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Water Management Solutions

Alberta Innovates

Report: Study of Water Impacts of Hydrogen Development in Alberta

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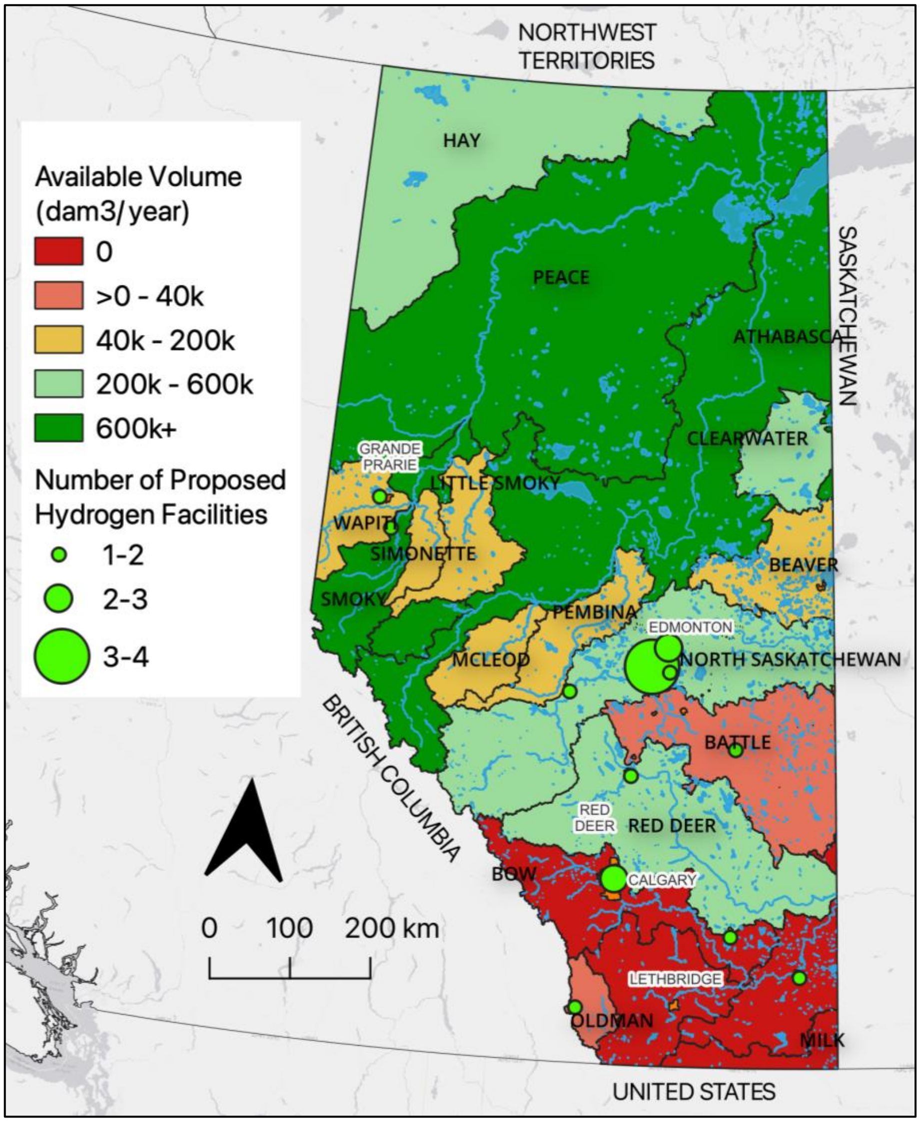
Executive Summary

Within the context of the global transition to net zero emissions by 2050, there is intense and mounting pressure on Alberta's resource sectors from a wide range of local, national, and international regulators, governments, shareholders, and stakeholders to take concrete and significant action towards achieving this goal. The hydrogen sector is a prominent example of one pathway being pursued within Alberta to achieve net zero 2050 targets. In pursuing emissions reduction and climate change mitigation pathways, it is critical to consider other environmental, social, and economic impacts and trade-offs within the context of the water-energy-food nexus. One of the most important considerations, and the focus of this report, is our shared, and finite, water resources.

WaterSMART Solutions Ltd. (WaterSMART) has prepared this report to assess the potential impacts of hydrogen development on water resources across Alberta, and to highlight locations in which available supply may limit hydrogen development. It is intended to inform policies, regulations, and investments which will best enable the hydrogen sector's growth, while strategically balancing trade-offs within the water-energy-food nexus context. Project developers and investors in particular should carefully review the analysis in this report on where water supply is likely to be sufficient for hydrogen projects, and where limited water supply will introduce material project risks.

The figure below overlays the anticipated hydrogen projects throughout Alberta onto a future water availability heat map. Given the significant water demands associated with hydrogen development, future hydrogen projects in some locations, such as the Edmonton region, may constrain other developments by limiting their water access. In addition, the hydrogen projects themselves will be forced to contend with water supply challenges across seasons and years. The Calgary and Medicine Hat regions are noteworthy examples of where hydrogen development ambition may exceed available water supply.



This report demonstrates that full development of the hydrogen sector within Alberta is likely to both cause water supply challenges and be limited by water availability. The extent of water risks varies across the province on a water basin and sub-basin level, and understanding local water context is critical to identifying and managing water risks and water-energy-food nexus trade-offs. When considered in the context of the net zero 2050 transition, which will involve other water-dependent technologies, and future development of all other types, it becomes even more critical to strategically manage our shared, and limited, water resources.

In response to these challenges, the following recommendations are provided for project proponents and investors:

1. Conduct detailed, site-specific analysis of the local water context to better understand how water availability will be impacted by the regulatory framework, stakeholder and Indigenous community concerns, other water users, and seasonal and inter-annual hydrologic dynamics.
    a. This analysis will materially impact project risks and costs and should be completed early

in project development before significant investments are made.

2. Carefully consider climate change risks, informed by location-specific analysis.
3. Develop approaches to manage water supply risks in an increasingly variable and unpredictable climate. These may include:
    a. Constructing water storage with sufficient capacity to supply operations during low flow periods.
    b. Working with other water users in the basin to develop water-sharing agreements, and/or collaboratively manage water on a basin level.
    c. Seeking opportunities to reduce overall consumptive water requirements, for example by using air cooling instead of evaporative cooling.
    d. Seeking alternatives to freshwater use, including saline groundwater and water reuse.

To develop better knowledge and tools for identifying and managing water-related challenges, the following next steps should be undertaken:

1. Utilize collaborative, data-driven processes to identify, understand, and manage water challenges on a river basin scale, while balancing water-energy-food nexus tradeoffs and environmental considerations.
    a. The North Saskatchewan River Basin should be a top priority for this work, given the absence of existing models and tools for this purpose and the abundance of hydrogen development planned for the region.
    b. This work should consider the implications of both consumptive and non-consumptive water use associated with future development.
2. Repeat this study to examine other technologies and sectors which will be involved in the net zero 2050 transition (e.g., carbon capture and storage, small modular nuclear reactors, critical minerals, etc.).
3. Recognizing that net zero 2050 commitments are being made across Canada, repeat this study in the other provinces and territories, which are currently grappling with many of the same challenges documented for Alberta.
4. Develop a better understanding of Alberta's groundwater resources and make this data available publicly in a consistent and usable format.

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1.0 Introduction

1.1 The transition to net zero 2050 as a project driver

Against the backdrop of the COVID-19 pandemic and recovery, severe supply chain bottlenecks, and the looming climate crisis, there is an intense focus across the globe on the transition to net zero emissions by 2050. In Alberta, this transition has generated a mix of trepidation and excitement, acting as a catalyst for transformative commitments and bold planning. There is intense and mounting pressure on Alberta's resource sectors from a wide range of local, national, and international regulators, governments, shareholders, stakeholders, and rightsholders to take concrete and significant action towards achieving this goal. Meanwhile, governments and regulators are working to both understand and define their evolving roles in the transition as regulators, convenors, enablers, and more.

For Alberta's diverse resource sectors, the transition to net zero 2050 is both an opportunity and a challenge. In this complex and rapidly changing context, it is critical that systems-based thinking and strategic approaches are deployed to identify and manage the water-energy-food nexus trade-offs associated with the energy transition. While much of the discourse about the transition to date has been focused on emissions reduction and climate change mitigation, other environmental, social, and economic impacts and trade-offs must be considered within the context of the water-energy-food nexus. One of the most important considerations, and the focus of this report, is our shared, and finite, water resources.

A prominent example of the potential trade-offs between climate action and water resource management is in the burgeoning hydrogen sector. In Alberta, hydrogen is seen as an exciting opportunity for the province, with a myriad of announcements for world-scale hydrogen projects of all types; the release of the Government of Alberta's Hydrogen Roadmap, which articulates a vision to become a world leader in clean hydrogen production, transportation, and use; the emergence of collaborative initiatives to explore and develop hydrogen hubs and centres of excellence; and more. However, attention must be paid to the potential environmental trade-offs between hydrogen production and water. Given the excitement, opportunity, and potential investment associated with Alberta's expanding hydrogen sector, it is essential to develop a better understanding of the sector's potential impact on Alberta's water resources, as well as how context-specific water availability may limit development.

WaterSMART Solutions Ltd. (WaterSMART) has prepared this report for the benefit of a broad audience of project developers and investors, policy makers and regulators, and hydrogen ecosystem participants. It is intended to inform policies, regulations, and investments which will best enable the hydrogen sector's growth, while strategically balancing trade-offs within the water-energy-food nexus. Project developers and investors in particular will benefit from this report's analysis on where water supply is likely to be sufficient for hydrogen projects, and where limited water supply will introduce material project risks.

The report's focus is on the potential water impacts of hydrogen development in Alberta. However, hydrogen is not the only sector which is evolving in response to net zero 2050 ambitions. Indeed, it is expected that a suite of technologies and sectors will all play a role in decarbonization. While this report focuses on hydrogen, it is acknowledged that the water impacts of technologies and sectors such as carbon capture and storage (CCS), small modular nuclear reactors, and critical minerals mining will also need to be studied. As the transition to net-zero 2050 occurs, this report can serve as a model for how to assess water availability and water risks for other resource sectors that are key to the transition.

1.2 Project scope

In this report, the potential water demands of future hydrogen development in Alberta are estimated and compared to Alberta's current and future water availability. As shown in Figure 1, this analysis was completed across Alberta. The investigation, evaluation, and conclusions are summarized in the following report sections:

- Section 2.0 details the net-new water demands expected to be associated with hydrogen development in Alberta. This reflects all currently identified hydrogen projects, including locations and estimated sizes, as well as ranges of per-unit water demands associated with common hydrogen production technologies.
  - A detailed summary of hydrogen project research is provided in Appendix A and Appendix B.
- Section 3.0 summarizes Alberta's present and future water context, with information on how water is regulated and managed within Alberta, as well as the results of water availability analyses completed in key areas throughout the province. A discussion on potential climate change impacts is also included.
  - Detailed, river basin specific information and analysis is provided in Appendix C.
  - An overview of the analysis methodology is provided in Appendix D.
- Section 4.0 presents the combined results of the preceding analyses on hydrogen water demands and Alberta's water availability. This is accompanied by discussion on the water-energy-food nexus tradeoffs which may be required to achieve Alberta's stated hydrogen ambition, highlighted by several locations where hydrogen water demands may exceed available water supply.
- Section 5.0 provides recommendations for how the information contained in this report can be used to support strategic decision making to manage the anticipated water-energy-food nexus tradeoffs associated with the hydrogen sector. Discussion on opportunities for further study within the net zero 2050 transition context is also provided.

Note that this report is focused on surface water supply within Alberta. It is acknowledged that groundwater is a significant source of water for various uses within the province, and groundwater may play a role in supplying technologies and projects associated with the net zero 2050 transition. However, both groundwater usage and available data are relatively limited in Alberta when compared to surface water. Historically, most Alberta projects of the scale contemplated in this report have used surface water. Therefore, a focus on surface water is expected to capture the majority of new water use for hydrogen, while further investigation into groundwater supply is an opportunity for future work.

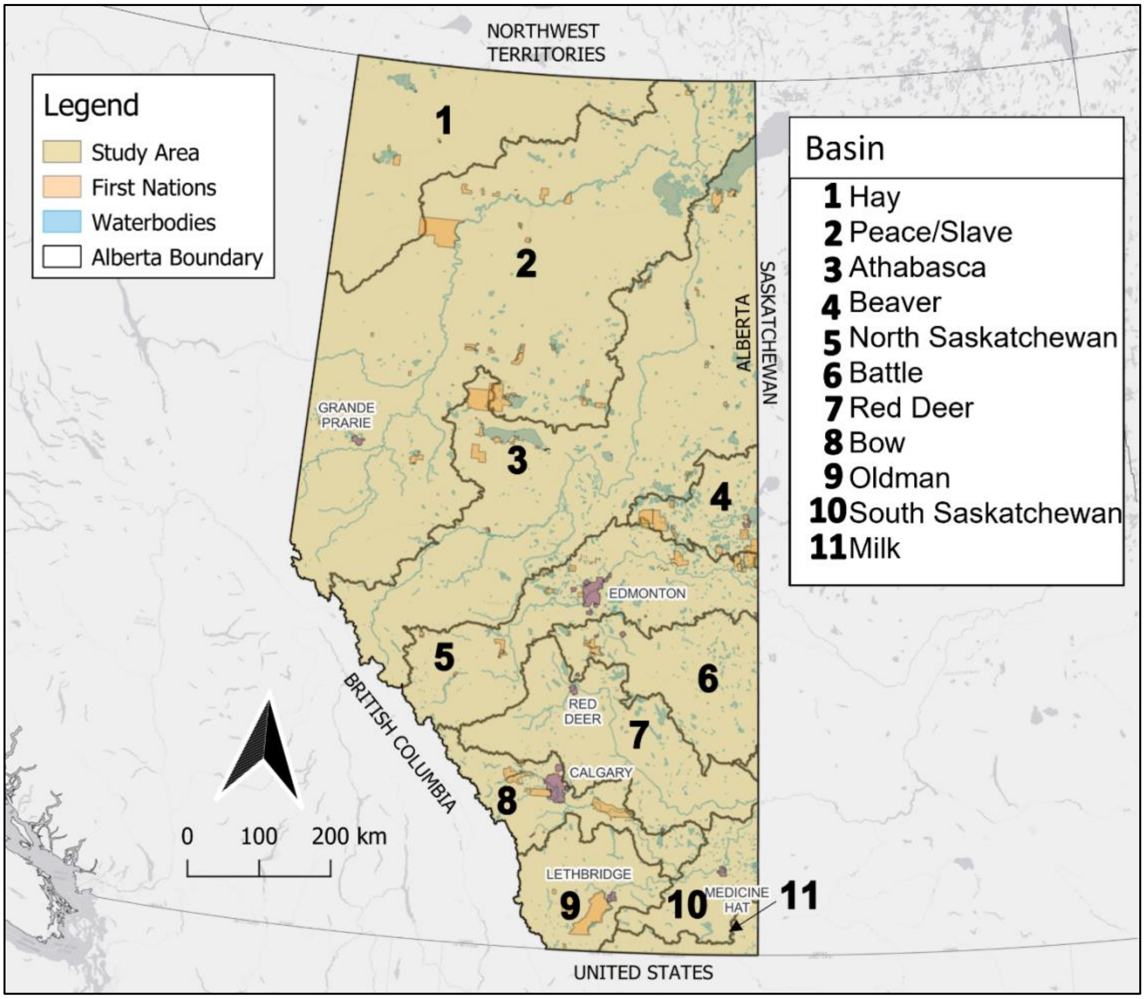

Figure 1. Map of the study area for this report, which covers all of Alberta.

2.0 Anticipated Hydrogen Water Demands in Alberta

This section documents the research completed to determine the water use intensity of various hydrogen production methods, identify projects within Alberta expected to deploy these technologies, and estimate the water use associated with hydrogen development throughout the province. Section 2.1 provides background on hydrogen as a resource, while Section 2.2 discusses the methodology for estimating project water demands. These projects, and the approach for identifying them, are discussed in Section 2.3. Finally, Section 2.4 presents the estimated water demands of future hydrogen projects in Alberta.

Note that this section and the associated analysis relies upon publicly available information and reasonable assumptions. As such, the results in Section 2.4 and the associated conclusions elsewhere in this report should be reviewed regularly as technologies develop and new hydrogen projects are announced.

2.1 Background

Hydrogen (H) is the most abundant element on earth, usually found combined with other elements, like in water (H_2O) and methane (CH_4). Hydrogen carries energy within its bonds, which is released when it is reacted and can be used for a multitude of purposes. For example, hydrogen fuel has the potential to offset the current use of fossil fuels in sectors such as transportation and heating. Hydrogen is considered a lower emissions alternative to fossil fuels because the only by-product of its combustion is water:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{energy}$$

In addition to being used directly as a fuel, hydrogen can also be used as a feedstock to make other products, such as ammonia and methanol. Ammonia is currently used primarily as agricultural fertilizer, while methanol is a key input for many common products, including plastics, paints, fabrics, fuels, antifreeze, and much more [1].

Since hydrogen is rarely found in nature as H_2, it must be extracted or "produced" from resources like water and methane. While there are many technologies being explored to produce hydrogen, there are only a few technologies currently considered commercial. These commonly used technologies include steam-methane reforming (SMR), autothermal reforming (ATR), and water electrolysis. Other emerging technologies include methane pyrolysis and biomass gasification. Further discussion on these technologies is included in Appendix A.

2.2 Per-unit water demands

Water is required in most hydrogen production technologies, either as a direct process input, for steam generation, for system cooling, for catalyst regeneration, or for some combination thereof. Many technologies which do not use water directly in the chemical reaction(s) to produce hydrogen typically still require water as part of the overall process, such as for system cooling or catalyst regeneration. Cooling is a critical element of hydrogen production because the reactions to produce hydrogen take place at high temperatures and pressures to increase reaction efficiency. In industrial processes, evaporative cooling is often employed, although air cooling is available as an alternative which is more expensive but less water intensive. By some estimates, replacing evaporative cooling with air cooling may reduce cooling water demands by 30 – 40% [2].

A critical factor for evaluating the water intensity of hydrogen production is the distinction between total water use and consumptive water use. Total water use refers to the volume of water which is used in the entire hydrogen production process, including internal recycling of water and water which is used and returned to the river basin from which it was diverted. Consumptive water use is a subset of total use and refers to the volume of water which is removed from a basin and is not returned to it. For hydrogen production, water is consumed primarily through chemical reactions and evaporative cooling. This report focuses on consumptive water use, because this has the largest impact on basin health and other users. Throughout this report, water demand and use are terms which refer to consumptive water use unless otherwise specified.

Building upon previous WaterSMART analysis [3], publicly available data, and input from project funders, the per-unit water demands (i.e., L H_2O/kg H_2) for the aforementioned hydrogen production technologies were estimated (Table 1). Low, Medium, and High water use scenarios were prepared, recognizing that individual hydrogen processes and facilities are highly variable. For each technology, the stoichiometric amount of water was derived from the relevant chemical equations for the process and used as a starting point, as described below and in Appendix A:

- The stoichiometric amount represents the theoretical minimum water volume which is required based on chemistry first principles.
- Low water use approximates an extremely water-efficient process, starting from the stoichiometric amount and assuming a modest cooling demand and 10 – 15% efficiency losses.
- Medium water use accounts for additional losses through steam generation, water cooling, and other water used throughout various production processes, such as catalyst regeneration in certain technologies.
- High water use accounts for further losses from evaporative cooling and lower efficiency. As more water is introduced to a process, whether it is consumed directly or not, the opportunity for water losses increases. Some allowance for water lost during treatment is also included in this scenario.

The estimates in Table 1 were validated against available literature sources, although they should be reviewed regularly as technologies and processes develop [2] [4]. One of the most important drivers for water use in industrial facilities is cooling since each cooling approach has dramatically different water requirements. For example, flow-through cooling (also called once-through cooling) requires a very high water intake, but most of this water is returned to the environment, which is used as a heat sink. Water-based cooling systems with recirculation consume water by using evaporation as a heat sink, which reduces the total water intake for cooling but increases the consumptive amount compared to flow-flow. Finally, air coolers can be used in place of water-based cooling, typically with higher costs but much lower water use [2] [4]. Larger industrial facilities may invest time and resources into optimizing cooling to reduce water use, although water losses from cooling are impossible to substantially avoid unless air cooling is used [4]. This uncertainty in cooling approach is reflected in the water use scenarios in Table 1. The Medium scenario is expected to reflect a well-optimized system, which is typical of larger industrial processes, although decision-making around water use during plant design is variable. Project proponents should complete detailed analysis for their facilities based on more specific information.

Water treatment is another important driver of overall water consumption, since hydrogen production processes require high quality process water, with specific criteria varying between SMR, ATR, and electrolysis. When raw water is treated, a portion of the total volume is rejected by the process as waste, which can be 40% of the feedwater volume or more, depending on inlet and outlet quality [2] [5]. The High water demand scenario indirectly accounts for some water loss during treatment, although the highly variable nature of raw water qualities and process water quality requirements precludes the estimation of the specific water consumption associated with treatment in this report.

Importantly, the water use associated with CCS was not included in Table 1. Once again, the water demands are highly variable, in the range of 0.50 to 3.16 m^3/tonneCO_2 for pre- and post-combustion capture technologies [6]. For hydrogen projects using natural gas feedstock and CCS, this will be an additional water demand which will need to be considered. Project-specific analysis and future aggregated review are recommended.

Table 1. Per-unit, consumptive water demands of different hydrogen production methods compared to the stoichiometric amount. See Appendix A for more details.

Technology	Stoichiometric amount (L H_2O/kg H_2)	Water consumed (L H_2O/kg H_2)		
		Low	Medium	High
ATR	3.9	4.8	11.3	21.7
SMR	4.5	5.5	13.0	25.0
Electrolysis	9	10	15.0	45.0
Pyrolysis*	0	1.0	8.5	16.3
Gasification**	*Variable*	8	18.9	36.4

Table notes:

**Water consumption depends on the specific methane pyrolysis technology. Method of system cooling and catalyst regeneration affects water demand.*

***Water consumption for gasification is highly dependent on the biomass feedstock and can vary greatly. Moisture content and biomass carbon to hydrogen ratio influences water demand.*

Water demands were also estimated for ammonia and methanol, which are expected to be produced by many of the projects identified in Section 2.3. As detailed in Appendix A, these demands were estimated by computing a hydrogen equivalency for ammonia and methanol on a mass basis. That is, a coefficient was calculated to convert kilograms of ammonia and methanol to kilograms of hydrogen. The water demands in Table 1 were then applied to these hydrogen-equivalent production rates to estimate the water demands of specific projects (see Section 2.4).

2.3 Alberta hydrogen projects

The projects considered in this study are for production of hydrogen and hydrogen-related products (e.g., ammonia and methanol) which are in the construction, proposal, or planning phase at the time of writing. They are all either completely new projects or expansions of existing facilities which would require net new water demands in the basins in which they are located. Other projects within the hydrogen ecosystem, such as research, transportation, and consumption projects were identified but are not included in the analysis because they do not directly represent a net new use of water.

