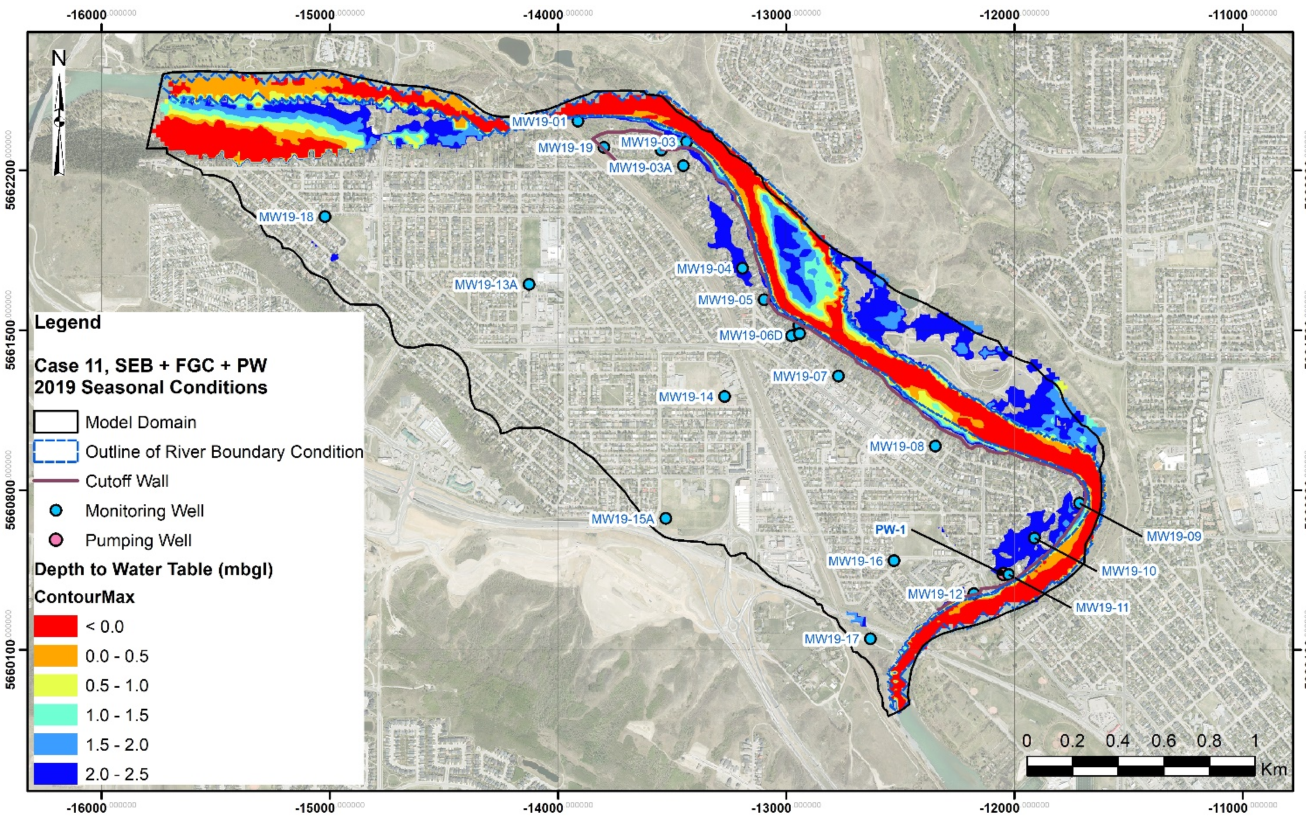


Figure V-1.18 Case 12: Depth to Peak Water Table, SEB + FGC + 1 Pumping Well, 1:200 Attenuated Event

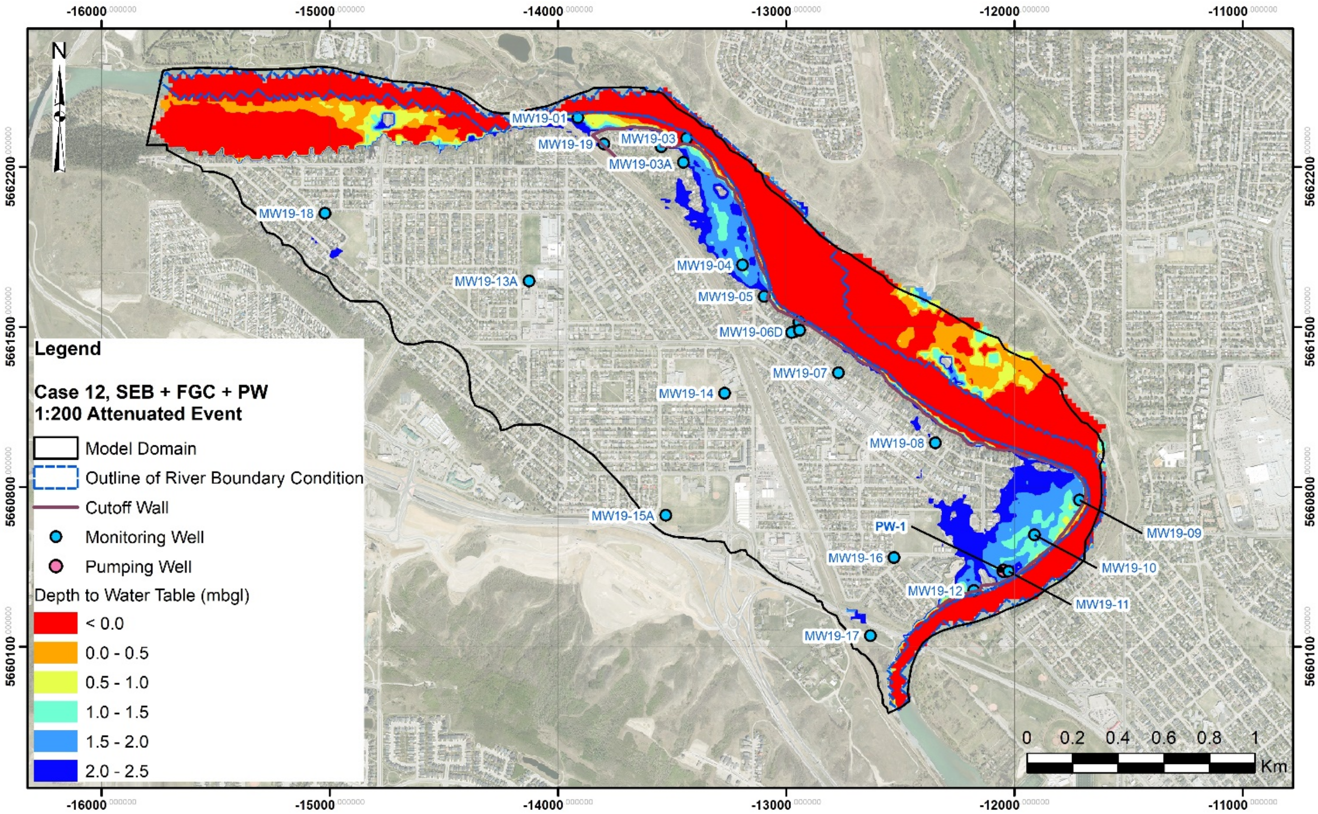
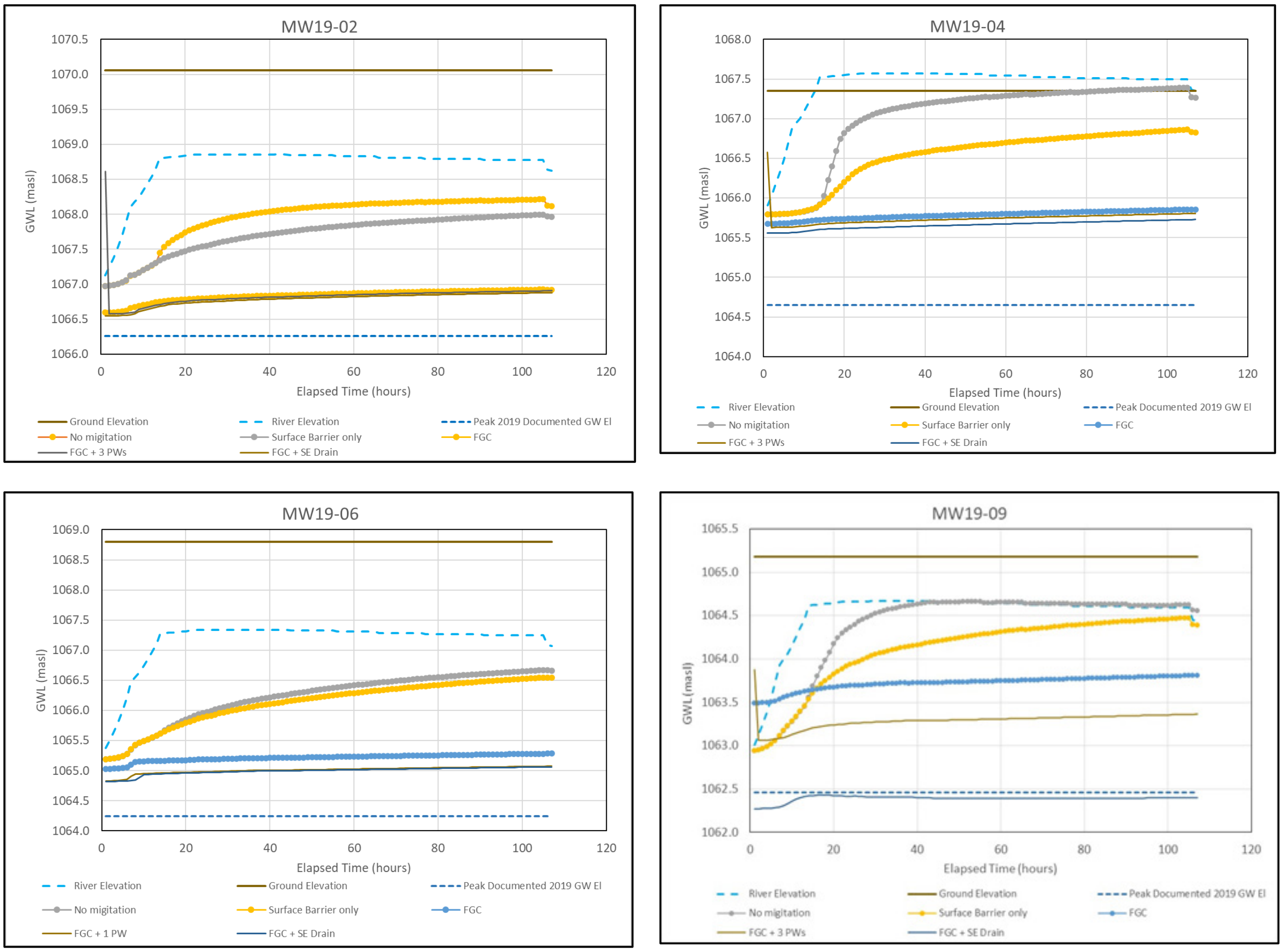


Figure V-1.19 Cases 9 to 12: Key Hydrographs, SEB + FGC + SE Drain or Pumping Wells, 1:200 Attenuated Event



Note: GWL – groundwater level

V-1.3.6 Case 13: 'Full' Barrier Drain

A Full Barrier Drain (FBD) was also evaluated for the entire length of the SEB alignment. The drain would have similar basic design to the Southeast Drain. The full interceptor drain design specifications are as follows:

Length:	3700 m
Installation Depth:	2.5 mbgs to 4.5 mbgs, up to 7.5 mbgs at Bowness Road NW
Drain Head Elevation:	NE end: (**Simulation 1**) 1067 metres above sea level (masl) and (**Simulation 2**) 1066 masl
	SW end: (**Simulation 1**) 1061 masl and (**Simulation 2**) 1060 masl
Drain Conductance:	Equivalent to highest Alluvial Aquifer hydraulic conductivity

