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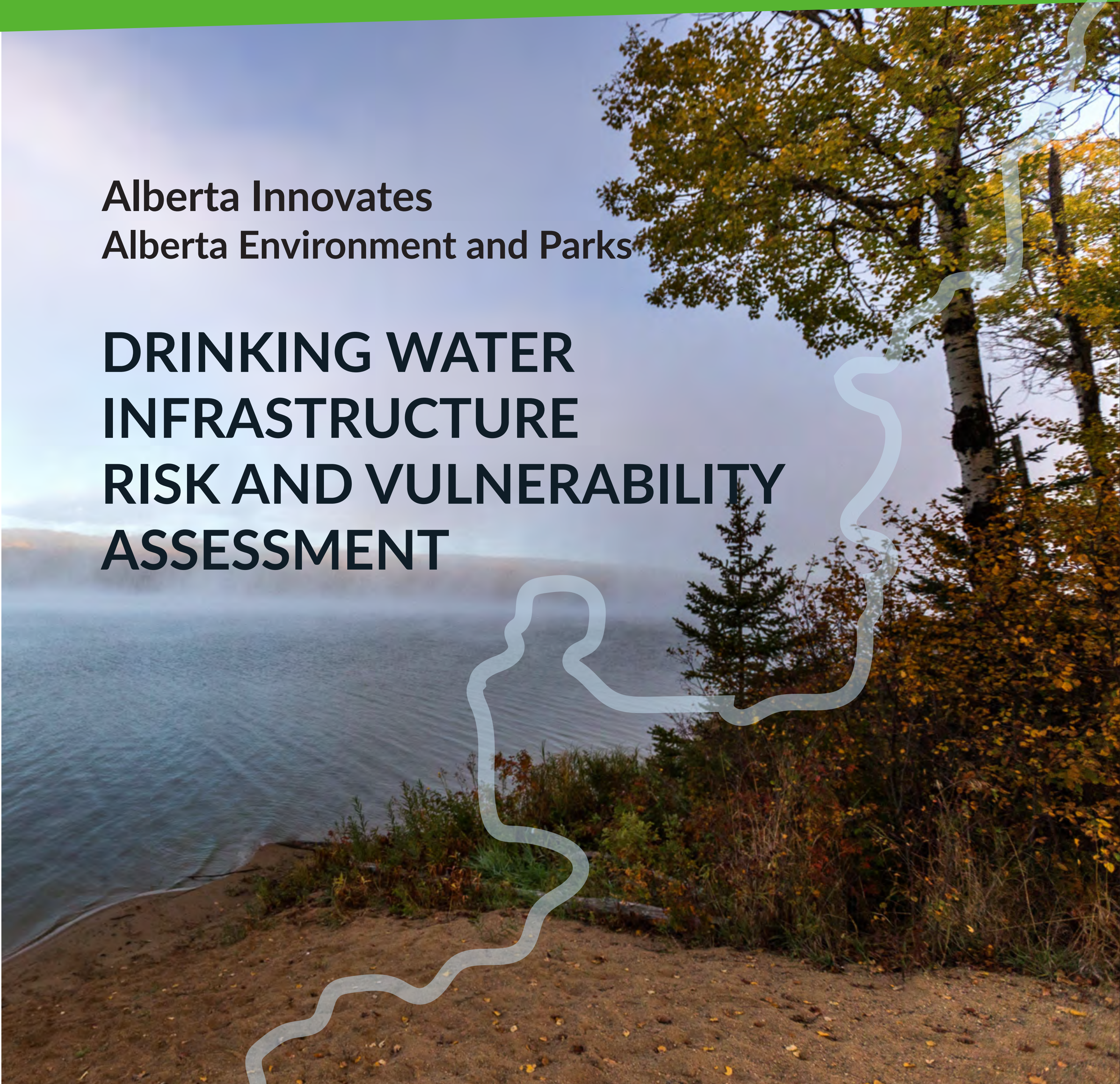
PROVINCIAL OVERVIEW REPORT



Alberta Innovates
Alberta Environment and Parks

DRINKING WATER INFRASTRUCTURE RISK AND VULNERABILITY ASSESSMENT

EXECUTIVE SUMMARY

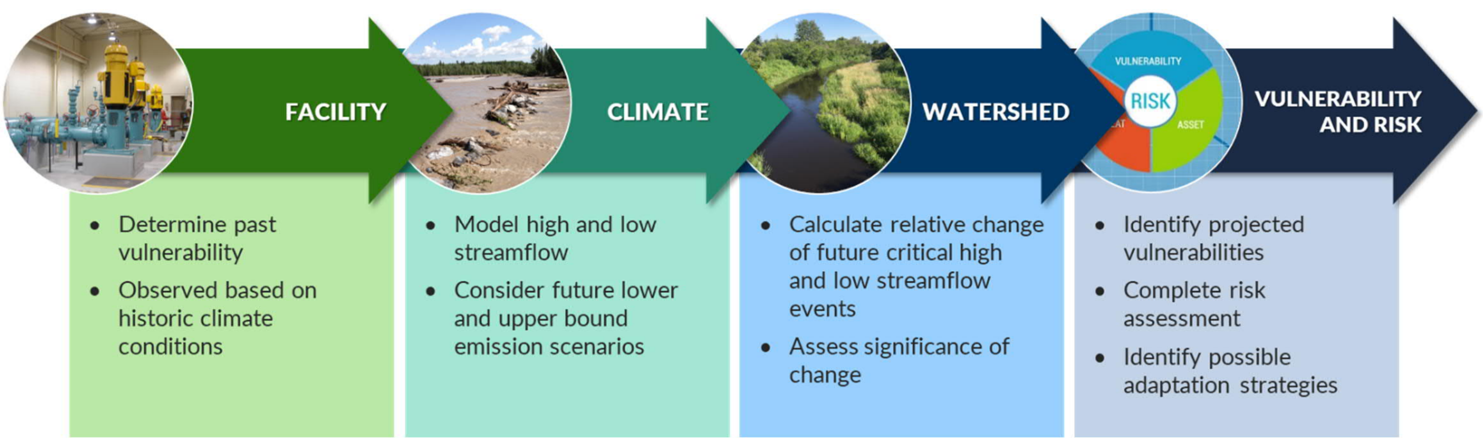
1 OVERVIEW

The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), along with numerous national, provincial and local-scale studies from across Canada, provide a substantial base of evidence that climate change is already altering natural hazard-based risks to local communities. This pattern will likely continue through the 21st Century. Drinking water facilities in the Province of Alberta are, by their nature, closely linked to climate conditions and changes to these conditions, as they reside near river, lake or groundwater systems, and extract and treat water for use across a range of sectors. These critical facilities have the potential to be impacted by climate-induced hydrological changes, in terms of physical damage and ability to access, treat, and convey water. It is thus important to assess the risk and vulnerability of climate change to these facilities, to ensure that vulnerable individual facilities (or classes of facilities) are recognized and potentially targeted for adaptation measures.

1.1 Objective and Process

Alberta Innovates and Alberta Environment and Parks partnered to complete this assessment of potential climate change impacts and resulting high and low river flow vulnerabilities at 48 small and medium sized municipal drinking water facilities, across the Province. This is intended to be a high-level assessment based on the evaluation or review of past vulnerability and likelihood of increased risks due to future climate change induced impacts to extreme streamflow events. Vulnerability and risk assessments are a critical stage within an overall adaptive management framework to increase resilience to climate variability and climate change. The overall project process is shown in **Figure ES-1-1**.

Figure ES-1-1-1
Project Scope Overview



2 FACILITY ASSESSMENT

The 48 facilities assessed represent a large proportion of the regulated drinking water facilities, in the Province of Alberta, based on population served, but did not include the Cities of Calgary or Edmonton, as they have similar initiatives already underway. To assess the current vulnerability, readily available information, such as the Facility Drinking Water Safety Plans (DWSPs), air photos of system layouts, and area topography, was reviewed and a questionnaire sent to the facility operators.

All facilities were evaluated for known vulnerabilities, based on historical events and system knowledge as reported by the facility owners as represented by the survey respondent. From this evaluation it was evident that most facility operators were familiar with potential impacts of past high and low streamflow events. Key findings included:

- 45 (94%) of the facility owners indicated completed DWSPs .
- 13 (27%) of the facility owners indicated they have Flood Readiness Plans and 7 (15%) have Drought Readiness Plans, which generally correlates with the fact that that the facility has had experience with some type of severe event in the past.
- 17 (36%) were evaluated with moderate to high vulnerability to past high flow events and 14 (29%) with moderate to high vulnerability to past low flow events.

Drinking water systems, within Alberta, are reliant on creeks, rivers, lakes, and groundwater for water supply. Components of the system that are most vulnerable to high and low streamflow are the source water systems (intakes, storage ponds, and pumphouses) and treatment systems (buildings, process systems, and pump stations). The distribution systems (pipelines and tanks) are generally less vulnerable, as they are usually physically removed from the major water bodies or are underground.

3 CLIMATE AND WATERSHED ASSESSMENT

The project team developed an innovative method to provide climate change induced streamflow projections in support of high level vulnerability and risk assessments of drinking water infrastructure. Associated Engineering (AE) collaborated with the University of Alberta Watershed Modelling Laboratory (UA WSML) to utilize an available model to facilitate emission scenario-based future streamflow projections. The UA WSML Soil and Water Assessment Tool (SWAT) model provided past and future sub-basin streamflow estimates that enabled an assessment of relative change for the various scenarios. This model considers critical topographic, land use, water cycle, and climate parameters to provide a means to assess the influence of future climate-related shifts on Alberta's streamflow.

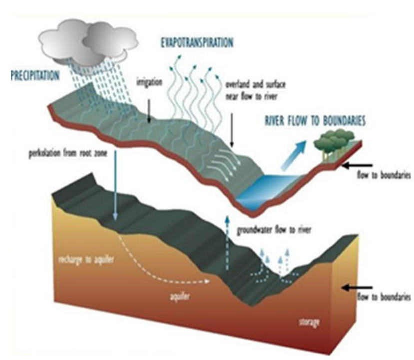


Figure ES-1-2
SWAT Model Diagram

Assessing climate change impacts to the extreme low and high flow 'tails' of local-scale hydrological conditions is perhaps one of the most challenging topics, in the field of applied climate vulnerability assessments to water resource facilities. This project uses available tools, techniques and workflows to address these substantial challenges. Nonetheless, uncertainty resulting from these challenges persist. Because of these inherent challenges, this assessment should not be taken as a definitive predictor of future events. It is a tool to evaluate the likelihood and potential consequences of potential severe hydrological events occurring in the future to understand the degree of risk it poses for the Province and the assessed facilities.

3.1 Regional Findings – High Flow Scenario

In general, provincial drinking water facilities should expect to brace for more extreme high-water conditions primarily related to higher precipitation in mid-winter, but also, potentially, to individual extreme storm events of sufficient strength to impact smaller stream systems.

While the predominant trend towards intensified high flow conditions holds for most facility locations, there are some important exceptions with distinct spatial patterns. In particular, facilities in the northern third of the Province within the Athabasca and Peace River basins and facilities in the far south-east, such as within the Milk River basin, shows results in contrary to the trend of intensified high flow conditions. The magnitude of high flow increases with the central/south portions of the Province varies with the most severe increases ranging from the Battle River to the South Saskatchewan basins.

3.2 Regional Changes - Low Flow Scenario

Presently in Alberta, the lowest annual flows largely occur during the winter, as water is sequestered on the landscape as snow and ice. This means that the most extreme low flow conditions, in the Province, tend to occur in the winter months. Climate change will cause two primary winter trends over the Province: increased warming, and increased precipitation falling as rain during shoulder seasons. Assessment of climate change-driven shifts to long-term annual low flows across watersheds, hosting Alberta drinking water facilities suggests overall increases to long-term average low flow conditions across the Province, attributed to these increased late fall and winter precipitation trends.

Small sub-basins are potentially most susceptible to climate-change driven changes to chronic, persistent low flow conditions. Assessment of chronic 6-month low streamflow shifts is consistent with shorter-term measures of winter low flows, because they are regulated by the same physical drivers. This suggests overall water availability is projected to be similar in the future across different measures of low flow, but with peaks and troughs of availability occurring at different times, requiring potential consideration of modified storage practices. Notably, many drinking water facilities in areas at greatest risk of changing low flow conditions rely on groundwater or surface storage to provide sustainable annual supplies, alleviating the impact of changes to low flow conditions.

Assessment of summer low flow conditions suggest a broad Province-wide increase to average summertime low-flow conditions. This change provides a suggestion that climate change alone may not substantially increase the risk of summer low flows at most provincial drinking water facility locations. As summer streamflows are related closely to both summer precipitation and temperature-controlled summer evapotranspiration, increased streamflows indicate that increased summer precipitation may outweigh the impact of increased evapotranspiration, in most areas, in the climate change analysis performed here. However, summer precipitation trends, especially in southern areas of Alberta, are uncertain, and the results of the present analysis could evolve with time, in response to improved climate modeling and downscaling in over the provincial landscapes. In addition, the assessment of low flow conditions does not consider changes to water use or allocation, based on industry, land use, or irrigation. Integration of these change factors into future low flow assessments could significantly alter findings presented here.

4 RISK ASSESSMENT

Vulnerability and risk assessments (VRAs) are widely recognized as an important prerequisite for developing robust climate adaptation strategies. VRAs provide a structured method for identifying, analyzing, evaluating, and ultimately prioritizing risk. In the current VRA, a risk matrix was employed to determine the overall vulnerability of each facility to the impacts of high and low streamflow periods in the future. A risk matrix is a tool that is common to VRAs and is used to assess the level of risk by considering both the likelihood of an event taking place based on the projected change to streamflow levels and the severity of the consequences based on the facility vulnerabilities.

The key findings were:

High Flow	• 37 (77%) of facilities were evaluated with moderate to critical risk after considering climate change induced increases to high flow events. This represents an additional 20 facilities or 41% increase in comparison to the risk assessment from past events. • 9 (19%) of the facilities were evaluated with a high to critical risk, indicating potential damage and impact to the facilities ability to produce potable water may occur.
Low Flow	• 24 (50%) of facilities were evaluated with moderate to critical risk after considering climate change induced decreases to low flow events. This represents an additional 10 facilities or 21% increase in comparison to the risk assessment from past events. • 4 (8%) of the facilities were evaluated with a high to critical risk, indicating potential impact to the facilities ability to produce potable water may occur.

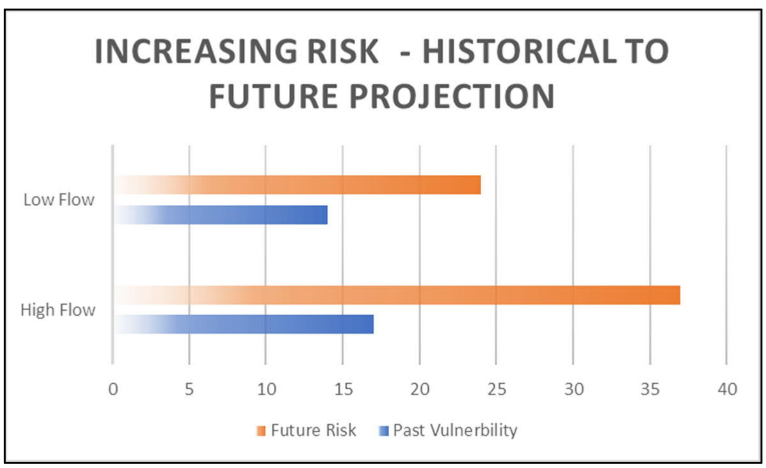


Figure ES-1-3
Increasing Risk Projection

5 CONCLUSIONS

This study provides a high-level assessment of plausible climate change impacts to extreme streamflow events expected to affect drinking water facilities throughout Alberta. The tools and techniques available to support this review are evolving and will improve as more efforts are focused on better understanding potential impacts of future climate change.

The assessment is not a predictor of future events. It is a tool to evaluate the likelihood and potential consequences of severe events occurring in the future to understand the degree of risk it poses for the Province and the facilities included. This study is intended to help inform provincial and municipal decision makers of potential changing future risks and to consider adaptation measures that may help build future resiliency.