Projects meeting these criteria were identified through a combination of research, engagement with project funders, and leveraging WaterSMART's industry knowledge. The most robust source was provided by the Government of Alberta, with information about publicly announced projects as well as several confidential projects which were noted but for which no information was provided [7]. Efforts were made to corroborate project details with multiple sources where possible, and to compare projects on a consistent basis. Where data was not available for certain projects, assumptions were made using the average of known values. A detailed summary of this research is provided in Appendix B.

Figure 2 shows the locations of new, announced hydrogen and hydrogen-related projects throughout Alberta. Variably sized circles are used to indicate where multiple projects are located within the same area (e.g., in the Edmonton region). Because only the announced projects are included in the figure (i.e., where a project location was identified), there are several projects which were included in the water demand analysis, but which are not displayed in the figure. Specifically, nine projects were included in the Government of Alberta source with the location redacted. These confidential projects are not on the map below but are included in subsequent numeric analysis.

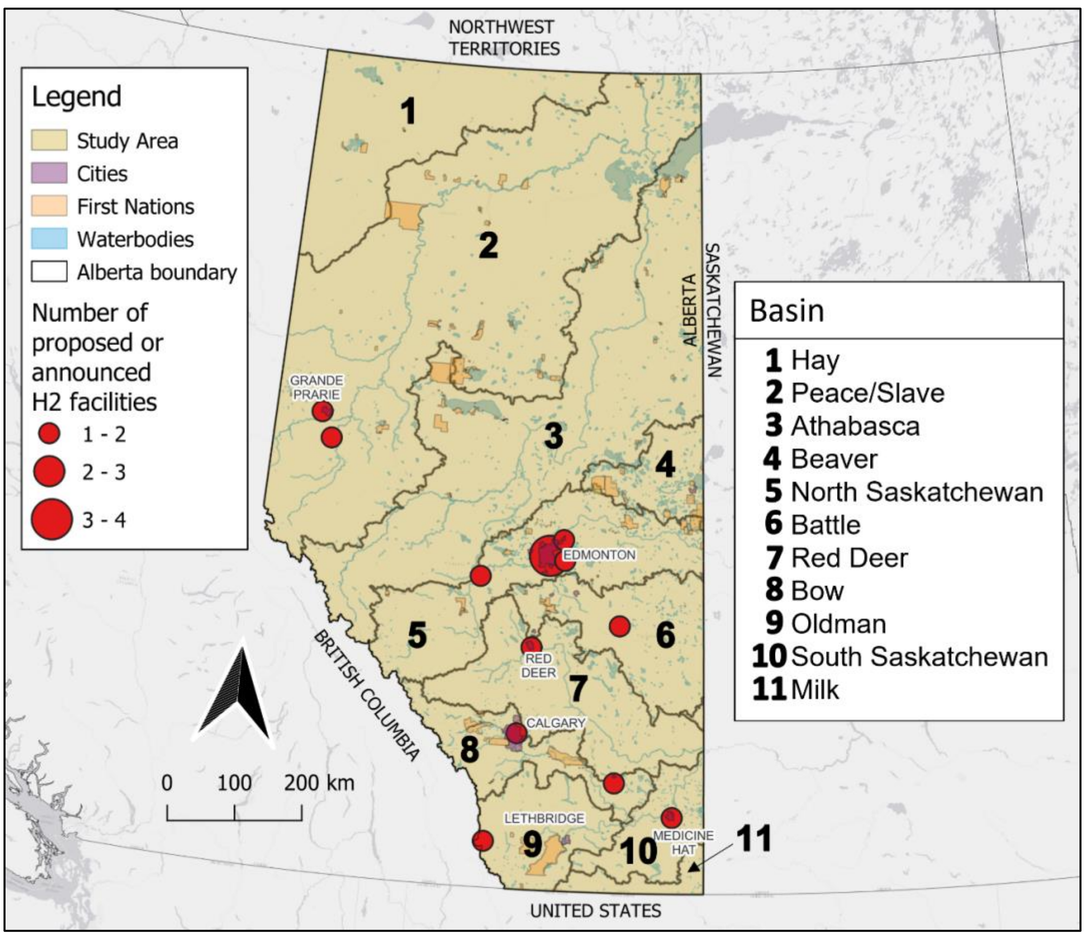

Figure 2. Locations of announced new hydrogen projects throughout Alberta. Note that the nine confidential projects discussed above are not reflected in the numbers included in this figure as their locations have not been disclosed. The actual count of hydrogen projects in the future could be higher across the province.

2.4 Potential hydrogen water demands

To estimate the water demands of hydrogen production throughout Alberta, the per-unit water demands from Section 2.2 were applied to the hydrogen production rates from Section 2.3. Table 2 summarizes the estimated hydrogen demands within each river basin in Alberta, in some cases divided into sub-basins where relevant (see Section 3.0). The estimated total water demand from new hydrogen projects across Alberta is between 121,100,000 m^3/yr and 500,360,000 m^3/yr, depending on the water demand scenario used. This demand is distributed across several basins, with a concentration in the Peace, North Saskatchewan, Bow, and South Saskatchewan basins. A value of zero in Table 2 does not mean that hydrogen production is not currently happening, nor will ever happen, in that basin. Rather, this indicates that publicly available information about new hydrogen projects in the region does not exist. As noted in Section 2.3, not all hydrogen projects have announced locations. To address this uncertainty, the estimated water demand associated with these projects was proportionally divided across the river basins with known hydrogen projects, based on the number of projects in each. Thus, the demand scenarios in Table 2 account for all potential projects announced, while the project count reflects only those projects with known locations, consistent with Figure 2.

Per Section 2.3, this analysis reflects a snapshot in time, with many projects in various stages of development. Depending on the selected size of a reference facility, the estimated hydrogen production represents between dozens and hundreds of future facilities, representing a massive investment. Not all of these projects will proceed to actual development, while more will likely be announced. It also takes many years to develop a project from announcement to operations. Given these development timelines and uncertainties, as well as the possible ranges in water demand per project, a specific "future" demand for hydrogen was not estimated in addition to the aforementioned water demand scenarios. The future will depend on many factors, such as hydrogen's continued role for decarbonizing energy systems, local and global demand, and the economics of production compared to competing jurisdictions. Instead, Table 2 illustrates, within the ranges documented, the potential water demands of future hydrogen development in different scenarios. Over time, as projects begin operating, new projects are announced, and the water demands of these projects are better understood and optimized, the water demands across Alberta should be re-evaluated.

Note that Table 2 includes both major river basins (e.g., the Athabasca River Basin) and select sub-basins (e.g., the Smoky River and the Wapiti River). This differentiation will be explored further in Section 3.0, and in the results in Section 4.0, the water demands are aggregated at a basin level without duplication. For example, the Smoky River has anticipated water demand and is a tributary of the Peace River, which does not have any expected hydrogen demands on the mainstem of the river and is not explicitly included in Table 2. In this report, the Smoky River's demand also appears in the Peace River's demand for visualization purposes, because the Smoky River is within the Peace Basin. However, these do not represent unique demands and are not duplicated in the total water demand noted above.

Table 2. Summary of the Low, Medium, and High hydrogen water demand cases, reflecting all announced new hydrogen projects, per basin. The anticipated water demands for projects announced without a location have been proportionally allocated to basins based on the number of projects with known locations in each. Note that the Wapiti is a sub basin of the Smoky, therefore the anticipated water demand of the Smoky includes that of the Wapiti. The Wapiti has been highlighted on its own, while some other sub basins have not, due to the highly constrained nature of the area.

Basin	*Sub-basin*	*New hydrogen projects*	*Anticipated water demand (1,000 m³/yr)*		
			Low	*Medium*	*High*
Peace	Smoky	2	17,090	29,350	47,110
	Wapiti (incl. within Smoky)	1	1,650	3,910	7,520
	Little Smoky	0	0	0	0
Athabasca		0	0	0	0
North Saskatchewan		7	52,660	111,400	220,740
Battle		1*	1,430	3,390	6,520
South Saskatchewan	Red Deer	1**	20	50	90
	South Saskatchewan Sub-Basin	1	28,470	52,660	128,650
	Bow	3	21,290	47,780	96,620
	Oldman	0	0	0	0
	Upper Oldman	1***	140	210	630
Hay		0	0	0	0
Beaver		0	0	0	0
Milk		0	0	0	0

Table notes:

**Battle River: The project is Heartland Generation's Battle River Carbon Hub (BRCH)* [8]*. The BRCH is a planned conversion of the existing natural gas-fired power plant to run on hydrogen, paired with CCS. On a conservative basis, this project is included as a new hydrogen-related water demand. However, Heartland Generation already has significant water licenses for their existing facility which may be utilized for this purpose. The potential water impacts of both hydrogen production and CCS will need to be better* *understood as the BRCH is developed.*

***Red Deer: The project is the Cvictus Mannville Enhanced Hydrogen Recovery Project, which is understood to be a demonstration of an underground coal-gasification project* [9]*. The technology proponents do not expect that a significant net new diversion of water will be required for their process, since the gasification process produces formation water. Until the demonstration project results can verify this prediction, a water demand associated with the Cvictus project has been included to be conservative.*

****Oldman: As discussed in Appendix C.7, the Oldman River Basin has a small volume of water available for new allocations upstream of the Oldman Dam. The Tent Mountain Renewable Energy Complex has been announced within the headwaters of the Oldman River Basin and may therefore be able to access this available water* [10]*. No projects were identified in the Oldman River Basin downstream of the Oldman Dam*.

3.0 Alberta's Water Context

Across Alberta, there is a high degree of variability in both the volume of water which is present in specific locations and how this volume is managed by regulators to meet ecological and human needs. This variability is especially apparent when comparing the southern and northern parts of the province. While 80% of Alberta's water resources are in the north, 80% of the population is in its south [11]. This dynamic has created significantly more competition for water in the southern river basins than the northern ones, as visualized in the Figure 6 water availability heat map below.

Another important water dynamic is the time variability of the water supply, both seasonally and year over year, which will be explored further in Section 3.1. Because of this variability, water users must diligently assess and manage water supply risks within the context of the prevailing regulatory regime for water (Section 3.2), regardless of where in the province they are located. This report provides a high-level water availability assessment (Section 3.3) and relevant background information (Appendix C) for the rivers identified in Figure 3. These rivers were highlighted within the study area because they satisfied one or more of the following criteria:

- Currently a water-short region, wherein water risks for new projects of any kind will be significant.
- Likely to be a water-short region in the near future, meaning the water risk environment is dynamic and must be understood by project developers.
- Likely to host future hydrogen projects, based on those already announced (Section 2.0).

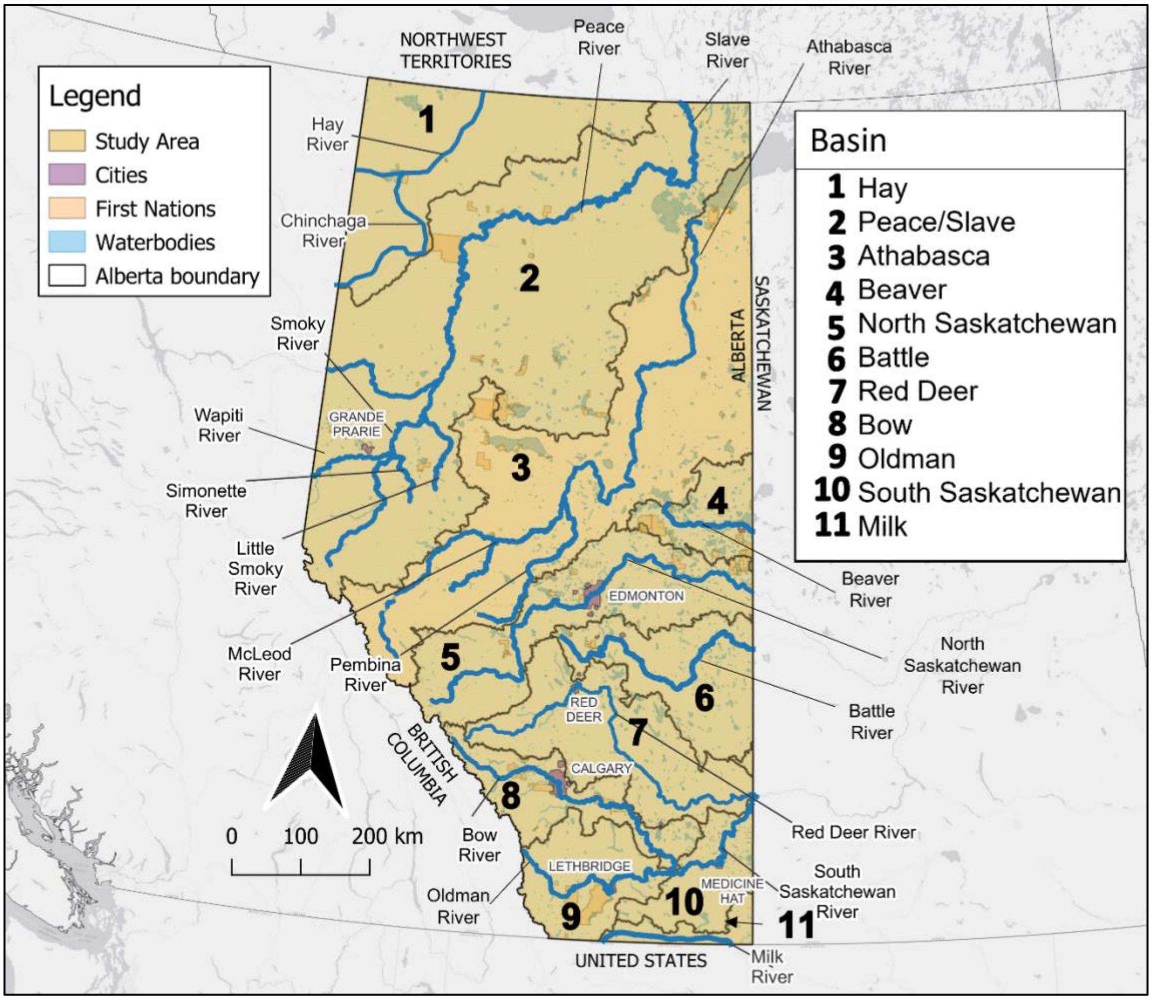

Figure 3. Map of the specific rivers which were analyzed for water availability in this report. These rivers were selected based on water supply and known and anticipated developments in hydrogen and other sectors.

3.1 Hydrology overview

Alberta's freshwater resources are generally grouped into three categories: groundwater, non-flowing surface water (i.e., lakes and ponds), and flowing surface water (i.e., rivers, streams and creeks). Flowing surface water bodies, most of which have headwaters in the eastern slopes of the Rocky Mountains, are the source of most water used in Alberta. There are very few naturally occurring lakes of significant volume, especially in the southern basins. Notably in the Bow and Oldman river basins, nearly all the large non-flowing water bodies are man-made reservoirs created by damming or diverting water from the major rivers. As noted in Section 1.2, groundwater availability varies widely across Alberta, and it is not used as frequently as surface water. The absence of high quality, consistent, and readily available groundwater data across Alberta can act as a barrier to its use since groundwater exploration can be expensive and with uncertain results.

Alberta's proportionally high reliance on flowing surface water bodies, along with its geographical location immediately east of the Rocky Mountains, makes the province's water supply vulnerable to seasonal variation. River flows across Alberta typically peak between May and July and are lowest between October and February. The May to June peaks are driven by snow and glacier melt from the Rockies, as well as a modest increase in precipitation compared to other months. River flows typically taper off into late summer and early fall and become lowest during the winter months when there is limited contribution from snow and glacier melt. In addition to low flows during the late fall and winter months, prolonged ice cover can create a barrier to access water on some rivers due to physical and regulatory constraints. Figure 4 illustrates the seasonal variability of several rivers in Alberta.

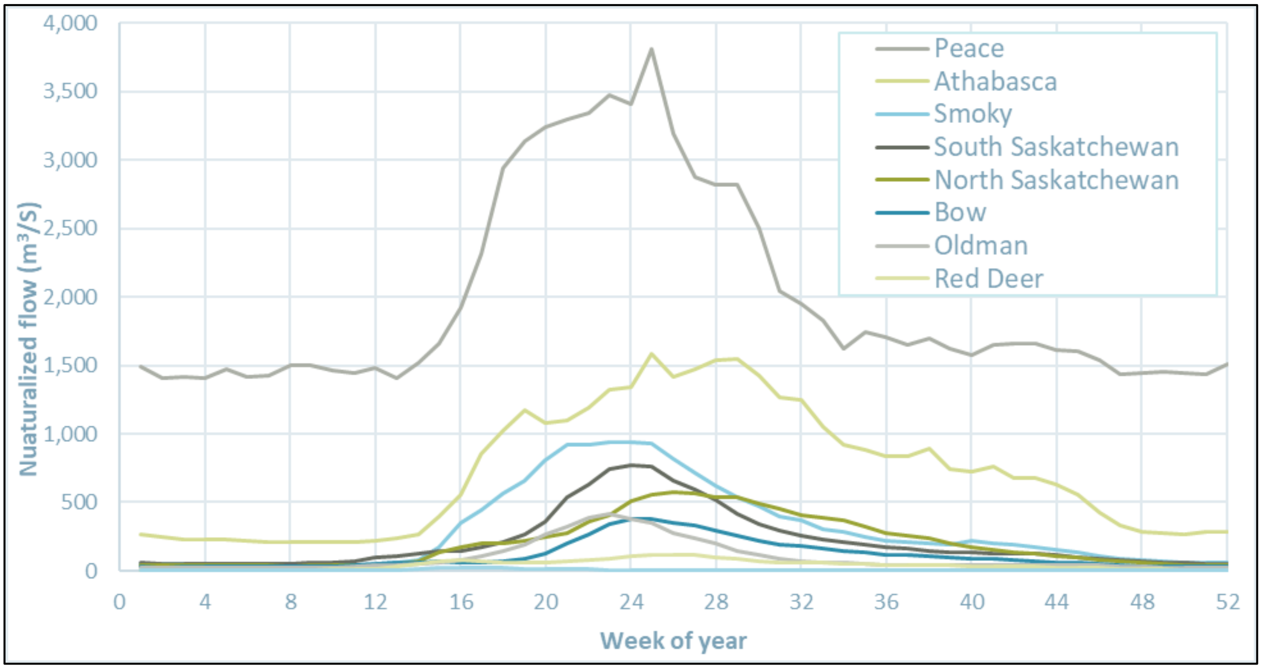

Figure 4. Illustrative naturalized flow hydrographs for several rivers in Alberta, which demonstrate the potential variability across seasons.

3.2 Water management and regulation

Water resources in Alberta are governed through a suite of regulatory instruments, which vary in type, level of authority, and enforcing body. The *Water Act* is the primary statute for governing water resources in Alberta. It seeks to balance the competing water needs of the environment, people (i.e., high quality drinking water), and industry by providing direction on water management planning, the right to divert water, issuance and administration of diversion licenses, construction of works, and conflict resolution, among other topics. The *Water Act* is enforced by the Alberta Energy Regulator (AER) for energy projects (i.e., oil, oil sands, natural gas, coal, geothermal, and brine-hosted mineral resources) and by Alberta Environment and Protected Areas (EPA) for all other (i.e., non-energy) uses. Hence, petrochemical facilities, such as hydrogen, are regulated by EPA.

An important consideration within this regulatory framework is the requirement for Indigenous consultation. The Aboriginal Consultation Office (ACO) provides direction on the regulatory requirements for consultation in Alberta, while some federal departments have additional requirements and processes for projects with elements falling under their jurisdiction. It is important for project proponents to consider whether their projects meet both the provincial and federal requirements for meaningful consultation and the extent to which they may adversely impact First Nations' Treaty rights or traditional uses and Metis settlement members' harvesting or traditional use activities. Beyond regulatory obligations, meaningful engagement around water can also provide important opportunities for both project proponents and Indigenous communities, with links to economic reconciliation.

Several key elements of the *Water Act* which may impact how a project accesses water include:

- **Inter-basin water transfers:** The *Water Act* stipulates that a licence cannot be issued which allows water transfer between major river basins unless it is authorized by a special Act of the Legislature. The major river basins named in the *Water Act* are the Peace/Slave, Athabasca, North Saskatchewan, South Saskatchewan, Milk, Beaver, and Hay River Basins. Hence, water resources are generally considered available for use only within the river basin in which they exist.
- **Environmental protection:** The *Water Act* provides mechanisms for determining the volume of water which should remain in a river for the sake of environmental protection (i.e., the volume which will not be licensed for people to utilize). These mechanisms include cabinet-approved Water Management Plans (WMPs), water conservation objectives (WCOs), and others. The Surface Water Allocation Directive (SWAD), issued under the *Water Act*, provides direction for all rivers and lakes without pre-existing management approaches.
- **Diversion rights:** Water users receive a licence to divert a specified volume of water at a specified rate, commonly referred to as a water allocation. Alberta uses a priority-based allocation system, which means that older (i.e., senior) licenses have higher priority to withdraw water than newer (i.e., junior) licenses. This includes senior licence holders who are downstream of junior licence holders. In situations where water availability is low, the junior licence holders may have their water access restricted, while senior licence holders may continue diverting water.
- **Demonstrated need for water**: Also known as a Development Plan, the *Water Act* requires that applicants for water licenses credibly demonstrate their anticipated water needs over the duration of the project. This requirement prevents speculation on the water resources in Alberta by ensuring only those with legitimate plans to use water can be granted a licence.
- **Construction of works:** The *Water Act* includes requirements and restrictions for the construction of water storage and intake works. Significant restrictions are placed on construction occurring within the river to minimize negative impacts to the aquatic environment.
- **Monitoring and reporting:** Water diversion licenses have requirements on them for monitoring and reporting, and it is expected that licence applicants will have a plan for monitoring quality and quantity criteria and reporting these to the regulator (e.g., annually).
- **Licence transfers:** The *Water Act* includes provisions to permanently transfer all, or a portion of, a water diversion licence from one user to another in basins with a cabinet approved WMP. Such transfers require that the original licence is in good standing, which typically requires that a substantial portion of the licence is currently being used. This restriction can make licence transfers challenging, since current licence holders may be unwilling to permanently transfer away the right to divert water which they currently use. In addition, in basins without an approved WMP, transfers can only be approved by an order of the Lieutenant Governor in Council, which is difficult to secure.
- **Licence assignments:** As an alternative to licence transfers, the *Water Act* also allows for licence

assignments, wherein a senior licence holder temporarily assigns their licence priority number to a junior licence holder, based on a contract negotiated between the parties. Functioning much like an insurance policy, this arrangement allows the junior licence holder to divert water during water-short periods, when they would not have otherwise been able to due to their junior priority. Assignments require that the assigned licence is in good standing.

Other provincial regulatory instruments which may be relevant to a project's water supply include the *Historical Resources Act,* the *Environmental Protection and Enhancement Act,* the *Public Lands Act,* the *Wildlife Act*, the Water (Ministerial) Regulation, the Wastewater and Storm Drainage Regulation, the Pipeline Rules, the Alberta Wetland Policy, and the Environmental Quality Guidelines for Alberta Surface Waters.