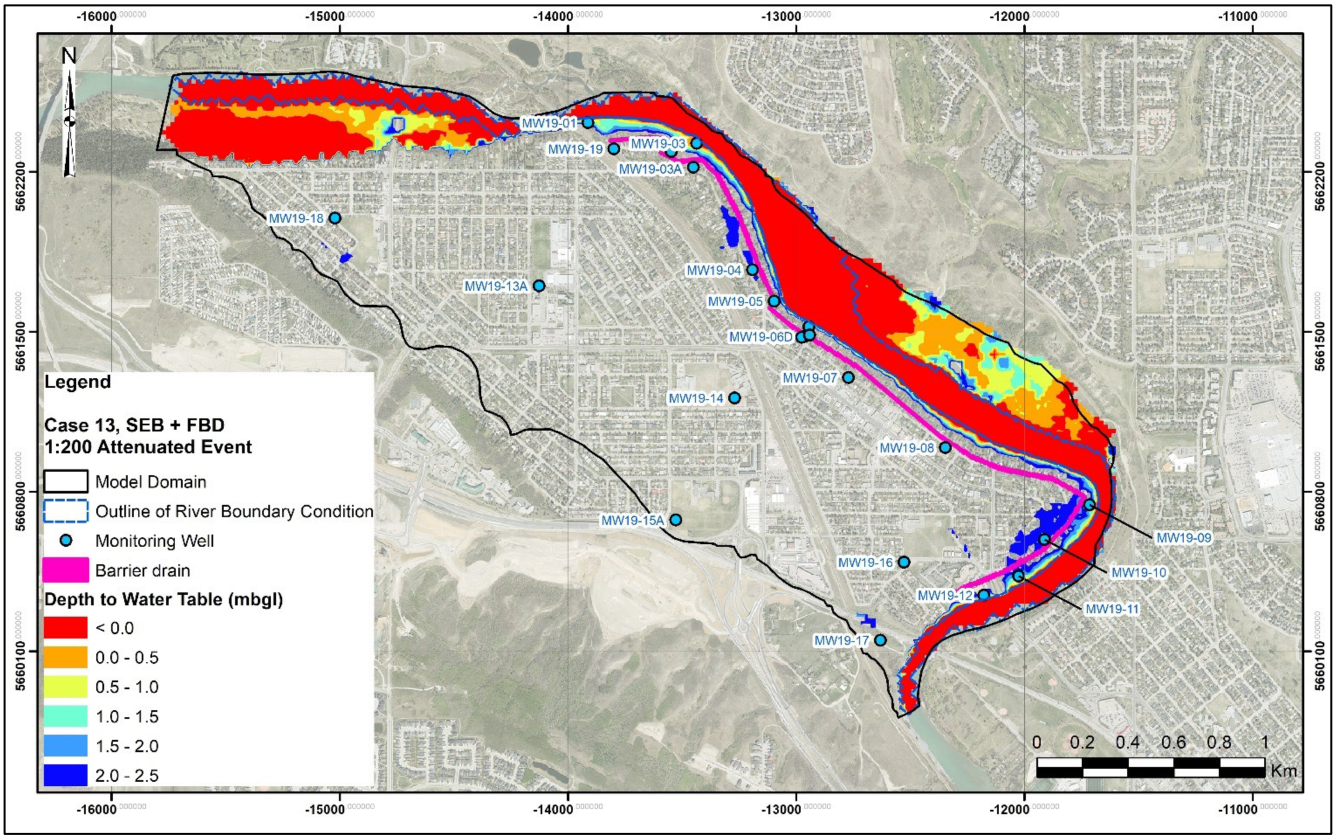
A plan view of the drain is provided in Figure V-1.20.

As envisioned, the drain would not be operated during normal river flow and water table conditions, but would be activated prior to and during a flood event. This drain, together with the SEB, was then evaluated to assess the system performance during the 1:200 Attenuated Event.

Figure V-1.20 shows the drain performance for Simulation 2 and indicates that the barrier drain is very effective in maintaining the water table close to 'normal' peak levels and ensuring no surface inundation occurs.

Best estimate pumped flows for the lower operating level (Full Barrier Drain) during the 1:200-year Attenuated Event are presented in Figure V-1.22. Indicated peak flows are expected in the range of 325 L/s for the entire drain length to maintain the water table at, or near, peak 2019 levels. Pumped volumes would be significantly higher should actual near-river Alluvial Aquifer K values be higher than represented in the "best estimate" model. Pumped volumes would be significantly lower for lesser drainage objectives. Barrier drain hydrographs are presented in Figure V2-1, Appendix V2.

Figure V-1.20 Case 13: Depth to Peak Water Table, 1:200-year Attenuated Event, SEB + FBD, Simulation 2 (Lower Operating Level)



V-1.3.7 Case 14: Split Barrier Drain

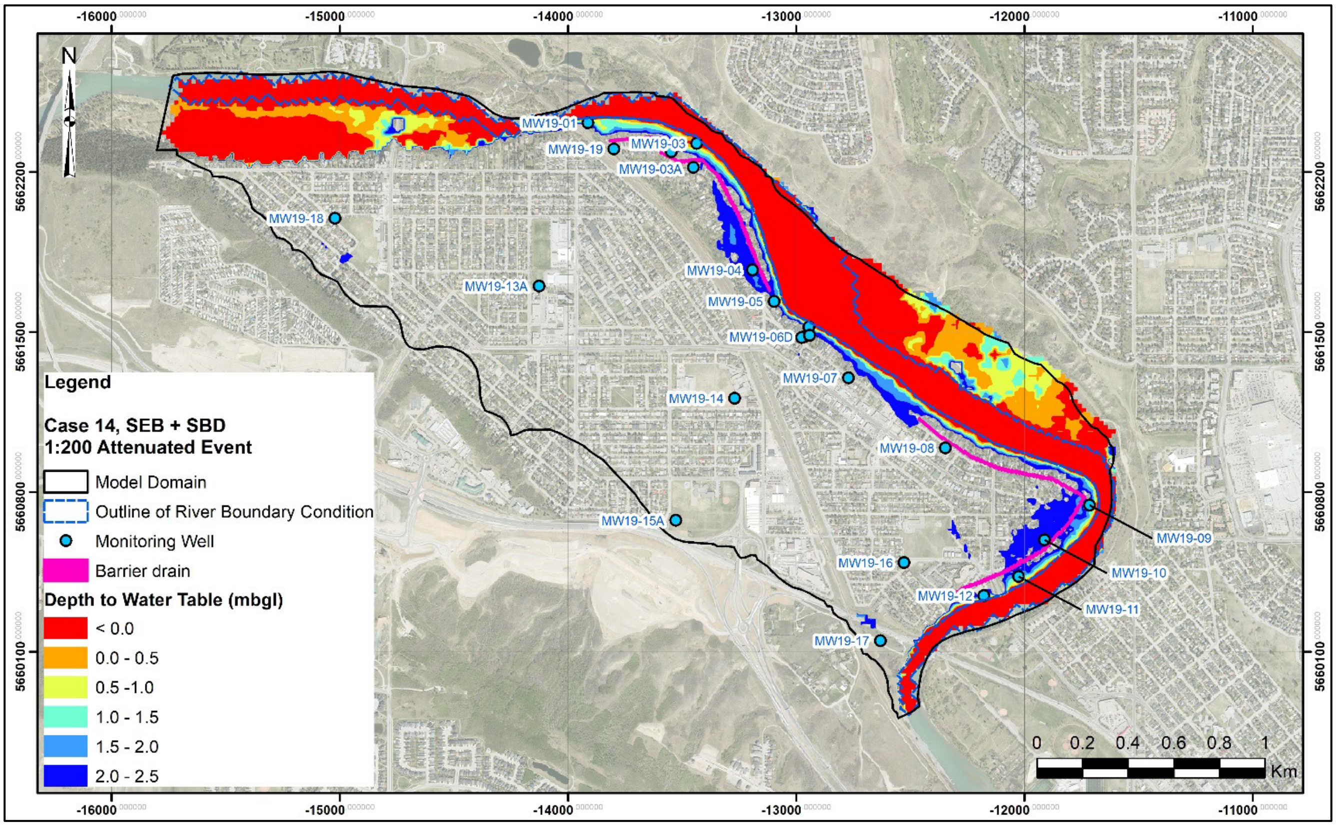
A further option was evaluated; the use of a 'Split' Barrier Drain (SBD), consisting of two barrier drain sections, whose locations correspond to the location of the SGC evaluated in Section V-1.3.3. The construction of this drain would be less invasive and lower cost than the FBD.

The drain specifications are as follows:

Aggregate Length:	2700 m	
Installation Depth:	3.5 to 4.5 mbgs	
Drain Head Elevation:	NE end:	1066 masl
	SW end:	1060 masl
Drain Conductance:	Equivalent to highest Alluvial Aquifer hydraulic conductivity	

A plan view of the drain is provided in Figure V-1.21.

Figure V-1.21 Case 14: Depth to Peak Water Table, SEB + SBD, (Lower Operating Level), 1:200 Attenuated Event



The results indicate that the SBD lowers piezometric levels to at or just above peak 2019 levels, along the two drain segments during the 1:200 Attenuated Event with a predicted peak pumping rate from both drain sections in the order of 230 L/s (Figure V-1.22), to meet or exceed peak 2019 water table along the two drain alignments. This rate is approximately 100 L/s less than that predicted for the FBD (Section V-1.3.6).

As a test of upper end drain flows, the Case B uncertainty testing model (see Section 6.1.3 of main report- K increased by a factor of 5 and recharge by a factor of 2) was used to re-simulate Case 14. Peak drain flows of about 510 L/s were encountered under this scenario. With higher Alluvial Aquifer K values, the K of the surficial Silty/ Clayey Topsoil unit increasingly restricts downward flow to the aquifer under this scenario.

Barrier drain hydrographs for key monitoring wells are shown in Figure V-1.23. Remaining hydrographs are presented in Figure V2-1, Appendix V2.

Figure V-1.22 SEB + FBD and SEB + SBD Drain Pumped Flows, 1:200-year Attenuated Flood Event

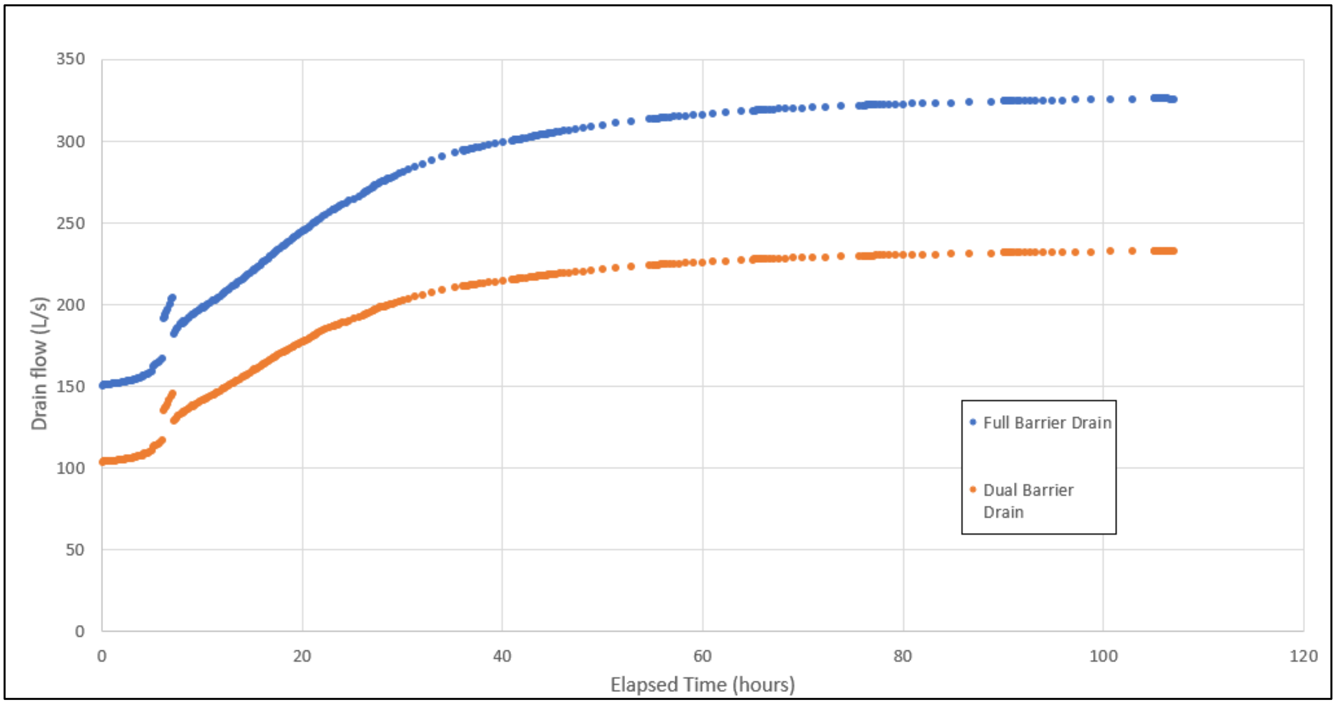
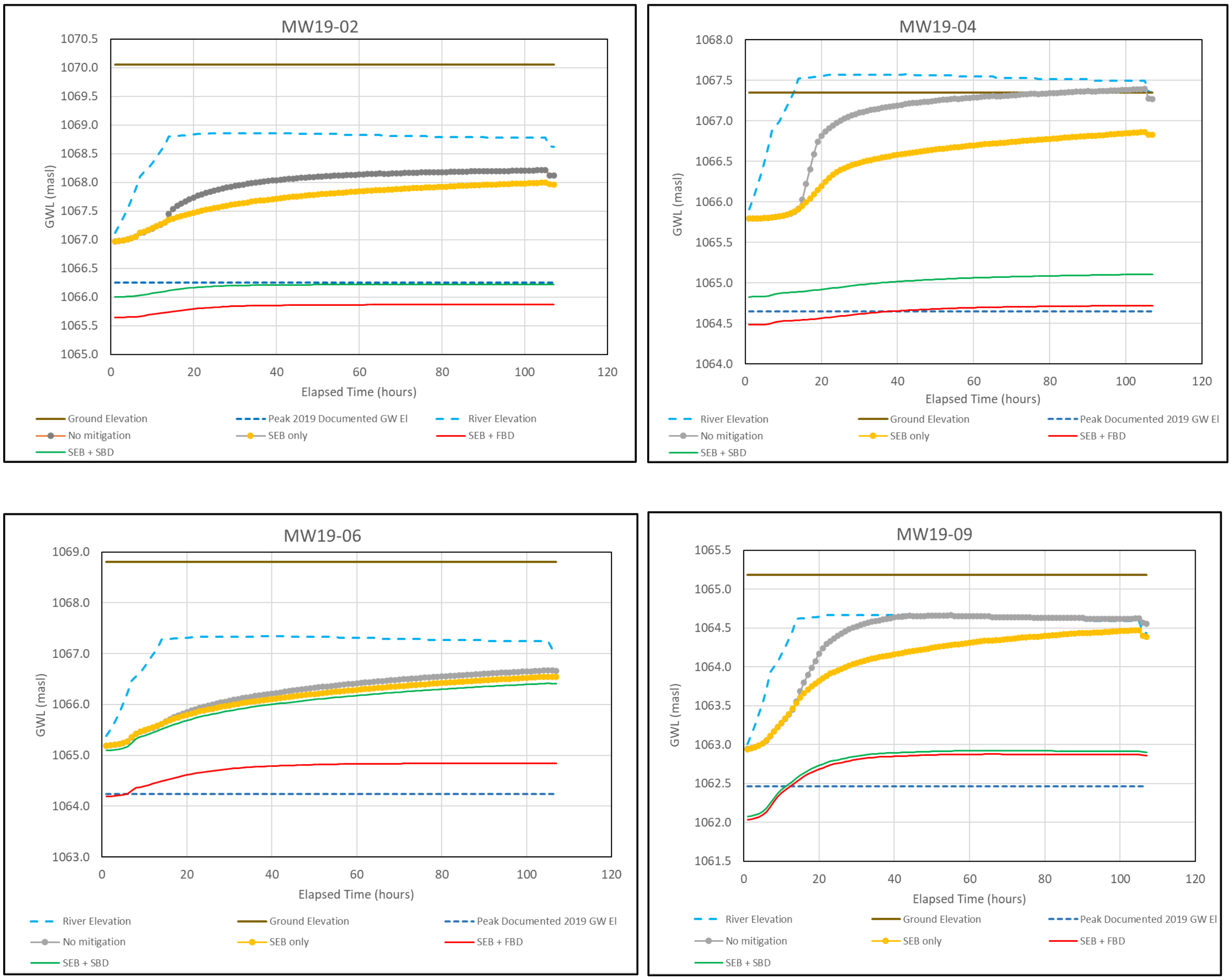