The primary conclusions, based on the vulnerability and risk assessment, are as follows:

- Many drinking water facilities are at risk of high and low streamflow conditions, causing subsequent risk to water supply and treatment systems. Changes to these risk profiles due to climate change may stress many systems beyond the design basis for flood levels, creek erosion, on-site overland flooding, and decreasing water quality.
- In most cases, increasing future risk occurs for both greenhouse gas emission scenarios (RCP 2.6 and RCP 8.5) and farther into the future (for example, by the middle of the 21st Century).
- The risk of increasing high streamflow and more frequent severe high flow events is most prevalent in central to southern Alberta. The majority of facilities with increasing risk have assets in close proximity to the Pembina, North Saskatchewan, Red Deer, Bow and South Saskatchewan Rivers.
- Risk of decreasing low streamflow is largely limited to the South Saskatchewan and Milk River Basins. The majority of facilities with increasing risk rely on large mounts of seasonal storage and/or on irrigation districts, where they may compete with other water users.
- Facilities at risk will need to acquire more detailed understanding of the location specific risks to enable capital and operations planning to consider future needs. Most drinking water facilities require some significant capital upgrades to rehabilitate or upgrade existing systems on 10 to 25-year cycles, depending on population growth and changing regulations. It will be important for future planning and design of these systems to consider the future uncertainty that climate change may impose on high and low streamflows.
- There are over 430 regulated municipal drinking water systems, within the Province of Alberta, many of which service smaller communities that have limited resources or knowledge in being aware of these changing risks. Based on the data provided in the Waterworks Facility Assessment Report Update Study, completed for Alberta Transportation (September 2016).

6 SUGGESTED ADAPTATION STRATEGY

Adaptation strategies are available at the provincial and facility levels to improve facility resilience to increasing risks stemming from climate change. The objective of these strategies would be to 1) help better identify future climate-change-driven risks; 2) assess whether these changes surpass facility risk thresholds; and 3) implement effective, practical risk treatments to reduce risk and make facilities more resilient to potential future change.

6.1 Province-wide Considerations

Suggested measures to inform adaptation practices to reduce **high flow risks**:

- Integrate climate change considerations into existing the Drinking Water Safety Plan (DWSP) process. The DWSP offers a framework to manage these risks, at the community level, by considering the implications of climate variability and change at various points in the DWSP process.
- Require facilities in at-risk river basins to complete detailed vulnerability and risk assessments, such as the Public Infrastructure Engineering Vulnerability Committee (PIEVC) Protocol supported by Engineers Canada, prior to major capital upgrades that require new or modified regulatory approvals or Provincial funding.

- Modify the Alberta Municipal Waterworks Design Standards and Guidelines to include requirements for facility designs to include climate change considerations.
- Update the findings of this report as available additional tools and information becomes available. **Section 3.5** provides additional suggestions for subsequent assessments.

Suggested measures to inform adaptation practices to reduce **low flow risks**:

- Update regional water management strategies in coordination with dam operations and irrigation districts.
- Review options for water demand management to protect water supply needed for Drinking Water Facilities, recognizing that potable water is an essential public health requirement.

6.2 Facility Considerations

The specific facility reports provide more specific adaptation suggestions for each location. Generally, more suggestions were provided for facilities identified with moderate to high risks.

The most common suggested strategies to address high flow risks were:

- Employ good operating practices, such as updating the Drinking Water Safety Plans and the Flood and Drought Preparedness Plans, which is intended to improve awareness.
- In many cases, existing river level gauges are not close enough in proximity to the facilities to provide a good historical basis of flood frequency analysis or facilitate extrapolation of future flood levels. It is suggested that local gauges could be installed with data collected by the Facility's computer systems.
- In cases where high and critical risks were identified it is suggested facilities complete detailed flood risk assessments prior to any major capital upgrades of the at-risk assets.

The most common suggested strategies to address low flow risks were:

- Good operating practices, such as preparation and/or update of the facility's Drought Preparedness (or Water Shortage) Plan.
- Consider options for increasing off-line storage capacity.
- Consider alternate water supply strategies, for those not directly connected to rivers or streams, such as adjacent reservoirs or groundwater aquifers.

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The Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report (AR5), along with numerous local-scale studies from across Canada, provide a substantial base of evidence to conclude climate change is already increasing physical risks to communities across the country, across a wide spectrum of climate change impacts. The trend of increasing physical risks as a result of climate change will likely accelerate through the 21st Century.

As with all jurisdictions, the Province of Alberta will need to be prepared to respond to changes in climate change impacts. Examples include more frequent and intense extreme weather conditions, such as rainstorms, snowstorms, heat waves, and droughts, as well as shifts in the average state and seasonality of temperature, precipitation, and other variables. Cascading impacts of these changes on water resources, hydrology, ecology, the built environment, public health and safety, the economy, and society in general, will pose significant challenges. Drinking water facilities in the Province of Alberta are by their nature closely linked to climate conditions: they reside near rivers, lakes or groundwater systems, and extract and treat water for use across a range of sectors. Thus, they have the potential to be impacted by climate-induced hydrological changes, both in terms of their physical robustness and in their ability to access, treat, and convey water. It is critical to assess the risks and vulnerabilities of climate change to these facilities, to ensure that vulnerable individual facilities (or classes of facilities) are recognized and highlighted for potential adaptation measures.

Alberta Innovates and Alberta Environment and Parks partnered to complete this assessment of potential climate change impacts and potential or probable high and low river flow vulnerabilities at 48 small and medium sized municipal drinking water facilities (listed in **Appendix A**), across the Province. This is intended to be a high-level assessment, based on assessment of past vulnerability and likelihood of increased risks due to future climate change induced impacts to extreme streamflow events. The assessment focuses on potential changes to near-future and farther-future high and low streamflow conditions based on regional climate change scenarios to enable identification of drinking water system vulnerabilities and risks. This work is directly intended to support development of a Provincial drinking water adaptation and resilience strategy.

This Vulnerability and Risk Assessment (VRA) provides an identification and prioritization of management actions, which may include capital and operational investments, to mitigate risks and vulnerabilities through implementation of counter measure strategies. While it provides preliminary information at the facility scale, it was not intended to be a detailed hydraulic or hydrologic assessment of site-specific conditions for any of the individual facilities.

The Vulnerability and Risk Assessments (VRA) were built on available drinking water facility information and targeted operator questionnaires to determine past impacts of "too little water" and "too much water". Climate projections of future streamflows were used to inform the hydrology assessment and define potential vulnerabilities related to shifts in extreme hydrological events (i.e., high/low flow) from historic levels.

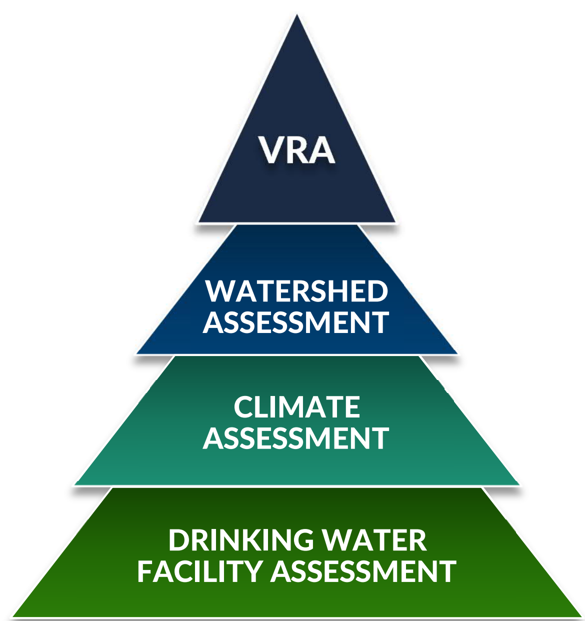

Figure 1-1
Project Assessment Components

1.1 Project Scope

The project scope required assessment of the drinking water infrastructure (supply, treatment, and distribution), the risks, and the vulnerabilities to severe high and low streamflow events.

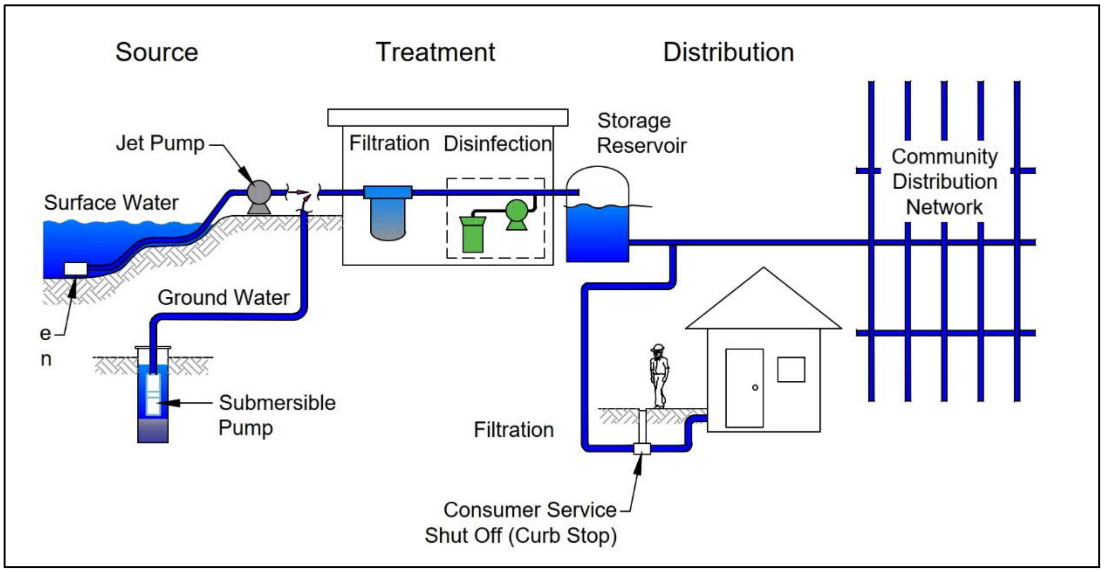

Figure 1-2
Water System Flow Chart Example

The scope of work included the following tasks:

Table 1-1
Task Listing

Drinking Water Facility Assessment	• Assessing all major components of drinking-water infrastructure at risk of failure, during high or low flow based on technical information made readily available to at the time of the Study. • Interviewing each drinking-water system operator to obtain qualitative data with respect to awareness and preparedness. • Assess operations staff preparedness for high and low flow, and whether preparations have been validated or tested. • Determining how operations staff have responded to past high and low flow events. • Identifying past vulnerability with respect to each major component of the drinking water system based on information received. • Quantifying the likelihood of an event resulting in streamflow of concern based on past events.
Climate Assessment	• Determining appropriate assessment methodology which included a collaboration with the University of Alberta Watershed Modelling Laboratory. • Confirming appropriate climate global climate models and two representative concentration pathway scenarios (RCP 8.5 and RCP 2.5). • Defining appropriate sub-basins for streamflow projections relative to each facility. • Collecting and analyzing model output data of future streamflow values.

Watershed Assessment	• Calculating recurrence intervals typical design for high/low flow events using historical baseline data. • Calculating recurrence intervals for future high/low flow events for a near future and Mid-Century timeframe. • Estimating relative projected change (or difference) of high and low streamflows for each sub-basin for scenarios and timelines. • Utilizing Water Survey of Canada to translate model data to local streamflow condition to determine impacts of projected values.
Vulnerability and Risk Assessment	• Producing a vulnerability risk assessment report for each drinking-water system. • Identifying possible adaptation strategies for future high and low streamflow changes and rationale. • Providing Provincial stakeholders a basis to identify potential technology/knowledge/ policy gaps in the understanding of high/low flow climate change risks to drinking water facilities. • Examining lessons learned from past high and low flow events and adaptive measures incorporated afterwards. • Assessing how climate change is currently incorporated into future operational plans through Drinking Water Safety Plans, Standard Operating Procedures or future capital projects. • Analyzing overall trends and areas of concern for drinking-water infrastructure in Alberta.

2 FACILITY ASSESSMENTS

The facility assessments examined vulnerability of provincial drinking water facilities based on historic observations of extreme streamflow events. This assessment focused on how facilities have managed extreme weather events in the past and/or how well they appear to be equipped to face events of similar magnitude in the future.

This report provides a provincial overview of the results of the facility assessments. Individual results for each facility are provided as separate reports, both to the Province and to each Municipality.

2.1 Methodology Overview

2.1.1 Information Sources

Forty-eight (48) facilities were selected to be part of the facility assessments (as listed in **Appendix A**). These facilities were selected to represent a large proportion of the regulated drinking water facilities in the Province of Alberta, based on population served. Large urban centres (Edmonton and Calgary) were omitted from this project, as they have ongoing initiatives to manage future planning and uncertainty.

The facility assessment included a review of the drinking water facility information from the following sources:

- Provincial Regional Water Strategy (Water for Life Reports 2004 and 2016 update);
- Drinking Water Safety Plans; and
- Survey of the drinking water system operators through a questionnaire.

The goal of the questionnaire was to fill in the information gaps left from the review of the available information and gain insight from in-house experience with the selected facilities. The questionnaire was sent to all facility operators or managers.

2.1.2 Facility Assessment Methods

To facilitate an understanding of the facility's resilience to historic high and low flow events, three categories of facility infrastructure were evaluated separately:

- **Source** category included the quality, reliability, and sustainability of the raw water source; as well as physical attributes, condition, and history of the intake, wells, raw water pumphouse and raw water reservoirs.

- **Treatment** category included the water treatment facility and treatment processes in use, as well as the facility's historical ability to meet water quality standards.

- **Distribution** category included distribution infrastructure, such as booster stations and treated water reservoirs.

Ranking criteria were developed for each of the three categories described above, for historic high and low streamflows events, based on engineering judgement of the severity of responses. The ranking criteria are shown in **Table 2-1**.

Table 2-1
Facility Assessment Evaluation Criteria

Infrastructure Category	Items Considered	Maximum Score (Points)
Source	Historical response to previous high/low streamflows (if any) from the point of view of raw water infrastructure	22
	Condition of the groundwater wells OR Condition of the intake, raw water pumphouse, riverbank	18
	Physical characteristics of the system, such as proximity of raw water infrastructure to the nearest body of water	10
Treatment	Historical response to previous high/low streamflows (if any) from the point of view of water treatment infrastructure	16
	Resiliency of the treatment system	24
	Physical characteristics of the system, such as proximity of treatment infrastructure to the nearest body of water	10
Distribution	Historical response to previous high/low streamflows (if any) from the point of view of the distribution infrastructure	16
	Physical characteristics of the system, such as proximity of distribution infrastructure to undesirable geographical features and nearest body of water	34

The overall facility score for both high and low streamflows was calculated from a maximum of 50 points. To calculate the overall score for high streamflows, source, treatment, and distribution scores, were weighed as follows: source was weighed as twice as vulnerable to streamflow changes when compared to treatment, and treatment was weighed as twice as vulnerable when compared to distribution. As such, the weighing for source, treatment, and distribution was 57.2%, 28.6%, and 14.3%, respectively. To calculate the overall score for low streamflows, source was weighed as twice as vulnerable to streamflow changes when compared to treatment. The distribution system was not assessed for low streamflows. Therefore, weightings for source and treatment were 66.6% and 33.3%, respectively.

A low score is indicative of a system that has experienced high or low streamflows but was able to manage the impacts of these events without notable issues. A higher score was indicative of a system that may have struggled to cope with the impacts of past high or low streamflows. Table 2-2 provides interpretations of various scores.

Table 2-2
Facility Score Interpretation

	Score Range	Score Interpretation
Less Vulnerable	0 - 10	Facility demonstrated no or minimal vulnerability to the impacts of high/low stream flows.
	11 - 20	Facility demonstrated low vulnerability to the impacts of high/low stream flows; some gaps in future ability to manage the impacts of high/low stream flows may exist.
	21 - 30	Facility demonstrated some gaps in future ability to manage the impacts of high/low stream flows and may have experiencing some issues while coping with these events in the past.
	31 - 40	Facility demonstrated considerable gaps in future ability to manage the impacts of high/low stream flows, and likely encountered issues, and/or incurred significant costs while coping with these events in the past.
More Vulnerable	41 - 50	Facility demonstrated critical gaps in future ability to manage the impacts of high/low stream flows. Facility may have struggled while coping with high/low stream flows in the past.

2.2 Awareness and Preparedness Observations

An additional goal of the questionnaire was to determine the level of awareness and preparedness of the facility operators, when it comes to extreme streamflow events. To this end, the respondents were asked:

- What documents have been completed for the facility that can be used as high and low streamflow risk management tools?
- Questions about history of high and low streamflow (but worded as floods and droughts for clarity for facility operators) experienced at the facility level, and their impacts.
- What high and low streamflow protection measures exist at the facility-level?