In addition, some elements of water access fall under federal jurisdiction, primarily via the *Fisheries Act* and the *Canadian Navigable Waters Act.* The *Fisheries Act* provides a framework for the conservation and protection of fish and fish habitat, with implications for water intake structure design and construction. The *Canadian Navigable Waters Act* provides rules for environmental protection and to promote the continued use of navigable water bodies within Canada by the public, which includes commercial or recreational vessels and Indigenous peoples exercising their Treaty rights. Other potentially relevant federal acts include the *Canadian Environmental Protection Act*, the *Species at Risk Act*, the *Migratory Birds Convention Act*¸ and the *Impacts Assessment Act*

An additional limitation on water use in Alberta is the 1969 Master Agreement on Apportionment, which requires Alberta to allow a volume of water to flow into Saskatchewan equal to half the natural flow in each river [12]. This requirement impacts the volume of water which is available for diversion from the rivers flowing into Saskatchewan. There is also an agreement through the International Joint Commission, which governs how water flows into the United States via the Milk River in Alberta's southeast.

3.2.1 Impact of regulations on water availability

Within this suite of regulatory instruments, each water body within Alberta has a unique regulatory context, which directly influences how water is managed and how much water is available for new uses. For example, the *Bow, Oldman and South Saskatchewan River Basin Water Allocation Order* (2007) closes the Bow Basin, the Oldman Basin, and the South Saskatchewan Sub-Basin to new water diversion licence applications [13]. However, the *Oldman River Basin Water Allocation Order* (2003) reserves a small volume of water upstream of the Oldman Dam for specific uses (see Appendix C.7 for more information). In addition, several other basins have prescriptive, cabinet approved WMPs, and still other basins are managed through application of the SWAD. Project proponents must understand the regulatory context and how this impacts water availability in areas they are considering.

Figure 5 illustrates how the regulatory regime impacts water availability from a river, using the Little Smoky River as an example. The SWAD is applied to the Little Smoky River, meaning that water available for allocations is calculated as a variable percentage of total flow. As noted in Section 3.2, water withdrawals are managed to ensure adequate water remains in the river for healthy aquatic species and habitats. Therefore, the SWAD percentage is scaled to be lower when river flow is lower, such that proportionally more water stays in the river during low flow periods (e.g., winter months). For licence holders on the Little Smoky and elsewhere throughout Alberta, this means that, although a water licence is granted as a yearly volume of water, there is no guarantee that a licensee will actually be able to divert that volume, and it is likely that their rate of diversion will need to vary throughout the year (i.e., lower in the winter, higher in the spring). These dynamics of intermittency and variability introduce water supply risks which must be managed (e.g., via water storage). See Section 3.3 for further discussion on water availability throughout the province.

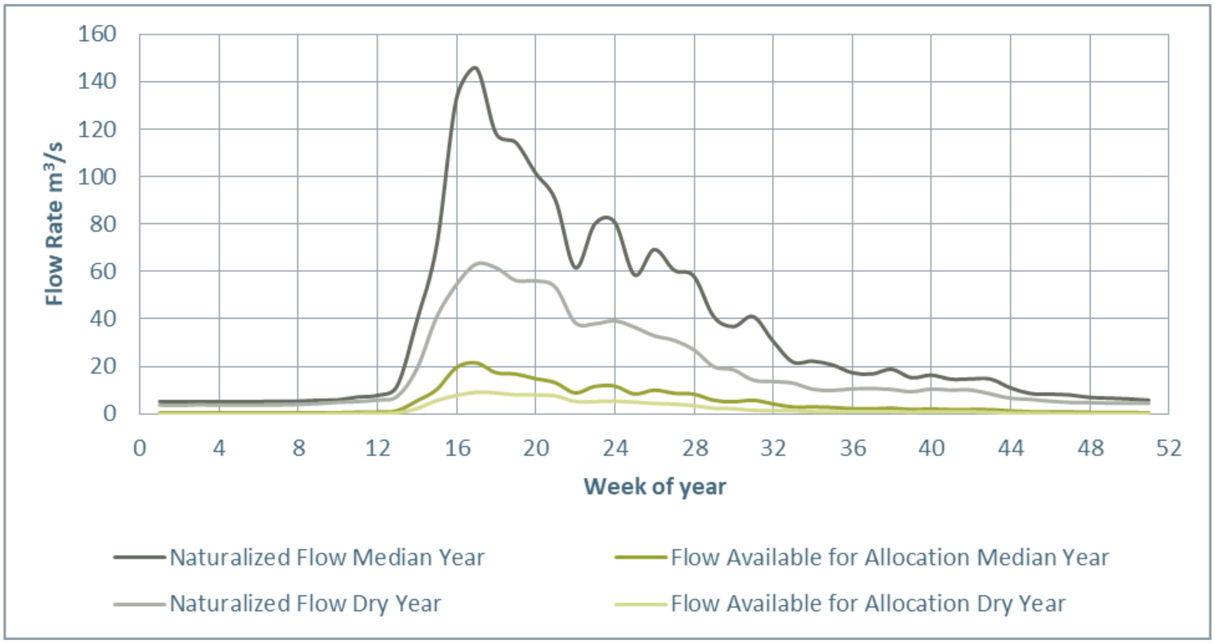

Figure 5. Hydrograph for the Little Smoky River, showing the seasonal variability of natural flow and how this impacts water available for allocation.

3.3 Water availability

The volume of water available for new consumptive use in Alberta (i.e., water availability) was estimated into the 2050 timeframe. This analysis required assumptions around how much water is currently used and how demand will increase into the future. The results, discussed below, provide a high-level water risk assessment across the province, with a focus on trends and comparisons between river basins, as opposed to the accuracy of specific numbers. Project proponents are encouraged to complete a more detailed, site-specific water risk analysis before investing significant time and money in developing a new project.

Water availability was assessed using publicly available data from several sources. River flow data was sourced from EPA and Water Survey of Canada gauge stations, while data on existing water licenses was pulled from an online database maintained by EPA [14]. For each river basin, the appropriate regulatory framework (e.g., WMPs, SWAD) was applied to calculate the water available for all allocations. From this, anticipated future water use was subtracted to estimate how much water will be available for new allocations, defined as water availability. Two different flow scenarios were utilized to capture the inter-annual variability in flows noted above. Specifically, a median year (also referred to as an average year) and dry year were modelled based on statistical analysis of the hydrometric period of record. See

Appendix D for more details on the water availability methodology.

The heat map in Figure 6 displays the results of the water availability analysis in each basin across the province. The colours indicate how much water is available for new allocations on an annual basis in a median year, and do not directly reflect the inter-annual and seasonal variability which is expected in each basin (per Section 3.1 and Appendix C). Efforts have been made to analyze and differentiate sub-basins on a relevant scale, in recognition that while a large river may have abundant supply, not all its tributaries will (e.g., the Wapiti River in the Peace River Basin). Consistent with the preceding discussion, this heat map provides a high-level comparison between basins, but detailed analysis will be required to confirm the water supply dynamics of a specific project location and develop management approaches.

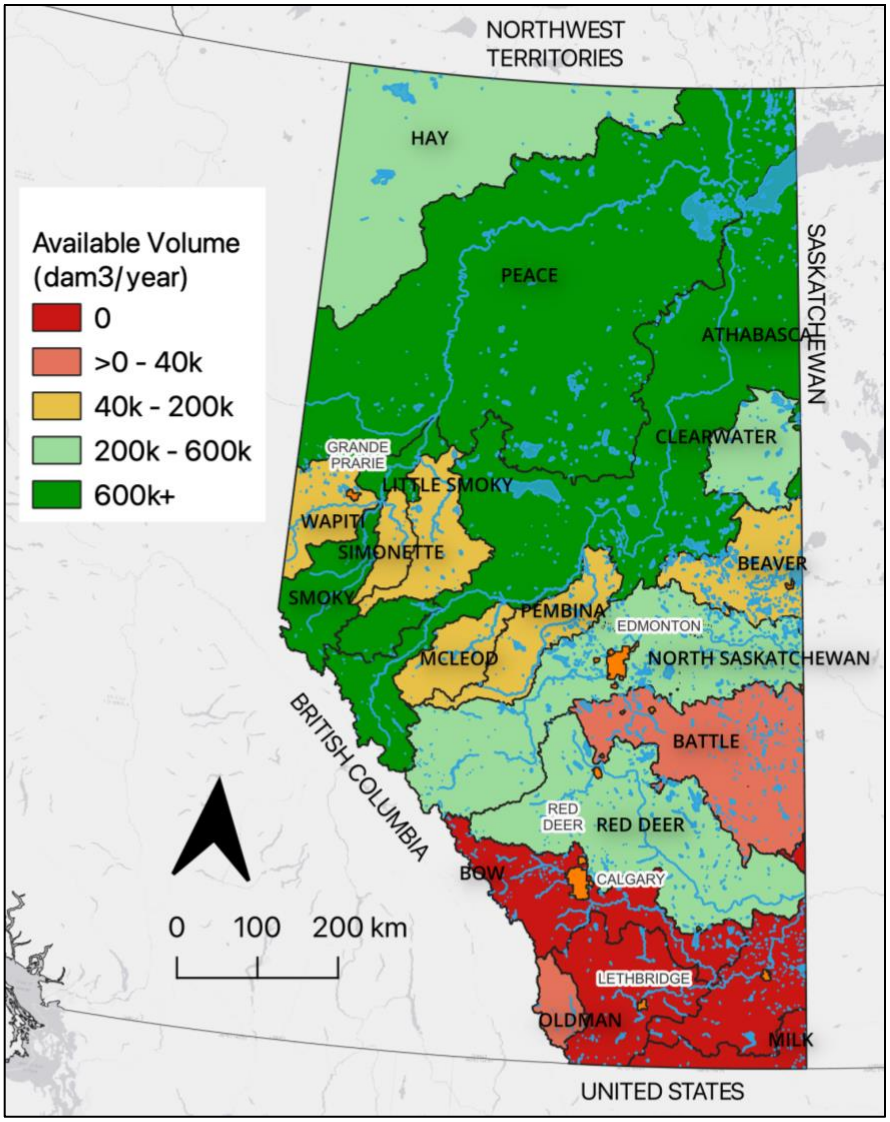

Figure 6. Heat map of water availability throughout Alberta in an average year. This is a near future estimate of the yearly net volume of water that is available for new uses per basin but may not be reflective of every tributary in that basin. Additionally, see Appendix B for details on seasonal and year over year availability per basin.

Table 3 was prepared to accompany Figure 6. In both median and dry year scenarios, Table 3 compares the total water flow in each river to the volume which is available for new allocations. The available volume in a median scenario is linked to the colours in Figure 6, and the dry year availability column illustrates how this availability can vary between years. Rivers are listed in descending order based on water availability.

Table 3. Summary of annual flow and water availability for basins and sub-basins in the study area, comparing median and dry year scenarios. The annual, aggregated data presented herein should be considered in combination with the seasonal variability of each river, discussed in Section 3.1 and Appendix C.

Basin	Sub-basin	Annual flow (1,000 m³/yr)		Available water (1,000 m³/yr)	
		Median year	Dry year	Median year	Dry year
Peace	Peace	62,263,800	47,938,500	9,182,000	7,033,210
Athabasca	Athabasca	22,424,790	18,274,640	2,822,160	2,199,640
Peace	Smoky	9,334,310	6,786,440	1,377,600	995,420
North Saskatchewan	North Saskatchewan	6,450,570	5,086,880	431,230	272,810
Hay	Hay	1,968,550	1,074,270	292,140	157,990
South Saskatchewan	Red Deer*	1,350,860	909,010	270,000	270,000
Peace	Little Smoky	1,077,400	565,150	146,840	70,010
Peace	Wapiti	2,585,100	1,853,580	53,220	50,800
Beaver	Beaver	396,810	209,060	33,780	9,200
Milk	Milk**	294,860	214,450	0	0
North Saskatchewan	Battle	168,230	93,060	8,670	1,690
South Saskatchewan	Oldman Upper Oldman***	3,044,380	2,151,700	0 1,450	0 1,450
South Saskatchewan	South Saskatchewan	6,757,200	5,167,210	0	0
South Saskatchewan	Bow	3,618,260	2,793,690	0	0

Table Notes:

**The water available in the Red Deer River reflects the Approved Water Management Plan for the South Saskatchewan River Basin (SSRB) and basin allocation data provided by EPA in 2022. Note that there is currently an irrigation project being scoped in the eastern portion of the basin that could apply for an allocation of a significant portion of the water remaining for allocation.*

***The analysis for the Milk River reflects the rules of the WMP, which are enforced at the Milk River Gauge Station. Water is reserved under the WMP for very specific uses, which do not include hydrogen. See Appendix C.9 for more information.*

****As noted in section 3.2 and Appendix C.7, there is a small volume of water available in the Upper Oldman River Basin. The Order which allocates this water predates the closure of the South Saskatchewan River Basin.*

3.4 Climate change impacts

Temperature and precipitation trends demonstrate that measurably climatic changes are already being experienced in Alberta [15]. For example, between 1951 and 2017 data shows that average winter temperatures in the province have already warmed 4 – 5^{o}C in southern Alberta and 6 – 7^{o}C in northern Alberta [15]. Continuing changes in both temperature and precipitation are driving changes in water availability across the province. These changes, detailed below, are best understood and managed in terms of trends, rather than through specific quantification. Therefore, detailed climate change modelling has not been integrated into the water availability analysis presented in Section 3.3. Instead, the water supply risks associated with climate change are implicitly considered within the different ranges and scenarios presented. Detailed and site-specific climate change modelling will be instructive for planning individual projects.

In 2020, WaterSMART completed an analysis of the projected impacts of climate change for the Prairie region using data from the Coupled Model Intercomparison Project Phase 5 [16]. The Radiative Emissions Pathway (RCP) that was selected for the study was RCP 4.5, which represents a relatively conservative (i.e., low) potential for impacts from climate change [16].

The study analyzed changes in temperature and precipitation, in combination with various other factors including topography and seasonal timing, to develop an understanding of changing conditions and challenges in the region [16]. Overall, the temperature in Alberta is expected to increase from the reference period of 1986-2005 to the projected near future period of 2020-2060. Particularly important from a hydrology perspective is that winter temperatures are projected to increase even more than summer and fall temperatures, especially in the northern part of the province [16]. Increasing winter temperatures may mean more winter precipitation falls as rain, spring snowmelt occurs earlier, and snow will intermittently melt during the winter. These changes are likely to impact water availability patterns. Warmer temperatures are also projected in the summer, which will increase the rate of evaporation and evapotranspiration and may consequently reduce the available surface water and soil moisture [16]. Simultaneously, higher ambient temperatures are likely to increase the demand for water from facilities using evaporative cooling, potentially exacerbating warm-weather water availability challenges.

Overall, the trends in precipitation for Alberta are expected to increase from the reference period of 1986-2005 to the projected near future period of 2020-2060, and particularly in the winter and spring [16]. The precipitation change is also projected to vary by latitude, with the northern half of Alberta projected to see a greater increase than southern areas [16]. Although the average precipitation is projected to increase, models also indicate that the year to year variability of precipitation is expected to increase as well. This means the reliability of river flows and water availability is likely to decrease, even though more water may be expected overall [16].

The anticipated hydrologic changes due to climate change can be generalized into trends for three regions of Alberta:

- The northernmost third of the province will likely experience increasing temperatures, increasing variability in annual precipitation, and on average quite a bit more precipitation relative to the period of 1986 to 2005. This may result in impacts such as higher snowpack, earlier snowmelt, unexpectedly high river flow in the winter, high water levels and flooding in the spring, low late-summer streamflow, and more low-flow years (i.e., droughts).
- The middle third of the province will likely experience increasing temperatures, increasing variability in annual precipitation, and generally somewhat more precipitation on average relative to the period of 1986 to 2005. This may result in impacts such as disappearing glaciers and very low late-summer streamflow, unexpectedly high river flow in the winter, earlier snowmelt, flooding in the spring, and more low-flow years (i.e., droughts).
- The southern third of the province will likely experience increasing temperatures, particularly hot and dry summers, a small overall increase in annual volume of precipitation, and increasing variability in annual precipitation relative to the period of 1986 to 2005. This may result in very low late-summer streamflow, rain and melting events during the winter, lower peak streamflow in the spring, lower snowpack, less reliable and predictable water availability, and more extreme low-flow years (i.e., extreme droughts).

3.4.1 Approaches to managing climate change impacts

Climate change is likely to increase the variability of water availability within Alberta, while simultaneously making it more difficult to predict future conditions based on historic data. Greater variability is linked to a higher likelihood of low flow years and droughts when water will not be available for diversion. These changes will make it more difficult for project proponents to assess and manage water risks. However, options exist for managing water risks in a changing climate.

Water storage is one way to increase the reliability of water access in the face of an increasingly variable water supply. In a changing climate, projects may require larger storage volumes than would have been built historically. Another option is to manage water risks by maintaining relationships with other water users in the basin and working together on water management and water efficiency projects. Collaboration with other water users may include establishing legal agreements, such as water assignments under the *Water Act* or water-sharing agreements, in advance of drought situations.

To appropriately deploy risk management approaches, it is critical to understand how water is managed on a local level, including the key decision drivers. Each basin within Alberta is unique, with different drivers, risks, and opportunities. A thorough understanding of local basin context and the existing regulatory system will enable creative solutions to managing future water risks.

4.0 Comparing Hydrogen Water Demands to Water Availability

This section presents a comparison of the estimated water demand for hydrogen in Alberta (Section 2.0) with the estimated water available for new allocations (Section 3.0). Figure 7 illustrates how water availability varies in basins across the province in median and dry years, and the extent to which this availability will satisfy the requirements of the Low, Medium, and High water demand scenarios for hydrogen. This is supplemented by Figure 8, in which the anticipated hydrogen projects in Figure 2 are overlaid onto the water availability heat map from Figure 6.

These results indicate that the potential water challenges associated with future hydrogen development vary widely across Alberta. In some basins, ample water is available throughout the year to support both hydrogen and non-hydrogen development, while in others, there are significant annual and/or seasonal water availability limitations. In locations with limited water availability, hydrogen development will directly compete with future municipal growth and industrial development, including sectors which will be critical for the net zero 2050 transition (e.g., CCS, critical minerals mining). As will be discussed in Section 5.0, further analysis will be required to evaluate future water availability accounting for all development, not just hydrogen.

As Section 4.1 will detail, the North Saskatchewan River Basin is likely to be home to significant hydrogen production. Based on available data and considered in isolation, there may be enough water on an annual basis to support hydrogen development. However, this ignores the future water demands of all other users in the basin, including the significant number of CCS projects which have been announced and will be necessary to enable SMR- and ATR-based hydrogen production. Also notable are the Bow River Basin and South Saskatchewan River Sub-Basin, which have significant hydrogen demands but no water available for new allocation. The implications of these disparities are discussed in Section 4.2 and 4.3 for Calgary and Medicine Hat, respectively.

This analysis relies on several assumptions, which are described throughout the report. For example, the unknowns of how many hydrogen projects will be built, where they will be built, and how much water they will consume, leads to uncertainty in the water demand estimates. However, considering the drivers documented in Section 1.0, it is clear that future water demands for hydrogen will be significant, regardless of what assumptions are made. While consumptive water use is the focus of this report, it will also be important to understand and evaluate the implications of non-consumptive water use, particularly in locations with low water availability. Non-consumptive water use (e.g., for flow-through cooling), could impact things like aquatic health (e.g., via temperature, quality) and the footprint of water storage.

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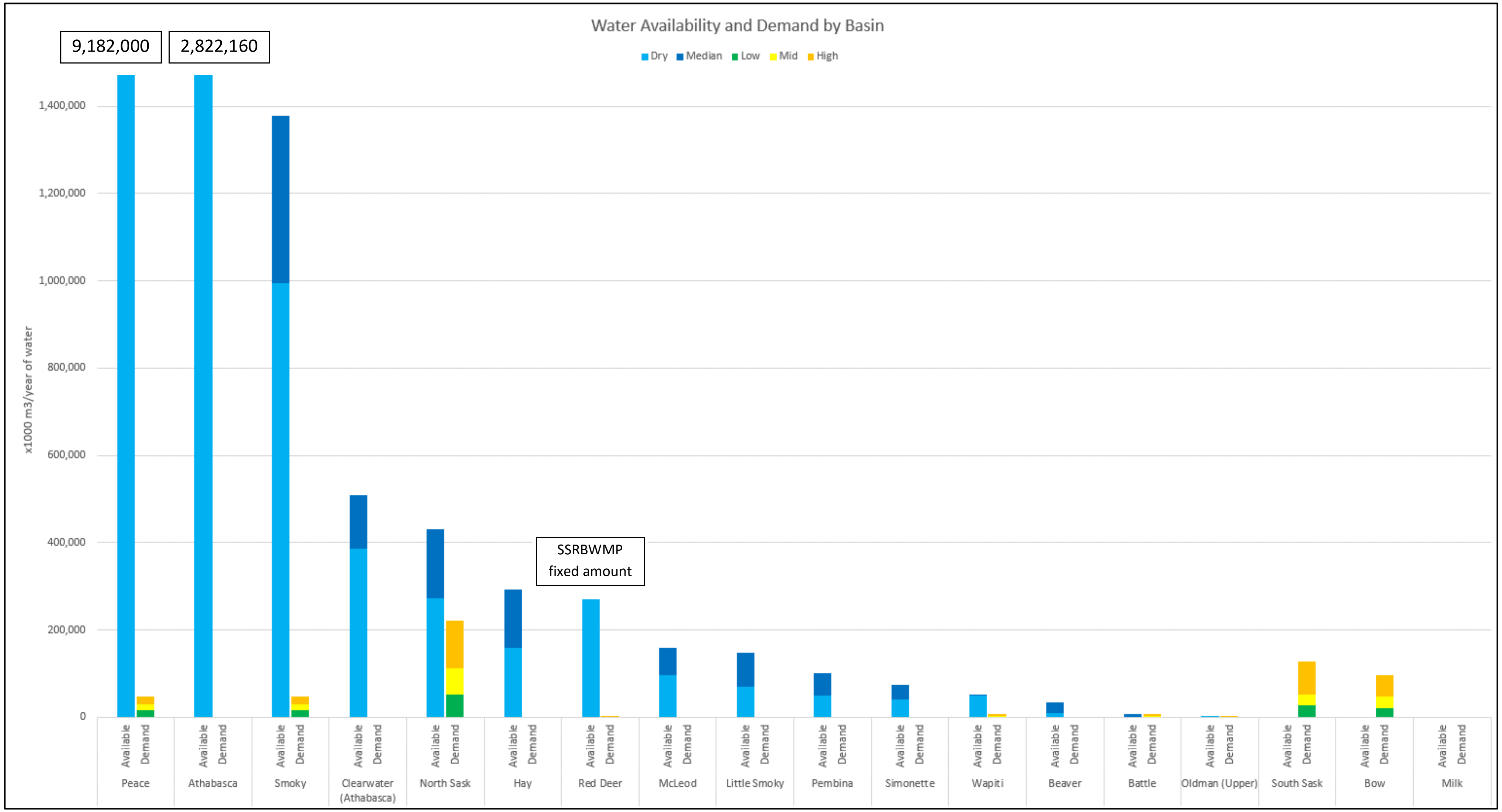

Figure 7. Available water in both cases (Median, Dry) compared to hydrogen demand in all three cases (Low, Medium, High), for each basin. When the blue bar, representing availability, is shorter than the green/yellow/orange bar, representing demand, there will be water shortages in that basin. This is most apparent on the right, in the South Saskatchewan and Bow basins, where demand is much larger than availability. Note that the Peace contains the Smoky, and the Smoky contains the Wapiti. Hence, the water demands in the Wapiti are copied into the Smoky, and the Smoky demands are copied into the Peace for visualization purposes.