Figure V-1.23 Case 14: Key Hydrographs for Barrier Drain Scenarios



V-1.3.8 Case 15: 'Barrier' Pumping Wells

Standalone 'Barrier' pumping wells were simulated in place of the Case 15 SBD, in view of the potential for a reduced construction impact associated with this option.

The nominal well specifications are as follows:

Quantity of Pumping Wells:	11 or 2
Depth:	~6 to 8 m (to ~ 1 m below base of aquifer)
Casing nominal diameter:	250 mm (10")
Well screen length/ design:	3 to 4.5 m, stainless steel continuous slot, wire-wound
Sump length:	1 to 2 m
Pumping rate:	5 L/s x Available Drawdown (AD = 2/3 aquifer thickness)
Well locations:	'Inside' SEB at accessible locations along SBD alignment

The wells were simulated under 1:200 Attenuated event conditions, with two drainage objectives:

1. Objective 1: 11 wells maintain groundwater levels during 1:200 Attenuated Flood below the simulated peak 2005 Flood levels (Section 4.5 of main report);
2. Objective 2: 2 wells eliminate groundwater-induced surface inundation.

Figure V-1.24 shows the depth to peak water table during the 1:200 Attenuated event for Objective 1 With the use of 11 notional pumping wells, groundwater water levels are largely maintained at, or below, peak 2005 flood levels. This is shown in the hydrographs for key monitoring wells in Figure V-1.27. Peak pumped flow is about 240 L/s, as shown in Figure V-1.26.

Figure V-1.25 shows depth to peak water table during the 1:200 Attenuated event for Objective 2. In this simulation, groundwater-induced surface flooding has been eliminated with the use of two pumping wells located in the southeast portion of Bowness. Peak pumped flow is about 50 L/s, as shown in Figure V-1.26.

Key hydrographs for the simulations are presented in Figure V-1.27. Remaining hydrographs are presented in Figure V3-1, Appendix V3.

Figure V-1.24 Case 15: Depth to Peak Water Table, SEB + Barrier Wells 1:200-year Attenuated Event – Objective 1 (11 wells, match 2005 levels)

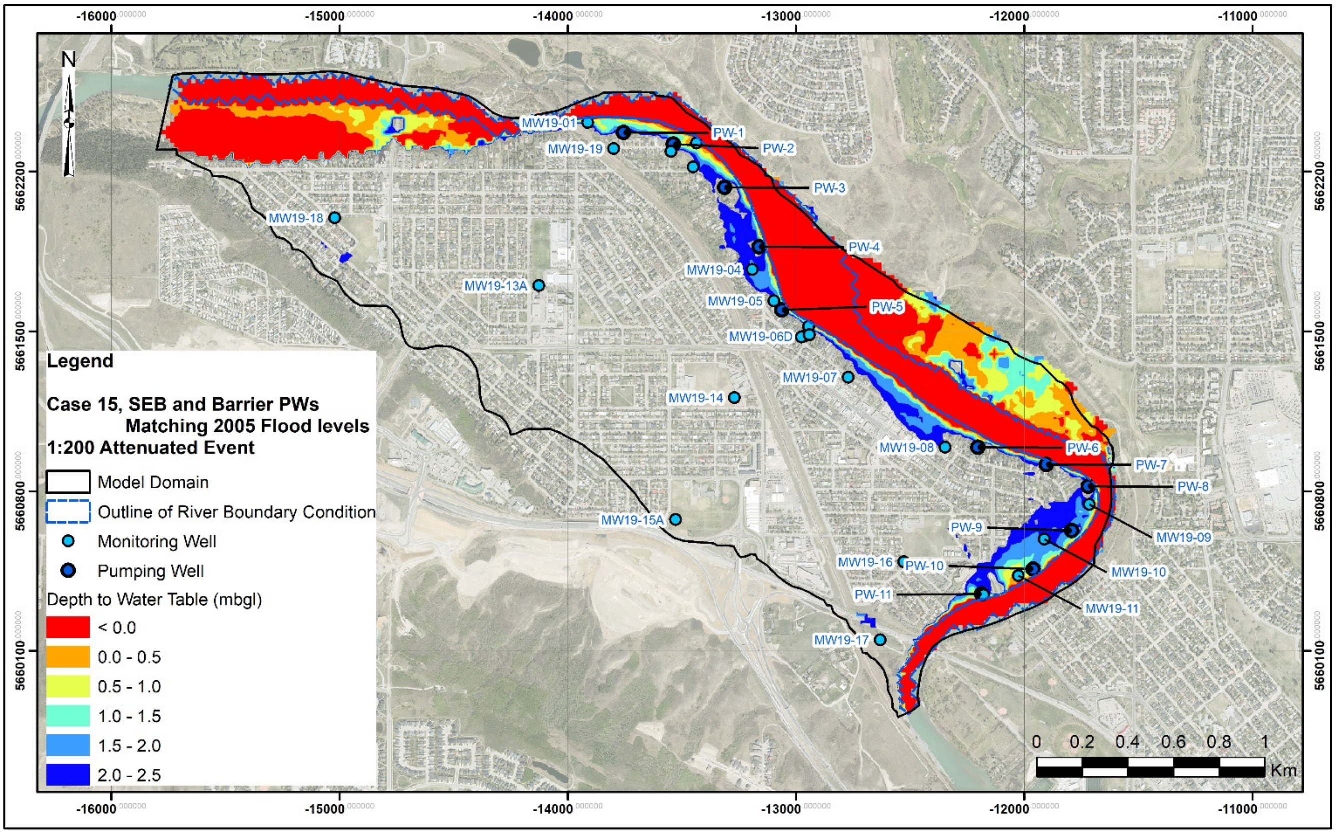


Figure V-1.25 Case 15: Depth to Peak Water Table, SEB + Barrier Wells 1:200-year Attenuated Event – Objective 2 (1 well, no groundwater-induced surface flooding)

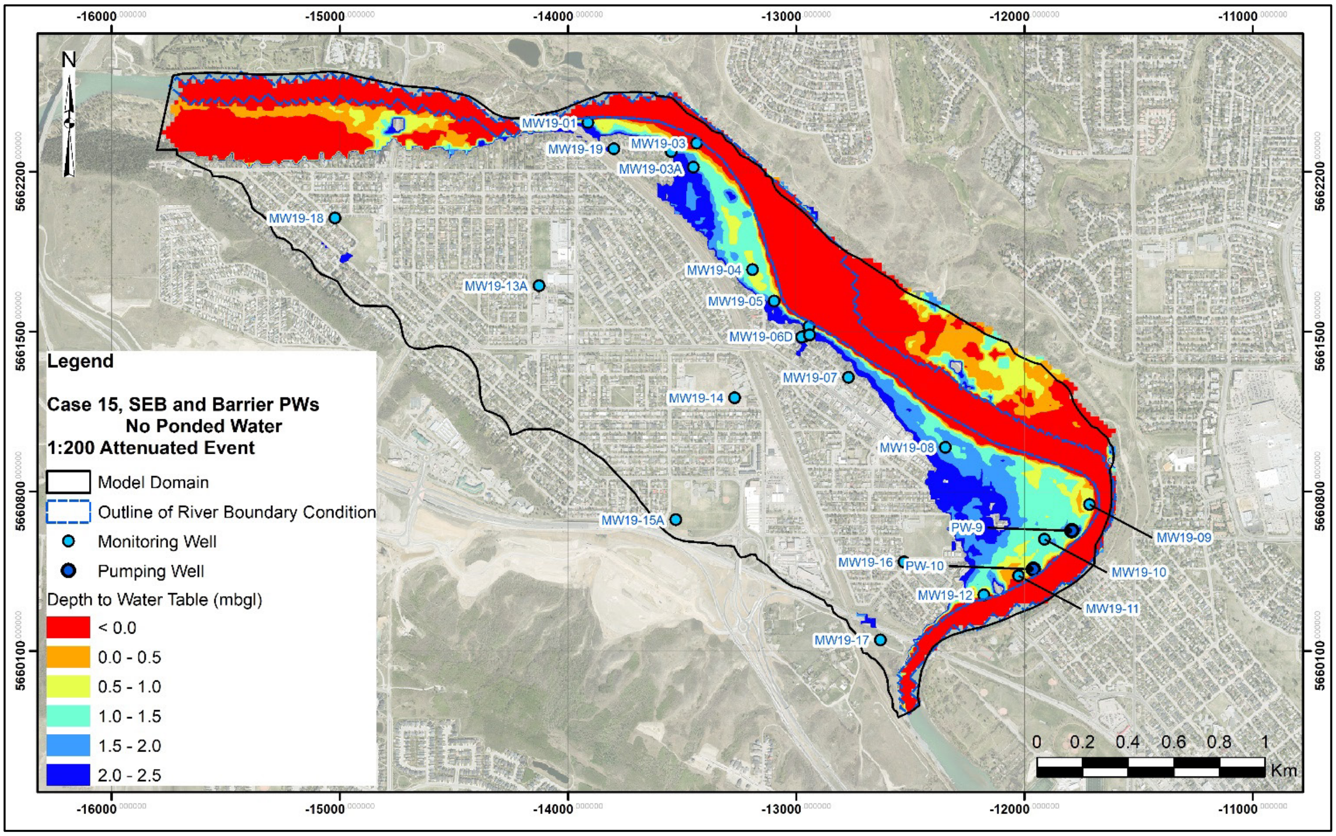


Figure V-1.26 Case 15: SEB + Barrier Well Pumped Flows, 1:200-year Attenuated Flood Event