When it comes to documents completed at the facility-level that can be used as flood and drought risk management tools, the following results were obtained (refer to **Figure 2-1**):

- 94% of the respondents indicated that their facilities have Drinking Water Safety Plans (DWSPs).
- 23% of the respondents indicated that their facilities have Source Water Protections Plans (SWPPs).
- 27% of the respondents indicated that their facilities have Flood Readiness Plans.
- 15% of the respondents indicated that their facilities have Drought Readiness Plans.

A completed DWSP is a mandatory requirement of an Approval to Operate, which may explain the high rate of DWSP completion. No observation can be made from the responses whether or not the DWSPs are being relied upon as a risk management tool and regularly updated or are simply being completed to meet regulatory requirements.

In contrast to the high DWSP completion rate, less than a third of facilities surveyed have completed SWPPs or Flood/Drought Readiness Plans. These plans are not mandatory or based on a prescriptive template; therefore, they may be quite different for the facilities, and as such, caution must be exercised against drawing firm conclusions.

Over three quarters of respondents appeared to be familiar with the history of floods and droughts or past impacts due to floods and droughts, experienced at their facility. This result indicates that past history of floods and droughts is mostly retained at the facility level. The majority of questionnaire respondents appeared to be a great source of information about past implications of floods and droughts at the facility level.

When asked whether flood and drought protection measures were currently in place at their facilities, over two thirds of the respondents answered affirmatively. However, upon review of measures listed, nearly half were found to be ineffective or not facility-specific. Half of those who indicated that flood and drought protection measures are in place could benefit from a better understanding of what these measures imply, in general and specifically, for their facility.

In summary, the following observations were made on the awareness and preparedness of the facility operators, when it comes to high and low streamflow events:

- Drinking Water Safety Plans have been completed for nearly all of the facilities that participated in the assessment.
- A majority of the respondents are aware of past impacts of floods and/or droughts, and nearly a third appear to be concerned about future implications of floods and/or droughts on their facility.
- A majority of the respondents could benefit from an increased understanding of what flood and/or drought protection measures are. This proportion of respondents corresponds to the proportion that has no Source Water Protection, Flood Readiness, or Drought Readiness Plans in place.

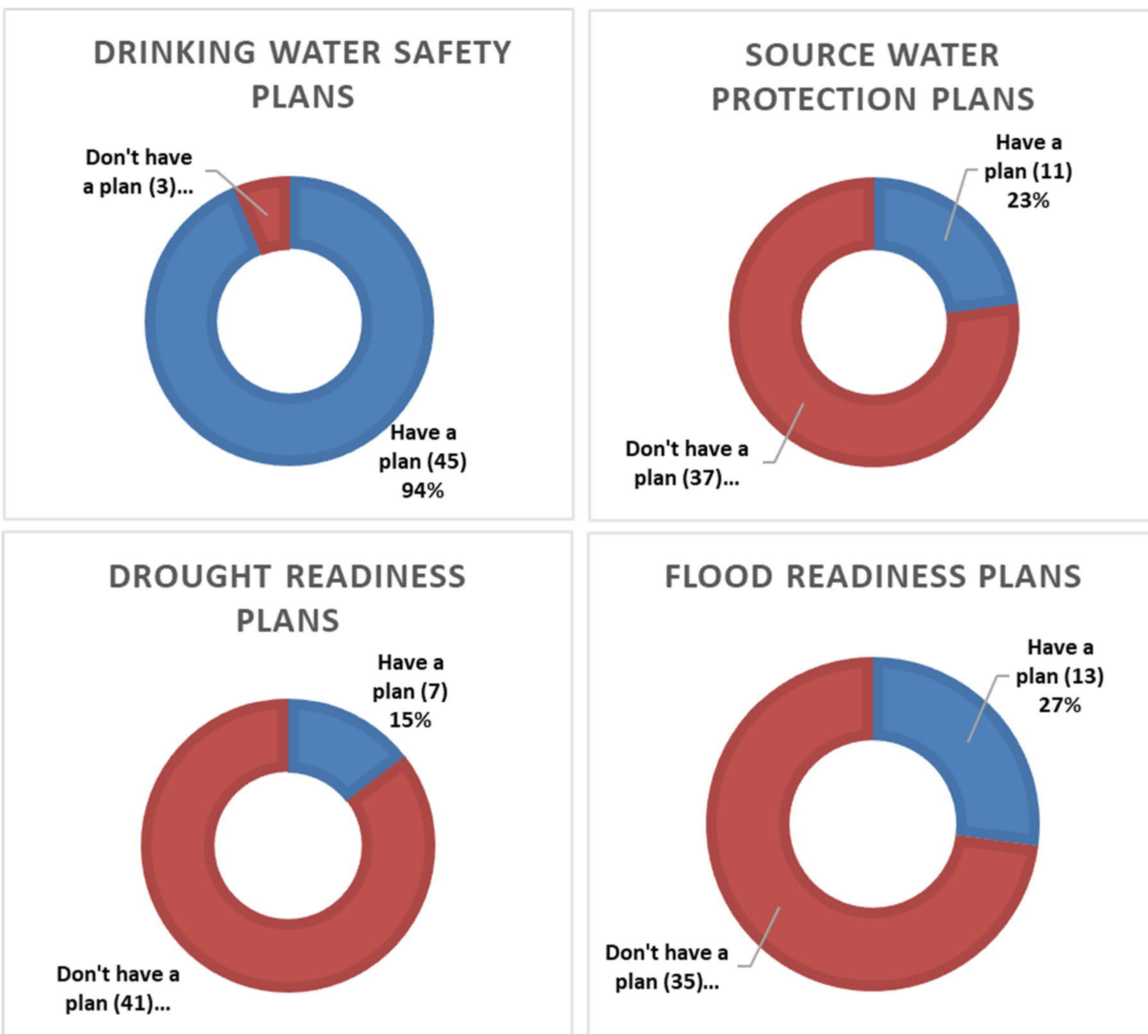

Figure 2-1
Awareness & Preparedness of Facility Operators

2.3 High Streamflow Observations (Historic Perspective)

Once the facilities were ranked, the following results were observed (**Figure 2-2**):

- 14% of the studied facilities indicated no or minimal vulnerability to the impacts of past high streamflows.
- 50% indicated low vulnerability to the impacts of past high streamflows; never-the-less some gaps to manage impact from past events may exist.
- 21% indicated some gaps to manage impacts of past high streamflows and may have experiencing some issues while coping with these events.
- 15% indicated considerable gaps to manage the impacts of past high streamflows, and likely encountered issues, and/or incurred significant costs while coping with these events.
- No facilities indicated critical gaps in their ability to manage the impacts of past high streamflows.

As is shown in **Table 2-1**, a facility's historical response to periods of low and high streamflow was a major factor in the outcome of the facility assessment. After all, the actual performance of the infrastructure during extreme weather events portrays a much more informative picture than theoretical performance. However, reliance on the operators' description of historical response produced an interesting trend in the outcomes of the facility assessment:

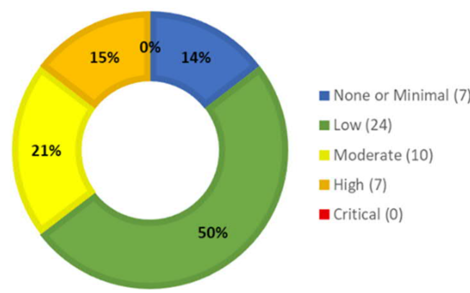

Figure 2-2 Facility Vulnerability to Historic High Stream Flows

- Operators of the facilities that are located in areas recently exposed to major high streamflow events tended to be very familiar with and descriptive about the facility's shortcomings when it comes to flood readiness.
- Operators of the facilities that are located in areas historically sheltered from floods, tended to describe their facility's flood readiness as high.
- This bias in responses resulted in some facilities scoring higher (i.e., more vulnerable) than others, not due to their actual flood readiness, but because their flood readiness has been recently put to test.

This trend can be observed in the following results: all but one of the facilities that scored 'High' (i.e., highly vulnerable to high streamflow events), and over half of the facilities that scored 'Moderate', are located in the South Saskatchewan River basin, where high flow events have placed a major strain on critical infrastructure in the past decade.

Figure 2-4 illustrates these results on the Provincial map.

2.4 Low Streamflow Observations (Historic Perspective)

Once the facilities were ranked, the following was determined (Figure 2-3):

- 13% of the studied facilities indicated no or minimal vulnerability to the impacts of past low streamflows.
- 58% indicated low vulnerability to the impacts of past low streamflows; some gaps in their ability to manage the impacts of low streamflows may exist.
- 27% indicated some gaps to manage the impacts of past low streamflows and may have experiencing some issues, while coping with these events.
- 2% indicated considerable gaps to manage the impacts of past low streamflows, and likely encountered issues, and/or incurred significant costs while coping with these events.
- No facilities demonstrated critical gaps in future ability to manage the impacts of low streamflows.

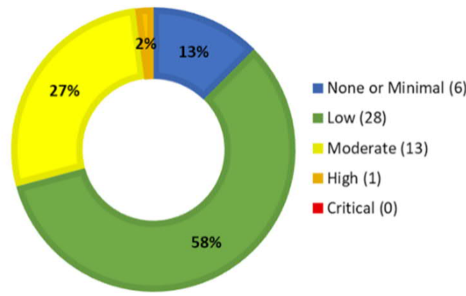

Figure 2-3 Facility Vulnerability to Historic Low Stream Flows

Similarly to a trend discussed earlier (refer to Section 2.3), facilities that have been exposed to detrimental impacts of low streamflows in the recent past have scored higher (i.e., more vulnerable) than others.

The vast majority of facilities that scored 'High' (i.e. highly vulnerable to low streamflow events) are located in the South Saskatchewan River and the Red Deer River basins, where low streamflows have been observed more frequently than in the north of the Province in the past.

Figure 2-4 illustrates these results on the Provincial map.

Legend:

Risks

- 0 to 10
- 11 to 20
- 21 to 30
- 31 to 40

Average Treated Water Production m³/day

- 0 to 2,500
- 2,501 to 5000
- >5,000

FIGURE 2-4
HIGH FLOW - FACILITY ASSESSMENT OUTCOME

ALBERTA INNOVATES
DRINKING WATER VULNERABILITY RISK ASSESSMENT

AE PROJECT No.	2018-3184
DATE	2020 MAY
SCALE	1: 5,000,000
COORD. SYSTEM	NAD 1983 CSRS 10TM AEP FOREST
DESCRIPTION	FINAL

Associated Engineering

BEST MANAGED COMPANIES
Platinum member

Legend:

Risks

- 0 to 10
- 11 to 20
- 21 to 30
- 31 to 40

Average Treated Water Production m³/day

- 0 to 2,500
- 2,501 to 5000
- >5,000

FIGURE 2-5
LOW FLOW - FACILITY ASSESSMENT OUTCOME

ALBERTA INNOVATES
DRINKING WATER VULNERABILITY RISK ASSESSMENT

AE PROJECT No.	2018-3184
DATE	2020 MAY
SCALE	1: 5,000,000
COORD. SYSTEM	NAD 1983 CSRS 10TM AEP FOREST
DESCRIPTION	FINAL

Associated Engineering

3 CLIMATE CHANGE AND WATERSHED ASSESSMENT

The substantial challenge of assessing climate change impacts to drinking water facilities required the development of new methods and analyses to enable estimates of drinking water infrastructure vulnerability and risk. The following sections provide an overview of the project methodology with more detailed descriptions in **Appendix B**.

3.1 Methodology Overview

The project required an assessment process that considered varying climate and watershed conditions to predict future streamflow conditions and relative deviations from historic streamflow conditions. Future climate change largely depends on the amount of greenhouse gas that is emitted globally in the future. Different global emission 'pathways' thus lead to different climate change impacts—and it is not certain which pathway global emissions will ultimately take. To address this uncertainty, this assessment considered two global emission pathways to represent the lower (RCP 2.6) and upper (RCP 8.5) bounds of emissions scenarios. Climate change projections also depend on the future timeframe in question (more change tends to occur for far-future conditions).

With support from Alberta Innovates (AI), Associated Engineering (AE) collaborated with the University of Alberta Watershed Modelling Laboratory (UA WSML) to utilize an available AI-funded hydrologic model to facilitate emission-scenario based future streamflow projections. The UA WSML Soil and Water Assessment Tool (SWAT) model provided past and future sub-basin streamflow estimates that enabled estimates of future change for various scenarios to be made. This collaboration integrated experience with Alberta's drinking water facilities with Alberta's hydrological and climate change modelling expertise, as shown in **Figure 3-1**. Within this collaboration, assessments of 'extreme' high and low streamflow conditions relevant to drinking water facility operation and level of service were targeted for primary analysis.

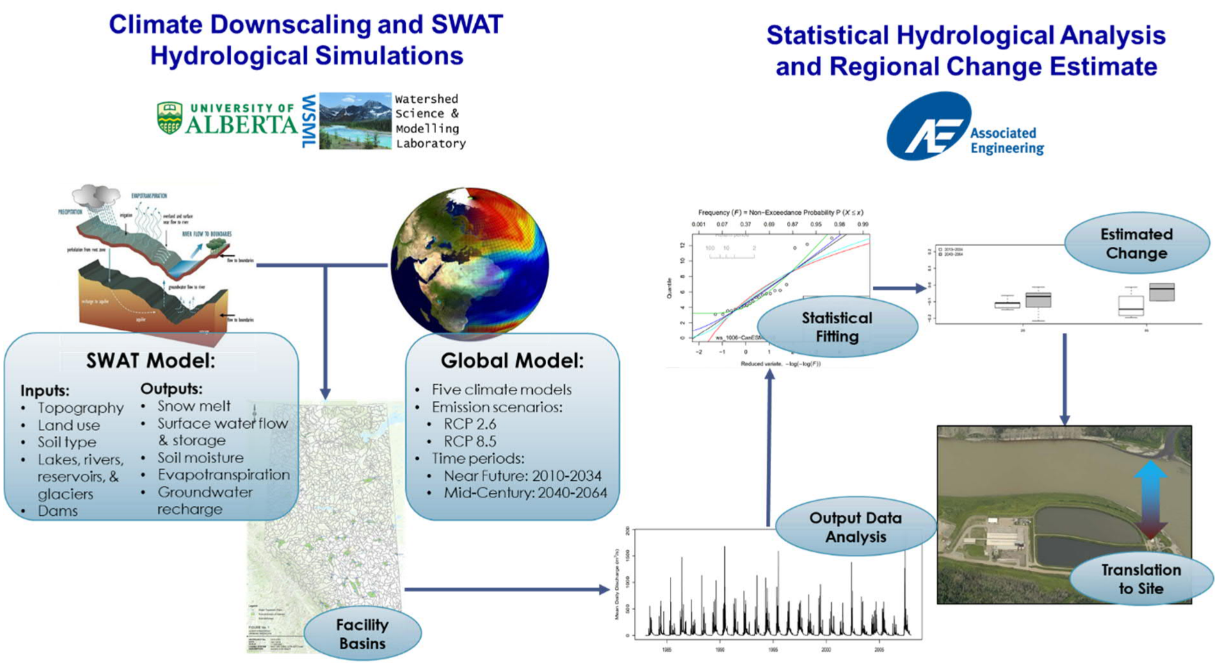

Figure 3-1
Climate Assessment Methodology Overview

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3.2 SWAT Modelling

The SWAT model simulation exercise provided a large database of simulated historical and future streamflow data, with individual 21-year continuous daily records of simulated streamflow for each sub-basin related to the drinking water facilities of interest, for each time period and future scenarios spanning 2010-2034 and 2040-2064 periods for which UA WSML generated hydrologic model output.

SWAT model simulations were undertaken for:

- The historical period 1983-2007.
- Two future time periods: 'Near Future' - 2010-2034 and 'Mid-Century' - 2040-2064.
- Two greenhouse gas emission scenarios: Representative Concentration Pathways (RCP 2.6 and 8.5):
  - RCP 2.6 represents a 'best case' climate change scenario associated with considerable reductions in emissions within the next few decades, although an unlikely scenario given the current global emissions trajectory; and
  - RCP 8.5 represents a more severe climate change scenario associated with continued increases in emissions throughout the 21st Century.
- Output from five different global climate models (CanESM2, CCSM4, MIROC5, CNRM-CM5 and MRI-CGCM3) developed by national climate modelling and analysis centres in Canada, the United States, Japan, and France. They are all widely accepted climate models, as demonstrated by their participation in the internationally-coordinated World Climate Research Program Coupled Model Inter-comparison Project 5 (WCRP CMIP5 2011).