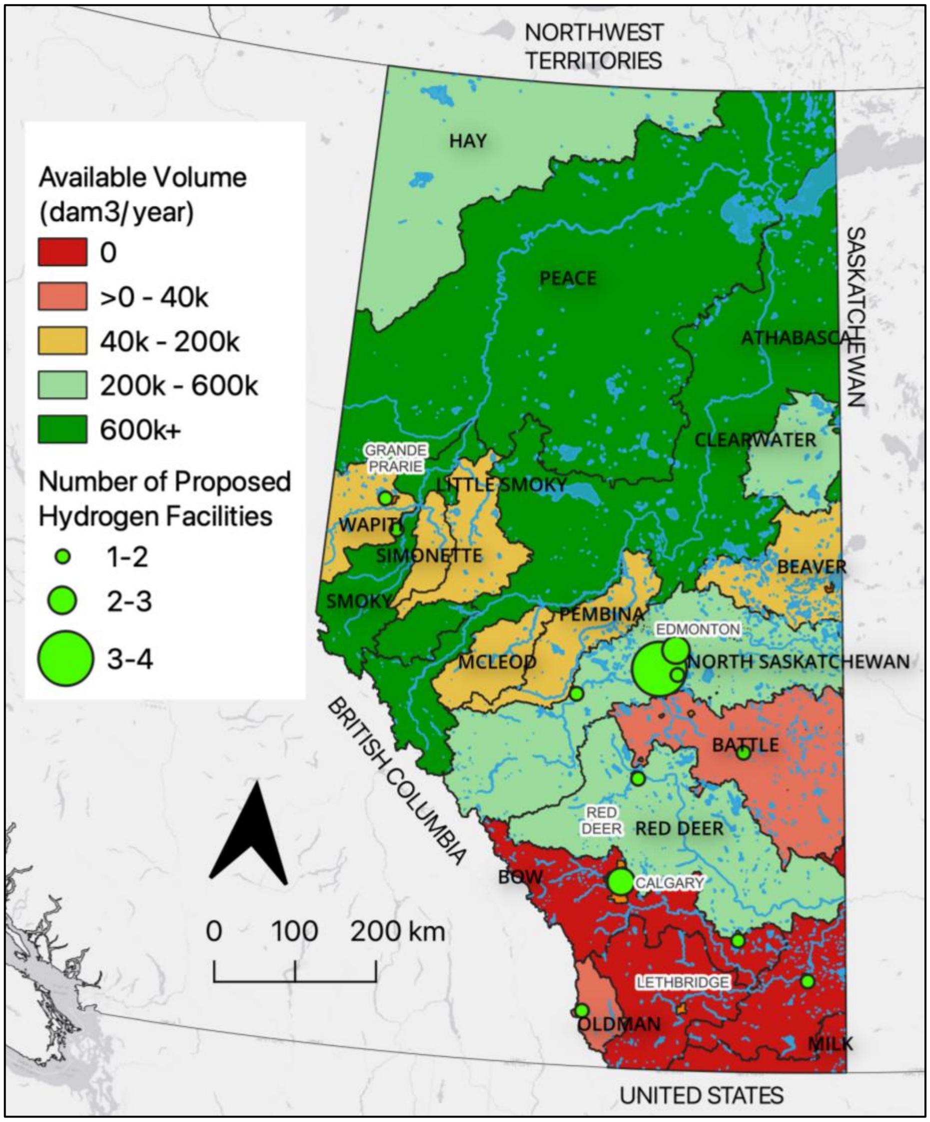

Figure 8. Announced hydrogen projects on top of an average year heat map, to provide visual context of demand per basin and water available in that basin.

Given the significant water demands associated with hydrogen development, future hydrogen projects in some basins may constrain other developments by limiting their water access. In addition, the hydrogen projects themselves will be forced to contend with water supply challenges across seasons and years. As part of strategically managing the transition to net zero 2050, project proponents, funders, and regulators must carefully evaluate the potential trade-offs associated with hydrogen development. This is illustrated in Figure 9, which presents a modified water availability heat map for a future scenario where the identified hydrogen projects have been built. Specifically, Figure 9 shows future water availability for other uses in a dry year, after water has been diverted for a High hydrogen demand scenario. See Table 4 for accompanying data.

Due to the sheer size of the Peace River and Athabasca River Basins, they remain relatively unimpacted. However, the significant hydrogen development planned in the North Saskatchewan River Basin will have a material impact on future water availability. Additionally, as noted in Section 3.0, most of Alberta's population lives in the southern part of the province, which is the region most vulnerable to both dry years and future hydrogen demands.

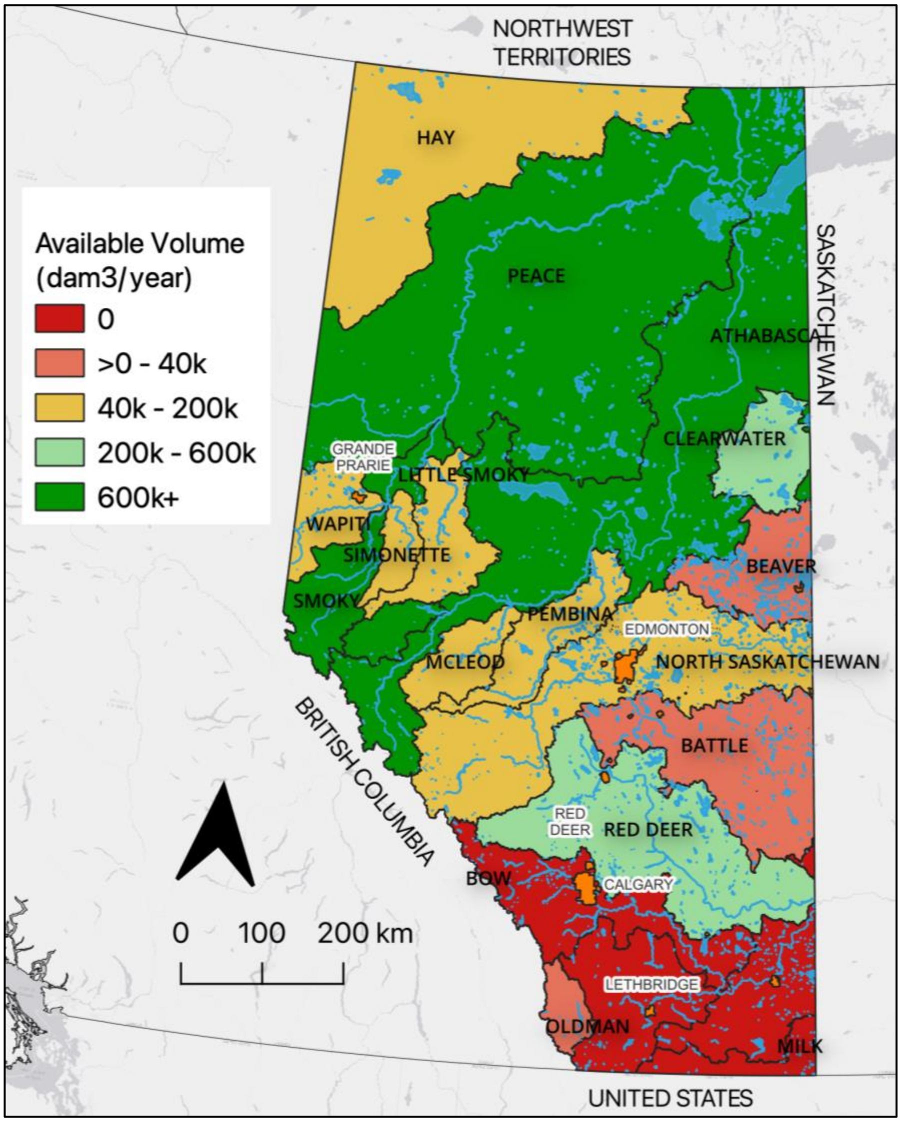

Figure 9. Annual Available Volume per basin in the case of High hydrogen demand in a dry year.

Table 4. Available water in the case of a dry year after High hydrogen demand.

Basin	*Sub-basin*	*High Hydrogen Demand (1,000 m³/yr)*	*Water Available in Dry Year After Hydrogen (1,000 m³/yr)*
Peace	Peace	47,110	6,986,100
Athabasca	Athabasca	*0*	2,199,640
Peace	Smoky	47,110	948,310
North Saskatchewan	North Saskatchewan	220,740	52,070
South Saskatchewan	Red Deer	90	269,910
Hay	Hay	*0*	157,990
Smoky	Little Smoky	*0*	70,010
Smoky	Wapiti	7,520	43,280
Beaver	Beaver	*0*	9,200
North Saskatchewan	Battle	6,520	-4,830
South Saskatchewan	South Saskatchewan	128,650	-128,650
South Saskatchewan	Bow	96,620	-96,620
South Saskatchewan	Oldman	0	0
	Upper Oldman	630	820
Milk	Milk	0	0

4.1 Edmonton region

The Edmonton region within the North Saskatchewan River Basin includes the City of Edmonton, the Alberta Industrial Heartland, and the surrounding municipalities (e.g., Strathcona County) [17]. Within this region, significant effort and attention has been directed at the potential to develop world-scale hydrogen projects [18]. Detailing these efforts is outside the scope of this report, and readers are referred to agencies such as Edmonton Global and the Transition Accelerator to learn more.

As noted in Section 2.4, there are many projects anticipated within the Edmonton region for the production of hydrogen and related products for regional and international use. Per Figure 7 and Table 4, the consumptive water demand for hydrogen is expected to require a significant proportion of the water available in the North Saskatchewan River Basin, as much as 80% in dry years. Over the lifetime of the proposed projects, it can be reasonably expected that the region will be subject to even drier conditions than those modelled, possibly including multi-year drought. In such cases, water demand for hydrogen could exceed the annually available water volume, introducing water supply risks for both hydrogen projects and other water users. Furthermore, this analysis compared availability to demand on an annual basis, but water supply can vary significantly on a seasonal basis (Section 3.1 and Figure 10). This introduces an additional dimension of water supply risk for future hydrogen projects which must be considered.

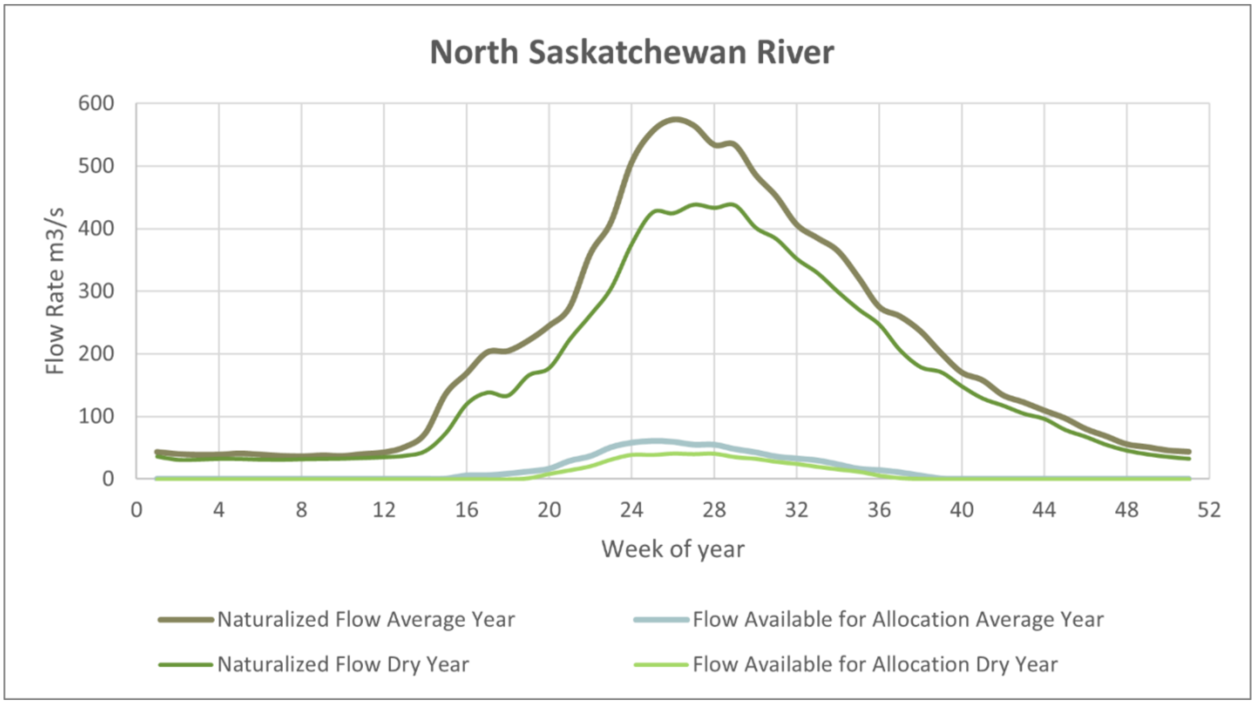

Figure 10. Comparison of water flow to water available in the North Saskatchewan River, in dry and average years. Under the SWAD, water availability drops significantly during the winter months (October – April).

Others have also studied the North Saskatchewan River's capacity to support future industrial development, including, but not exclusive to, hydrogen. In 2022, the regional water system within the Industrial Heartland was analyzed to assess its capacity to meet current and future water requirements for industrial development [19]. The study authors projected future industrial water use within the region by estimating the current water use, on a per-area basis, and multiplying this rate by the total area of industrial land (including future industrially zoned land). The 50-year water demand estimated in this study is an order of magnitude higher than the demand presented in Section 2.4 because the study considered all industrial uses, not just those associated with the hydrogen economy (e.g., it included gas-to-liquids facilities, electricity generation, fractionation plants, etc.). Although both the scopes and findings vary between the 2022 study and this hydrogen-focused report, consistent conclusions can be drawn from both efforts. Indeed, the 2022 study emphasizes the potential water access risks to future project development of all types, when considered together. This reinforces the importance of conducting site-specific water risk assessments as part of project development, and links to opportunities for regional water management.

Both this report and the 2022 study identify seasonal variability as an important contributor to water supply risk. Constructing water storage is an obvious, though expensive, approach to address seasonal water supply challenges. The 2022 study also recommended a regulatory change to address this issue. Currently, water licenses are issued on the North Saskatchewan River using the SWAD, which calculates available water as a percentage of naturalized flow. By definition, naturalized flow does not account for the positive impacts of the Brazeau and Bighorn dams on winter stream flows. Therefore, it has been argued that the SWAD effectively under-predicts the volume of water, which is present in the river during the winter, and hence how much can be withdrawn [19]. The 2022 study recommended that a new Directive be issued which allows licenses to be granted while accounting for the increased winter flows caused by upstream dams, which would thereby increase the volume of water available both annually and during low flow periods. This approach is likely to involve significant engagement of stakeholders and Indigenous communities who may be affected by the change, and it is unknown if the necessary political will is currently in place to support this process.

In recognition of the importance of systems-based approaches to water management, an alternative way to address water supply challenges in the North Saskatchewan River Basin should be considered. A basin-scale, collaborative, and data driven process could be effectively deployed to confirm and quantify water risks relevant for hydrogen production as well as other water users and the environment. This would inform water management approaches which satisfy the needs of as many water users as possible, including for hydrogen, while balancing water-energy-food nexus tradeoffs and environmental considerations.

4.2 Calgary region

As Figure 7 indicates, there is significant hydrogen development planned within the Bow River Basin, even though no new water licenses can be applied for. Based on the research documented in Section 2.0, it is understood that the majority of this new hydrogen development will occur within the City of Calgary and surrounding area [20]. Already, there are many industrial activities in Calgary which utilize water under the City's existing water licenses, and it is therefore assumed that future hydrogen development would also primarily draw on water which is already allocated to the City.

The City of Calgary holds numerous water licenses for a variety of purposes, with a total annual allowable diversion of 461,645,481 m^3/yr. Based on the details of the City's licenses, 99% of this diverted volume is designated for urban use, which includes domestic, commercial, and industrial use. Of the 461,645,481 m^3/yr that the City is allowed to divert, approximately 80% must be returned to the environment. This means that the City currently has a maximum annual consumptive allocation of 90,669,335 m^3/yr, some of which is already being used. As discussed in Section 2.0, it is this consumptive volume, which is particularly important when considering new hydrogen production, which will consume water. Table 5 compares the City's consumptive allocation to the consumptive volume associated with the anticipated hydrogen demand in both the Bow River Basin and in the Calgary Hydrogen Production

Hub [20]. The existing consumption within the City is not included in this comparison.

Table 5. Water demands for hydrogen within the Bow River Basin and the Calgary Hydrogen Production Hub as percentage of the Calgary's existing consumptive water licence (90,669,335 m³/yr).

H2 demand scenarios	Bow River Basin		Calgary Hydrogen Production Hub	
	Annual consumptive water demand (1,000 m^3/yr)	% of total City consumptive volume licensed	Annual consumptive water demand (1,000 m^3/yr)	% of total City consumptive volume licensed
Low	21,290	23%	10,120	11%
Medium	47,780	53%	23,930	26%
High	96,620	107%	46,020	51%

As Table 5 reveals, future hydrogen development could require up to 50% of the City of Calgary's total consumptive allocation, even if the Calgary Hydrogen Production Hub is the only project to proceed. This ratio increases to more than Calgary's entire consumptive allocation if all potential hydrogen projects are built in the Bow River Basin and draw water from the City. These consumptive water demands for hydrogen could have a material impact on the City's water supply and will directly compete with current and future water use for all other domestic, commercial, and industrial purposes within the City.

The planned hydrogen development in Calgary illustrates the potential tension between water for people and water for energy within the context of the water-energy-food nexus. Table 5 highlights the importance of informed and strategic decision making around how to best use our shared water resources. The City of Calgary and surrounding region will need to evaluate priorities for water use relative to future population growth, industrial development, environmental protection, and risk management, and integrate these priorities into decision making around hydrogen projects. For developers, this analysis indicates that careful planning will be required to identify a viable water source and manage its risks, whether water is sourced from the City or via a water licence transfer under the *Water Act*.

4.3 Medicine Hat region

Southeastern Alberta, particularly the Medicine Hat region, has been identified as a location suitable for future hydrogen development, called the Southeast Alberta Hydrogen HUB (SAHH) [20] [21]. With the region already producing about 10% of Alberta's hydrogen annually, it is estimated that as much as 8,850 t/day of new hydrogen production could come online by 2050, to bring the total to 10,000 t/day in the region [20]. This new hydrogen production would meet a combination of demands within the region (e.g., transportation, agri-food processing, power generation), and would service significant export markets, both domestically and internationally [20].

While the region is well positioned for hydrogen production from the perspectives of natural gas feedstock availability, access to renewable energy, and proximity to transportation corridors, future hydrogen development in Southeastern Alberta will be challenged by access to water. As noted in Section 3.2, the South Saskatchewan River Basin, where Medicine Hat is located, is closed to new water licence applications. Therefore, new hydrogen production will need to identify alternative sources of water. Two such alternatives which have been proposed are water licence transfers from irrigation licence holders (authorized under the cabinet approved WMP for the South Saskatchewan River Basin) and sourcing brackish water from locally producing natural gas wells (i.e., produced water reuse) [20].

It is possible that irrigation water licence transfers and produced water reuse will be suitable options for individual projects, following detailed and specific analysis (e.g., technical and logistical feasibility, economics, and environmental net effects). However, it will be challenging for these sources to provide sufficient water supply for the entire development ambition of the SAHH to 2050, as currently envisioned.

Table 6 compares the anticipated consumptive volume of water required for full build out of the SAHH to the volumes available from produced water and irrigation sources in the region. For this comparison, it is assumed that half of the hydrogen production in the SAHH will come from electrolysis and half from SMR, based on information from the Transition Accelerator [20]. For context, Table 6 also compares all the licenses currently issued in the South Saskatchewan River Sub-Basin in the bottom row. Table 6 is specific to the SAHH and does not include any additional hydrogen demands which may occur in the region, which were discussed in the context of projects without known locations in Section 2.3.

Table 6. Comparison of consumptive water demands for the Southeast Alberta Hydrogen Hub to potentially available produced water and irrigation licenses, as well as to existing licenses for all purposes.

	Hydrogen production scenario		
	Low	Medium	High
Annual water demand for hydrogen (1,000 m^3/yr)	25,034,438	45,223,500	113,058,750
% of produced water supply	28%	51%	127%
% of existing irrigation licenses	47%	85%	212%
% of all existing consumptive licenses in the basin	14%	25%	62%

The Transition Accelerator estimates that 7,400,000 m^3 of produced water is generated in the region each month (i.e., 88,800,000 m^3/yr) [20]. The extent to which a significant portion of this produced water can be used for hydrogen production will require further, detailed study to address logistical and treatment considerations while confirming economics. As Table 6 indicates, even if all produced water in the region is utilized for hydrogen development, the full consumptive demands of the SAHH would not be supported under a high hydrogen water demand scenario.

Critically, hydrogen production requires clean water, especially for electrolysis. Even with a high-quality source of raw water, as much as 40% of an available volume can be disposed of as part of the treatment process to meet process water specifications [5]. With a lower quality produced water, the proportion which is disposed of is expected to be higher. Hence, Table 6 is likely an ambitious estimate for how much hydrogen production can be supported by the available produced water in the region. In addition to the available volume, the capacity to dispose of water treatment waste products must be considered for the SAHH. The implementation of centralized water treatment hubs may improve the economics of produced water treatment and disposal of residual waste; however, supply-side limitations on water are expected to persist regardless of how it is gathered and treated.

For irrigation licence transfers, only 52,257,599 m^3/yr of consumptive use is currently allocated for a combination of private irrigation and irrigation districts. As Table 6 indicates, even if all current allocations were transferred for hydrogen production, the consumptive demands of the SAHH would not be met. The likelihood of even one project being supported by an irrigation water licence transfer must be evaluated against the current global context. Exacerbated by a changing climate and Russia's invasion of Ukraine, the global food crisis is becoming more acute. Both irrigators and the provincial government in Alberta have expressed a clear commitment to increase food production in the face of these challenges, which is expected to require a greater proportion of existing irrigation licenses are used, meaning less water will be available for licence transfers [22].

For additional context, Table 6 compares the consumptive use associated with the SAHH to the existing licenses in the South Saskatchewan River Sub-Basin. With the SAHH being equivalent to 14 – 48% of all licenses currently issued for all other purposes, this reinforces the significance of hydrogen's demands for water and the associated water-energy-food nexus considerations which must be made by water managers and policymakers. For project proponents in the region, the above analysis indicates the extent to which a secure water supply is likely to be a material risk. Robust analysis will need to be completed early in project development to assess and manage water supply risks and costs.

5.0 Recommendations & Next Steps

This report demonstrates that full development of the hydrogen sector within Alberta is likely to both cause water supply challenges and be limited by water availability. The extent of water risks varies across the province on a water basin and sub-basin level, and understanding local water context is critical to identifying and managing water risks and water-energy-food nexus trade-offs. When considered in the context of the net zero 2050 transition, which will involve other water-dependent technologies, and future development of all other types, it becomes even more critical to strategically manage our shared, and limited, water resources.