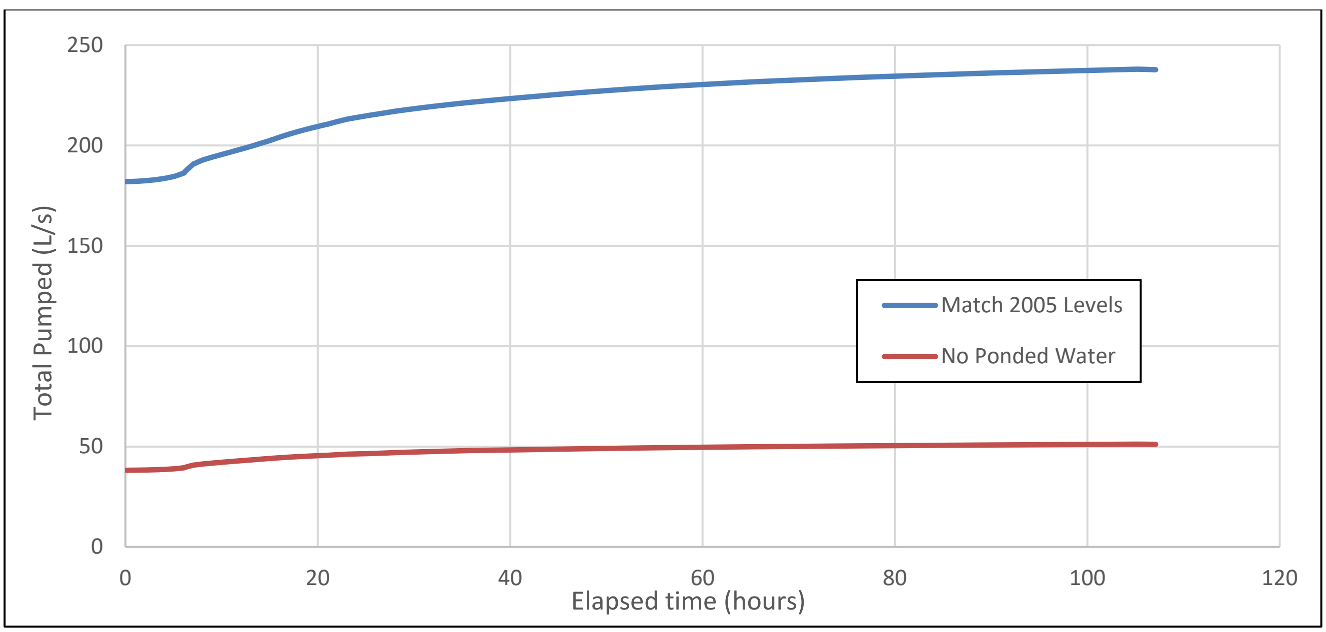
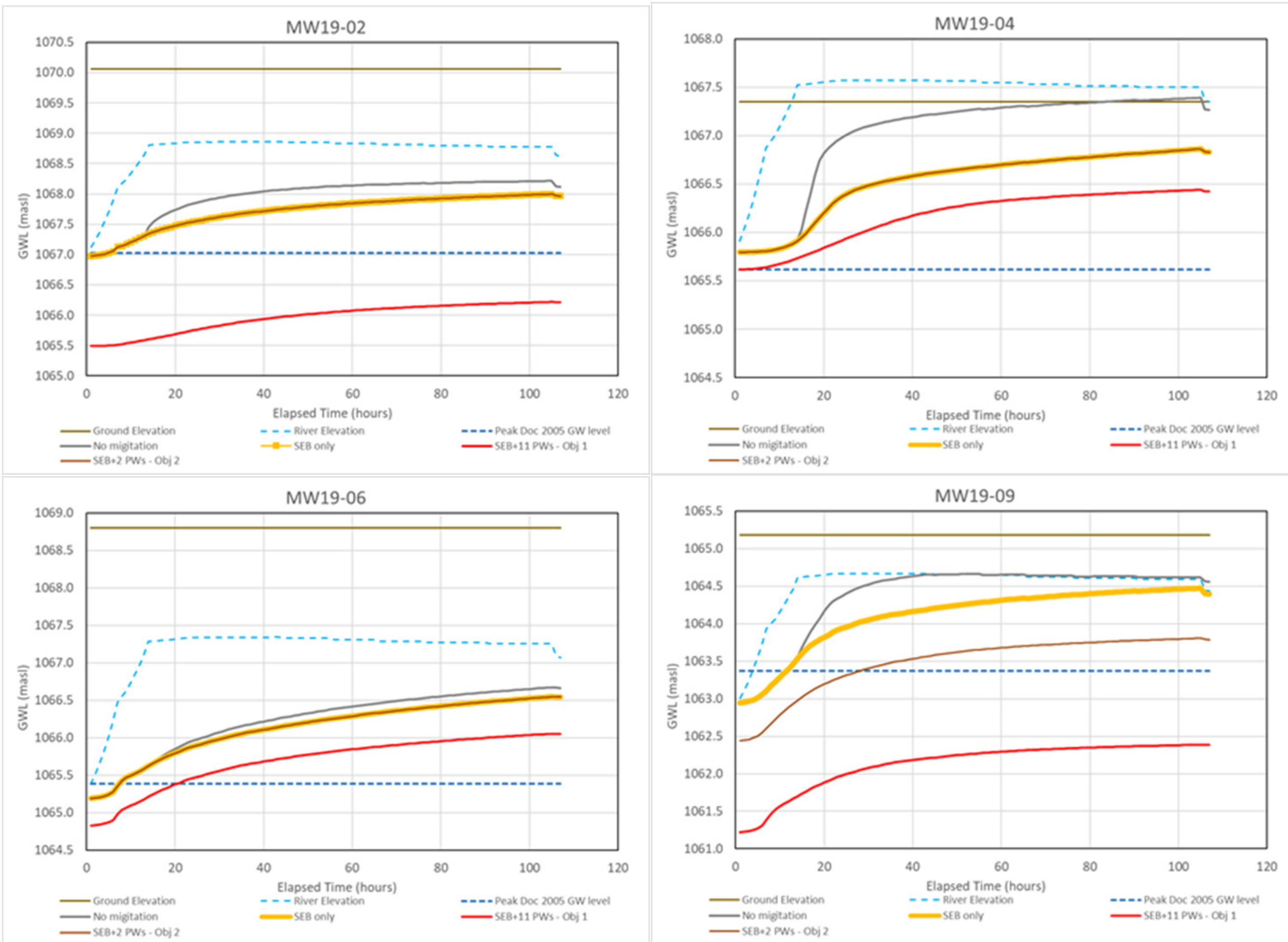


Figure V-1.27 Case 15: Key Hydrographs for Barrier Well Scenarios



V-1.4 Conclusions

A summary of the key outcomes from the conceptual groundwater flood mitigation design simulations undertaken are:

- There is no single passive option available to mitigate groundwater flooding across the entire Bowness community.
- Simulation of the SEB together with a Full Groundwater Cut-off (FGC) wall, or sheet-pile cut-off installed to the base of the Alluvial Aquifer (3 m to 8 m depth), indicates this option would provide some overall protection during flood events, but will result in higher pre-flood water tables, particularly in the southeastern portion of the alignment. To provide effective flood protection, some means of mitigating the higher water levels will be required, particularly in the southeast.
- Simulation of the SEB together with a full groundwater cut-off (FGCD) wall installed to the top of unweathered bedrock (estimated between 5 m and 16 m deep) will provide a high level of flood protection but raises normal seasonal water table levels further than the FGC, necessitating increased mitigation. The significant increase in sheet-pile depth would also increase the cost for this option.
- Simulation of the SEB with a Truncated Groundwater Cut-off (TGC), a 3 km long, 3 m to 8 m deep cut-off wall which extends to the point bar on the southeast end of Bowness only, significantly reduces the groundwater 'damming' effect which occurs behind the barrier while providing up to 1.2 m reduction in the peak water table during the 1:200-year flood. Simulation of the SEB with a Split Groundwater Cut-off (SGC), consisting of two shorter cut-off wall sections, with an aggregate length of 1.8 km and depth of 3 m to 7 m, also significantly reduces the groundwater 'damming' effect, while providing up to 1 m reduction in the peak water table during the 1:200-year flood. However, this latter option does not reduce flood water table levels in the extreme southeast of Bowness, hence some further mitigation is required in this area.
- Simulation of the SEB and FGC together with an 800 m long, approximately 4 m deep, interceptor drain on the inside of the southeast end of the FGC alignment (Southeast Drain) provides a high degree of flood protection, while maintaining water tables at levels similar to current seasonal conditions. The drain would incorporate sumps for pump installation and periodic cleanouts for drain maintenance. Modelled seasonal pumping rates required to maintain 'normal' water tables are estimated at approximately 1 to 4 L/s for the months of June through August. Predicted flows required to maintain water tables at, or near, 'normal' peak water levels during the 1:200 Attenuated Event are estimated at between 4 L/s and 18 L/s.
- A high level of protection can be achieved by combining the southeast interceptor drain with the TGC or SGC at a lower cost than the SEB with FGC and SE Drain.
- Use of one or two pumping wells in southeast Bowness would reduce the groundwater buildup due to the cut-off wall and would likely be less invasive. With the FGC, these wells

would need to pump approximately 2 L/s or slightly more during peak seasonal periods to maintain levels at normal seasonal peaks. During a large flood, pumped flows would likely be in the range of 4 L/s to 18 L/s, which may be accommodated by one or two wells.

- As an alternative to the sheet-pile cut-off walls and interceptor drain combinations, a Full Barrier Drain (FBD) was evaluated. This interceptor drain would extend from 2 m to 7.5 m below ground, with a similar design to the Southeast Drain, and would have an overall length of 3.9 km. The greatest drain depth below ground would occur at Bowness Road NW, and it is possible that a short 'break' in the drain could be incorporated in the design. Much of the remaining drain would be installed less than 4 m below ground. The drain would only be operated during significant flood events. Simulation of the 1:200-year Attenuated Event indicates the best estimate pumping rates could range up to about 325 L/s during the event for the entire alignment to maintain water tables at or near peak 'normal' levels. Pumping flows could be significantly higher if actual Alluvial Aquifer hydraulic conductivity values are higher than in the "best estimate" model.
- A Split Barrier Drain (SBD), which has a central gap of about 1.2 km, hence approximately 2.7 km long, would also provide good flood protection and the best estimate peak 1:200-year Attenuated Event drain flows are estimated at up to 230 L/s.
- 'Barrier' pumping wells may also be considered as an alternative to the interceptor drains (FBD or SBD), although this option is slightly less efficient than the drains, due to the geometry of the required pumping system, and will result in higher overall pumping flows and greater operational and maintenance complexity. However, construction impact may be lesser than that for a drain. It is estimated that 11 pumping wells along the same alignment as the SBD would provide a good level of protection, with similar best estimate peak flows of 240 L/s. The elimination of groundwater-induced surface inundation would require a peak pumping rate of about 50 L/s, using two wells installed in the southeast Bowness area.

V-1.5 Recommendations

If the City of Calgary decides to incorporate groundwater flood protection into the Bowness flood barrier design, the following is recommended (over and above the recommendations provided in Section 7.3 of the report) to further refine the assessment of groundwater flood mitigations options for the Project:

- 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.
- Undertake further hydraulic testing at the following existing monitoring wells: MW19-01, -02, -03A, -03A, -06A, -06D, -07, -08, -09, -10, -11 and -18. This testing should be undertaken when static water levels are their seasonal highs to obtain best results. Testing methods should include rising-head and constant-head testing.

- Drill and test additional monitoring wells of the Alluvial Aquifer where information gaps exist (e.g., away from Bow River, but within the identified river-aquifer ZOI). The wells should be installed on public land, where possible, to avoid any issues associated with access to private properties.
- Following review of the geophysical survey and foregoing test results, install three 254 mm (10”) nominal diameter pumping wells within the Alluvial Aquifer within the zones of estimated highest transmissivity (hydraulic conductivity x thickness), where the risk of groundwater-induced surface flooding is highest. One of these wells would be located in the northeast portion of the alignment, and two wells within the southeast portion of the alignment. The wells would be installed to a depth of 2 m below the base of the Gravel and Sand Aquifer and would include a 3 m long stainless-steel continuous wire-wound well screen and a 2 m-long sump. These wells would serve as test pumping wells but could also likely be utilised for flood protection in the longer term. This installation should precede peak groundwater levels for the year (i.e. late spring) so that test pumping may be undertaken under normal seasonal peak level conditions.
- Conduct step-drawdown and constant-discharge pumping tests on each test pumping well during a period of seasonal peak groundwater levels (July is preferable). The duration of the constant-discharge tests should be guided by the aquifer response – up to 72 hours, but shorter if testing indicates stabilization of water levels due to a strong hydraulic connection with the Bow River.
- Compile and analyse this data and use as input to the next design phase.

APPENDIX V1

Numerical Groundwater Model – Surface Event Barrier and Groundwater Cut-off Wall

Figure V1-1 Case 3: Peak Water Table Change, with/without SEB + FGC, June 25, 2019