3.2.1 Relevant Climate Change Metrics

A key aspect of any climate change assessment is the identification of climate change metrics that are most relevant to the system(s) in question. Drinking water facilities are naturally most vulnerable to extreme excesses of water, and extreme lack of water supply. AE identified the following key metrics of high- and low-flow for further analysis:

- High-flow: A metric of 1-in-100 year maximum annual 1-day streamflow (hereafter termed Q_{100}) was chosen to represent facility-relevant high-flow conditions. Most simply, Q_{100} magnitudes can be interpreted as the highest daily flow that has a 1% chance of occurring per year.
- Low-flow: Several metrics were chosen to represent potential low flow conditions: 1-in-10 year minimum summer-centered (May-October), winter-centered (November-April) and annual 7, 90, and 180-day streamflows (e.g., 9 low-flow metrics, [7/90/180]Q10[S/W/A]). These low flow metrics enabled the most representative metric to be selected for each facility depending on facility storage capacities and water withdrawal winter/summer operating periods.

Once these streamflow values were obtained, relative future changes, termed the 'delta' of change, were calculated for low and high flow metrics. The 'delta' presents a percentage change in the magnitude of each high and low flow metric. Between the modelled historic period and each future modelled period. For example, a DQ_{100} value of +10% indicates that the magnitude of streamflow associated with 1-in-100 year daily annual maximum streamflow (a measure of flooding) will increase by 10%, relative to historic conditions.

3.2.2 Model Limitations

SWAT is a standard hydrological model for developing understanding of hydrologic systems, including Alberta streams and rivers. For this study, SWAT was used to predict changes to extreme high and low flow conditions which could, in turn, impact drinking water facilities and facility operations. Model simulations and results must be interpreted with care, in recognition of challenges inherent in assessments of climate change impacts to extreme events, and in conjunction with actual hydrological streamflow observations and drinking water facility assessments.

With respect to the model framework itself, SWAT limitations include the following:

- As with any hydrological model, SWAT cannot capture every aspect of the hydrological systems that it represents. For example, in many cases, dams and reservoirs that exist on small waterways are not included in the provincial-scale SWAT framework.
- Since future water and land management decisions are not clearly known, SWAT simulations do not consider future land management changes, despite a high likelihood of occurring.
- To avoid SWAT representation of natural process being idealized, actual measured conditions were used to calibrate modelling and improve reliability. Calibrations were not specific to facility locations, but rather intended to reduce average model error across large regions of the Province, relative to gauge station measurements of streamflow.
- Simulations used here were calibrated to monthly scale, while daily-scale output was used to develop high and low flow metrics in this study.

These, and other model limitations, in no way precludes SWAT from assisting with understanding future climate impacts on streamflow conditions. However, the results require careful interpretation and should be used in conjunction with actual streamflow observations and drinking water facility assessments, and ideally augmented in the future by additional investigations with other hydrologic models in a multi-model framework. The current study is considered a screening assessment and any extrapolation of the model results to a single site for design grade guidance is not appropriate. Site-specific designs and upgrades will require additional analysis.

3.3 Watershed Assessment

Available streamflow records from Water Survey of Canada's (WSC) nearby gauge stations were analyzed to provide further context to the SWAT delta values, where possible. WSC stations closest to each drinking water facility were utilized to determine historic high and low flow indices and relevant sub-basin SWAT delta values applied to the resultant high and low flow indices for each scenario. This provided an approximate proxy for future streamflow conditions at each WSC gauge and estimated water level changes.

This analysis is useful to provide high-level context to how changes in streamflow conditions may affect water level at the water facility location. It is important to note that stage-discharge relationships, which relate the volume flux of water past a particular point, to actual water level at that point, are only applicable at the corresponding WSC stations, since site-specific channel geometry is a critical control on these relationships, and channel geometry is almost certainly different at water facilities than at gauge stations. Therefore, it is not appropriate to directly apply estimated water level changes at WSC stations to drinking water facility locations without site specific channel geometry and assessment. Instead, water level changes at WSC stations assessed here should be used in a qualitative context to frame water facility location changes.

3.4 Provincial Trends in Climate

3.4.1 Climate Variability and Climate Change

Climate change-driven shifts to provincial streamflows will stem from future changes to temperature and precipitation over the Alberta landmass that reflect broader global climate trends. Provincial-scale temperature and precipitation changes will in turn impact the complex set of hydrologic processes that regulate local streamflow conditions. For example, changes to the cumulative amounts of precipitation that fall over periods ranging from minutes to years are an important direct control on stream flow levels. Additionally, long-term changes to regional seasonal temperatures can modify rates of evaporation from soils and determine whether precipitation falls as snow or rain—with important impacts on streamflow timing and magnitude.

The Delta method, applied to a large collection of model outputs, provides one approach for isolating the climate change-derived signal to extreme hydrologic metrics, from the large natural variability in local hydrology (e.g. as shown in **Figure 3-2**) that results from day-to-day weather and natural climate cycles that range in length from several years to many decades.

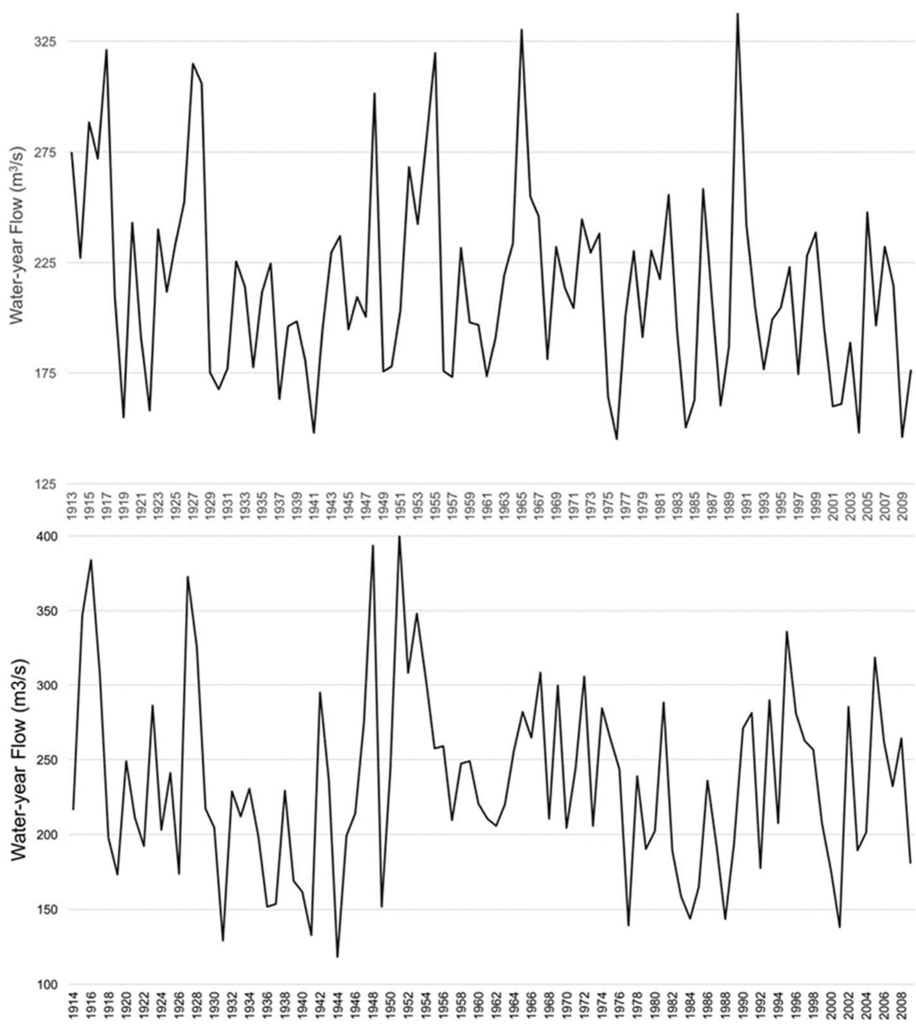


Figure 3-2
Mean Annual Directly Gauged Naturalized North Saskatchewan River at Edmonton (top) and South Saskatchewan River at Medicine Hat (bottom) – Sauchyn et al. (2017)

This shows large swings in stream flow result from natural climate variability, and this variability is further magnified for year-to-year occurrence of extreme high and low flow conditions. **Figure 3-2** from Sauchyn et al. (2017), based on Water Survey of Canada data. Clear understanding of these cycles in the context of assessing changes to high and low flows of relevance to provincial drinking water facilities is of key importance, particularly in the shorter term when the impact of these cycles may dominate over the longer-term climate signal. For example, recent work to understand provincial climate variability has highlighted the role of the Pacific Decadal Oscillation (PDO) and El Nino, in determining broad provincial temperature and precipitation patterns (e.g., Sauchyn and Illich, 2017). Over longer time windows, a unique tree ring record (Sauchyn and Illich, 2017) has highlighted the role of natural cycles in causing multi-decadal oscillations in low flow conditions that are not captured by standard hydrological and meteorological records. Over shorter time windows, ongoing research is developing a clearer picture of controls on Rocky Mountain spring snow melt, and Prairie summer convective storms, both of which are potentially responsible for regional high streamflows. Improved understanding of these natural variations is important for placing the long-term regional climate change signal in an accurate regional context.

The regional future climate change signal that is applied to the SWAT model is described in detail in recent SWAT studies (Masud et al., 2018; Vaghefi et al., 2019). The amount of projected change is different across both different climate model projections, future time periods, spatial regions, and RCP scenarios. SWAT-simulated streamflow changes can be placed in a broader context by averaging across global climate model projections. Such projections, - when downscaled to Alberta using statistical techniques to better reflect provincial and regional climate conditions and minimize global climate model biases over the Alberta region - provides general temperature and precipitation changes relative to the 1983-2007 ('historical') period and the 2010-2034 and 2040-2064 periods. Provincial 21-year annual average temperatures (taken as the median across 9 downscaled climate model projections for each projection and time period, for the hydrological regions assessed by the above-noted studies), are expected to increase similarly by 1.35°C/1.4°C for the 2010-2034 period under RCP2.6/RCP8.5 scenarios. In contrast, the scenarios increasingly diverge in their projections of warming for the farther-future 2040-2064 period, with model-median warmings of 1.7°C/3°C projected under the RCP2.6/RCP8.5 scenarios. Warming will likely be greater for the winter, than the summer (Canada in a Changing Climate Report, 2019). These temperature changes, which are relatively well constrained and qualitatively similar the same across climate models are consistent with other estimates of future temperature change (Canada in a Changing Climate Report, 2019).

The downscaled precipitation signal over Alberta derived from the same downscaled global climate projections used to project future temperatures, estimates model-median 0%/5% increases in annual average precipitation over the 2010-2034 period relative to 1983-2007 under the RCP2.6/RCP8.5 scenarios. This increases to 5%/20% for the 2040-2064 period under the RCP2.5/RCP8.5 scenarios. Ranges in future projected precipitation—over Alberta and the broader Prairies—varies much more than temperature projections, with most models projecting overall wetter annual-average conditions but some models projecting overall drier conditions (Canada's Changing Climate Report, 2019). On average across models, downscaled precipitation developed and assessed by the UofA's WMSL increased over both winter and summer months, with important implications for seasonal cycles in projected changes to streamflow trends within this assessment.

These temperature and precipitation changes are key factors that influence SWAT-simulated changes to provincial hydrological streamflow, the key factor in determining facility-scale climate-derived changes to high and low flows.

3.4.2 Changes to High Flow Magnitudes

Province-wide changes to high flow magnitudes at assessed drinking water facilities and calculated by the Delta Q_{100} metric provides a high-level overview of projected changes. Figure 3-3 shows mean Delta Q_{100}, at all assessed facilities. The picture that emerges provides a high-level, Province-wide view of SWAT-estimated high-flow changes.

Provincial drinking water facilities should by default expect to brace for more extreme high water conditions primarily related to higher snow and rain accumulations in mid-winter, but also potentially to individual extreme storm events.

An emergent finding of the analysis is that SWAT simulations of changes high flows (DQ_{100}) are expected to increase at most drinking water facility locations. This increase particularly emerges in the 2040-2064 period. This change suggests that, on average, provincial drinking water facilities should, by default, expect to brace for more extreme high streamflow conditions.

This result is qualitatively echoed by other recent studies and reports (e.g., Canada in a Change Climate, 2019, Guar et al., 2019), and is consistent with first-principles understanding of regional hydrological response to climate change. In particular, climate model-characterized trends towards increasing precipitation across seasons in the input climate data to SWAT simulations likely plays a major factor in driving increased Delta Q_{100}. In particular, higher late-winter precipitation that will add to peak spring freshet flows, but also potentially to individual extreme storm events which are also expected to become more commonplace because of climate change.

While the predominant trend towards intensified high flow conditions holds for most facility locations, there are some important exceptions with distinct spatial patterns. In particular, facilities in the northern third of the Province and facilities in the far south east may be most likely to 'buck the trend' and not experience increases in Q_{100}. In the case of the former, peak freshet conditions may be moderated by increased rainfall during the shoulder spring season, which lessens the impact of spring warming on snow melt conditions. In the far southeast, where flows are somewhat less regulated by Rocky Mountain melt and more controlled by local snowpack, decreases to local snowpack may also be a key differentiator. Finally, an additional control on high flow changes may be watershed size and associated background streamflow magnitude: facility locations that are projected to experience decreased DQ_{100} are generally located on smaller water courses, typical of south eastern pothole-dominated areas.

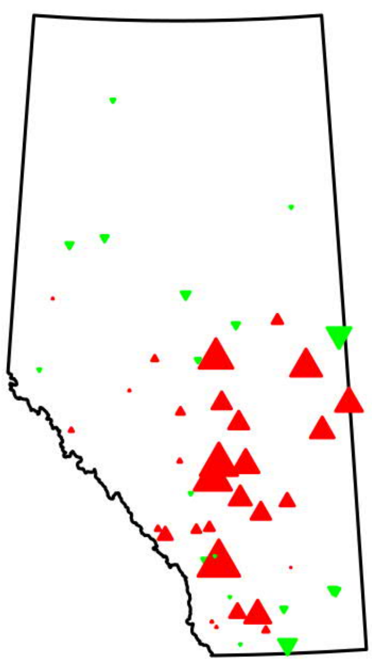


Figure 3-3
Simulated Trends in High Flow Conditions under Climate Changes Conditions*

*Red upward arrows indicate increasing flood magnitude & flood risk.

An additional control on high flow conditions is active management of watersheds. SWAT accounts for the management of 15 major provincial dams and reservoir facilities in terms of regulation; however, many smaller management assets are not accounted for—and regulation of the major facilities are kept constant at present-day levels, into the future. Thus, there is potential for management of water levels to significantly lessen or even entirely ameliorate the impact of climate change on Q_{100} values, although consideration of increased management is beyond the scope of this report.

3.4.3 Changes to Low Flow Magnitudes

Province-wide SWAT-simulated changes to low flow magnitudes are provided by the D7Q10 and D90Q10 summer and winter low flow conditions, and D180Q10 for annual low flow conditions.

Winter low streamflow conditions: Presently in Alberta, lowest flows predominantly occur during the winter, as water is sequestered on the landscape as snow and ice. This means that the most extreme low flow conditions in the Province tends to occur during winter months. Against this baseline and superimposed on regional natural climate variability, climate change will cause two primary winter-time trends over the Province: both substantially increased warming, and modestly increased winter precipitation. In combination, these trends will cause more precipitation to fall as rain—particularly, in the early spring and late fall 'shoulder' seasons—causing a trend towards increases to winter-season extreme minimum flows. In addition, accelerated melting snow packs will tend to further enhance late winter flows.

The results suggest that climate change into the Mid-Century alone may not substantially increase the risk of summer low flows at most facilities.

Taken in combination these climate change signals (increased precipitation as rain and late winter snow melt) generally suggest streamflow increases within watersheds hosting drinking water facilities, based on Province-wide SWAT-simulated D7Q10 and D90Q10 streamflow metrics (Figure 3-4). These provincial-scale changes are generally consistent with broader understanding of winter streamflow processes in the Prairies (e.g., Canada's Changing Climate Report, 2019).