In response to these challenges, the following recommendations are provided for project proponents and investors:

1. Conduct detailed, site-specific analysis of the local water context to better understand how water availability will be impacted by the regulatory framework, stakeholder and indigenous community concerns, other water users, and seasonal and inter-annual hydrologic dynamics.
    a. This analysis will materially impact project risks and costs and should be completed early in project development before significant investments are made.
2. Carefully consider climate change risks, informed by location-specific analysis.
3. Develop approaches to manage water supply risks in an increasingly variable and unpredictable climate. These may include:
    a. Constructing water storage with sufficient capacity to supply operations during low flow periods.
    b. Working with other water users in the basin to develop water-sharing agreements, and/or collaboratively manage water on a basin level.
    c. Seeking opportunities to reduce overall consumptive water requirements, for example by using air cooling instead of evaporative cooling.
    d. Seeking alternatives to freshwater use, including saline groundwater and water reuse.

To develop better knowledge and tools for identifying and managing water-related challenges, the following next steps should be undertaken:

1. Utilize collaborative, data-driven processes to identify, understand, and manage water challenges on a river basin scale, while balancing water-energy-food nexus tradeoffs and environmental considerations.
    a. The North Saskatchewan River Basin should be a top priority for this work, given the absence of existing models and tools for this purpose and the abundance of hydrogen development planned for the region.
    b. This work should consider the implications of both consumptive and non-consumptive water use associated with future development.
2. Repeat this study to examine other technologies and sectors which will be involved in the net zero 2050 transition (e.g., CCS, small modular nuclear reactors, critical minerals, etc.).
3. Recognizing that net zero 2050 commitments are being made across Canada, repeat this study in the other provinces and territories, which are currently grappling with many of the same

challenges documented for Alberta.

4. Develop a better understanding of Alberta's groundwater resources and make this data available publicly in a consistent and usable format.

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Appendix A Hydrogen Water Demands Details

This appendix provides details on several of the most common methods for producing hydrogen, including the relevant chemical formulas. There are many other hydrogen production technologies that exist, such as direct solar, bioethanol to H_2, microbe light conversion, and many more in development. Within each of the main technologies are also different subtypes. The technologies below are the most common and established methods that are relevant to the list of projects identified in this study (Appendix B).

A.1 Hydrogen production technologies

A.1.1 Steam-Methane Reforming (SMR)

SMR is the most widely used technology for hydrogen production. While there are many different forms of SMR that use various catalysts and gaseous mixtures, the underlying method uses high temperatures to reduce methane (CH_4) with water (H_2O) into hydrogen (H_2) and carbon dioxide (CO_2). The CO_2 can be captured with CCS technologies [2].

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Example Calculation: The stochiometric per-unit water demand can be calculated using molar mass conversion [3]*:*

$$1\ mol\ H_2 / 2.016\ g\ H_2 * 2\ mol\ H_2O / 4\ mol\ H_2 * 18.015\ g\ H_2O / 1\ mol\ H_2O * 1\ L\ H_2O / 1\ kg\ H_2O$$

$$= \underline{4.5\ L\ H_2O / g\ H_2}$$

This methodology was applied for each technology to determine the lowest possible volume of water required to produce a kilogram of hydrogen (i.e., the stoichiometric amount).

A.1.2 Autothermal Reforming (ATR)

Emerging as a competitor to SMR is ATR, which uses a similar process to SMR combined with partial oxidation. The main difference is that oxygen is also used along with the steam-reforming reaction to oxidize the methane into hydrogen [3]. Overall, less heat and water are required. Carbon dioxide is also more easily captured with ATR [23].

$$4CH_4 + O_2 + 2H_2O \rightarrow 10H_2 + 4CO$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$4CH_4 + O_2 + 6H_2O \rightarrow 14H_2 + 4CO_2$$

A.1.3 Water Electrolysis

Water Electrolysis is fundamentally the splitting of water into hydrogen and oxygen. Electrolysis is a well-established technology and can be combined with renewable sources of electricity to produce hydrogen that does not involve any carbon fuels. The reaction for water electrolysis is the exact opposite of combusting hydrogen. The main drawback of water electrolysis is the large amount of energy needed to split the water. If the energy is not derived from renewables, it will still be tied to carbon emissions. Electrolysis requires significant cooling, which is typically from evaporative cooling [2]. In addition, the process water for electrolysis must be of a high quality. Depending on the raw water quality, treatment can be an expensive and water intensive process.

$$2H_2O + \text{energy} \rightarrow 2H_2 + O_2$$

A.1.4 Methane Pyrolysis

Methane pyrolysis is the thermal decomposition, or breaking down, of methane using energy. Methane is split directly into hydrogen and carbon. Because solid carbon (C) is the only byproduct and is more easily manageable than CO_2, proponents of pyrolysis argue it is a cleaner alternative for producing hydrogen, especially if renewable electricity is used to generate the heat needed for pyrolysis. While water is not a direct input, depending on the specific methane pyrolysis technology, water may be required for cooling and catalyst reformation [24].

$$CH_4 \rightarrow CH_3 + H$$

$$CH_3 \rightarrow CH_2 + H$$

$$CH_2 \rightarrow CH + H$$

$$CH \rightarrow C + H$$

$$CH4 \rightarrow C + 2H_2$$

A.1.5 Biomass Gasification

Biomass gasification is a broad term for burning organic matter to produce fuels. Organic matter feedstock can include anything from residual wood fibers, to agricultural plant byproducts, to animal wastes, and much more. This technology is considered “net zero” because it is recycling the carbon stored in common waste products, rather than using a fuel that was recovered from underground. Because there can be so many different feedstocks, there are many different types of biomass gasification, all of which require different inputs (such as water) and yield different amounts of products (such as hydrogen) [25]. The water content and carbon to hydrogen ratio of the biomass feedstock impacts overall water demand [2]. An example of a simplified reaction using glucose (which is a basic building block of many organic materials) is:

$$C_6H_{12}O_6 + O_2 + H_2O \rightarrow 3CO + 3CO_2 + 7H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$C_6H_{12}O_6 + O_2 + 4H_2O \rightarrow 6CO_2 + 10H_2$$

A.2 Production of hydrogen-related products

As noted in the body of the report, the water demands associated with the hydrogen-related products, ammonia and methanol, were estimated using a hydrogen-equivalent production rate, described below.

A.2.1 Ammonia

The Haber-Bosch process is the conventional method of producing ammonia. It is a well understood reaction where Nitrogen (N_2) is combined with hydrogen (H_2) to produce ammonia (NH_3) [26] [27].

$$N_2 + 3H_2 \rightarrow 2NH_3$$

While there is no direct water input in this reaction, water will be used to produce the hydrogen used in this process. Therefore, determining the water intensity of ammonia requires understanding how many units of hydrogen go into one unit of ammonia, on a mass basis. Once this is known, the estimated water demand can be calculated using the L H_2O/kg H_2 unit demands from the hydrogen-producing technologies determined above. The mass ratio of hydrogen to ammonia can be calculated based on mole ratios and molar mass:

$$1 \text{ mol } NH_3 / 17.03 \text{ g } NH_3 * 3 \text{ mol } H_2 / 2 \text{ mol } NH_3 * 2.016 \text{ g } H_2 / \text{mol } H_2 \underline{= 0.1775 \text{ g } H_2 / \text{g } NH_3}$$

For example, if 1,000 tonnes (i.e., 1,000,000 kg) of ammonia is produced, the amount of hydrogen needed would be:

$$1{,}000{,}000 \text{ kg } NH_3 * 0.1775 \text{ kg } H_2 / \text{kg } NH_3 = 177{,}500 \text{ kg } H_2$$

Next, if the technology used to produce the hydrogen is SMR, the estimated water demand would be:

$$177{,}500 \text{ kg } H_2 * 5.5 \text{ L } H_2O / \text{kg } H_2 = \underline{976{,}250 \text{ L}} \text{ or } \underline{976.25 \text{ m}^3}$$

A.2.2 Methanol

Conventional methanol production involves synthesis gas and hydrogenation of CO and CO_2 along with various catalysts. The syngas undergoes SMR and similar processes to yield the CO, CO_2, and H_2 required for the hydrogenation process [28] [29]. The reactions involved are:

$$2H_2 + CO \rightarrow CH_3OH$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

$$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$$

$$1 \text{ mol } CH_3OH / 32.04 \text{ g } CH_3OH * 3 \text{ mol } H_2 / 1 \text{ mol } CH_3OH * 2.016 \text{ g } H_2 / \text{mol } H_2 \underline{= 0.1887 \text{ g } H_2 / \text{g } CH_3OH}$$

Water, in the form of steam, is also a product of methanol production. Individual methanol facilities take various approaches to optimize water use, including capturing the product steam and reusing it internally. Alternatively, it is released as water vapor in some cases. Taking a conservative approach, it is assumed that the product water is not returned to the river basin from which it is withdrawn, nor does it materially reduce makeup water requirements.

This assumption was tested using Nauticol Energy's proposed methanol production facility [30]. Nauticol Energy had a proposed methanol production facility that would produce 3,400,000 tonnes/yr of methanol and had an estimated requirement of 8,000,000 m^3/yr of water. It would produce its required hydrogen using SMR. Using the hydrogen-equivalency ratio above and the Medium water use scenario for SMR, the following test was completed:

$$3{,}400{,}000{,}000 \text{ kg } CH_3OH * 0.1887 \text{ kg } H_2 \text{ / kg } CH_3OH * 13 \text{ L } H_2O \text{ / kg } H_2$$

$$= \underline{8{,}340{,}540{,}000} \text{ L } H_2O \text{ or } \underline{8{,}300{,}000 \text{ m}^3 \text{ } H_2O}$$

Using the Medium SMR water intensity of 13 L H_2O/kg H_2, the estimated water demand for Nauticol's facility is 8,300,000 m^3/yr. This is within a reasonable range of Nauticol Energy's proposed 8,000,000 m^3/yr.

Appendix B Hydrogen Project Details

The table below summarizes all the projects used in the study. As noted throughout the report, the analysis focused on projects representing net new hydrogen production, and therefore new water demands. Research identified many other projects in the hydrogen sector which were not included in this study due to some combination of a complete lack of data for production, demand, and technology used; no new water demand (i.e., they are existing projects); hydrogen consumption but no production (and therefore no new water demand); and probability that the project is already included in the confidential projects listed below. Examples of projects which were identified but not included in the analysis include the ATCO Fort Saskatchewan Blending Project, CP Rail Hydrogen Engine Project, Rocky Mountain GTL Carseland Gasification Expansion Project, Imperial Oil Strathcona Renewable Diesel Refinery, and the ATCO Bremner community.

For most of the projects, water demand was calculated based on the type of product, the technology used, and the production rate. To estimate water requirements, the production rate is first converted to kg per year. Next, if the product is ammonia or methanol, the amount of hydrogen equivalent is determined (Appendix A). Finally, the kg/yr of hydrogen equivalent is multiplied by the per-unit water demands (Section 2.2) to yield the Low, Medium, and High water demands for the project.

The water required to produce electricity for electrolysis has not been accounted for in this analysis; in cases where renewable energy is utilized, water requirements for energy production would be relatively low. The water requirements to produce methane for hydrogen production were also not included in this analysis. Note that all SMR and ATR projects in the table are expected to use CCS. While CCS uses additional water, that amount is not included in the water use estimations (see Section 2.2). Future work will be required to confirm the water use associated with CCS, since it is known to be variable [6].

Several assumptions were required to overcome limitations in publicly available data:

- When the hydrogen production technology is unknown, SMR is assumed. This reflects the current popularity of SMR and the number of publicly announced projects planning to use it.
- For some projects, the production rate is unknown, but their water licence quantity is known (e.g., the Greenview Industrial Gateway). To determine the water demand, the High intensity was assumed to use 100% of the water licence, Medium to use 75%, and Low to use 50%.
    - For project expansions within an existing licence, such as Dow Chemical's ethylene facility, the water required refers is the additional amount of water required by the project expansion to the maximum of the allocation amount (i.e., if the project is a 3x expansion, it is assumed the facility is currently only using 33% of its licence, and the expansion would utilize the remaining 66%).
- When both the production rate and licence is unknown, the production rate is estimated to be the average of the known production rate of projects with the same product and technology.
- Enhanced Hydrogen Recovery (HER) gasification, which is a form of coal gasification, is estimated to be similar to biomass gasification based on the information available. As noted below the table, this was included on a conservative basis.

#	Name	Location & Watershed	Description/ type of production	Technology used	Production rate (per year)	H_2 Equivalent (t H_2/yr)	Water Demand (1,000 m³/yr) Low	Medium	High	Development stage	Ref
	Planned Projects										
1	Gold Creek Ammonia and Methanol Production Facility by Northern Petrochemical Corp.	MD of Greenview No. 16 Greenview Industrial Gateway - Peace	Ammonia & Methanol	Assumed SMR	Assumed from water licence application[1]	2,594,595	12,000	18,000	24,000	Planning	[31]
2	Net-Zero Emissions Ethylene and Derivatives Facility by Dow Chemical Canada	Fort Saskatchewan - North Saskatchewan	H2 & Ethylene Derivatives	SMR	Assumed from water licence allocation[2]	1,549,550	7,167	10,750	14,333	Proposed	[32]
3	Suncor & ATCO World-Scale Clean Hydrogen Project	Fort Saskatchewan - North Saskatchewan	H2 & Cogen	ATR	300,000 t H_2	300,000	1,430	3,380	6,500	Proposed	[33]
4	Heartland Blue Ammonia & Methanol Production Complex by ITOCHU & Petronas & Inter Pipeline	Strathcona County - North Saskatchewan	Ammonia & Methanol	SMR	1,000,000 t each of ammonia & methanol	366,249	2,014	4,761	9,156	Proposed	[34]
5	Western Canada's Net-Zero Hydrogen Energy Complex - Hydrogen Production and Liquefaction Facility by Air Products	Edmonton - North Saskatchewan	H2	ATR	547,500 t H_2	547,500	2,610	6,169	11,863	Under construction	[36]
6	Mitsubishi-Shell Low-Carbon Hydrogen Facility	Edmonton - North Saskatchewan	H2 & Ammonia	SMR	620,000 t H_2	620,000	3,410	8,060	15,500	Planning	[37]
7	Aurora Hydrogen Demonstration Methane Pyrolysis	Edmonton - North Saskatchewan	H2	Methane Pyrolysis[3]	73 t H_2	73	0	0	0	Proposed	[38]
8	Brazeau River Complex Integrated SMR-CCS-Cogen Project by Tidewater	Drayton Valley - North Saskatchewan	H2 & Cogen	SMR	Assumed average of known production	300,750	1,654	3,910	7,519	Proposed	[39]
9	Battle River Carbon Hub by Heartland Generation	Battle River - Battle	H2 & Power	ATR	Assumed average of known production[4]	300,750	1,434	3,388	6,516	Proposed	[8]
10	The Mannville Project by Cvictus	Red Deer - Red Deer	H2 & Methanol[5]	EHR Gasification	2,555 t H_2	2,555	20	48	93	Under construction	[9]
11	Crossfield Low-Carbon Hydrogen Production Hub by TC Energy & Nikola	Crossfield - Bow	H2	SMR	54,750 t H_2	54,750	301	712	1,369	Planning	[40]
12	Calgary Hydrogen Production Hub by H-GEN Initiatives & Aperion Resources	Calgary - Bow	H2	Majority SMR	1,840,695 t H_2	1,840,695	10,124	23,929	46,017	Planning	[41]

#	Name	Location & Watershed	Description/ type of production	Technology used	Production rate (per year)	H_2 Equivalent (t H_2/yr)	Water Demand (1,000 m^3/yr) Low	Medium	High	Development stage	Ref
13	Kitsim Hydrogen Project by IEPS	Newell County - Bow	H2	Electrolysis	55,000 t H_2	55,000	550	825	2,475	Planning	[42]
14	Southeast Alberta Hydrogen Hub by Southeast AB Hydrogen Task Force	Medicine Hat, Southeast AB - South Saskatchewan	H2	SMR & Electrolysis	3,230,250 t H_2	3,230,250	25,034	45,224	113,058	Planning	[21]
15	Tent Mountain Renewable Energy Complex by Montem Resources & TransAlta	Crowsnest Pass - Oldman	H2	Electrolysis	14,000 t H_2	14,000	140	210	630	Planning	[10]
16	JERA and Petronas MOU Project (Un-named)	TBA - Multiple	H2 & Ammonia	Electrolysis	Assumed average of known production	1,193,615	11,936	17,904	53,713	Planning	[43]
17	H2 Naturally Hydrogen Project	TBA - Multiple	H2	Wood Gasification	22,265 t H_2	22,265	178	421	810	Planning	[44]
	Confidential Production Projects										
1	Hydrogen Canada	Confidential	Ammonia	Not disclosed	Not disclosed	1,193,615	6,565	15,517	29,840	Planning	[7]
2	Kiwetinohk Energy Corp.	Grande Prairie, Wapiti (Peace)	Hydrogen	Not disclosed	Not disclosed	300,750	1,654	3,910	7,519	Planning	
3	Confidential	Confidential	Hydrogen	Not disclosed	Not disclosed	300,750	1,654	3,910	7,519	Planning	[7]
4	Confidential	Confidential	Hydrogen	Not disclosed	Not disclosed	300,750	1,654	3,910	7,519	Planning	[7]
5	Confidential	Confidential	Hydrogen	Not disclosed	Not disclosed	300,750	1,654	3,910	7,519	Planning	[7]
6	Confidential	Confidential	Hydrogen	Not disclosed	Not disclosed	300,750	1,654	3,910	7,519	Planning	[7]
7	Confidential	Confidential	Ammonia	Not disclosed	Not disclosed	1,193,615	6,565	15,517	29,840	Planning	[7]
8	Confidential	Confidential	Ammonia	Not disclosed	Not disclosed	1,193,615	6,565	15,517	29,840	Planning	[7]
9	Confidential	Confidential	Ammonia & Methanol	Not disclosed	Not disclosed	1,193,615	6,565	15,517	29,840	Planning	[7]
10	Confidential	Confidential	Ammonia & Methanol	Not disclosed	Not disclosed	1,193,615	6,565	15,517	29,840	Planning	[7]

Legend: *Blue = Technology is assumed* *Gold = Estimated from average of known demand for each technology and product* *Pink-Beige = Various phases of development*

[1]The Gold Creek Ammonia and Methanol Production Facility by Northern Petrochemical Corp will be one of several projects located within the Greenview Industrial Gateway (GIG). The Municipal District of Greenview No. 16, which is the GIG's proponent, has applied for a water licence of 24,000,000 m^3/yr. Water demands are shown for the entire buildout of the GIG, with Low, Medium, and High water demands equal 50%, 75%, and 100% of the licence volume, respectively. The full build out of the GIG is expected to take decades. The annual hydrogen equivalent was estimated using the SMR average of Low and Mid per-unit water demands summarized in Section 2.2.

[2]The Dow Chemical expansion project is assumed to be using only 1/3 of its 21.5M m^3 water licence based on Dow's announcement to triple its production capacity [32]. Water demand is calculated using the remaining 2/3 of water available (14,300,000 m^3/yr).
[3]The methane pyrolysis technology in this specific project is assumed to not use any water in its entire process, based on confidential communications.
[4] As noted in Section 2.3, the BRCH project is included on a conservative basis. Heartland Generation already has significant water licenses for their existing facility, though the water impacts of hydrogen production and CCS will require further study.
[5] As noted in Section 2.3, the Cvictus project is included on a conservative basis. The technology is not expected to require significant net new water diversions, but this has not yet been confirmed through piloting.

Appendix C Watershed Details

This appendix provides summary information for the major river basins in Alberta, which are discussed in the body of the report. The intent is to provide readers with a high-level understanding of the hydrologic, regulatory, and water availability and use dynamics across Alberta. As discussed in the body of the report and illustrated throughout this appendix, each river basin has a unique context which must be understood as part of project development and risk management. Figure 11 and Figure 12 illustrate the variation across the province in terms of mean annual river discharge and precipitation in each basin, respectively.

The high-level information in this appendix can contribute to a first pass review of water-related risks and opportunities (current as of the release date of this report), but further analysis should be completed to quantify and mitigate water risks specific to a project. This analysis should occur before a significant time and capital is invested in project development. As noted in Appendix D, water availability analysis was prepared using publicly available datasets for river flow and existing water licenses.

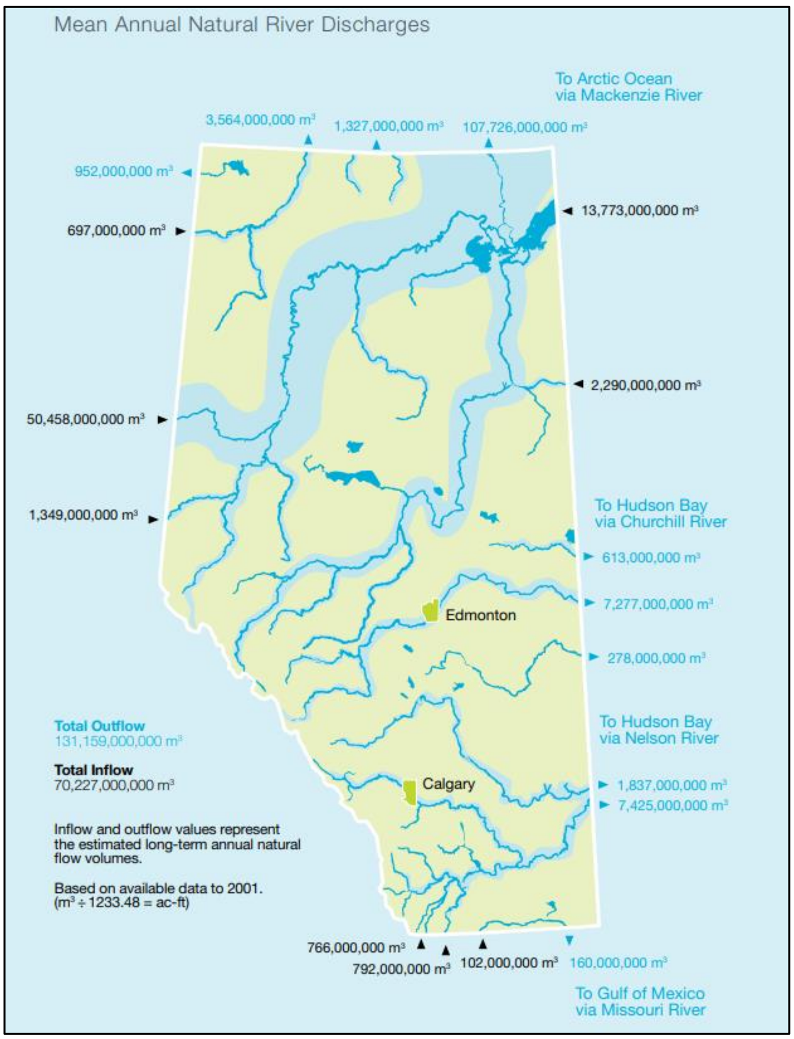


Figure 11. Estimated mean annual natural river discharges (data from 2010) [45]. This figure is illustrative and may not be directly comparable to analyses presented in the body of the report.