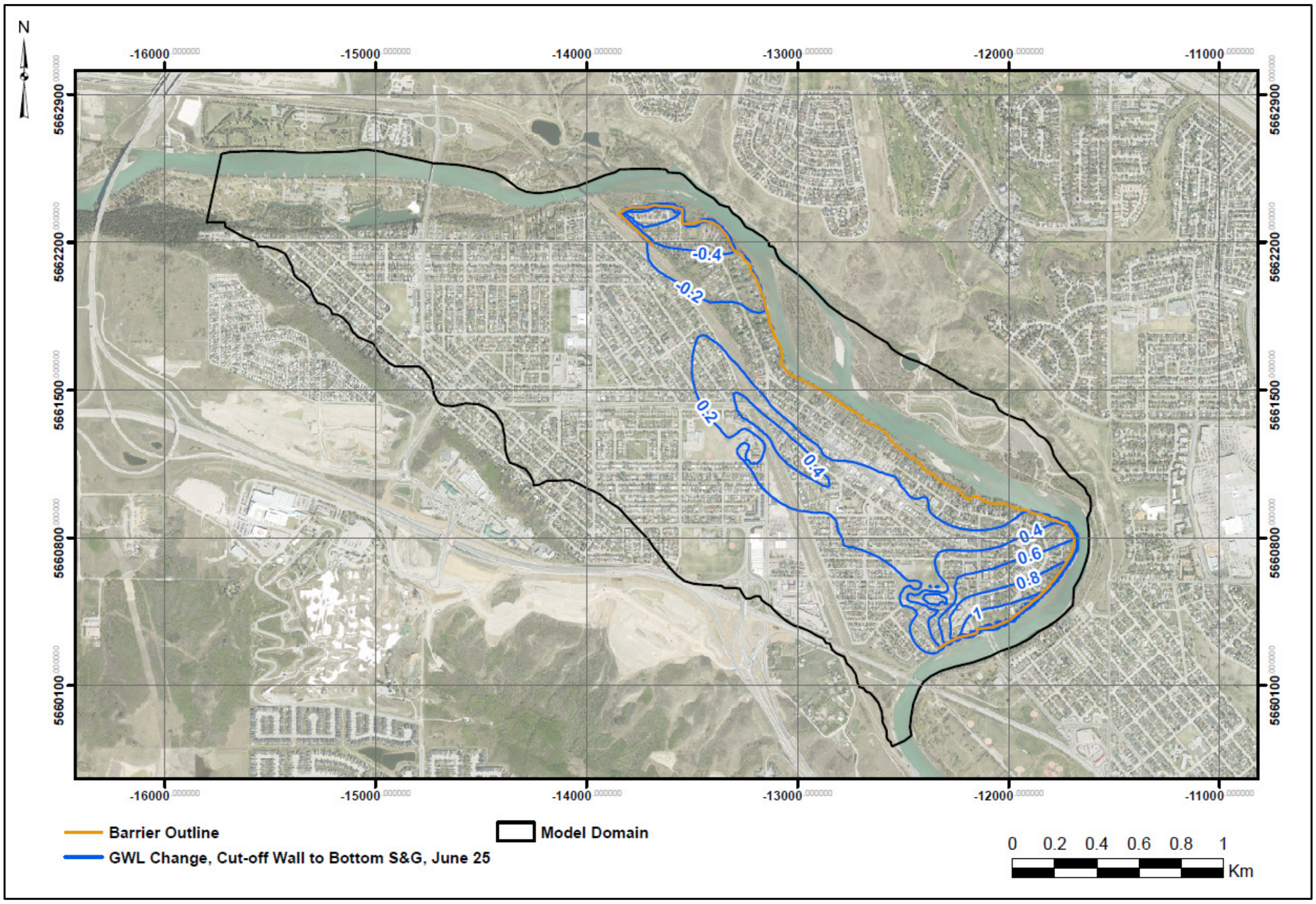


Figure V1-2 Case 5: Peak Water Table Change, with/without SEB + FGCD, June 25, 2019

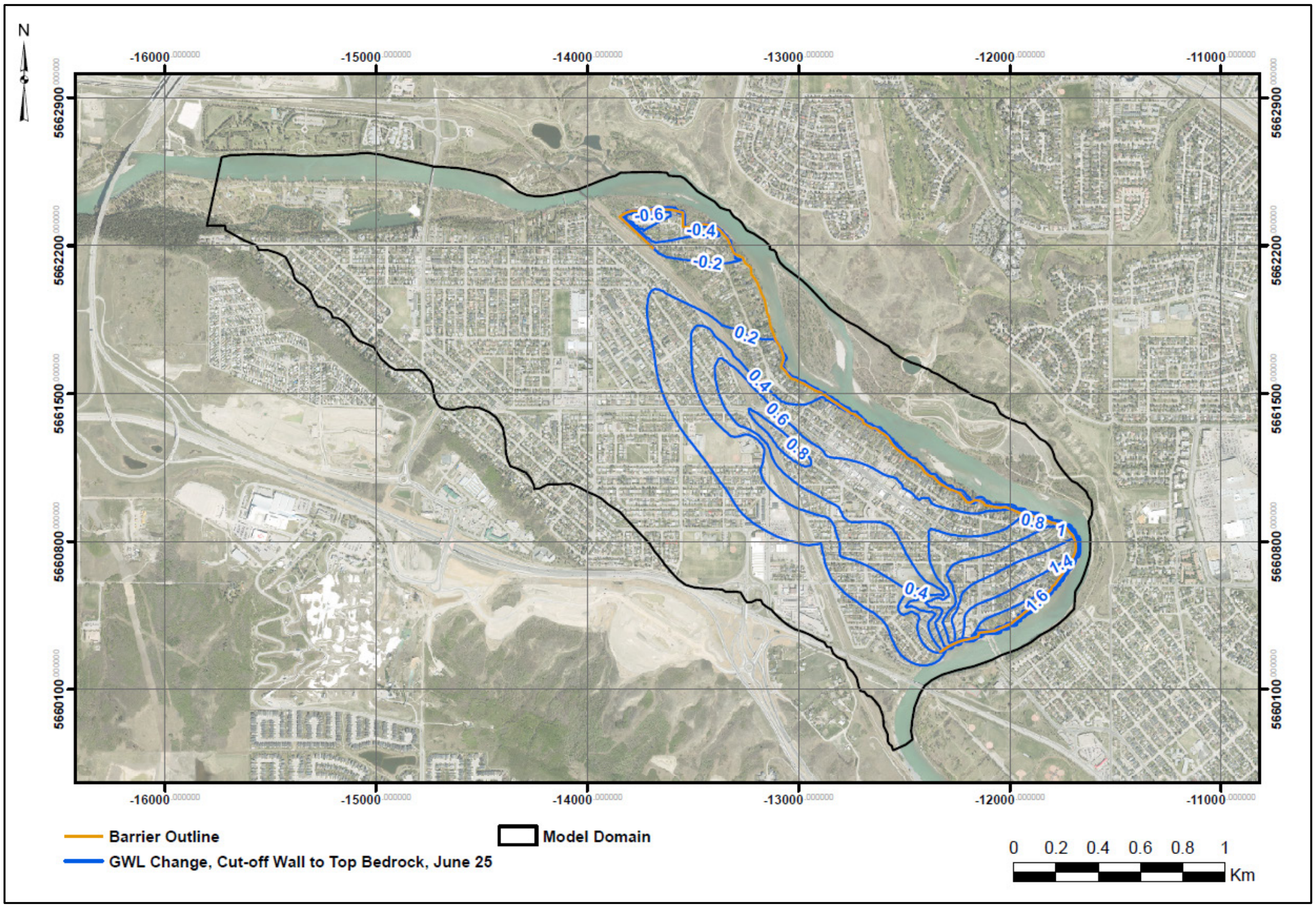


Figure V1-3 Cases 3 and 5: Remaining Hydrographs, SEB + FGC and SEB + FGCD, 2019

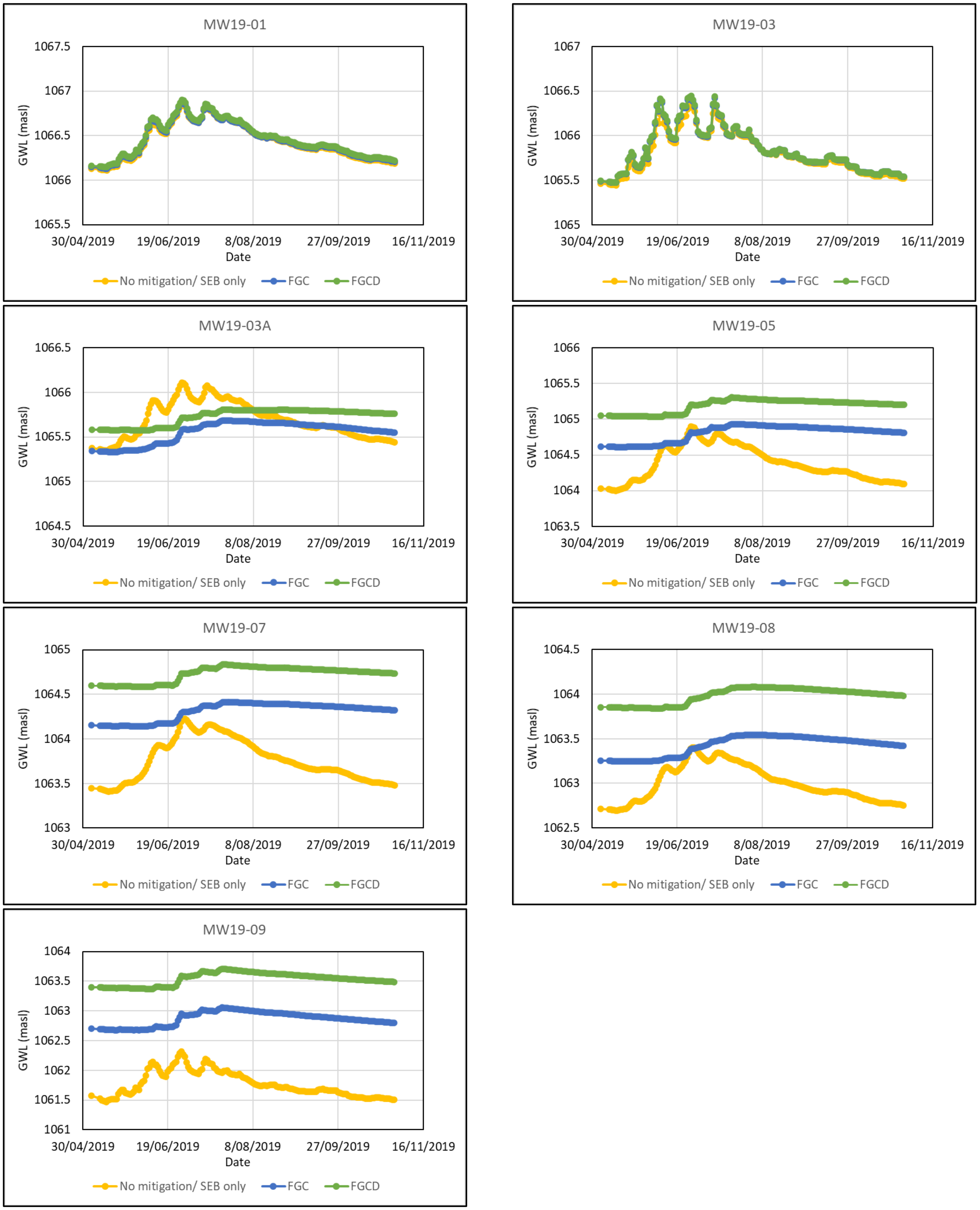
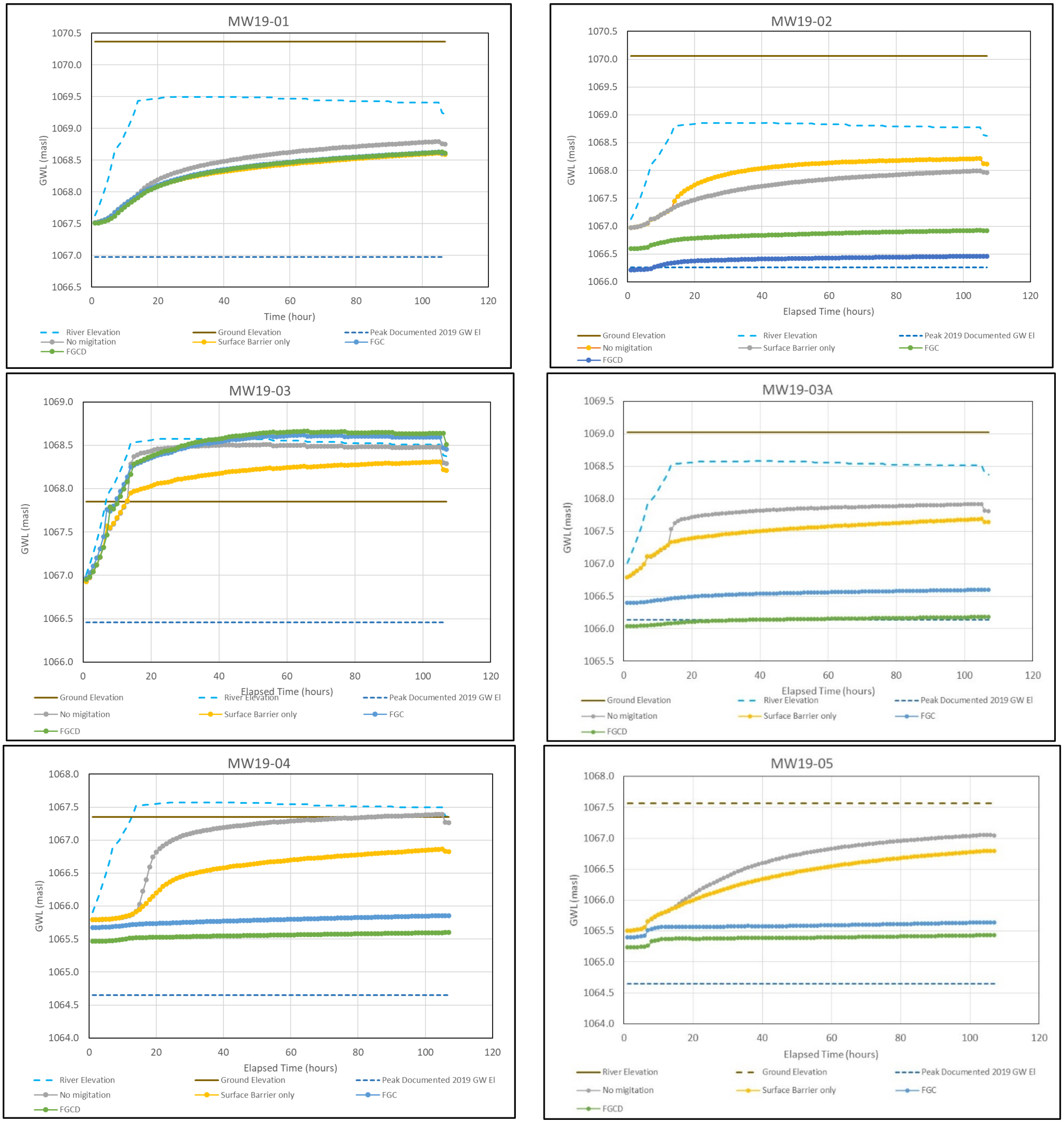
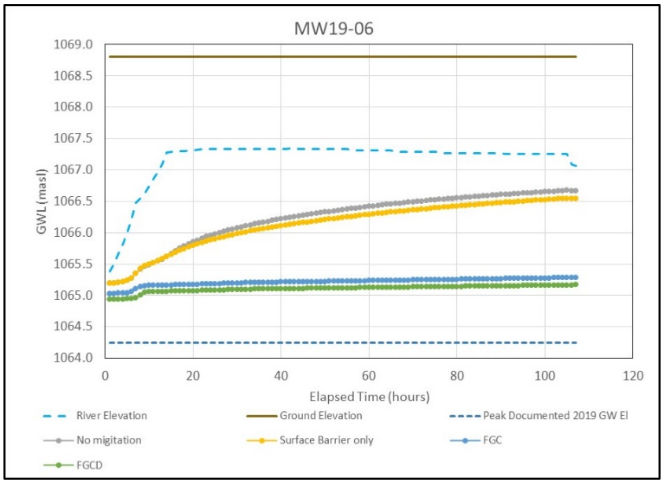
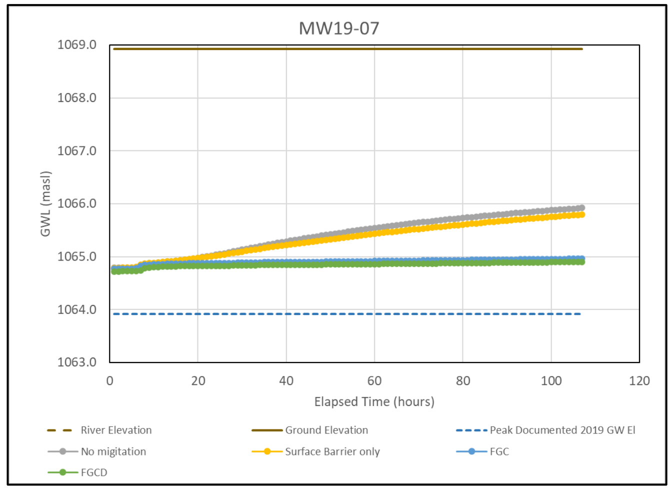
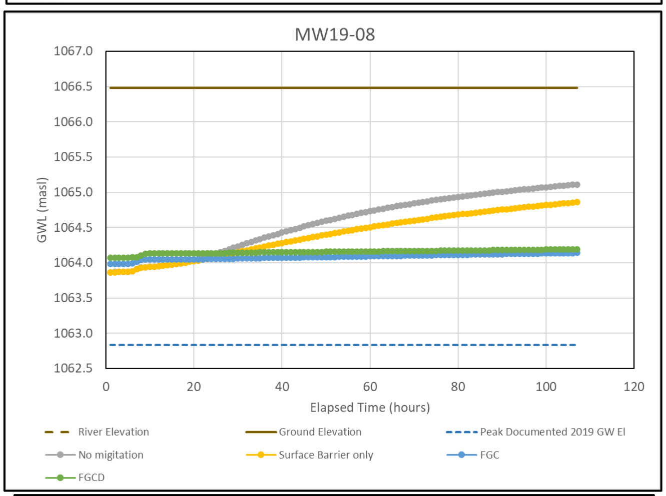