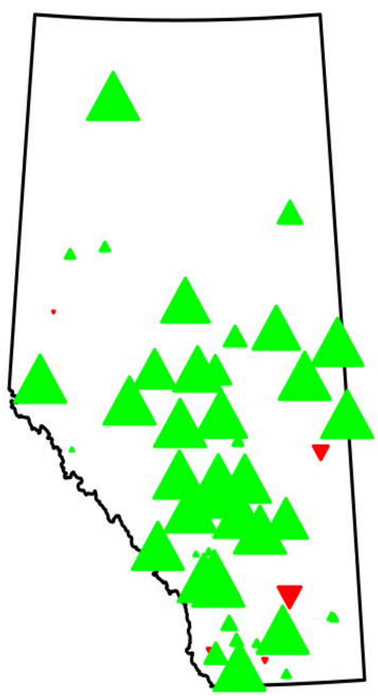


Figure 3-4
Simulated Trends in Winter Low Flow Conditions under Climate Change Conditions*

*Green upward arrows indicate increasing low flow magnitude and decreasing low level risk.

Variations at the Sub-Basin Level: within sub-basins containing provincial drinking water facilities, there is substantial scatter in the spatial pattern of winter low flow changes simulated by SWAT. Within this scatter, there are several facility-relevant sub-basins that counter the overall trend of overall increases to winter streamflow by exhibiting lower wintertime low flows as measured by the week-scale and multi-month D7Q10 and D90Q10 metrics. Unlike SWAT-simulated changes to high flows, there is less geographic clustering of these sub-basins, suggesting that broader-scale climate or whole watershed-scale effects are not the cause of these outlier sub-basin results. Rather, an assessment of D7Q10 and D90Q10 changes against sub-basin size highlights that these outliers predominantly occur in sub-basins with smaller average flows, that tend towards eastern Alberta geographies. This points to small Prairies sub-basins as potentially most susceptible to climate-change driven decreased wintertime low flow conditions.

Annual Low Streamflow Conditions: Assessment of climate change-driven shifts to long-term annual low flows across watersheds hosting Alberta drinking water facilities is facilitated by the D180Q10 metric, which captures changes to half-year 'chronic' low flow conditions that tend to manifest during the fall and winter periods. As a result, SWAT-simulated changes to D180Q10 broadly mirror changes to winter-specific D7Q10 and D90Q10 shifts, in portraying overall increases to long-term average low flow conditions across the Province related to increased late fall and winter precipitation.

Additionally, the lack of clear geographic clustering of the minority of sub-basins with decreasing D180Q10 is a result that mirrors the spatial pattern of changes exhibited by the D7Q10 and D90Q10 winter metrics, highlighting that small sub-basins are potentially most susceptible to climate-change driven changes to chronic low flow conditions. In net, the assessment of 6-month low streamflow shifts is consistent with shorter-term measures of wintertime low flows, as they are regulated by the same physical drivers.

Summer Low Streamflow Conditions: Assessment of summertime low flow conditions simulated by SWAT is carried out via application of the D7Q10 and D90Q10 metrics, applied to summer season conditions. Lowest flows in snowmelt-dominated streamflow regimes typical of Alberta watersheds very predominantly occur towards the end of summer, after the spring snowmelt-driven freshet has subsided. After freshet, streamflow becomes dominated by a combination of residual high altitude snowmelt, base flow from groundwater and precipitation and net evapotranspiration (direct soil evaporation, plus water transfer from soils to the atmosphere via plants), both of which increase substantially during summer.

Against this backdrop, SWAT-simulated streamflow projects suggest a broad Province-wide increase to average summertime low-flow conditions and extreme measures of these conditions as represented by the applied D7Q10 and D90Q10 metrics. This change suggests that climate change alone may not substantially increase the risk of summertime low flows at most provincial drinking water facility locations. Conversely, SWAT-specific results tentatively suggest that climate change may partially alleviate extreme summer low flow conditions that are caused by natural patterns of climate variability such as El Nino. Increases to SWAT-simulated summer low flow magnitudes are consistent with the downscaled climate model input datasets provided to SWAT, which contain—in addition to a broad warming signal—a signal of increased summer precipitation. As summer streamflows are related closely to both summer precipitation and temperature-controlled summer evapotranspiration, increased streamflows indicate that in the SWAT simulations assessed here, increases to summer precipitation outweigh the impact of increased evapotranspiration, by a notable margin.

Projections of summer low flow changes generated by SWAT simulations forced by the range of downscaled climate data produced by the WMSL tend to counter other assessments of projected future Prairies streamflow changes, which tend to describe overall decreases to average flow by several broad-scale measures (e.g. average flows by month or season) – albeit with very large spread, and with no focus on extreme events such as drought indices. This difference is consistent with the downscaled and bias-corrected climate data that is provided to SWAT, which projects increases to average summer precipitation. In contrast, other projections of summer precipitation changes developed by the climate modelling community, suggest the potential for little future change, or even decreases, in Alberta's summer precipitation, resulting from climate change. Why are projections of changes to summer precipitation and related streamflows more variable than, for example projections to climate conditions relevant to winter streamflow? In part, winter streamflow increases stem from increases in winter precipitation, which are largely related to warmer atmospheric conditions. Winter streamflow increases are also in part dependent on projected winter temperature increases, which is also a common aspect of model projections. In contrast, projected summer precipitation changes are much more uncertain, in part because the details of the atmospheric processes associated with summer precipitation events are not yet well captured in climate models.

3.5 Local Uncertainties and Suggestions for Future Progress

Assessing future changes to the extreme low and high flow 'tails' of local hydrological conditions is perhaps one of the most challenging topics of applied climate vulnerability assessments. Challenges can arise across multiple fronts, including:

- Integration of regional conditions into pointwise streamflow locations.
- Calibrated modelling of complex natural and human-influenced hydrological systems.
- Simulation and downscaling of extreme climate events in global climate models.
- Extrapolation of rare long-return-period extreme events, from limited information.
- Separation of global climate change signal and local natural variability.
- Choice of future climate scenarios, future time periods, and climate model frameworks.

These challenges highlight the need to regularly update the findings of this report, and similar reports, as better data, models, and techniques emerge from both academic research and provincial hydrologic initiatives. To that end, the following recommendations provide a guideline for subsequent assessments:

- **Increase facility-specific hydrometric measurement and monitoring efforts:** key to translating changes from streamflow volumes to actual water level changes are *stage discharge curve* relationships. Such relationships are developed via site-specific watercourse cross section profile mapping and flow measurements. Lacking such measurements, it is challenging to map projected streamflow changes to site-specific water level changes. Development of facility-specific stage discharge curves is thus a key step, in allowing output from hydrological models (such as SWAT) to be integrated into local-scale facility climate vulnerability and risk assessment exercises.
- **Assess climate-driven hydrological changes from multiple downscaling and hydrological modelling methods:** a key aspect of many climate change impacts, vulnerability and risk studies is use of multiple model frameworks to identify the widest potential spread in future projections and identify potential outlier model frameworks. To this end SWAT simulation effort carried out by the UofA WMSL assesses hydrological responses across different climate model projections from multiple climate models. However, significant additional spread exists from the results of different downscaling methods and hydrological model design (Wilby and Dessai, 2010). This is not sampled in the current study, with potentially important but currently unknown consequences for local-scale risk assessments. To integrate this spread into local-scale vulnerability and risk assessments, multiple downscaling methods and hydrological models should be used to develop a 'consensus' hydrological response for each climate model forcing, in line with broader climate modelling methodologies.
- **Develop hydrological research that targets priority provincial water vulnerabilities:** The UofA WMSL is a unique provincial capability, tasked with support from Alberta Innovates to develop applied Alberta and Prairies-specific assessments of hydrological change. However, given the potentially large scale of climate-driven hydrological impacts, support for further research capacity is encouraged to better characterize past, present, and future hydrological system behavior—particularly in relation to priority provincial water vulnerabilities, such as provincial drinking water facility risks.

- **Monitor national, and global climate and hydrological research:** Climate and hydrological research and development is rapidly evolving at national and global levels. For example, improvements in climate model design, downscaling methods, and validation against improved observational datasets holds the promise of better resolved provincial climate change signals. And emerging hydrological models display increasing sophistication, such as better representation of key water/groundwater interactions. Provincial agencies should maintain a clear vision of the outcomes of national and global research progress, in relation to drinking water facility resilience.
- **Develop customized local-scale risk-focussed hydrological projections:** For all locations identified in this report, additional local, detailed, hydrological modelling that utilizes local hydrological model calibration, climate downscaling, and management practices will be critical for better resolution of potential climate impacts. Improved resolution of these factors may even provide significantly different results than are presented here, as key local-scale factors that are not captured in provincial-scale models are better resolved.
- **Improve understanding of regional climate variability and climate change signals:** Alberta is home to remarkable scientific initiatives that are working to understand the relationship between natural climate variability, such as that responsible for multi-decadal drought in the past, and human-caused climate change (e.g., Sauchyn et al., 2015). Understanding the relation between regional hydrological variability and change is a key to developing better projections of future extreme hydrological conditions that impact drinking water facilities. Both direct hydrological observations and climate and hydrological modelling have key roles to play in developing this understanding further, with large implications for improving facility climate vulnerability assessments such as the one described in this report.

4 VULNERABILITY AND RISK ASSESSMENT (VRA)

Vulnerability and risk assessments (VRAs) are widely recognized as an important prerequisite to development of a robust climate adaptation strategy. VRAs provide a structured method for identifying, analyzing, evaluating, and ultimately prioritizing risk. VRAs can aid planners and decision makers in understanding the impacts of different climate events or conditions in a consistent fashion across various assets, services and sectors. The overarching goal is to prioritize climate-related impacts so evidence-based risk management strategies can be developed and implemented for those risks that pose the most significant threat to an organization or community.

VRAs are a critical stage within an overall adaptive management framework to increase resilience to climate variability and climate change. In the context of adaptive management, VRAs provide baseline information that can be used to track the impacts of climate change over time and determine the effectiveness of strategies implemented to reduce risk. Figure 4-1 illustrates the VRA pathway conducted here-in.

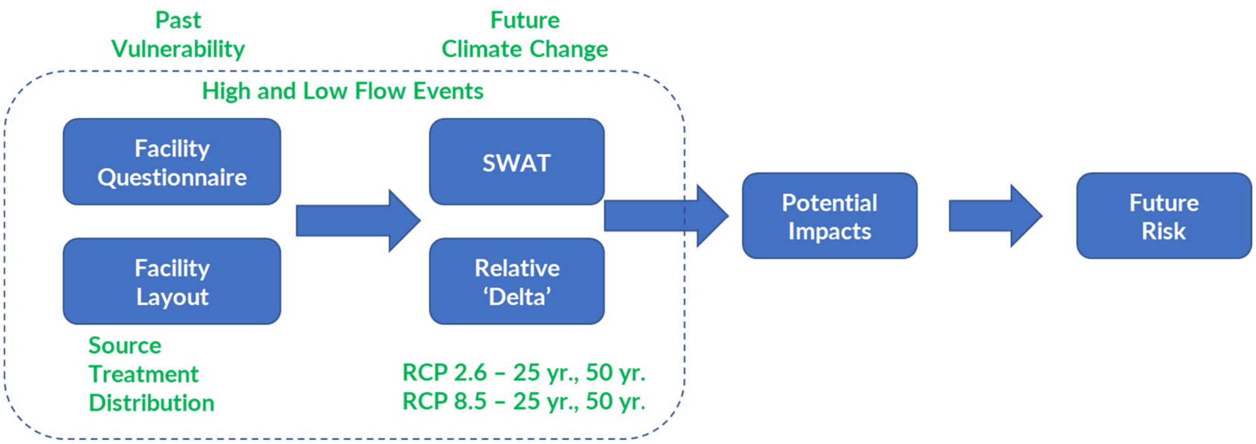


Figure 4-1
VRA Impact Tracking

4.1 Methodology Overview

A risk matrix was employed to determine the overall vulnerability of each facility to the impacts of high and low streamflow periods, in the future. A risk matrix is a tool used to assess the level of risk by considering both the likelihood of an event taking place, as well as the severity of the consequences due to an event taking place.

In this case, the results of the climate assessment were considered as a 'likelihood' input into a risk assessment matrix (RAM), and the results of the facility assessment were considered as a 'severity' input into a RAM (refer to Figure 4-2). These results were plotted for both climate changes scenarios (RCP 2.6 and RCP 8.5), for the near future (2010-2034) and into the Mid-Century (2040-2064).

In total, four values were plotted on each RAM for high and low streamflow:

- Overall risk for years 2010-2034, climate scenario RCP 2.6 ('best case' climate change scenario associated with considerable and potentially unrealistic reductions in emissions within the next few decades).
- Overall risk for years 2010-2034, climate scenario RCP 8.5 (more severe climate change scenario associated with continued increases in emissions throughout the 21st Century).
- Overall risk for years 2040-2064, climate scenario RCP 2.6.
- Overall risk for years 2040-2064, climate scenario RCP 8.5.

In addition, a fifth value was plotted on the RAM for high streamflows:

- Maximum potential change, across all years and climate scenarios.

The plotted values for high streamflow were based on Q_{100} values, and the plotted values for low streamflow were based on summer, winter, or annual, 7-, 90- or 180-day Q_{10}, depending on when the facility pumps water, and its raw water storage capacity. In the case of a facility with less than a month of raw water storage and pumps raw water throughout the year, the $7Q_{10}$ (7-day Q_{10}) winter low streamflow delta was used.

As an output, the RAM provides one of the following risk categories:

- **Low Risk:** The facility does not appear to be vulnerable to impacts of high or low streamflow periods.
- **Moderate Risk:** The facility was found to have some vulnerability to the impacts of high or low streamflow periods, whether due to anticipated watershed changes brought on by climate change, or due to the facility's current level of preparedness. Some adaptation measures may be recommended.
- **High Risk:** The facility is vulnerable to impacts of high or low streamflow periods. Adaptation measures are recommended.
- **Critical Risk:** The facility is extremely vulnerable to impacts of high or low streamflow periods. Adaptation measures are strongly recommended. Appropriate emergency response should be developed further.

		Impact of High or Low Streamflows on the Facility (Facility Assessment Outcome)				
		Most Likely Able to Manage Event (0 – 10)	Likely Able to Manage Event (11 – 20)	Some Gaps in Ability to Manage Event (21 – 30)	Significant Gaps in Ability to Manage Event (31 – 40)	Major Gaps in Ability to Manage Event (41 – 50)
Likelihood of Facility Experiencing Greater Impacts Due to High or Low Streamflows (Climate Assessment Outcome)	Very Unlikely	Low	Low	Moderate	Moderate	Moderate
	Unlikely	Low	Moderate	Moderate	Moderate	High
	About as Likely as Not	Moderate	Moderate	Moderate	High	High
	Likely	Moderate	Moderate	High	High	Critical
	Very Likely	Moderate	High	High	Critical	Critical

Figure 4-2
Risk Assessment Matrix (Figure A-2)

4.2 High Streamflow Observations (Future View)

The following results were observed:

- 23% of the studied facilities did not appear to be vulnerable to impacts of high streamflow periods.
- 58% were found to have some vulnerability to impacts of high streamflow periods, whether due to anticipated watershed changes, or due to the facility's current level of preparedness. Some adaptation measures are recommended.
- 17% were found to be vulnerable to impacts of high streamflow periods. Adaptation measures are recommended.
- 2% were found to be extremely vulnerable to impacts of high streamflow periods. Appropriate adaptation measures and emergency response should be developed further.

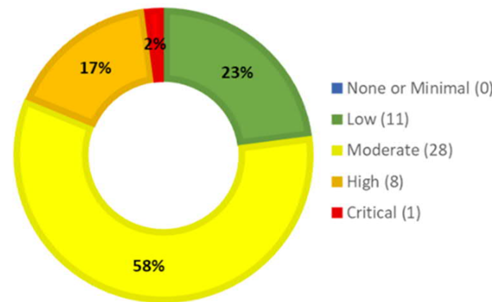


Figure 4-3
VRA Outcome -High Streamflows

In summary, a quarter of the facilities were found to be vulnerable to future impacts of high streamflows, which is a significant portion of the facilities studied. This result warrants further investigation into how the resiliency of drinking water facilities to high streamflow impacts can be improved.