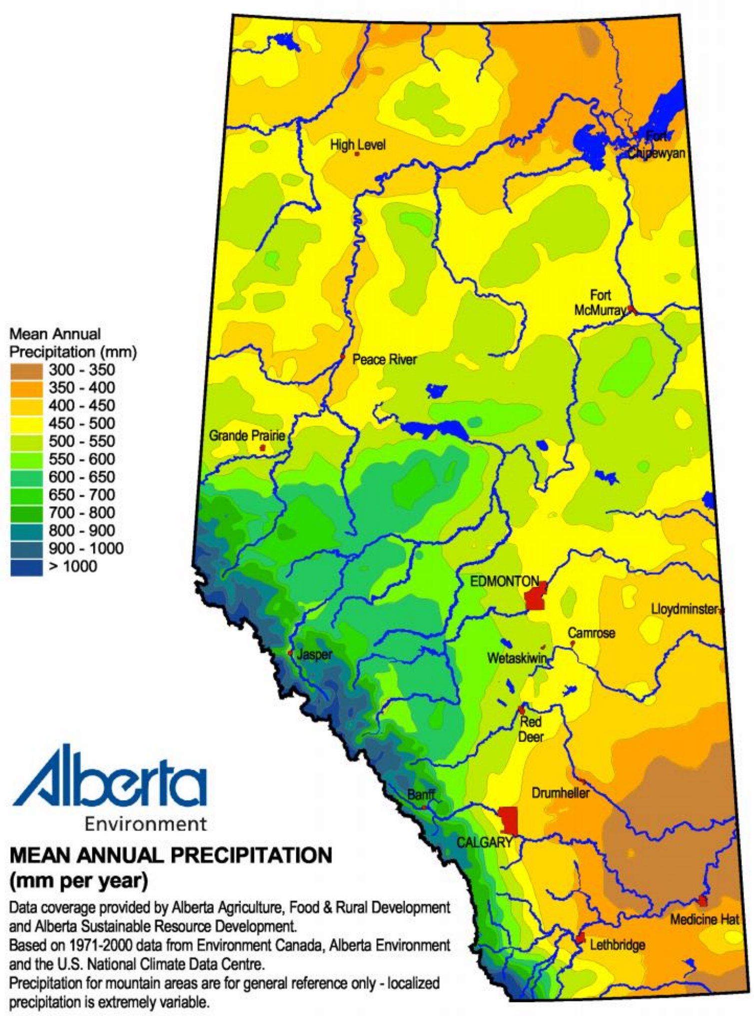


Figure 12. Mean annual precipitation across Alberta (data from 1971 – 2000). This figure is illustrative, and actual values may vary [46].

C.1 Peace River Basin

Primary Natural Ecoregions
Boreal Forest, Rocky Mountain, Foothills, Parkland, Canadian Shield [47]

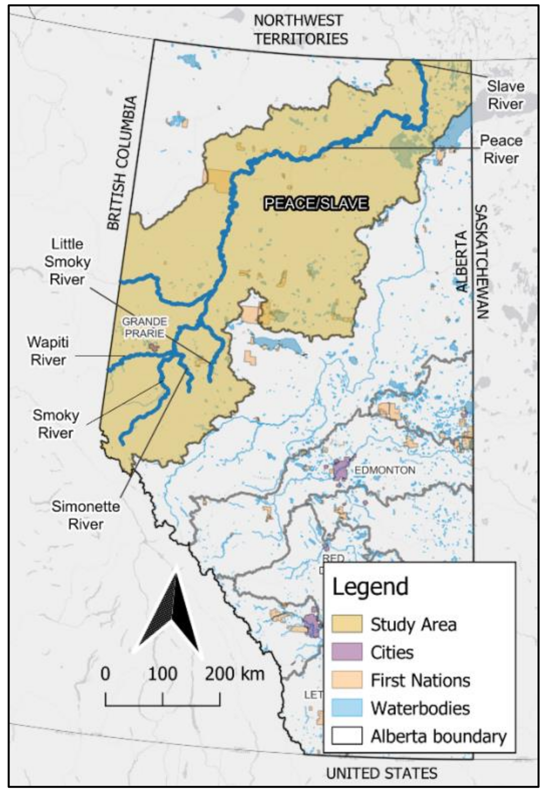
Headwater Source
Rocky Mountains in British Columbia [48]

Gross Drainage Area
~208,834 km^2 within Alberta, 31% of Alberta [47]

Major Tributaries
Little Smoky River, Wapiti River, Smoky River, Notikewin River, Wabasca River, Cadotte River, Mikkwa River, Buffalo River, Wentzel River, Boyer River [48]

Population Centers
Grand Prairie, Peace River, High Level, Grand Cache

Major Water Uses
Oil and gas, coal mining, pulp and paper, municipal, thermal generation, recreation, habitat enhancement, watershed management [48]



C.1.1 Hydrology

The Peace River is very large compared to other rivers in Alberta. The total annual flow is over 50,000,000,000 m^3/yr which is more than three times the combined annual flow of all the rivers in southern Alberta [48]. The Smoky River is the largest tributary, bringing significant streamflow from the Rocky Mountains and foothills areas.

The Peace River originates in British Columbia at Williston Lake, the reservoir contained by the WAC Bennett hydroelectric dam. The WAC Bennett dam, along with the Peace Canyon dam directly downstream of it, controls the Peace River flow. These dams have altered the seasonality of flow in the Peace River by reducing the natural peak flows in June and increasing the flow at naturally low flow periods in the winter months [48]. After it crosses the border into Alberta, there are no additional dams controlling the flow of the Peace River.

Overall, the area experiences cool, short summers and long, cold winters. The Peace River flows northeast over almost seven degrees of latitude, meaning it has a range of climate zones and regional precipitation. The highest levels of precipitation are in the southeast part of the basin, at higher elevations [48]. The Peace River Basin has naturally greater precipitation and lower evapotranspiration than much of Southern Alberta.

C.1.2 Licensing and regulation

New surface water licenses in the Peace River Basin are issued under the SWAD, except for in the Wapiti River Basin where a WMP is in place. In 2015, less than 1% of the Peace River annual streamflow was allocated in surface water licenses, making it one of the least allocated rivers in the province [48]. There are some sub-basins with much higher relative allocations than the overall basin (i.e., the Wapiti and Little Smoky Rivers). In these locations where surface water is constrained, regulatory emphasis has been placed on reducing the use of freshwater (e.g., for hydraulic fracturing in the Duvernay play). Although groundwater is not a focus for this report, it is notable that the AER has designated areas within the Wapiti and Little Smoky sub-basins as locally constrained groundwater areas [49]. See the subsections below for further details.

Because the Peace River originates in BC and contributes to the flow going to the Northwest Territories, there is a transboundary agreement regarding flow across the political borders concerning water quantity and quality, and flow regime for wetlands. The overarching agreement, called the Mackenzie River Basin Transboundary Waters Master Agreement, established the principles of managing the transboundary waters (including the Peace River) and bilateral agreements between each set of two parties for all the waterways are schedules to this master agreement [50]. The bilateral agreement between Alberta and the Northwest Territories is indirectly relevant to the Peace River as a major tributary to the Slave River. The bilateral agreement does not limit river diversions from the Peace River in Alberta; however, it does commit to an approach to management of the transboundary rivers and includes water quality objectives and consistent monitoring [51].

The Peace River Basin is not considered stressed in terms of available water volumes, but water quality concerns are important to consider, and there is sensitivity and heightened awareness around the Peace-Athabasca Delta, which is highly dependent on the seasonality and volume of flows from the Peace and Athabasca rivers.

C.1.3 Water availability in the Peace River

The Peace River is the largest in Alberta, delivering significant volumes to the Peace-Athabasca Delta. It has relatively low existing water allocations compared to its capacity. The AER has not made any surface water designations in the Peace River Basin. See Figure 13 for a visualization of river flow and availability in the Peace River, and the subsections below for further details about its tributaries.

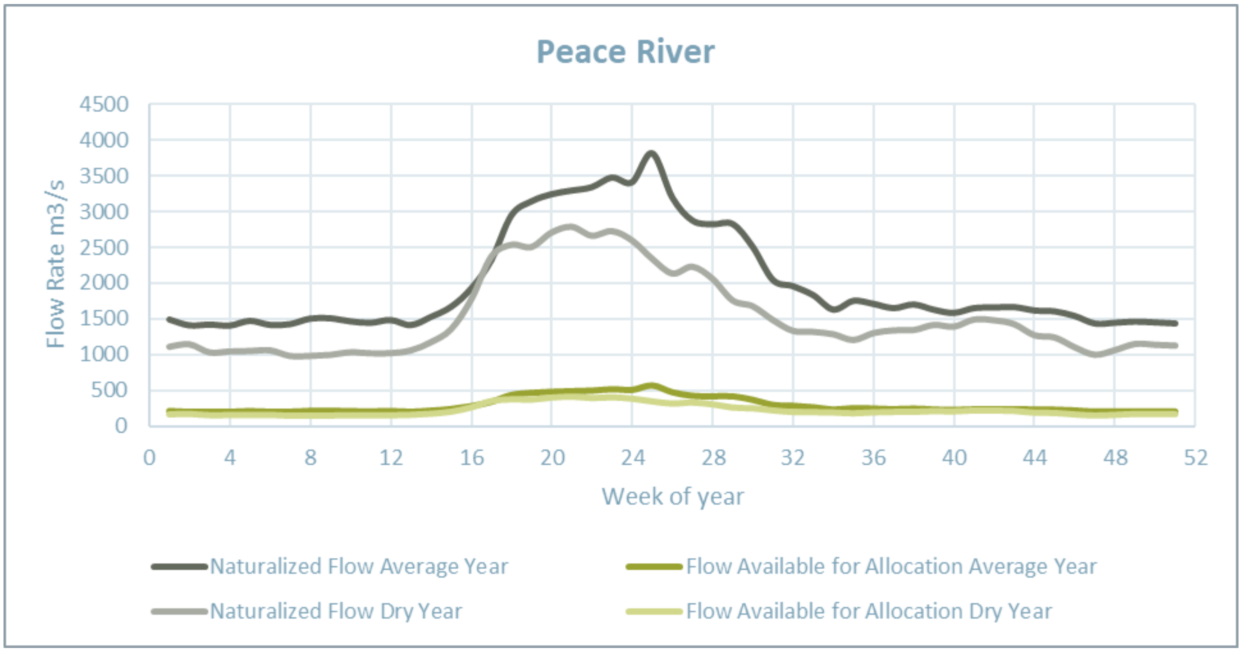


Figure 13. Comparison of water flow to water available in the Peace River, in dry and average years.

C.1.4 Tributaries of interest

Smoky River

The Smoky River is a tributary of the Peace River, with headwaters near Grande Cache. Although there is some existing and planned industrial activity on the Smoky River, it currently has relatively low allocations compared to available flow. Figure 14 illustrates the variability of the Smoky River and the significant volumes available for allocation.

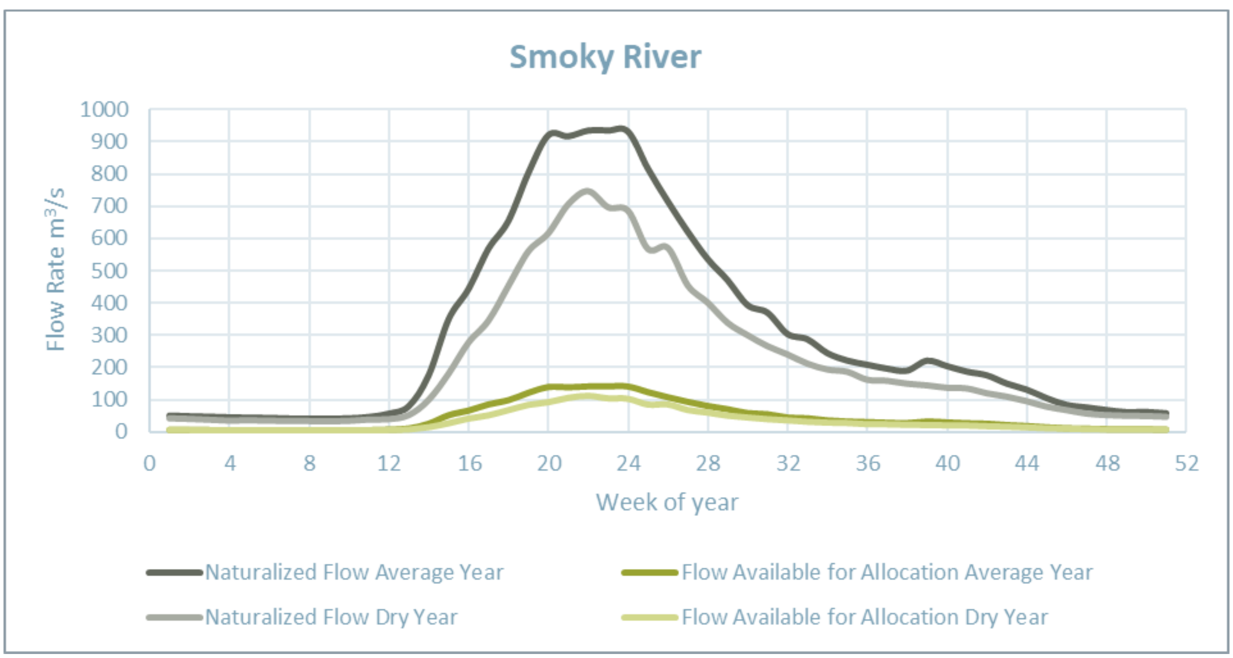


Figure 14. Comparison of water flow to water available in the Smoky River, in dry and average years.

Wapiti River

The Wapiti River flows through the City of Grande Prairie and into the Smoky River. It is an important source of water for both industrial and municipal use in the region. Due in part to high water allocations from the Wapiti River relative to its capacity, a cabinet approved WMP for the Wapiti River was prepared and came into effect in 2020 [52]. Via a WCO, this plan stipulates how much water can be withdrawn during different river flow conditions, with a goal to balance the current and future needs of industrial and municipal users and the environment. Figure 15 illustrates how the management plan limits water diversions, even when river flows are high. Although groundwater is not a focus for this report, it is notable that the AER has designated areas within the Wapiti River sub-basin as locally constrained groundwater areas [49].

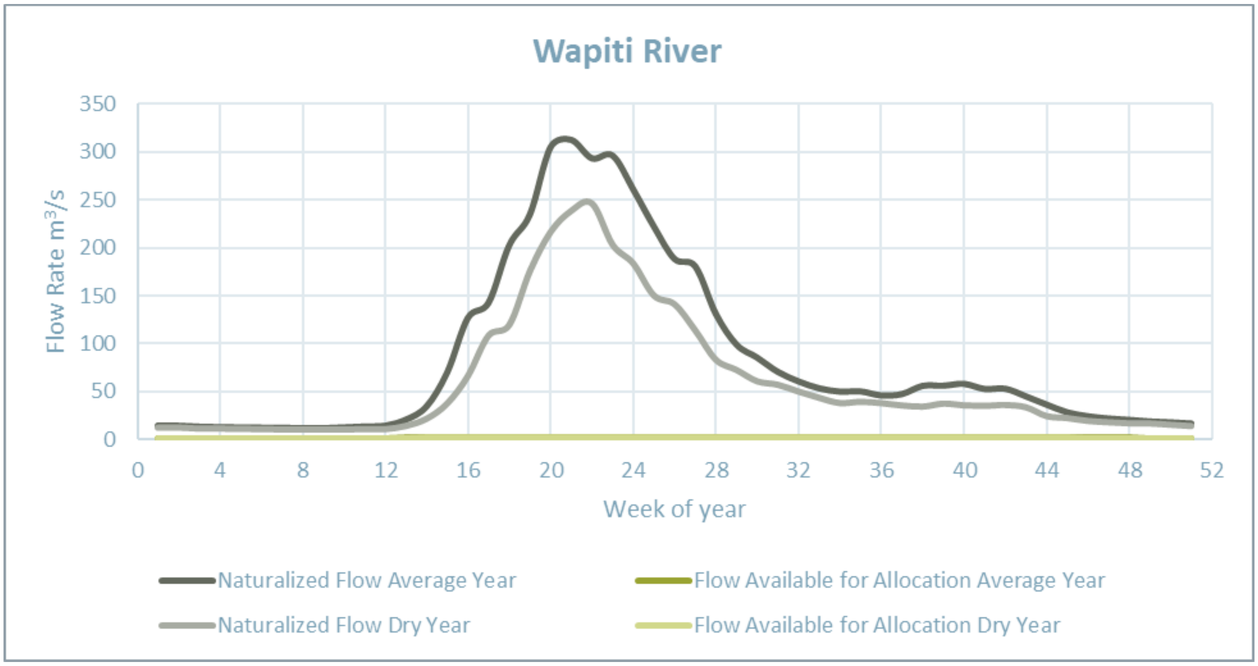


Figure 15. Comparison of water flow to water available in the Wapiti River, in dry and average years. Note that the Wapiti River is governed by a WCO which states that if the natural flow is greater than 20m³/s, 2m³/s may be diverted. If the flow is between 10 and 20m³/s, only 1m³/s may be diverted, and if the flow is less than 10m³/s, then 8% of the flow may be diverted.

Little Smoky

The Little Smoky Is a tributary of the Smoky River which runs through the Fox Creek and Valleyview areas. The region is home to significant industrial development, particularly for oil and gas, and the Little Smoky has substantial water allocations relative to its capacity. Many of these allocations have been issued within the last several years for hydraulic fracturing, contributing to a situation of regional water constraint. Water is especially limited during the winter months as flows dwindle and significant ice coverage occurs (see Figure 16). Although groundwater is not a focus for this report, it is notable that the AER has designated areas within the Little Smoky River sub-basin as locally constrained groundwater areas [49].

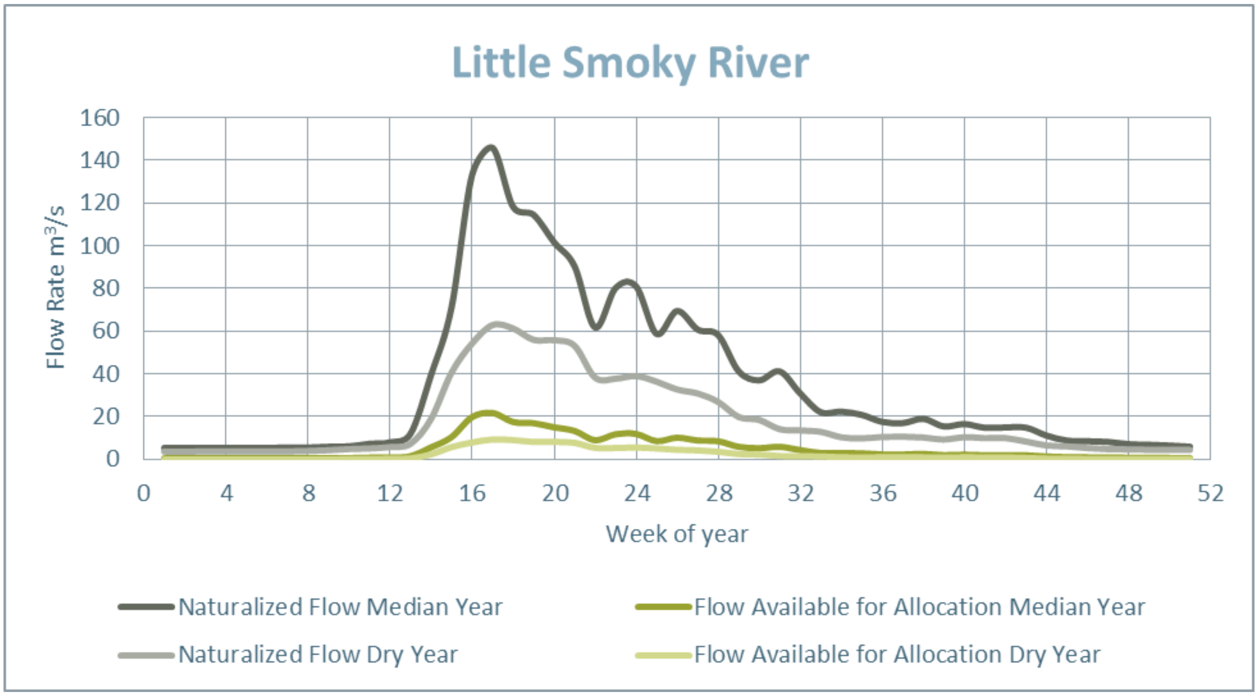


Figure 16. Comparison of water flow to water available in the Little Smoky River, in dry and average years. Water availability is extremely limited during the winter months due to low flows and ice cover.

C.2 Athabasca River Basin

Primary Natural Ecoregions
Rocky Mountains, Foothills, Boreal Forest [53]

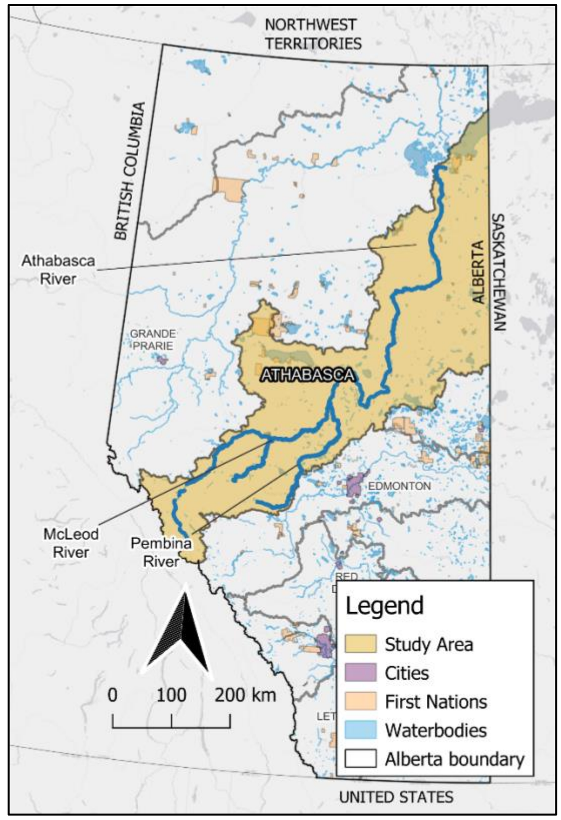
Headwater Source
Rocky Mountains (headwater sub-region)

Gross Drainage Area
150,000 km² (including some area in Saskatchewan), 24% of Alberta [53]

Major Tributaries
Berland, McLeod, Pembina, Lesser Slave, La Biche, Clearwater, Muskeg, Firebag, MacKay, Ells [53]

Population Centers
Jasper, Hinton, Edson, Whitecourt, Swan Hills, Slave Lake, Fort Assiniboine, Athabasca, Fort McMurray, Lac La Biche [53]

Major Water Uses
Oil and gas, agriculture, commercial (particularly pulp mills), municipal [54]



C.2.1 Hydrology

The Athabasca River is a large river with relatively limited human water demands. It also receives relatively high precipitation over much of its area, relative to other parts of the province. Travelling more than 1,400 km from the Rocky Mountains to the northeast corner of the province, the Athabasca River drains into Lake Athabasca [53]. The Athabasca River, along with the Peace River and the Birch River, forms the very large wetland area known as the Peace-Athabasca Delta at the west end of Lake Athabasca. The Peace-Athabasca Delta is a key ecological area and a designated UNESCO World Heritage Site [54].