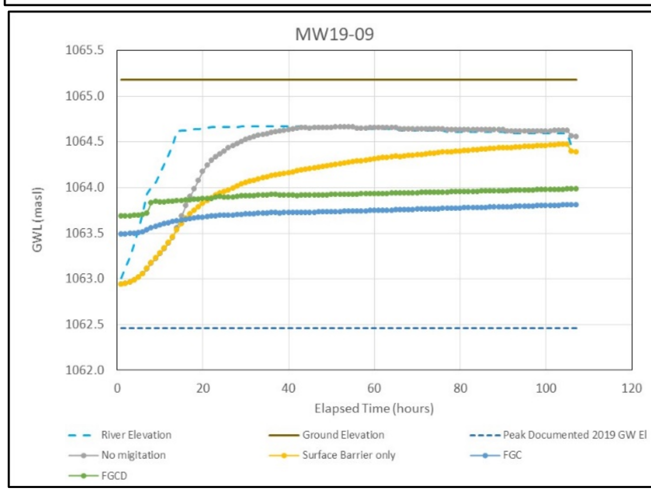
Figure V1-4 Cases 4 and 6: Hydrographs, SEB + FGC and SEB + FGCD, 1:200 Attenuated Event

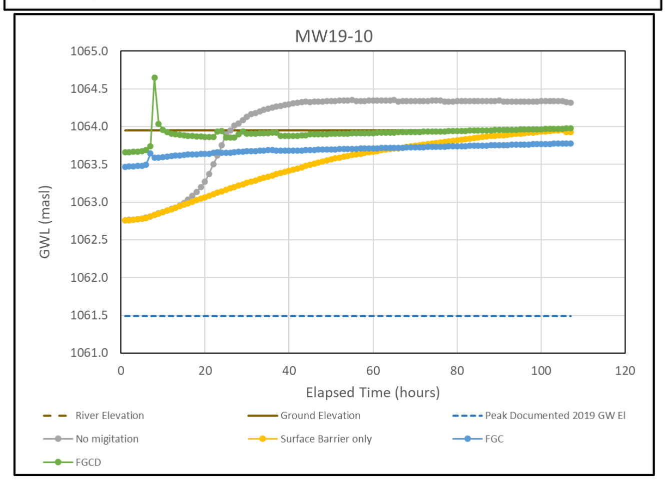



MW19-06
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGCD


MW19-07
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGCD


MW19-08
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGCD


MW19-09
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGCD


MW19-10
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGCD

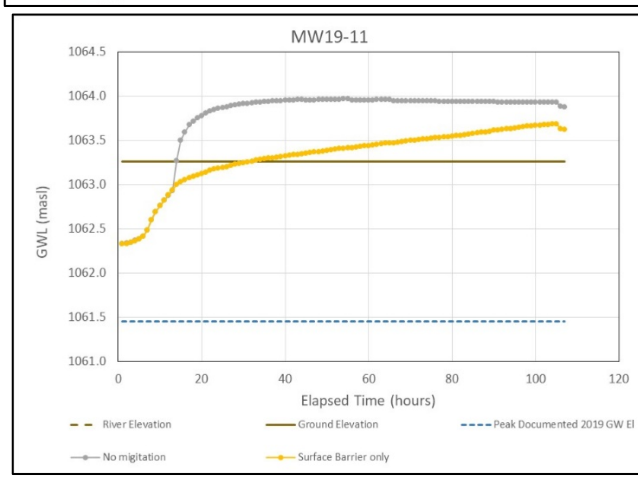

MW19-11
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only

Figure V1-5 Case 7: Peak Water Table Change w/wo SEB + TGC, 1:200 Attenuated Event

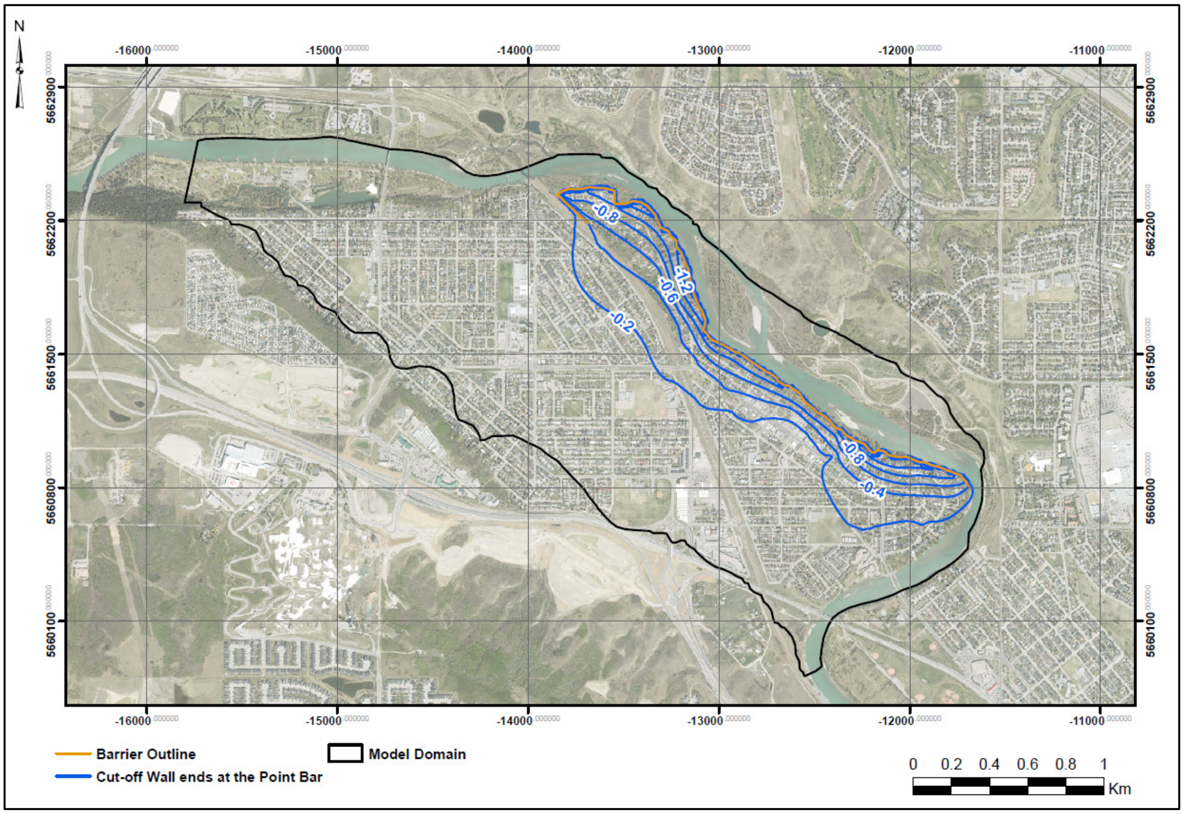


Figure V1-6 Case 8: Peak Water Table Change w/wo SEB + SGC, 1:200 Attenuated Event