Majority of facilities that are high and critical are located in the Red Deer River and the South Saskatchewan River basins, which reflects the results of the climate assessment for these river basins. Figure 4-7 illustrates the VRA outcome on the Provincial map.

As mentioned earlier in the Methodology Overview section, the overall vulnerability to high streamflow was determined based on the outcome of both the facility assessment and the climate assessment. However, the climate assessment had four outcomes – one for each of the two different climate scenarios, and the two different future timeframes.

In most cases, all four outcomes were the same and therefore resulted in the same overall risk category on RAM. In some instances, however, climate assessment outcomes varied according to climate change scenarios examined, and one facility's RAM could reflect two or more categories of risk.

For this reason, a 'Worst Case' value (maximum change) was selected to represent the climate change outcome of concern; this value was the determining factor in the overall vulnerability. The VRA outcomes based on the 'Best Case' value (minimum potential change, typically the RCP 2.6) are compared to the 'Worst Case' on Figure 4-4. Generally, facilities would end up in a lower risk category in the best case scenario, than they did in the worst case scenario. This also demonstrates the results did not differ dramatically based on the climate scenario.

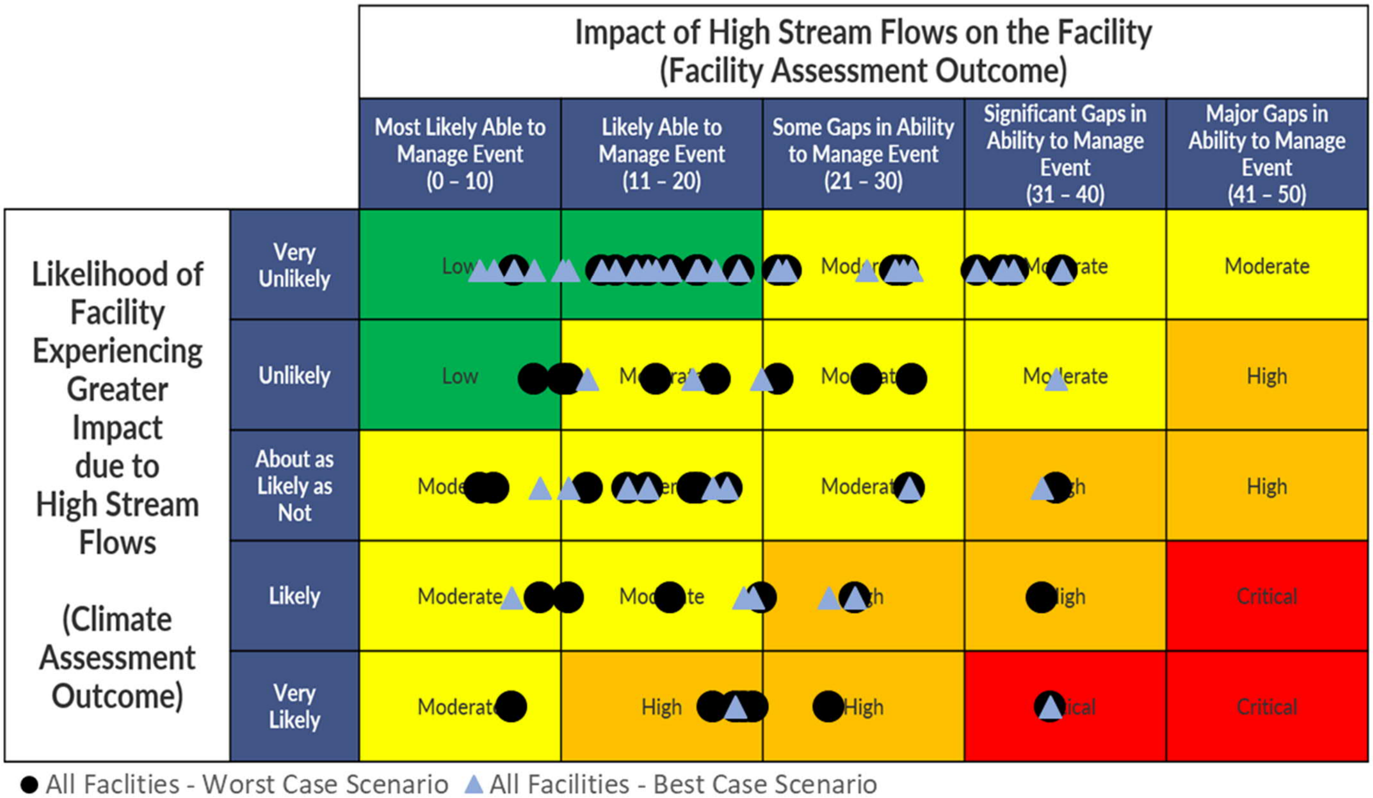


Figure 4-4
All Facilities, High Streamflow, Best Case and Worst Case Scenario

4.3 Low Streamflow Observations

The following results were observed:

- 50% of the studied facilities did not appear to be vulnerable to impacts of low streamflow periods.
- 42% were found to have some vulnerability to impacts of low streamflow periods, whether due to anticipated watershed changes, or due to the facility's current level of preparedness. Some adaptation measures are recommended.
- 6% were found to be vulnerable to impacts of low streamflow periods. Adaptation measures are recommended.
- 2% of facilities were found to be extremely vulnerable to impacts of low streamflow periods.

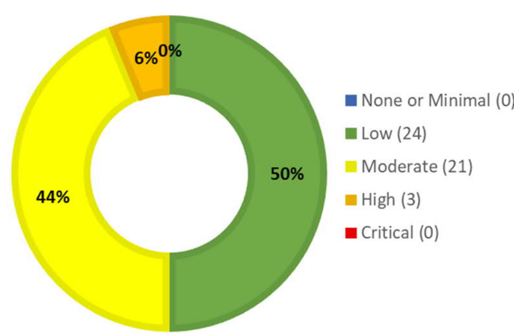


Figure 4-5
VRA Outcome - Low Stream Flows

In summary, only one facility was found to be highly vulnerable to future impacts of low streamflows, which is not a significant portion of the facilities studied. Majority of facilities that are high and moderate are located in the Red Deer River and the South Saskatchewan River basins, which is a reflection of the results of the climate assessment.

This result indicates that future periods of low flows are not likely to pose increased risks to drinking water facilities. Figure 4-8 illustrates the VRA outcome on the Provincial map.

Similar to the high flow analysis 'Worst Case' value (maximum change) was selected to represent the climate change outcome of concern; this value was the determining factor in the overall vulnerability. The VRA outcomes based on the 'Best Case' value (minimum potential change, typically the RCP 2.6) are compared to the 'Worst Case' shown in Figure 4-6. Generally, facilities would end up in a lower risk category, in the best case scenario, than they did in the worst case scenario.

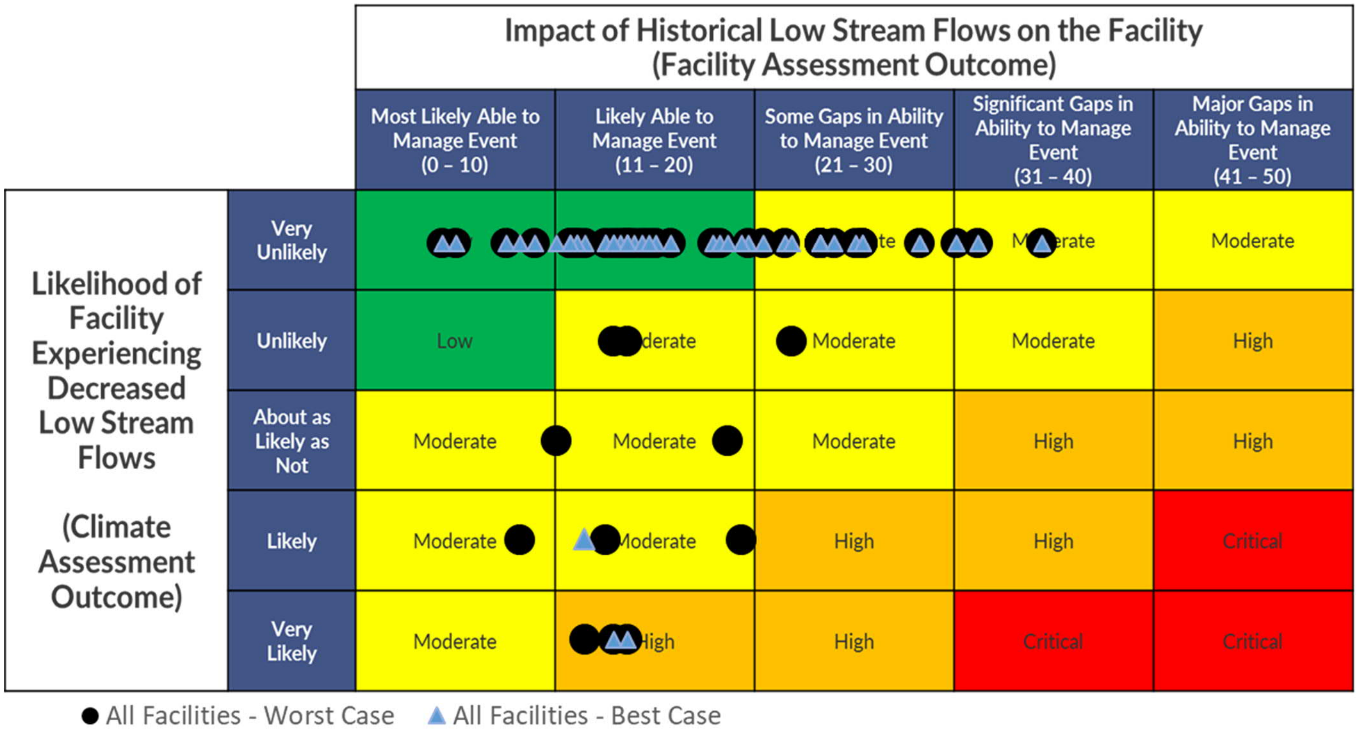
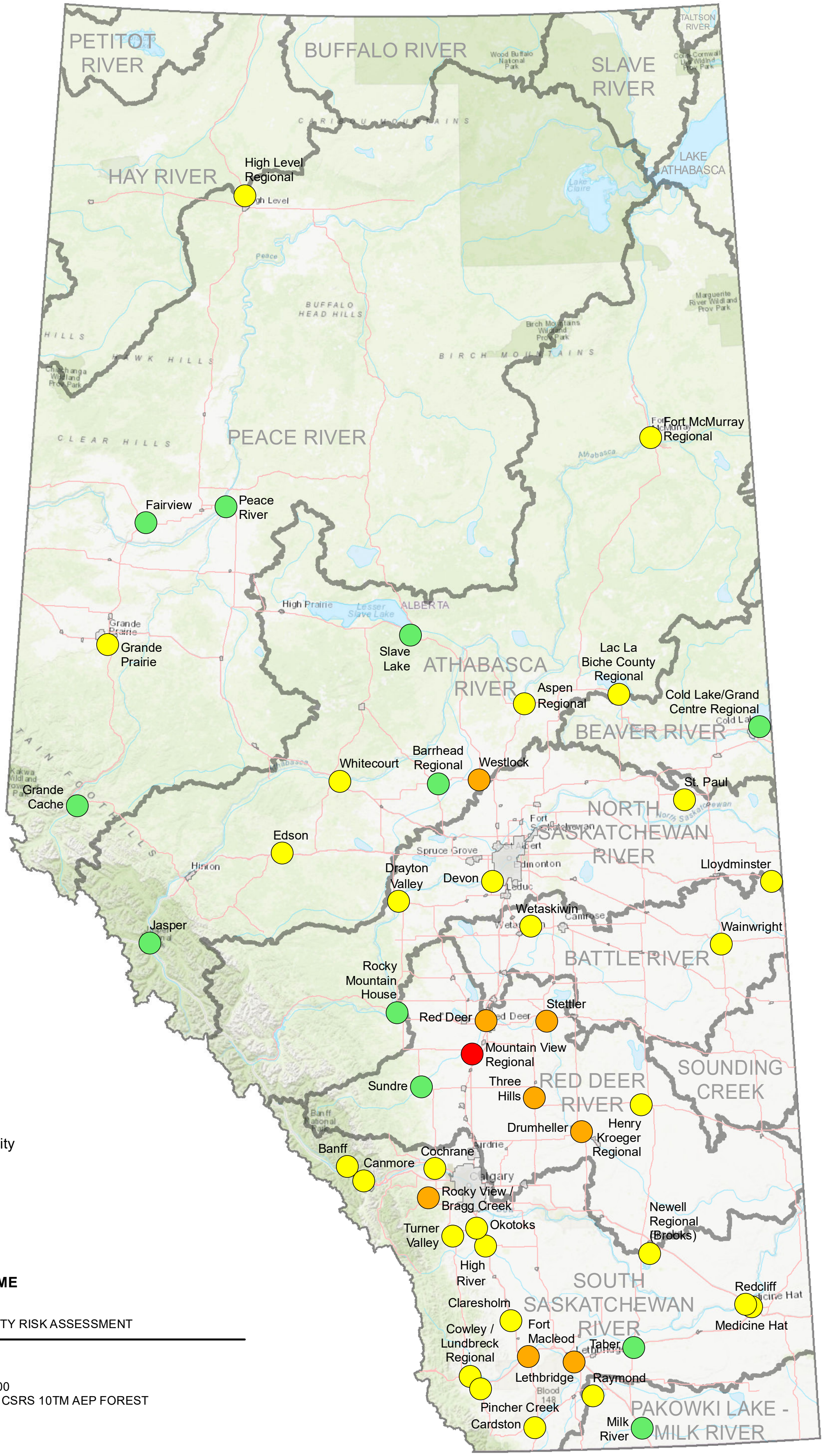


Figure 4-6
All Facilities, Low Streamflow, Best Case and Worst Case Scenario



Legend:

- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability
- Critical Vulnerability

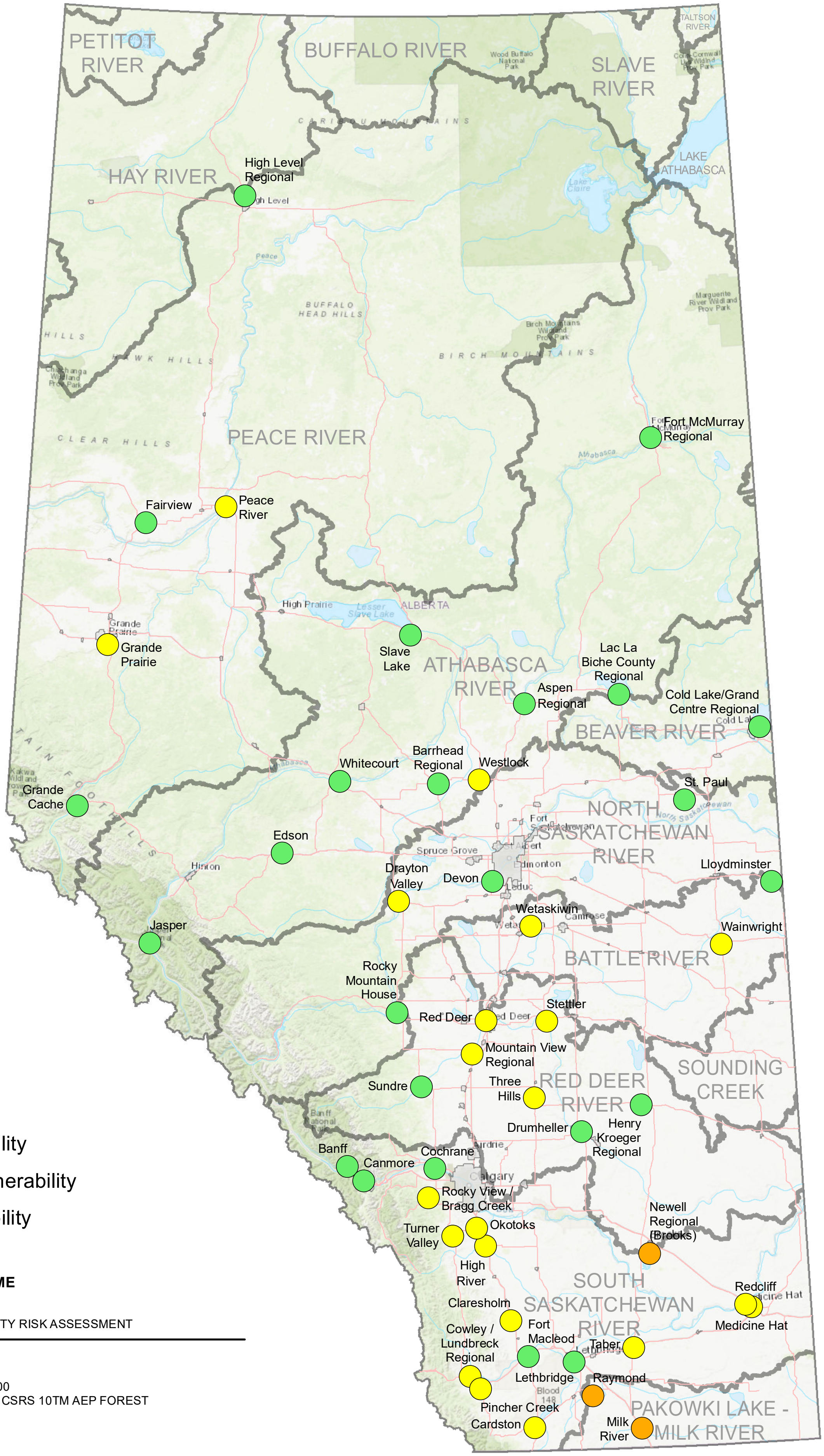
FIGURE 4-7
HIGH FLOW - VRA OUTCOME

ALBERTA INNOVATES
DRINKING WATER VULNERABILITY RISK ASSESSMENT

AE PROJECT No.	2018-3184
DATE	2020 MAY
SCALE	1: 5,000,000
COORD. SYSTEM	NAD 1983 CSRS 10TM AEP FOREST
DESCRIPTION	FINAL

Associated Engineering

CANADA BEST MANAGED COMPANIES
Platinum member



Legend:

- Low Vulnerability
- Moderate Vulnerability
- High Vulnerability

FIGURE 4-8
LOW FLOW - VRA OUTCOME

ALBERTA INNOVATES
DRINKING WATER VULNERABILITY RISK ASSESSMENT

AE PROJECT No.	2018-3184
DATE	2020 MAY
SCALE	1: 5,000,000
COORD. SYSTEM	NAD 1983 CSRS 10TM AEP FOREST
DESCRIPTION	FINAL

Associated Engineering

5 CONCLUSIONS

This study provides a high-level assessment of plausible climate change impacts to extreme streamflow events expected to affect drinking water facilities throughout Alberta. The tools and techniques available to support this review are evolving and will improve as more efforts are focused on better understanding potential impacts of future climate change. The assessment is not a predictor of future events. It is a tool to evaluate the likelihood and potential consequences of severe events occurring in the future to understand the degree of risk it poses for the Province and the facilities included. This study is intended to help inform provincial and municipal decision makers of potential changing future risks and to consider adaptation measures that may help build future resiliency.

The study did not include site specific assessments such as detailed mapping of existing assets and flood levels. This study may guide municipalities and the Province with identifying which facilities warrant further site specific data collection and analysis.

The primary conclusions, based on the vulnerability and risk assessment, are as follows:

- Many drinking water facilities are at risk of future high and low streamflow conditions imposing increasing risk to water supply and treatment systems. The future risks are likely to stress systems beyond the design basis for flood levels, creek erosion, on-site overland flooding, and decreasing water quality.
- In most cases, the increasing future risk is prevalent for both greenhouse gas emission scenarios (RCP 2.6 lower emissions and RCP 8.5 higher emissions) and anticipated to be more severe into the Mid-Century timeframe.
- The risk of increasing high streamflow and more frequent severe high flow events is most prevalent in central to southern Alberta. Where facility assets are in close proximity to the Pembina, North Saskatchewan, Red Deer, Bow and South Saskatchewan Rivers.
- The risk of decreasing low streamflow is more limited to the South Saskatchewan and Milk River Basins. Where the majority of facilities with increasing risk rely on large mounts of seasonal storage and/or on irrigation districts, they may compete with other water users.
- Facilities at risk will need to acquire more detailed understanding of the location specific risks to enable capital and operations planning to consider future needs. Most drinking water facilities require significant capital upgrades to rehabilitate or upgrade existing systems on 10 to 25-year cycles, depending on population growth and changing regulations. It will be important for future planning and design of system at-risk to consider the future uncertainty that climate change may impose on high and low streamflow.
- This study considered 48 facilities representatives of the majority of the provincial population outside the Edmonton and Calgary areas. There are over 430 regulated municipal drinking water systems within the Province of Alberta with many servicing smaller communities that have limited resources to assess or knowledge of the impact of climate interactions and changing risks.

6 ADAPTATION CONSIDERATIONS

Adaptation strategies are suggested at the provincial and facility levels to improve resilience over time to better protect facilities from increasing climate change risks. The objective would be to introduce strategies that would help better identify future risks and implement change that would make facilities more resilient to the future uncertainties over time.

6.1 Province Wide

Possible measures that could help inform best fit adaptation practices to reduce **future risks** on the **provincial scale** include:

- Integrate climate change considerations into the existing Drinking Water Safety Plan (DWSP) process. The DWSP offers a framework to manage these risks, at the community level, by considering the implications of climate variability and change at various points in the DWSP process.
- Require all facilities in at-risk river basins to complete more detailed vulnerability and risk assessments, such as the PIEVC process support by Engineers Canada, prior to major capital upgrades that require new or modified regulatory approvals or Provincial funding.
- Modify of the Alberta Municipal Waterworks Design Standards and Guideline to include requirements for facility designs to include climate change considerations.
- Update the finding of this report as additional tools and information becomes available. **Section 3.5** provides additional suggestions for subsequent assessments.
- Review regional water management strategies incoordination with dam operations and irrigation districts considering increasing low flow risk and changing overall water availability in critical regions.
- The Province may want to consider options for water conservation measures, during extreme low flow periods to protect the limited water supply needed for Drinking Water Facilities, considering this is an essential public health requirement.

6.2 Facility Highlights

The individual results for each facility are provided as separate reports, both to the Province and to each Municipality. Common adaptation recommendations among the facilities with moderate to critical high flow risk include:

- Update the Drinking Water Safety Plan on an annual basis to reassess risk or create a facility-specific risk that was not considered before.
- Prepare or update emergency response plans, such as a Flood Readiness Plan.
- Explore measures to protect raw water infrastructure from physical damage that may result in the event of a major flood.
- Review resiliency of the raw water pumphouse and the water treatment facility's electrical system such as; confirming all motors, instruments and electrical gear above the projected Q_{100} elevation.
- Installation of river level gauge in the vicinity of the raw water intake (for surface water facilities), in the event there is no existing Government of Alberta gauge. Data from the level gauge should be captured in the SCADA for improved monitoring and projection of high and low-flow events.
- Complete detailed flood risk assessments prior to any major capital upgrades of at-risk assets for facilities with high or critical risks.

Adaptation suggestions for **low flow risk** were:

- Update facility Drought Preparedness (or Water Shortage) Plan annually.
- Explore options to increase on-site off-line storage.
- Explore alternate water supplies, such as adjacent reservoirs or groundwater aquifers.

A summary of the all adaptation suggestions for the 48 facilities is provided in Table 6-1.

Table 6-1
Adaptation Considerations and Number of Facilities Applicable

No Adaptations Suggested	8
Detailed Flood Assessment	**22**
Prepare Drinking Water Safety Plan	3
Update Drinking Water Safety Plan	37
Prepare Flood Plan	24
Update Flood Plan	12
Prepare Drought Plan	13
Update Drought Plan	9
Emergency Treatability Plans High Flow	**25**
Emergency Treatability Plans Low Flow	**10**
Procure Backup Power Raw Water Pumphouse	**17**
Procure Backup Power Water Treatment Plant	**7**
Bank Stability for Raw Water Pumphouse	**7**
Take Measures to Minimize Potential Flooding of Raw Water Pumphouse	12
Take Measures to Minimize Potential Flooding of Raw Water Pumphouse AND Water Treatment Plant	4
Review Resiliency of Raw Water Pumphouse Electrical System Above Q100	**10**
Review Resiliency of Raw Water Pumphouse AND Water Treatment Plant Electrical System Above Q100	**6**
Mitigate Risk of Delayed Chemicals	3
Investigate Additional Raw Water Storage	**13**
Relocate Intakes/Intake Upgrades	**8**
Install Level Gauges	24
Monitor OR Install Level Gauges	11

Note:

[blue] - Adaptation suggestion for moderate to critical high flow risks
[yellow] - Adaptation suggestion for moderate to critical low flow risks

CLOSURE

This report was prepared for Alberta Innovates and Alberta Environment and Parks partnered as the assessment of potential climate change impacts and resulting high and low river flow vulnerabilities at 48 small and medium sized municipal drinking water facilities, across the Province of Alberta. This is intended to be a high-level assessment, based on assessment of past vulnerability and likelihood of increased risks due to future climate change induced impacts to extreme streamflow events.

The services provided by Associated Engineering Alberta Ltd. in the preparation of this report were conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions. No other warranty expressed or implied is made.

Respectfully submitted,
Associated Engineering Alberta Ltd.

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Signature ____________
Chad Maki 2020-05-31
PERMIT NUMBER: P 03979
The Association of Professional Engineers
and Geoscientists of Alberta

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APPENDIX A – FACILITIES LIST

APPENDIX A – FACILITY LIST

The following facilities were a part of this study:

- Aspen Regional Waterworks System
- Banff Waterworks System
- Barrhead Waterworks System
- Bragg Creek Waterworks System
- Canmore Waterworks System
- Cardston Waterworks System
- Claresholm Waterworks System
- Cochrane Waterworks System
- Cold Lake/Grand Centre Regional Waterworks System
- Cowley/Lundbreck Regional Waterworks System
- Devon Waterworks System
- Drayton Valley Waterworks System
- Drumheller Waterworks System
- Edson Waterworks System
- Fairview Waterworks System
- Fort Macleod Waterworks System
- Fort McMurray Regional Waterworks System
- Grande Cache Waterworks System
- Grande Prairie Aquatera Regional Waterworks System
- Henry Kroeger Regional Waterworks System
- High Level Regional Waterworks System
- High River Waterworks System
- Jasper Waterworks System (Municipality of Jasper)
- Lac La Biche County Waterworks System
- Lethbridge Waterworks System
- Lloydminster Waterworks System

APPENDIX A – FACILITY LIST

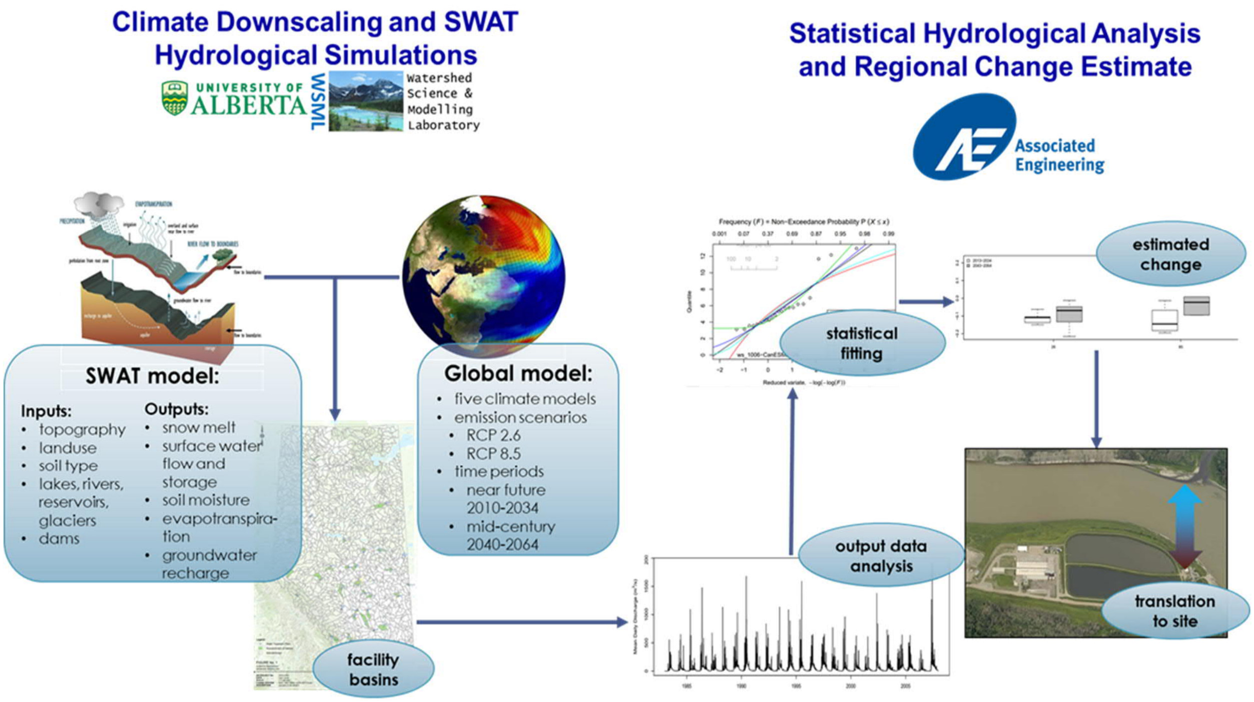
- Medicine Hat Waterworks System
- Milk River Waterworks System
- Mountain View Regional Waterworks System
- Newell Regional Waterworks System
- Okotoks Waterworks System
- Peace River Waterworks System
- Pincher Creek Waterworks System
- Raymond Waterworks System
- Red Deer Waterworks System
- Redcliff Waterworks System
- Rocky Mountain House Waterworks System
- Slave Lake Waterworks System
- St. Paul Waterworks System
- Stettler Waterworks System
- Taber Waterworks System
- Three Hills Waterworks System
- Turner Valley Waterworks System
- Wainwright Waterworks System
- Westlock Waterworks System
- Wetaskiwin Waterworks System
- Whitecourt Waterworks System

APPENDIX B – PROJECT METHODOLOGY

APPENDIX B - CLIMATE CHANGE ASSESSMENT METHODOLOGY DETAILS

1 CLIMATE CHANGE ASSESSMENT OVERVIEW

To arrive at facility-specific estimates of future change, a collaboration between Associated Engineering (AE) and the University of Alberta Watershed Modelling Laboratory (UA WSML) was formed. This collaboration integrated experience with Alberta drinking water facilities with expertise in Alberta hydrological modelling and climate change. Within this collaboration, assessments of 'extreme' high and low streamflow conditions relevant to drinking water facility operation and level of service were targeted for primary analysis.



The key contribution of the UA WSML was simulations of historical and future streamflow conditions for regional basins representative of facility locations, provided by the Soil and Water Assessment Tool (SWAT) hydrological model. By comparing SWAT simulations of past streamflow to equivalent simulated streamflow for near and mid-term future periods upper and lower-bound global emission pathways, relative changes to historic low and high flow conditions could be explored. The selection and statistical analysis of these low and high flow conditions and their simulated change into the future—considering model strengths and weaknesses—was the key contribution of AE.

SWAT simulations were performed to assess the role of two greenhouse gas scenarios and future change to relevant hydrology changes at each Alberta drinking water facility. Simulations were undertaken for two future time periods (2010-2034, e.g., 'near future'; and 2040-2064, e.g., 'mid-century'), two projections of greenhouse gas concentrations (Representative Concentration Pathways 2.6 and 8.5, representing lower and upper bounds of climate change, respectively), and five different climate models (CanESM2, CCSM4, MIROC5, CNRM-CM5 and MRI-CGCM3; all participants in the World Climate Research Program Coupled Model Intercomparison Project 5, "WCRP CMIP5").

1.1 SWAT MODELLING

1.1.1 Model Overview

The Soil and Water Assessment Tool is a time-evolving[1], process-based[2] hydrological model that simulates watershed processes. Watershed water balances[3] are impacted by natural and human factors. Natural factors represented in SWAT include topography, vegetation cover, flow from upstream basins, ponds and lakes, precipitation (rain or snow), snowpack growth and melt, evaporation and evapotranspiration, groundwater recharge and outflow. Human factors (included in SWAT) include irrigation, major dams, and other water extraction activities.