The Athabasca River does not have any dams regulating the flow and therefore the annual streamflow regime is based on natural water supply. The annual hydrology for the overall river system is dominated by the trend of snowmelt from the Rocky Mountains in the early summer. However, some tributaries that are not in mountainous regions follow a different pattern and contribute flow based on precipitation through the year [54]. Glacier meltwater contributes to the river flow in late summer, and winter is when the lowest river flows are seen.

C.2.2 Licensing and regulation

New surface water licenses in the Athabasca River Basin are issued under the SWAD (i.e., there are no cabinet approved WMPs in place). As of 2023, there are water licenses issued for a total of 905,069,000 m^3 /yr of allocated water, which on annual average is only 4% of the total natural flow [53]. The majority of water licence volume is allocated for industrial purposes, especially oil and gas [53].

The Athabasca River Basin is not considered stressed in terms of available water volumes, but water quality concerns are important to consider, especially in the Fort McMurray area. There is also significant pressure from Indigenous communities and environmental organizations around protecting and restoring the Peace-Athabasca Delta, which is highly dependent on the seasonality and volume of flows from the Peace and Athabasca rivers.

The Lower Athabasca Regional Plan (LARP) was approved by cabinet and implemented in 2012. The LARP established a long-term vision for robust growth, vibrant communities, and a healthy environment for the Lower Athabasca Region for 50 years [55]. The LARP uses a cumulative effects management approach and establishes water quality and air quality limits and management framework [55]. It identifies surface water quantity management triggers (weekly volumes) for the Athabasca River and additional licence conditions for oil sands water licenses [56].

C.2.3 Water availability in the Athabasca River

The Athabasca River hosts industrial and municipal uses along its length, with a concentration of oil and gas activity in the Fort McMurray region. Across the entire basin, allocations are low relative to the river's capacity (see Figure 17). However, the AER has designated areas downstream of Fort McMurray on the Athabasca River as being locally constrained from a surface water perspective. Additionally, small tributaries in the Swan Hills area are also designated as locally constrained for surface water [49].

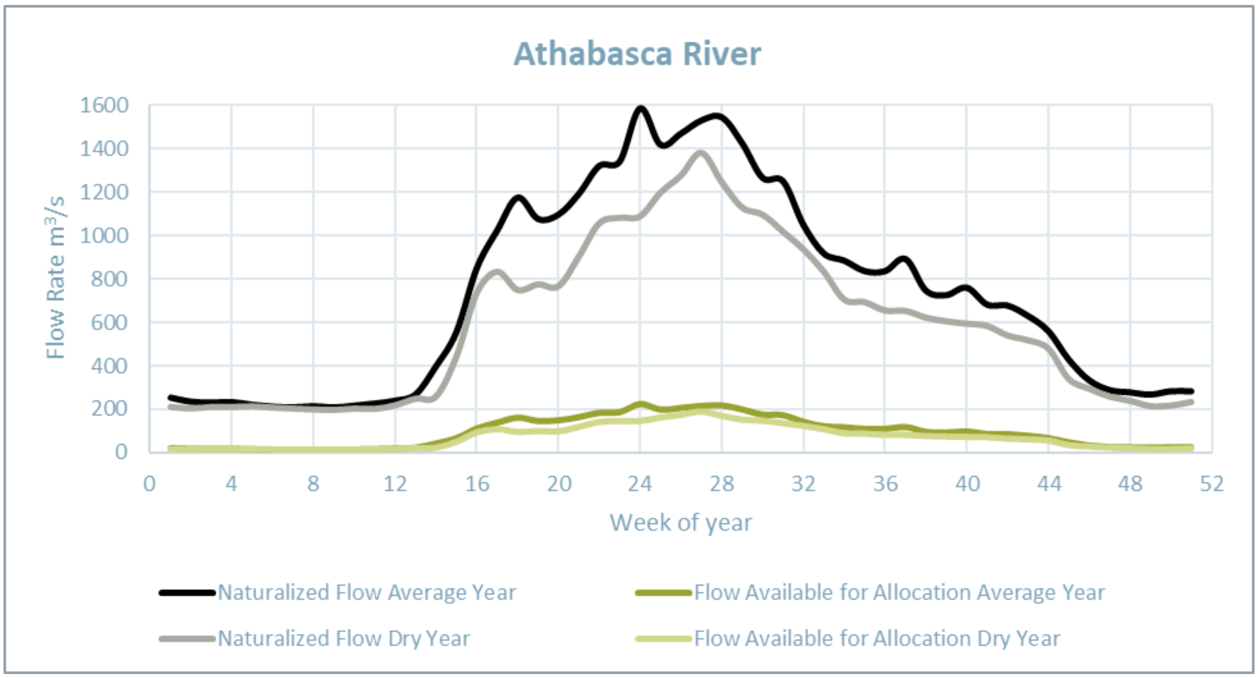


Figure 17. Comparison of water flow to water available in the Athabasca River, in dry and average years.

C.2.4 Tributaries of interest

Clearwater River

The Clearwater River is a tributary of the Athabasca River. Water availability in the Clearwater River is informed by the SWAD and plotted on the hydrograph below (Figure 18). The region has a relatively low population with a limited number of water allocations currently held by municipal and industrial water users. The Clearwater River currently has water available throughout the year that could be used to support hydrogen production.

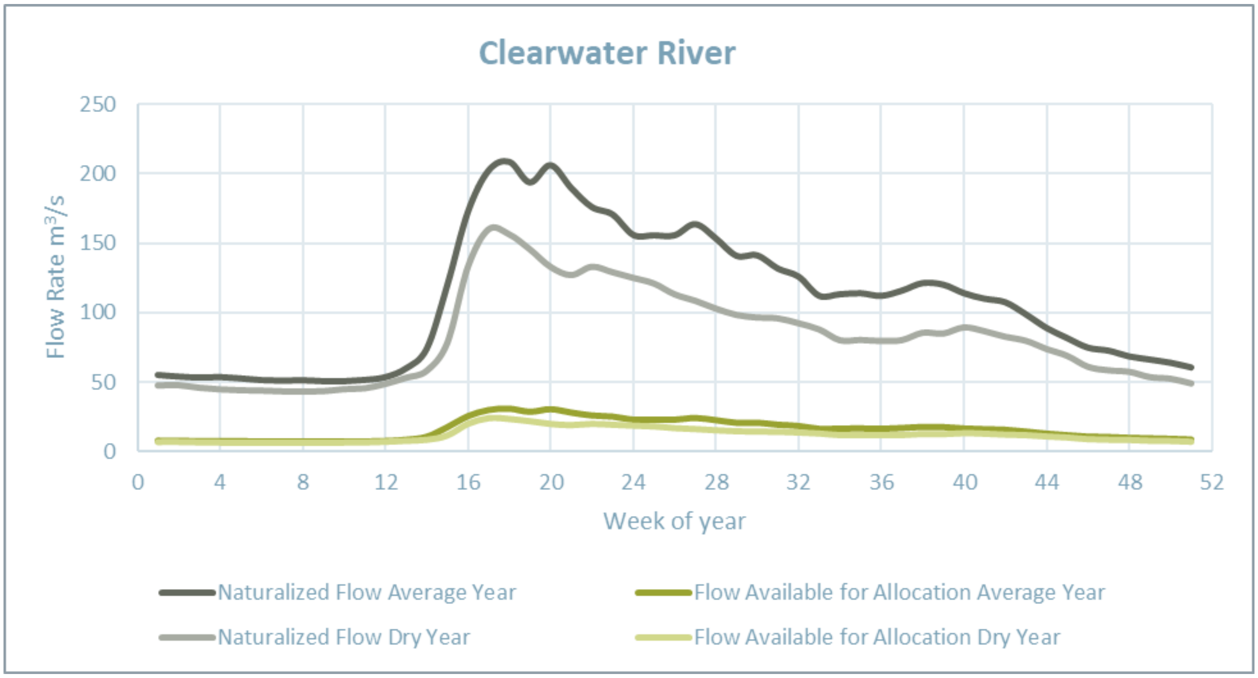


Figure 18. Comparison of water flow to water available in the Clearwater River (Athabasca Basin), in dry and average years.

McLeod River

The McLeod River is a tributary of the Athabasca River. Water availability in the McLeod River, in dry and average years is informed by the SWAD and plotted in Figure 19 below. The region has a relatively low population with a limited number of water allocations currently held by municipal and industrial water users. The McLeod River currently has water available throughout the year that could be used to support hydrogen production.

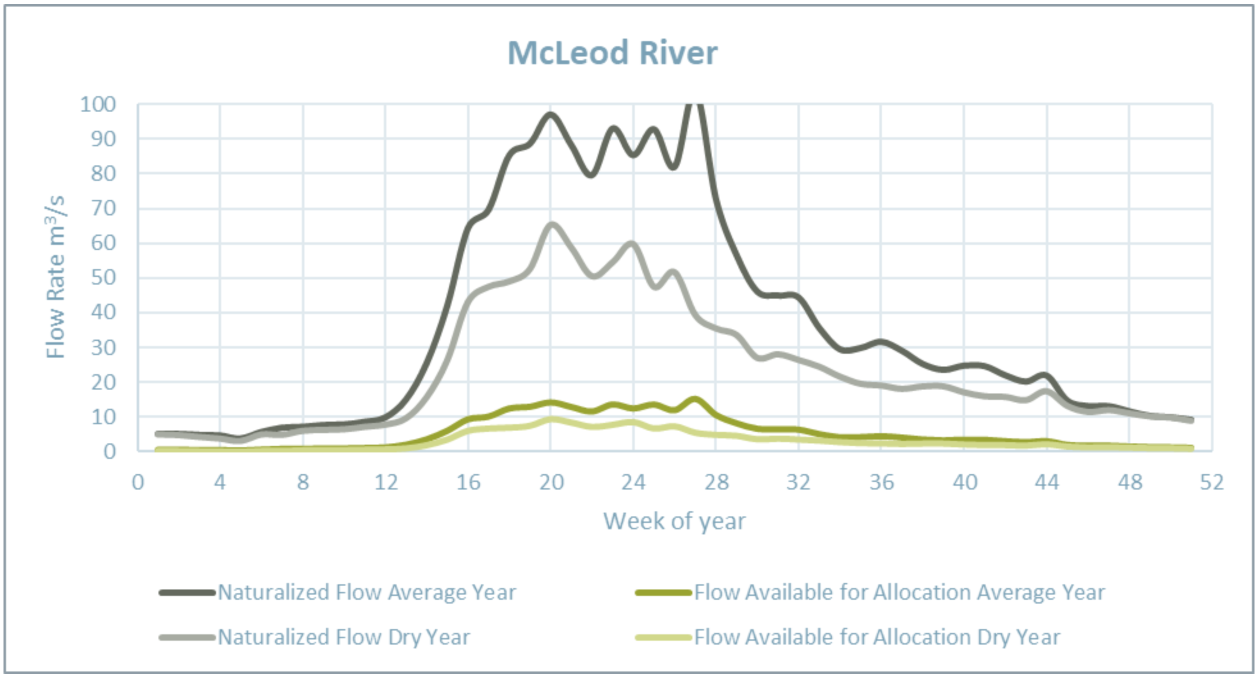


Figure 19. Comparison of water flow to water available in the McLeod River, in dry and average years.

Pembina River

The Pembina River is a tributary of the Athabasca River with headwaters located on the eastern slopes of the Rocky Mountains. The region has a relatively low population with a limited number of water allocations currently held by municipal and industrial water users. Water availability in the Pembina River is informed by the SWAD and plotted in Figure 20. The Pembina River currently has water available throughout the year that could be used to support hydrogen production.

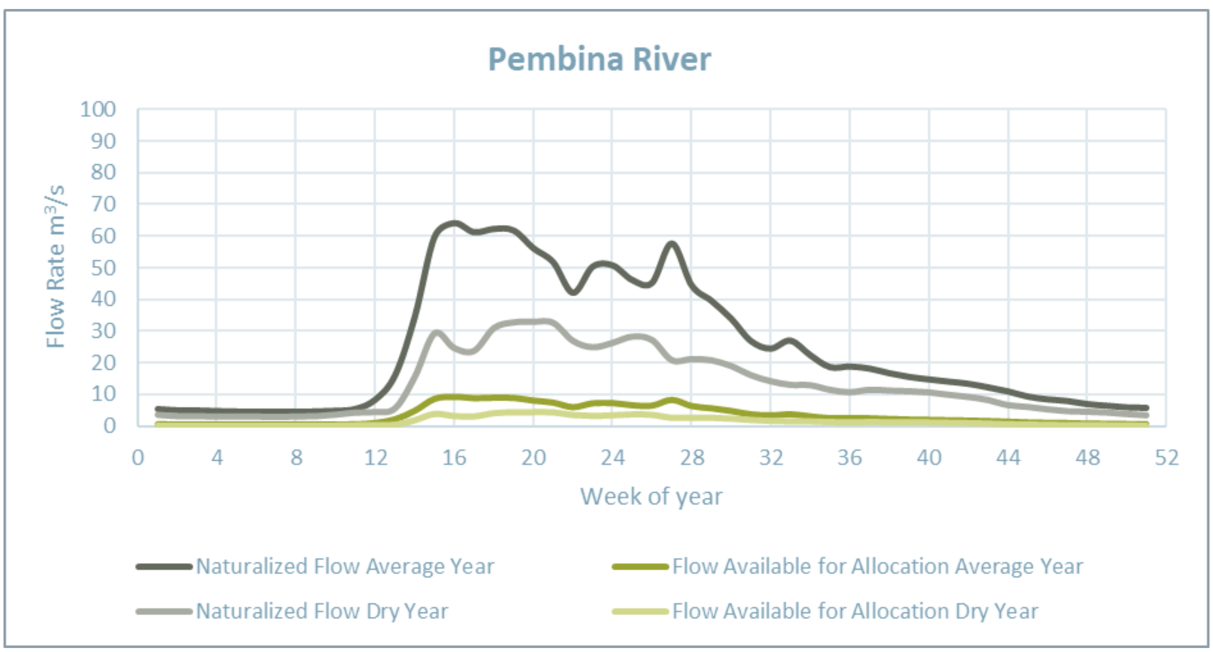


Figure 20. Comparison of water flow to water available in the Pembina River, in dry and average years.

C.3 North Saskatchewan River Basin

Primary Natural Ecoregions
Alpine, Foothills, Boreal Forest, Parkland [57]

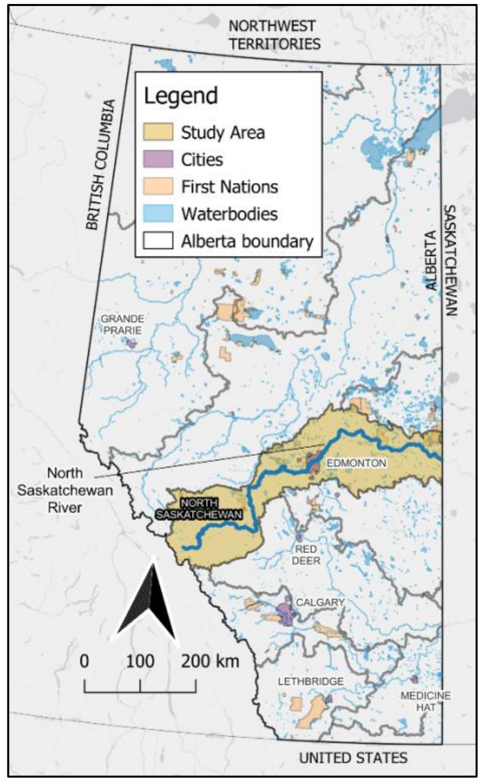
Headwater Source
Rocky Mountains

Gross Drainage Area
~57,000 km², 9% of Alberta [58]

Major Tributaries
Clearwater, Cline, Ram, Brazeau, Modeste, Strawberry, Sturgeon, Beaverhill, White Earth, Frog, Vermillion, Monnery [58]

Population Centers
Edmonton, St. Albert, Spruce Grove, Rocky Mountain House, Leduc, Fort Saskatchewan, Vermillion, Lloydminster [58]

Major Water Uses
Industrial, petroleum, municipal, commercial, agriculture, other [58]



C.3.1 Hydrology

The headwaters of the North Saskatchewan River are in Banff National Park and the Rocky Mountain region north of Banff. The river flows generally northeast to Edmonton and then angles directly east to the border with Saskatchewan. The North Saskatchewan River joins the South Saskatchewan River near Prince Albert, Saskatchewan, to become the Saskatchewan River.

The majority of water yield (88%) is from the headwaters in the Rocky Mountain region, due to the high precipitation in this area [58]. The annual flow pattern is dominated by snowmelt, resulting in low flows in the winter and high peaking flows in the summer [16]. There are large areas of glacier coverage in the headwater region, and glacier melt contributes critical streamflow to the North Saskatchewan River in later summer [16]. The basin is considered fairly wet compared to southern areas in the province, although eastern areas of the basin have lower annual precipitation and high evapotranspiration, resulting in less moisture availability [58].

There are two major dams regulating the streamflow for the North Saskatchewan River and generating hydroelectricity. The Bighorn Dam creates a reservoir known as Abraham Lake, located near Nordegg, and the Brazeau Dam is on the Brazeau River, forming the Brazeau reservoir located near Drayton Valley [16]. The Bighorn Dam is the largest hydroelectric power producer in Alberta. In the downstream portion of the basin there are no major dams, but there are two water control structures on the Vermillion River that mitigate flooding and retain water in low flow periods for municipal and agriculture uses [16].

C.3.2 Licensing and regulation

The total water allocated for use in the North Saskatchewan River Basin is about 1,853,600,000 m^3/yr, which is considered low to medium water stress compared to the naturally available water [16]. The majority of water demands are in downstream areas of the basin where precipitation is lower and its contribution to flow is limited. Therefore, most water users are reliant on streamflow from the headwaters [16].

Most water licenses are for industrial and commercial uses, including hydroelectric generation, oil and gas extraction, and mining [58] [16]. There is currently no specific limitation on applying for new water licenses in the basin, which are issued under the SWAD. There is an integrated WMP developed and published by the North Saskatchewan Watershed Alliance in 2012. However, it has not been implemented as legislation [59].

C.3.3 Water availability in the North Saskatchewan River

Generally, the North Saskatchewan River has above average water availability compared to rivers in the southern part of the province. Significant volumes of water are available during the spring and summer months as seen in Figure 21. Water availability during the winter months is more constrained, with implications for water storage requirements. The AER has designated several sub-basins around the Edmonton region as locally constrained in terms of either surface water or groundwater, particularly around the Edmonton area and downstream. Additionally, the Sturgeon River, Atim Creek and Beaverhill Creek sub-basins are designated as potentially water-short areas [49].

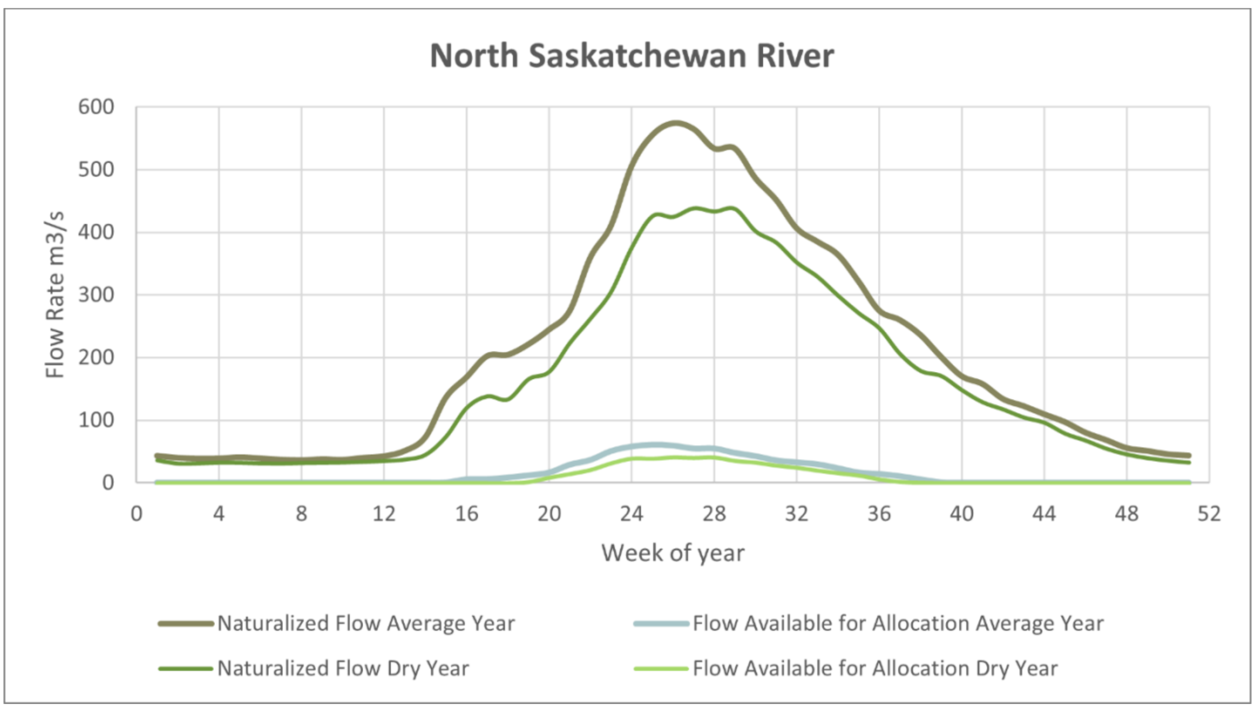


Figure 21. Comparison of water flow to water available in the North Saskatchewan River, in dry and average years.

C.4 Battle River Basin

Primary Natural Ecoregions
Parkland, Grassland [16]

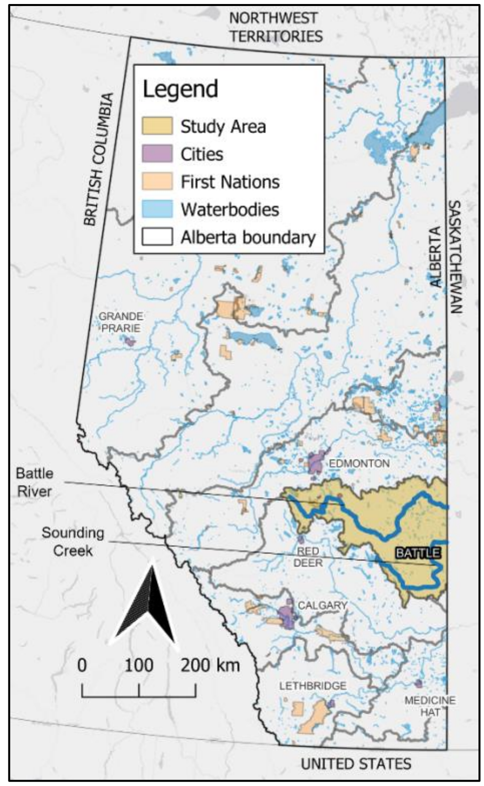
Headwater Source
Battle lake (western areas, parkland subregion) [60]

Gross Drainage Area
21,500 km^2, ~3% of Alberta [16] [16]

Major Tributaries
Iron Creek, Bigstone Creek, Paintearth Creek, Ribstone Creek [60]

Population Centers
Blackfalds, Lacombe, Wetaskiwin, Camrose, Ponoka

Major Water Uses
Commercial (electricity generation), municipal, habitat management, water management, irrigation and agriculture, industrial, other [60]



C.4.1 Hydrology

Unlike other rivers in Alberta, the Battle River Basin does not have headwaters originating in the Rocky Mountains. Therefore, the flow in the Battle River is dependent on the snow and rain that naturally occurs in the region, and the total volume can vary considerably from year to year [60]. The highest flows are typically in April and May, corresponding to melting snow and spring rain, and the lowest flows are generally in fall and winter [60].