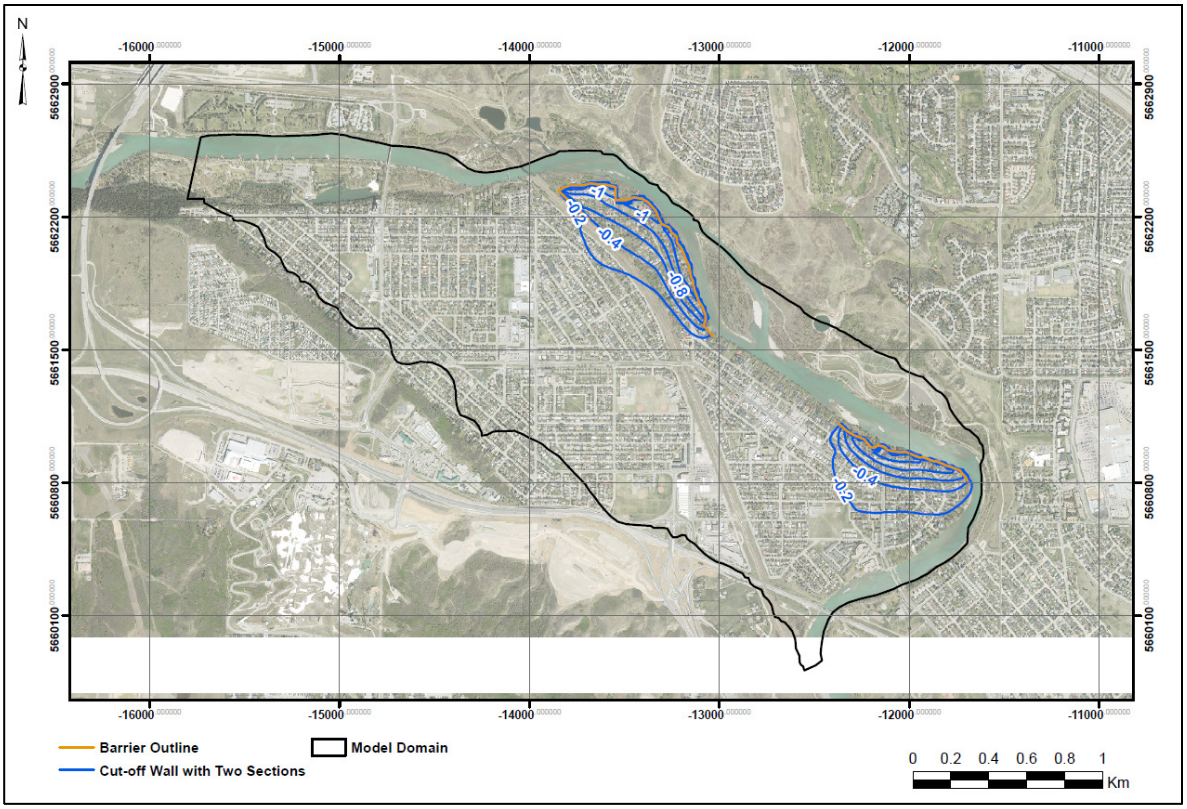
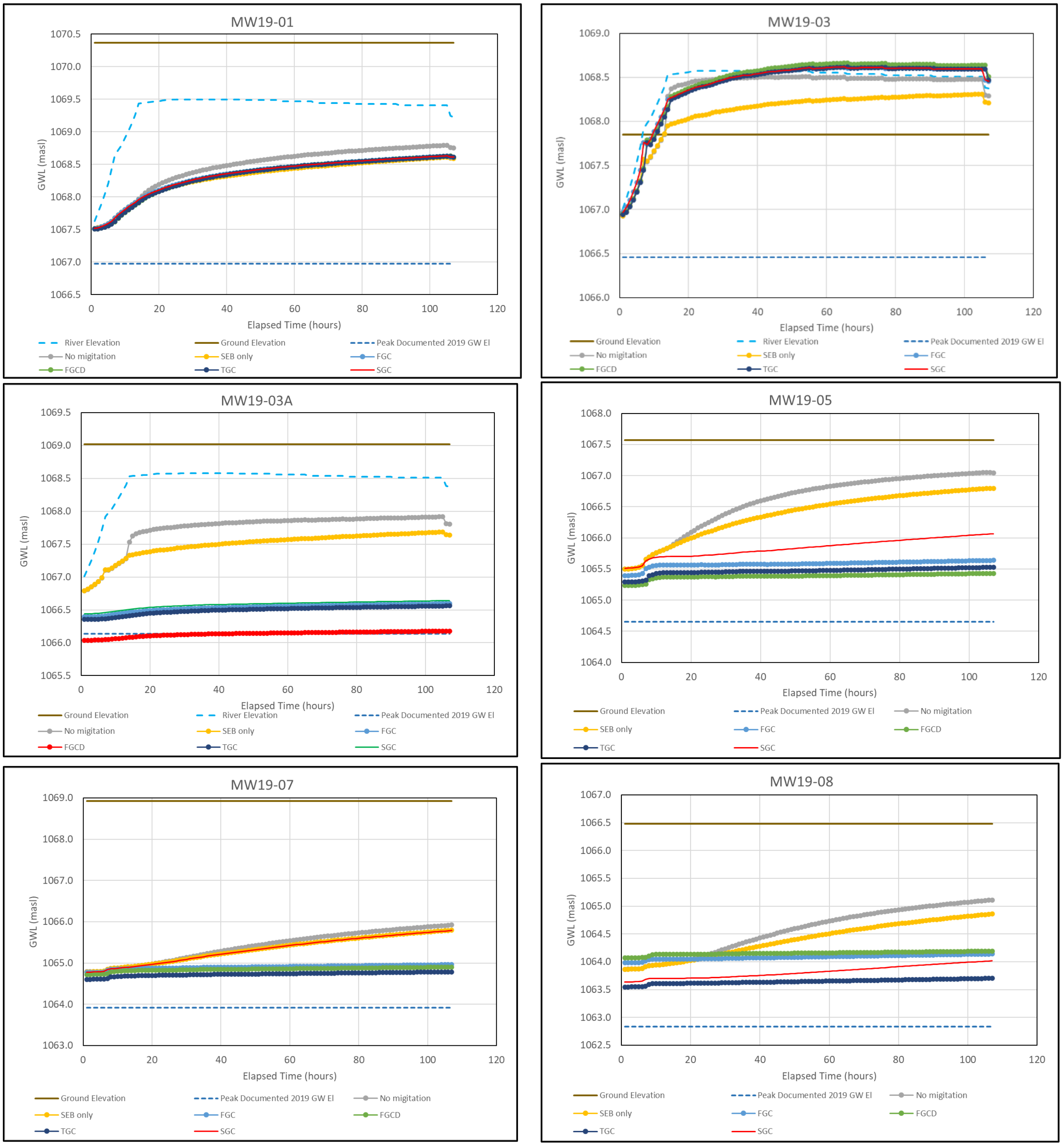
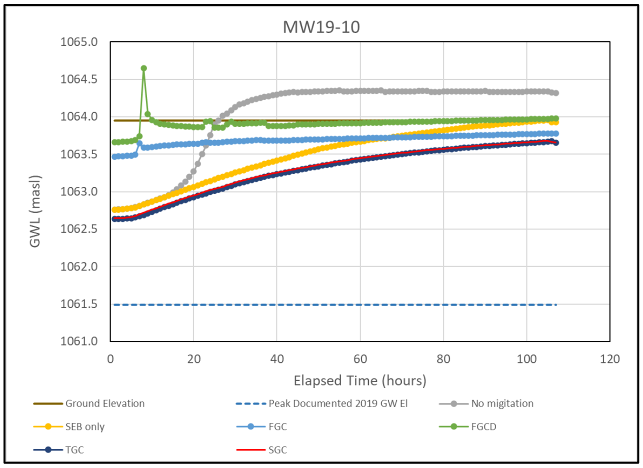


Figure V1-7 Cases 3 to 8: Remaining Hydrographs, all Cut-off Wall Options




MW19-10
GWL (masl)
Elapsed Time (hours)
Ground Elevation
Peak Documented 2019 GW El
No migitation
SEB only
FGC
FGCD
TGC
SGC

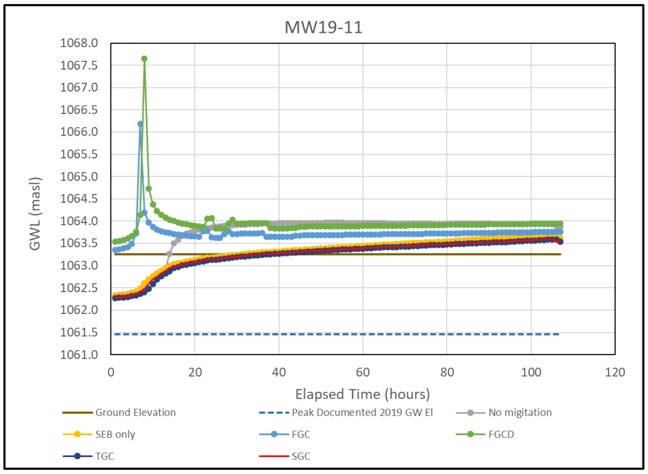
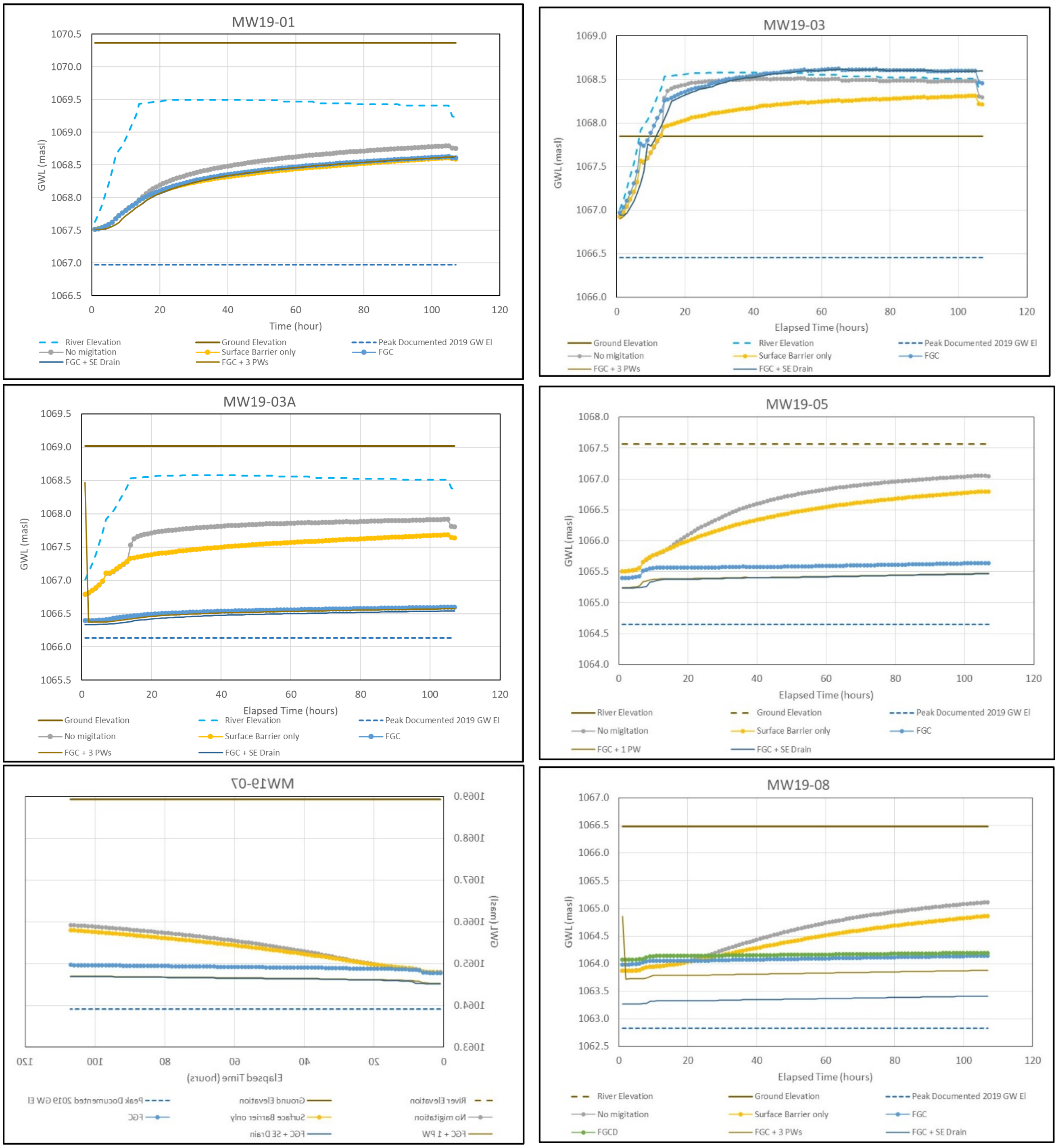
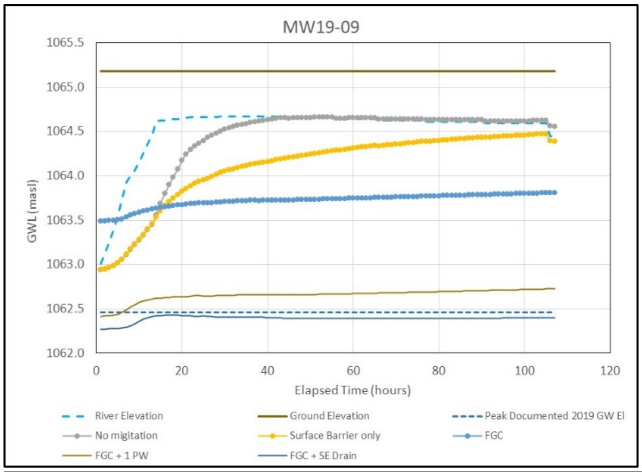
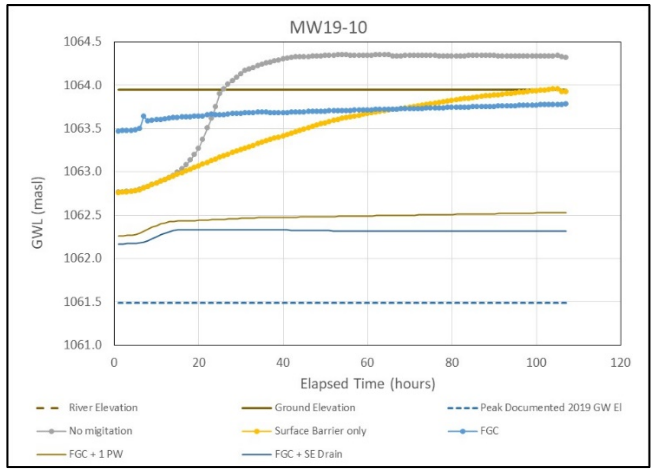
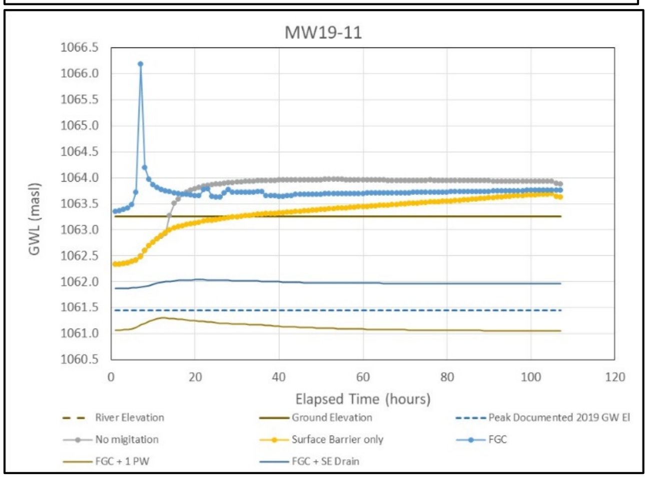

MW19-11
GWL (masl)
Elapsed Time (hours)
Ground Elevation
Peak Documented 2019 GW El
No migitation
SEB only
FGC
FGCD
TGC
SGC

Figure V1-8 Cases 9 to 12: Remaining Hydrographs, SEB + SGC + SE Drain or 1 Pumping Well, 1:200 Attenuated Event