The SWAT model is open source[4] and is used worldwide by academics and government analysts (TAMU, 2019). While it is actively developed by a community, it is centrally maintained at the Texas A&M University Agrilife Research Center in conjunction with the US Department of Agriculture. Agricultural expertise of the developers reflects a SWAT focus on simulation of long-term hydrological changes to irrigated landscapes such as Southern Alberta. SWAT has been used for over 3,500 scientific publications as of September 2018, with widespread usage indicating that the model is trusted by hydrology practitioners. To quantify impacts to Alberta water resources, the University of Alberta Watershed Science and Modelling Laboratory - with Alberta Innovates support - applied SWAT at a provincial scale developed the application to represent all landscapes across Alberta including; forests and grasslands. This effort is detailed in a series of publications (e.g. Faramarzi et al. 2015, Faramarzi et al. 2017, and Faramarzi et al. in review). For the purposes of usage over Alberta, the 17 large provincial river basins were segregated into a total of 2,255 sub-basins (Figure 2) with a threshold sub-basin size of 200 km^2 (or roughly 14 km resolution). It is within this large modelling framework that drinking water facility-specific simulations are performed.

1.1.1 Input Data

The SWAT model incorporates climate, hydrologic and land surface data that are used to define the parameters and bounds of the hydrologic system being simulated. Input data captures geographic, human, and climatic controls on sub-basin water balances. The SWAT model is primarily driven by climate data (i.e., precipitation, air temperature, humidity, winds speed, and solar radiation) derived from observed or climate model-based data. This flexibility allows the SWAT model to be used to assess projections of past and future hydrological changes across the province. For the purposes of this study, geographic and human input data (e.g., crop practices and dam operations) were assumed constant across historic and future scenarios. A summary of geographic and human input data is provided below:

---

[1] SWAT is a time-evolving (or time-continuous) model, meaning it captures the time-dependent response of regional hydrology to time-evolving climate inputs. This differs from – for example – statistical models that relate statistical distributions of precipitation to expected hydrologic responses, or single-event modelling that captures the pulsed hydrological response to a single storm.

[2] SWAT is a process-based model, meaning it directly describes the primary processes of hydrological systems based on physical, chemical, biological or socioeconomic understanding, as represented in internal SWAT computer code. This differs from – for example – purely statistical models, which apply relationships based on past observations to project future change, without directly modelling the actual relationship between predictor(s) and predictand(s).

[3] The water balance equation ($P=R+E+\Delta S$, where P=precipitation, R=streamflow, E=evaporation, ΔS=change in storage) captures the full water budget of a defined region. By determining P, E, and ΔS, R can be calculated as a model output.

[4] Open source means the underlying model code is free to download and use. It is not proprietary or commercial in nature.

- Geographic input data for Alberta SWAT simulations are described and referenced in Faramarzi et al. (2015). These inputs include:
  - 90-meter resolution gridded digital elevation model derived from the Shuttle Radar Topography Mission.
  - 30-meter resolution GeoBase Land Cover Product, detailing 23 land use classes in the Alberta SWAT domain.
  - Soils data from Agriculture Agri-Food Canada, Soils Landscapes of Canada V3.2, detailing 90 soil types in the Alberta SWAT domain.
  - Natural pothole, lake, reservoir and glacier distributions from various sources.
- Input data related to human activities includes:
  - Daily operations of 15 large reservoirs/dams.
  - Seasonal cycles of agricultural practices.

1.1.2 Climate Data

Different sources of climatic input data can be used by SWAT, with implications for the representation of simulated past, present and future Alberta streamflows. Faramarzi et al (2015) compared the quality of uncalibrated SWAT output stream flows to various combinations of input climate datasets. They found a combination of Environment and Climate Change Canada (ECCC) meteorological weather station data and National Centre for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR) gridded climate data provided the highest quality SWAT model outputs over the historical period.

Climatic input data may also be derived from downscaled and bias-corrected climate model simulation output instead of observationally-derived products. This capability enables SWAT to be applied to model future projections of provincial hydrological change. The WSML has identified regionally optimized downscaling[5] and bias correction[6] methods to apply over Alberta. In general, the method is intended to improve the quality of global climate model information based on comparisons between this data and real historical observations. It also increases the spatial resolution of this data by incorporating observation-derived understanding of local climate conditions. After passing downscaling bias correction procedures, information on future climate conditions provided by global climate models can used as climatic input data for SWAT.

Climatic input data for the WSML analysis vary in space and in time on a daily time step[7]. These input fields include:

- Precipitation;
- Temperature;
- Humidity;
- Wind speed; and
- Solar radiation.

---

[5] Downscaling refers to techniques that obtain finer-scale spatial information from coarse-scale global climate model simulation output. For example, Alberta SWAT sub-basins are approximately 14 km resolution, whereas global climate models operate on ~100 km resolution grids.

[6] Bias correction techniques are typically necessary to minimize biases in global climate model output. For example, a regional may be 2ºC warmer in a climate model simulation relative to reality, and this bias must be corrected before the model projections of climate change are utilized.

[7] A time step in a process-based model represents the finest time increment that the model 'time marches' on. With a daily timestep, SWAT is unable to directly capture the impact of sub-daily precipitation events on hydrological processes.

1.1.3 Model Output

After being provided geographic, human, and climatic input information, SWAT applies mechanistic understanding of hydrological and land surface processes to derive primary model outputs. The primary output variable of interest to the WSML modelling effort is streamflow at the outlet of each simulated sub-basin. To calculate net streamflow, SWAT model calculates basic water balance sub-component variables - which are also potentially available as model outputs. These include:

- Snow melt;
- Blue water (surface and groundwater) storage and fluxes;
- Green water (soil moisture) storage and fluxes;
- Evapotranspiration; and
- Groundwater and deep aquifer storage and recharge.

Calculation of these fields by SWAT allows for full water balance and streamflow estimates at each model timestep, and for each sub-basin, in the Alberta SWAT domain.

1.1.4 Model Calibration

A key aspect of hydrological modelling is model calibration. Calibration efforts for hydrological models apply complex statistical methods to find a set of best model internal settings[8] that are physically realistic and result in model output fields that closely resemble past observations. The WSML modelling effort performed extensive model calibration (Faramarzi et al. 2017) with a focus on a best comparison to streamflows from 130 Alberta hydrometric stations and crop yields obtained from the Alberta Agricultural Financial Services Corporation. SWAT calibration was performed separately for each of the 17 major Alberta river basins and targeting monthly average streamflows, leading to substantially improved basin wide water balance streamflow simulations (Figure 3). However, since calibration was not performed for each of the thousands of individual sub-basins or at a daily scale, differences between sub-basin calibrated model streamflow and pointwise observations (e.g. on river and stream reaches with WSC stations or drinking water facilities) remain. Given the provincial scale of the SWAT simulations, this is a trade-off, that allows for a consistent province-wide picture of hydrological change to emerge. However, detailed hydrologic studies targeted at these individual sites would require site-specific calibration efforts as a key initial study aspect.

Multiple calibrations were performed, to provide a range of reasonable model representations of Alberta hydrology. The present report describes the result of a single calibrated model from this suite of representations, which provides the overall best SWAT-based representation of province-wide historical hydrological conditions. Within this single best model calibration, it is important to realize that differences between observed and simulated streamflows – particularly at local spatial scales and short timescales – can still persist. Further information on the calibration procedure is available within literature produced by the UofA WMSL (Faramarzi et al 2017).

[8] Model settings refer to adjustable internal values within model code. Model parameters that have large control on model results but are poorly quantified in observations are typically “tuned” during model calibration. Tuned SWAT model parameters included runoff lag time, plant moisture uptake factor, soil optical reflectivity, and pothole retention parameters.

1.1.5 Model Limitations

SWAT is a hydrological model that can be used for predicting the influence of future climate-related shifts on Alberta streamflows and serves as a tool for exploring different future climate scenarios and their potential impacts. For this study, SWAT was used to predict changes to extreme low and high flow conditions which could, in turn, impact on drinking water facilities and facility operations. Model simulations and results must be interpreted with care and in conjunction with actual hydrological stream flow observations and drinking water facility assessments. Limitations of SWAT include the following:

- As with any hydrological model, SWAT cannot capture every aspect of the hydrological systems that it represents. For example, in many cases, dams and reservoirs that exist on small waterways are not included in the provincial-scale SWAT framework.
- Since future water and land management decisions are not clearly known, SWAT simulations do not consider changes to this management into the future, despite the high likelihood that management changes will indeed occur.
- SWAT representation of natural processes can be idealized—for example, through simple representations of groundwater flow in the model—and SWAT calibration on monthly average flows means that assessments of daily-scale hydrological measures are not specifically constrained by observations.

While these and other model limitation in no way preclude SWAT from assisting with understanding future climate impacts on drinking water facility operations, they should be clearly recognized so that model simulations are interpreted cautiously and in conjunction with hydrological stream flow observations and drinking water facility assessments.

1.2 SWAT OUTPUT AND SYNTHESIS

1.2.1 SWAT Simulations

For each of the historical and future time periods assessed in this study, SWAT was run continuously by UofA WMSL for a period of 24 years at a daily timestep. The first three years of each simulation were discarded from further analysis. Historical SWAT simulations were driven by hydrologically validated historical daily climate data (Faramarzi et al., 2015). Future data was generated following the 'change factor' method (Chen et al., 2011). As a first step to this method, regional historical and future climate model-generated downscaled future projections were obtained from the Pacific Climate Impacts Consortium (PCIC, https://pacificclimate.org). The difference or 'delta' between the historical and future simulations was then calculated (Chen et al., 2011). Finally, this delta was then applied to the historical daily climate data, to generated province-wide estimates of future conditions.

After discarding the first 3 years to allow model equilibrium to be achieved (a common practice in hydrological and climate modelling), this model simulation exercise provided a large database of data, with individual 21 year continuous daily records of simulated streamflow for each sub-basin containing identified drinking water facilities (*48*), for:

- Historical streamflow (1983-2007) (*1 record*)
- 2010-2034 streamflow, for:
  - RCP2.6, for 5 models (*5 records*)
  - RCP8.5, for 5 models (*5 records*)

- 2040-2064 streamflow, for:
  - RCP2.6, for 5 models (*5 records*)
  - RCP8.5, for 5 models (*5 records*)

In total, approximately 380,000 historical and 7,800,000 future daily SWAT-simulated Alberta streamflow data points were simulated and analyzed.

1.2.2 SWAT Data Analysis

A key aspect of any climate change assessment is the identification of climate change metrics that are most relevant to the system(s) in question. In terms of water quantity, drinking water facilities are naturally most vulnerable to extreme excesses of water, and extreme lack of water supply. Based on this understanding, key metrics of high and low flow were identified for further analysis, based on the SWAT-simulated streamflow at the mouth of each sub-basin containing a drinking water facility:

- A metric of 1-in-100 maximum annual daily streamflow (hereafter termed Q_{100}) was chosen to represent facility-relevant high flow conditions. Most simply, Q_{100} magnitudes can be interpreted as the highest daily flows that have a 1% chance of occurring per year, for a given climate state. To estimate Q_{100} values given 21 year simulation lengths, a standard extreme value statistical fitting technique using the Log-Pearson IV distribution[9] was applied to estimate underlying distribution of high flow occurrences and extrapolate to return periods beyond 21 years.
- To estimate low flow Q_{10} values given 21 year simulation lengths, a standard extreme value statistical fitting technique using the Weibull distribution[10] was applied. This approach provided a better estimate of nominal events that have a 10% chance of reoccurring each year.
- Several metrics of low flow were chosen to represent potential facility-relevant low flow conditions: 1-in-10 minimum summer-centered (May-October), winter-centered (November-April) and annual 7, 90, and 180-day streamflows (e.g. 9 low flow metrics, [7/90/180]Q10[S/W/A]). These various low flow metrics were selected to best represent the diversity of Alberta drinking water facility storage capacities and modes of winter/summer operation.

In net, the combination of locations, future time frames, scenarios, models, and high/low flow analyses resulted in a large number (n=10,080) of low flow and high flow values. Distillation of this collection through a set of measures then provided an estimate of climate-induced hydrological changes that worked to minimize the impact of natural variability. An important data distillation step involved calculation of relative future changes to each of the high and low flow metrics, for each location and future simulation. Calculation of these relative future changes followed a similar approach to the generation of the future climate data used as input to SWAT. Termed the 'delta' of change to low and high flow metrics (D), it was calculated as:

$$D=(Q_{future}-Q_{historical})/Q_{historical}*100$$

Where the Delta (D) presents a percentage change in the magnitude of each high and low flow metric. For example, a DQ_{100} value of +10% indicates that the magnitude of streamflow associated with 1-in-100 year

[9] The Gumbel distribution was chosen based on the qualitative goodness of fit across all simulation results, relative to a selection of other tested statistical distributions.

[10] The Gumbel distribution was chosen based on the qualitative goodness of fit across all simulation results, relative to a selection of other tested statistical distributions.

daily annual maximum streamflow – a measure of high flow events – is projected to increase by 10%. This change was computed for each climate model/scenario, and then averaged as a final step.

Through these measures, SWAT simulation results were assessed to provide key information on measures of change relevant to provincial drinking water facilities. This approach is closely related to another method of communicating changes to high and low flows, namely shifts in the return period, for a given flow magnitude. The latter approach which forms the basis for some other recent assessments of climate-driven changes to Canadian flood hazard (e.g. Guar et al., 2019). In general, results that cast changes in terms of *increases/decreases* in flow magnitude for a given return period (such as presented in this report) are very likely equivalent to *decreases/increases* in flow return period, for a given magnitude.

2 INTEGRATION OF ANALYSIS: RELATION TO STREAM STAGE

The delta values were analyzed in the context of streamflow records from nearby Water Survey of Canada (WSC) stations when relevant data was available. Established stage-discharge curves were obtained from WSC for stations located closest to drinking water facilities. The delta values obtained from SWAT simulation analysis were applied to the resultant high and low streamflow indices to provide indirect context for nearby facilities experiencing a greater impact due to high or low streamflow periods, according to the evaluation criteria presented in **Table A-1**. If nearby WSC stations were not relevant the general guide was applied with confirmation of possible local conditions.

APPENDIX B - CLIMATE CHANGE ASSESSMENT METHODOLOGY DETAILS

Table A-1
Climate Assessment Evaluation Criteria

Likelihood of Greater Impact at Facility Level	High Stream Flows	Low Stream Flows	Delta Value Guide
VERY UNLIKELY	No anticipated change to water quality. No anticipated change to channel or bank erosion. Stream flows are not anticipated to result in more damage to the facility than historic stream flows.	No anticipated change to water quality. No impact to water availability for withdrawal or storage.	< 10%
UNLIKELY	Some deterioration of water quality is anticipated, but likely within manageable limits.	Some deterioration of water quality is anticipated.	< 33%
	Limited (non-critical) change to channel or bank erosion is possible.	Potentially minor impact to water availability for withdrawal is anticipated, the impact is manageable within storage capabilities.	
	Stream flows are not anticipated to result in more facility damage than historic stream flows.		
ABOUT AS LIKELY AS NOT	Water quality deterioration that will challenge treatment processes is anticipated. Additional channel or bank erosion is anticipated. Additional erosion could become a concern and may require maintenance. Potential risk for facility damage beyond historic levels is anticipated. Damage may require emergency measures and maintenance.	Some deterioration of water quality is anticipated, but likely within manageable limits. Impact to water withdrawal availability that may challenge storage capabilities is anticipated. Some water conservation initiatives may be required.	33-66%
LIKELY	Water quality deterioration that will challenge treatment processes and may require emergency measures is anticipated.	Water quality deterioration may occur that will challenge treatment processes.	66-100%
	Additional channel or bank erosion that will require maintenance or reconstruction is anticipated.	Impact to water withdrawal availability that will likely deplete storage capabilities is anticipated.	
	Likely risk for facility damage beyond historic levels, that would require emergency measures, maintenance and potential reconstruction.	Widespread water conservation initiatives will be required.	
VERY LIKELY	Water quality deterioration that will challenge treatment processes and may long-term require emergency measures is anticipated. Additional channel or bank erosion that will require reconstruction is anticipated. Very likely risk for catastrophic facility damage beyond historic levels that would require emergency measures and reconstruction.	Water quality deterioration that will challenge treatment processes is anticipated. Likely loss of supply water withdrawal availability and depleted storage capabilities. Will require severe water conservation initiatives and consideration of alternate supply.	> 90%