MW19-09
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGC + 1 PW
FGC + SE Drain

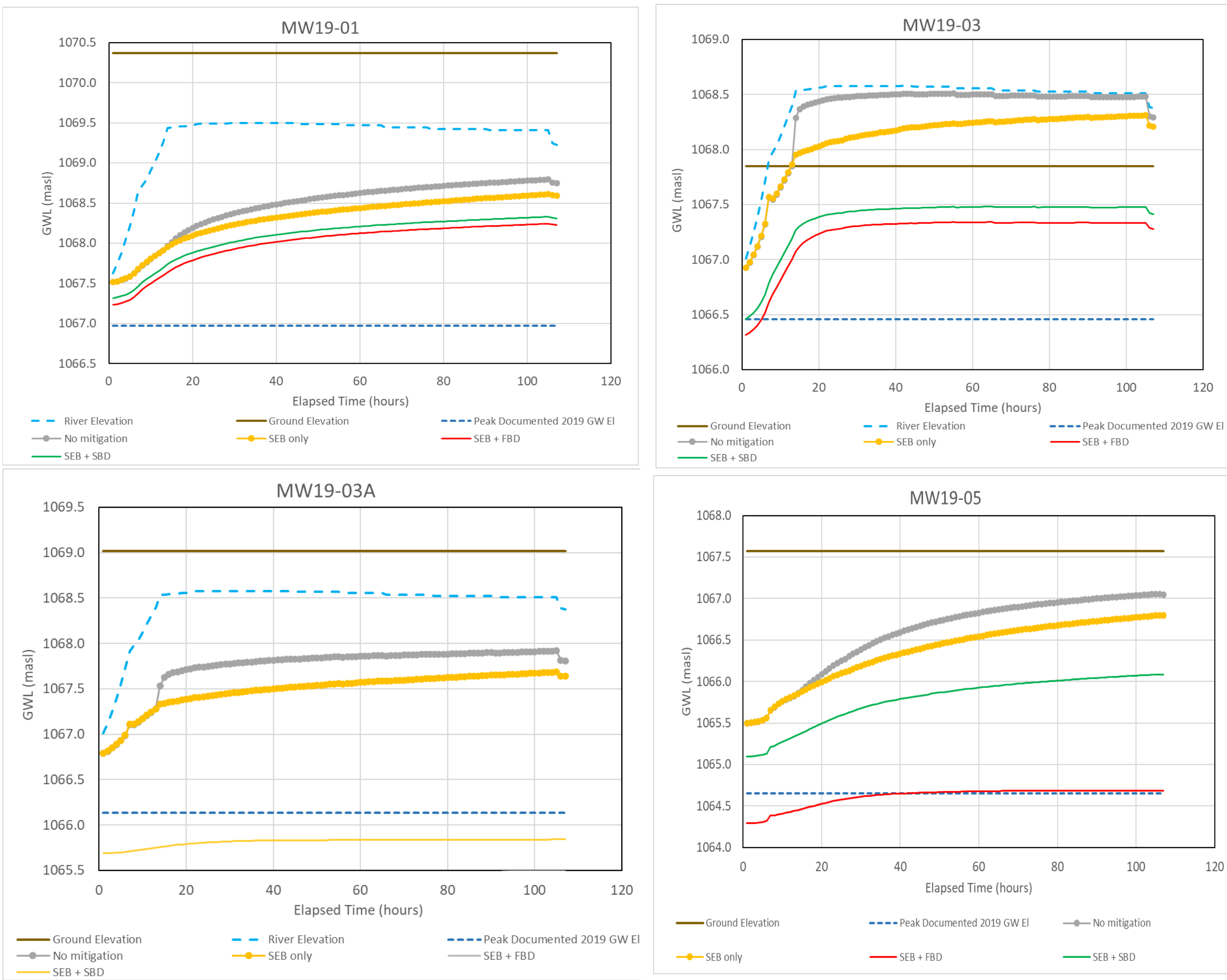

MW19-10
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGC + 1 PW
FGC + SE Drain

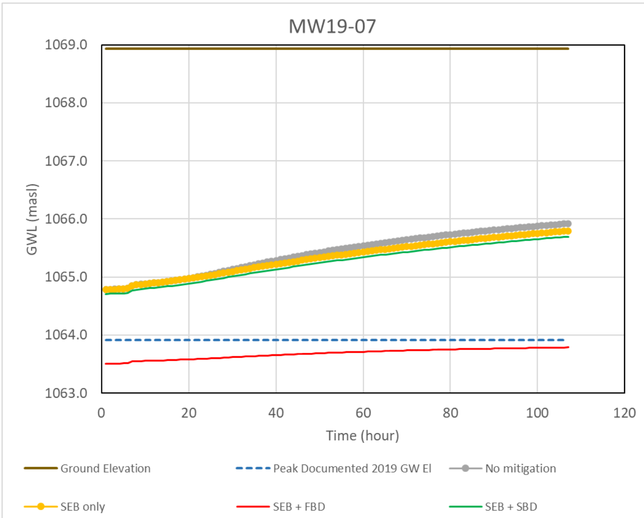

MW19-11
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No migitation
Surface Barrier only
FGC
FGC + 1 PW
FGC + SE Drain

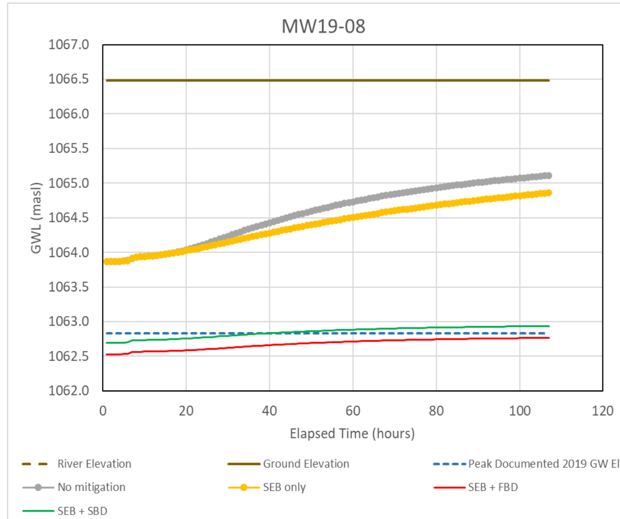
APPENDIX V2

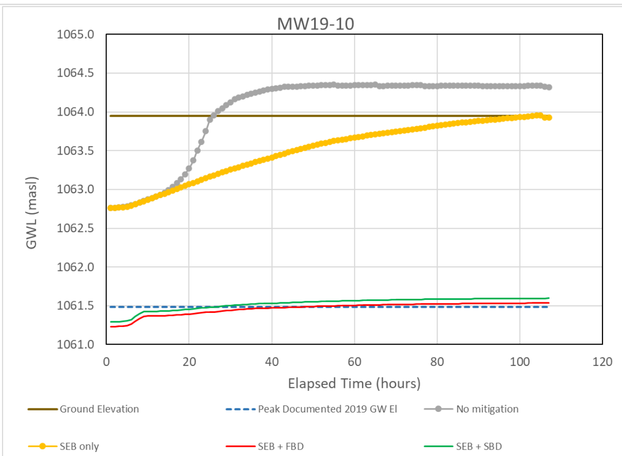
Numerical Groundwater Model – Surface Event Barrier and Barrier Drain

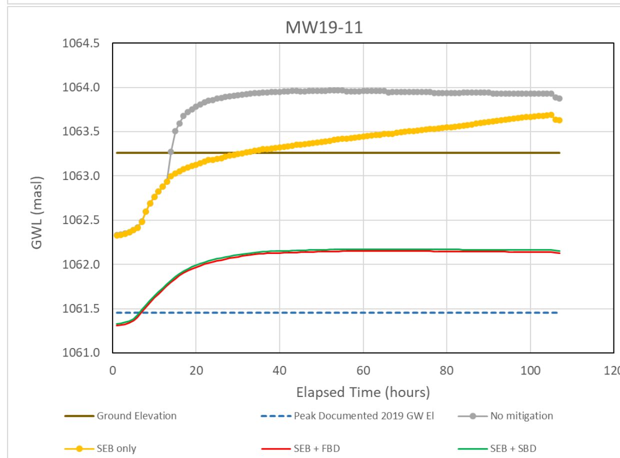
Figure V2-1 Cases 13 and 14: Remaining Hydrographs, SEB + Barrier Drain Scenarios, 1:200 Attenuated Event




MW19-07
GWL (masl)
Time (hour)
Ground Elevation
Peak Documented 2019 GW El
No mitigation
SEB only
SEB + FBD
SEB + SBD


MW19-08
GWL (masl)
Elapsed Time (hours)
River Elevation
Ground Elevation
Peak Documented 2019 GW El
No mitigation
SEB only
SEB + FBD
SEB + SBD


MW19-10
GWL (masl)
Elapsed Time (hours)
Ground Elevation
Peak Documented 2019 GW El
No mitigation
SEB only
SEB + FBD
SEB + SBD


MW19-11
GWL (masl)
Elapsed Time (hours)
Ground Elevation
Peak Documented 2019 GW El
No mitigation
SEB only
SEB + FBD
SEB + SBD

APPENDIX V3

Numerical Groundwater Model – Surface Event Barrier and Barrier Pumping Wells

Figure V3-1 Case 15: Remaining Hydrographs, SEB + Barrier Wells, 1:200 Attenuated Event

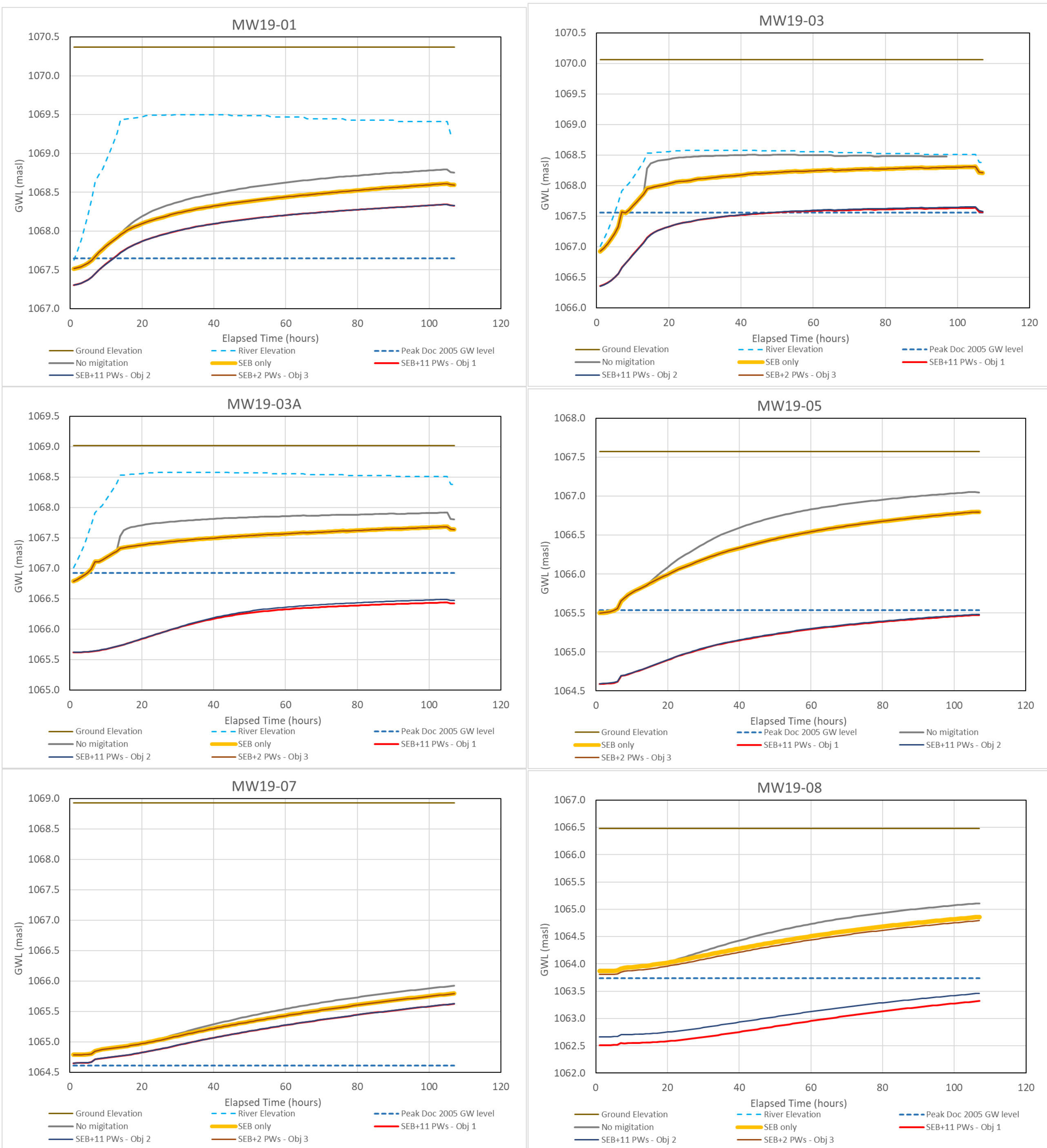


Figure V3-1 Case 15: Remaining Hydrographs, SEB + Barrier Wells, 1:200 Attenuated Event (cont'd)