Battle Lake is the designated headwater of the Battle River, which flows generally eastward and into Saskatchewan, where it joins the North Saskatchewan River. The region has limited precipitation and is considered a drier area of Alberta.

There are numerous small dams and water management structures in the Battle River Basin, with many of them playing key roles in maintaining water levels for municipal water demands and minimum lake and river water levels. Notable reservoirs include Coal Lake, Driedmeat Lake, and the Forestburg Reservoir at the Heartland Generation power plant.

C.4.2 Licensing and regulation

The *Battle River Water Management Plan* (BRWMP) was approved by Alberta's cabinet in 2014 and is now a key policy document guiding water licensing and management in the basin. The BRWMP allows new water licenses to be issued up to a total allocation limit, although new licenses are issued with tight restrictions on water diversion timing. Water licence transfers are also allowed within the Battle River

Basin, although such transfers are not commonplace while the allocation limit has not yet been reached [61].

C.4.3 Water availability in the Battle River

The Battle River is one of the smallest major rivers in Alberta and has become heavily allocated over the past 50 years. The 2014 BRWMP indicates how much water is available for new allocations and sets a WCO for any new licenses issued in the basin. Based on the hydrograph in Figure 22, water can only be reliably accessed in most years during peak flow between April-June. Due to the pattern of the hydrograph and high existing allocations, storage will be a critical component for any new water licence holders looking to use water year-round. The AER has designated all of the Battle River Watershed as either water short or potentially water short, with the water short designation applied to the southeast portion of the basin [49].

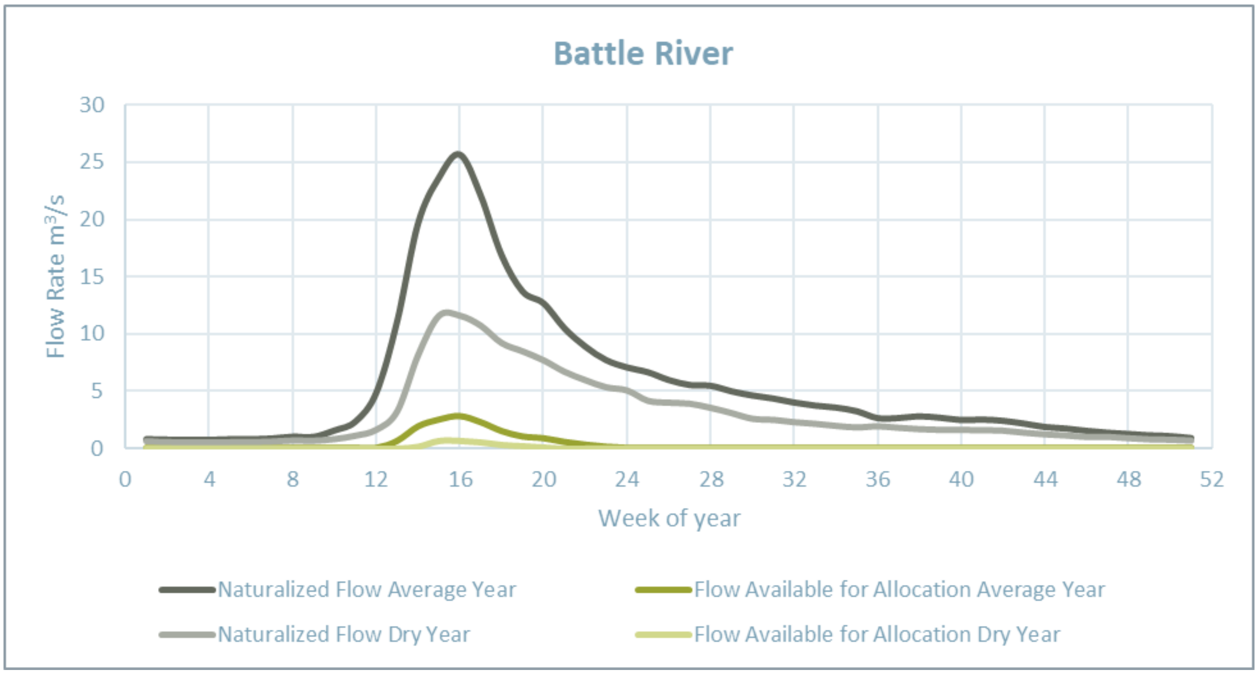
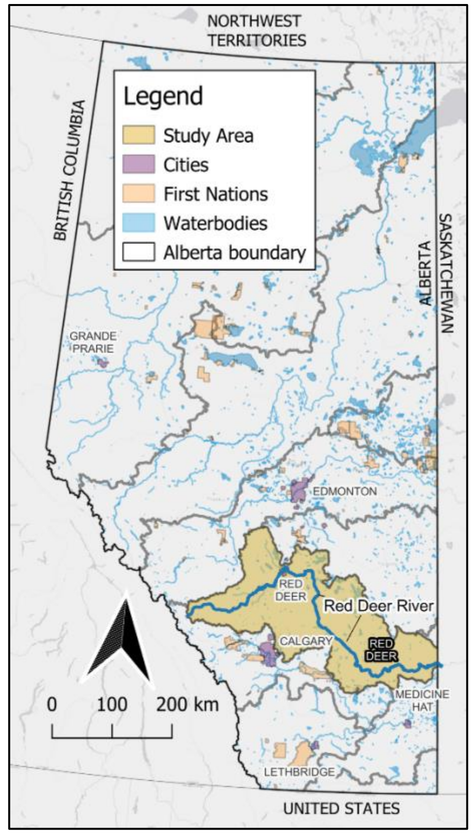


Figure 22. Comparison of water flow to water available in the Battle River, in dry and average years.

C.5 Red Deer River Basin

Primary Natural Ecoregions *Rocky Mountains, Boreal Forest, Foothills, Parkland, Grassland* [62]	
Headwater Source *Rocky Mountains (headwater sub-region)*	
Gross Drainage Area *49,650 km², ~7% of Alberta* [62]	
Major Tributaries *Little Red Deer, Medicine, Blindman, Rosebud, Waskasoo, Raven*	
Population Centers *Red Deer, Sylvan Lake, Strathmore, Brooks, Drumheller*	
Major Water Uses *Municipal, irrigation, commercial, industrial* [16]	



C.5.1 Hydrology

The Red Deer River begins at the Drummond Glacier in Banff National Park and flows east and southward across the province and into Saskatchewan, where it joins the South Saskatchewan River [62]. The streamflow in the Red Deer River comes primarily from snowmelt in the Rocky Mountain headwaters [16]. Precipitation is highest in the spring and early summer months, which happens concurrently with snowmelt to produce peak river flows. The majority of annual flow generally occurs at this time. The Red Deer River Basin is more arid than much of Alberta to the north, although it typically receives more rain than areas to the south [16]. The western portion of the basin gets more natural precipitation than the eastern areas.

Dickson Dam is the single major dam and reservoir system (called Gleniffer reservoir) on the Red Deer River. The dam releases water to support water licence demands and to maintain minimum river flow volumes.

C.5.2 Licensing and regulation

As part of the greater South Saskatchewan River Basin, the Red Deer River Basin is subject to the *Approved Water Management Plan for the South Saskatchewan River Basin*, which was implemented in 2006 [63]. The process to get a new surface or groundwater licence in the Red Deer River Basin follows the legislated standard process (i.e., the SWAD). However, as part of the WMP, there is a cap of 600,000,000 m^3/yr on the total volume that can be allocated in the Red Deer River Basin. As allocations approach this cap into the future, there will be constraints on future water availability, and the basin may one day be closed to new licenses.

As of 2022, approximately 330,000,000 m^3 of the annual water supply is allocated through water licenses in the Red Deer River Basin [16]. This total allocated volume is about 55% of the allocation cap set by the WMP. Note that there is currently an irrigation project being scoped in the eastern portion of the basin that could apply for an allocation of a significant portion of the water remaining.

C.5.3 Water availability in the Red Deer River

Water availability in the Red Deer River is currently moderate. Driven by the rules of the WCO in the Red Deer River, there is a significant amount of water available for allocation during the spring and summer months, while water availability is more constrained during the late fall and winter months (Figure 23). Water availability in the Red Deer River will become more constrained as future allocations push the basin towards its WMP-mandated allocation limit of 600,000,000 m^3/yr. The AER has designated all sub-basins in the Red Deer River Basin as either potentially water short or confirmed water short, especially in the downstream portions of the basin [49].

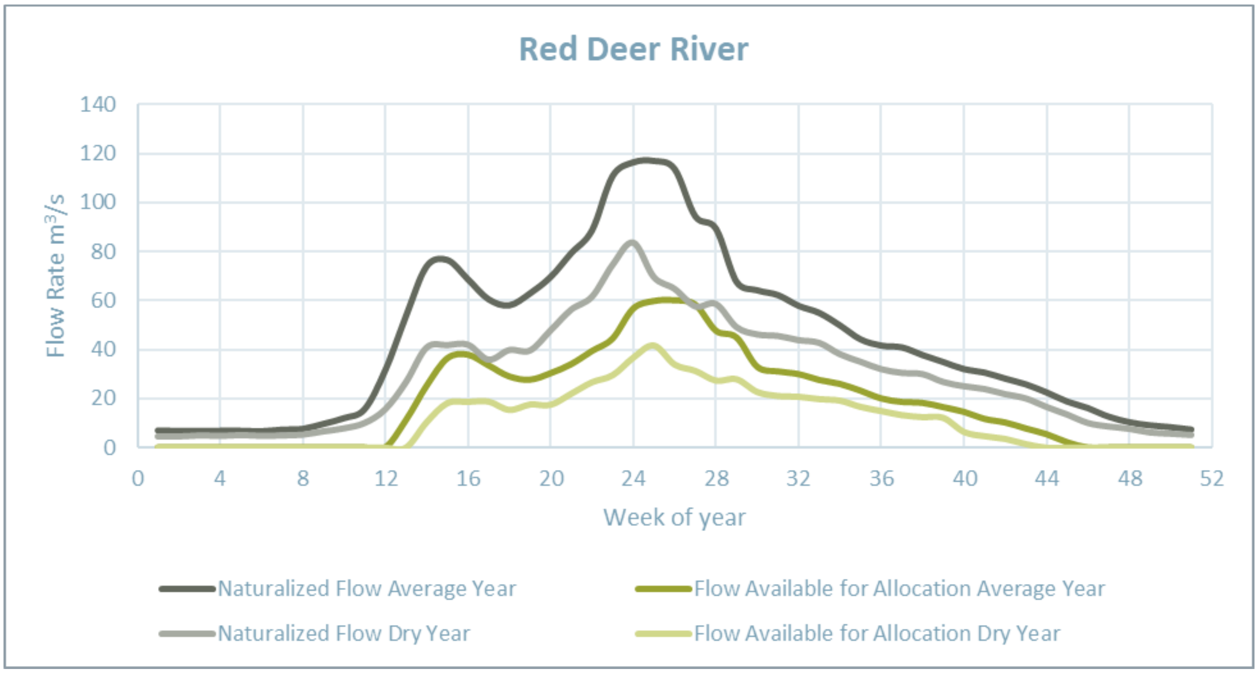


Figure 23. Comparison of water flow to water available in the Red Deer River, in dry and average years.

C.6 Bow River Basin

Primary Natural Ecoregions
Rocky Mountains, Foothills, Parkland, Grassland

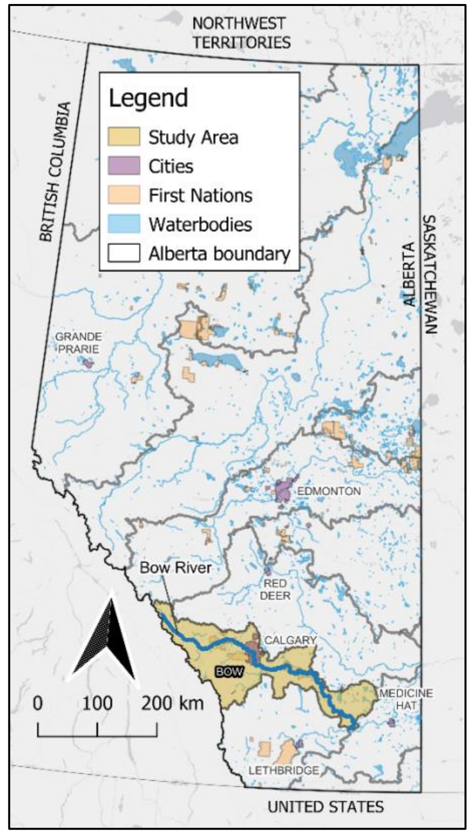
Headwater Source
Rocky Mountains (headwater sub-region)

Gross Drainage Area
25,300 km^2, ~4% of Alberta [64]

Major Tributaries
Ghost River, Kananaskis River, Elbow River, Sheep River, Highwood River, Nose Creek [64]

Population Centers
Calgary, Canmore, Cochrane, Banff, Okotoks, Chestermere [65]

Major Water Uses
Irrigation, hydropower, municipal, industrial



C.6.1 Hydrology

The hydrology of the Bow River is dominated by its headwaters in the Rocky Mountains. The mountainous headwaters receive the highest precipitation annually, significantly more than downstream in the basin. The highest streamflow is in May and June, corresponding with snow melt in the mountains. Spring and early summer is also typically when the most precipitation occurs in the basin, with June being the wettest month. Later summer and fall are generally dry with limited precipitation. There are several glaciers in the headwaters that contribute to the streamflow in the river in late summer when natural precipitation is very limited [16]. Relative to the rest of Alberta, the Bow River Basin is fairly arid with lower total streamflow.

There are 15 major dams and weirs in the Bow River Basin, and significant volumes of water storage in reservoirs. This engineered system allows the high spring streamflow to be captured and used throughout the year for the many water uses in the basin, as well as other purposes such as hydropower generation and flood mitigation [65].

C.6.2 Licensing and regulation

The Bow River Basin is highly allocated, with over 2,500,000,000 m^3/yr allocated through water licenses. The majority of the water allocations are for the purpose of irrigation and agriculture [16]. The *Approved Water Management Plan for the South Saskatchewan River Basin (Alberta)* was implemented in 2006, which pertains to the Bow River as a sub-basin of the South Saskatchewan River Basin, and which includes recommendations regarding the regulation, management and planning for water in the Basin [63]. The Bow River Basin has been closed to new surface water licence applications since 2007 when the *Bow, Oldman and South Saskatchewan River Basin Water Allocation Order* was issued by the provincial government. This order enacted recommendations in the approved WMP specifically regarding limiting new surface water licenses in some basins. The order does not limit groundwater licenses that are not connected to surface water, and temporary diversion licenses can still be applied for. Existing surface water licenses can be transferred to a new licensee under specific circumstances, when approved by the regulator. See Section B.6 for further details on the Oldman River Basin, which joins the Bow River.

C.6.3 Water availability in the Bow River

The Approved WMP for the SSRB has created a moratorium on new licence allocations in the Bow River as of 2007. Water in the basin for new projects must be accessed through transfers of existing licenses. The AER has designated all sub-basins in the Bow River Basin as water short, which is consistent with their closure under the 2007 WMP [49]. As Figure 24 reinforces, there is no water available for new allocations.

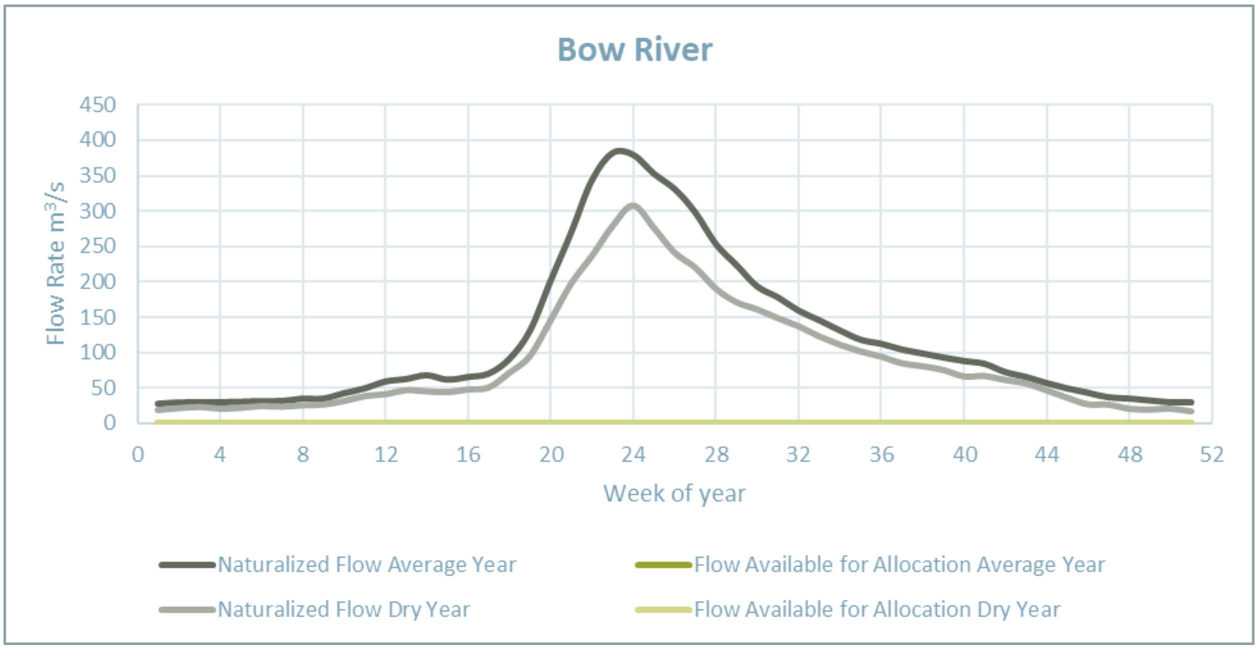


Figure 24. Comparison of water flow to water available in the Bow River, in dry and average years.

C.7 Oldman River Basin

Primary Natural Ecoregions
Rocky Mountains, Parkland, Grassland [66]

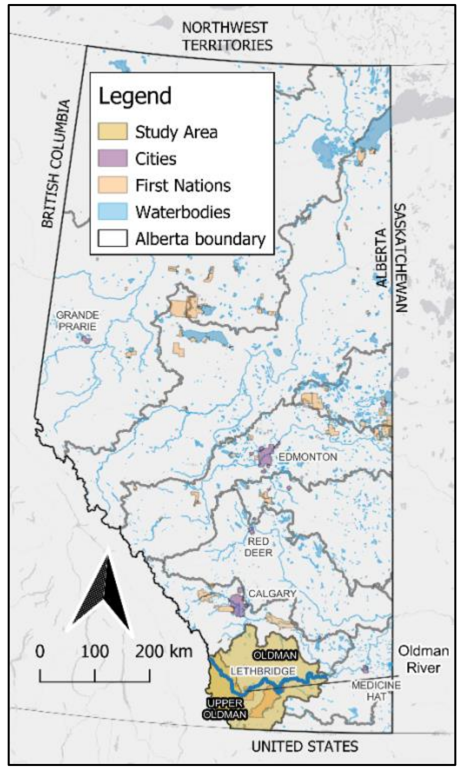
Headwater Source
Rocky Mountains (headwater sub-region) [66]

Gross Drainage Area
23,000 km^2, ~3% of Alberta [16]

Major Tributaries
Crowsnest, Castle, Waterton, St. Mary, Belly, Little Bow,

Population Centers
Lethbridge, Crowsnest Pass, Pincher Creek, Fort Macleod

Major Water Uses
Irrigation, agriculture, commercial, municipal, industrial, other [66]



C.7.1 Hydrology

The headwaters of the Oldman River Basin are in the Rocky Mountains, both in Alberta and across the border in Montana. The Oldman River joins with the Bow River to form the South Saskatchewan River at Grand Forks, Alberta. The Oldman River Basin is considered a semi-arid climate and is recognized as the driest region of Alberta. Natural precipitation varies considerably across the basin, with much higher annual rates in the mountains and lower rates in the prairie region [66]. The annual water flow in the Oldman River is dominated by the melting snowpack in the mountains, with a peak in streamflow in the spring and low flows in the fall and winter [66]. Extreme drought has been experienced in the basin at multiple points in the past one-hundred years, as well as extreme flooding [66].

There are numerous large reservoirs and dams managing water flow in the Oldman River and its tributaries. They play an extremely important role in holding water from the spring runoff to support water demands later in the year. Notably, the St. Mary, Waterton, and Oldman River dams are managed to control large reservoirs which supply the water for many major water users in the basin, particularly irrigation districts and municipalities. Reservoirs are also managed to release water to meet instream flow targets for environmental health, as well as other benefits like flood control, recreation and meeting river flow obligations to Saskatchewan.

C.7.2 Licensing and regulation

As part of the greater South Saskatchewan River system, the Oldman River Basin is subject to the *Approved Water Management Plan for the South Saskatchewan River Basin*, which was implemented in 2006 [63].

The Oldman River Basin has been closed to new surface water licence applications since 2007 when the *Bow, Oldman and South Saskatchewan River Basin Water Allocation Order* was issued. This order enacted recommendations in the approved WMP, specifically regarding limiting new surface water licenses in some basins. The order does not limit groundwater licenses that are not connected to surface water, and temporary diversion licenses can still be applied for. Existing surface water licenses can be transferred to a new licensee under specific circumstances, when approved by the regulator.

In 2003 and prior to the WMP, the *Oldman River Basin Water Allocation Order* was enacted. This order reserved 11,000 acre-ft/yr (13,568,280 m^3/yr) of water for several specific purposes in locations upstream of the Oldman dam. This enables new water licence applications to be accepted in the Upper Oldman area, despite the *Bow, Oldman and South Saskatchewan River Basin Water Allocation Order*. The total quantity of water allocated under the order that is specified for industrial purposes cannot exceed 185,022 m^3/yr [67].

The Oldman River Basin is highly allocated and considered a basin under a high degree of water stress [16]. The majority (~83%) of all water licence allocations are for the purpose of irrigation [66]. Other agricultural and agri-food uses including stock watering and processing facilities also have water licence allocations [66].

The St. Mary River, Belly River and Waterton River are known as the Southern Tributaries, and they contribute key water flow volumes for the overall basin system. Portions of the headwaters of the Southern Tributaries are in Montana, USA. There is an international treaty between Canada and the United States that dictates the sharing of these water resources. For water users in the Oldman River Basin, this adds is a layer of complexity and uncertainty specifically because some of the water originates outside of Canada [68].

C.7.3 Water availability in the Oldman River

The Approved WMP for the SSRB has created a moratorium on new licence allocations in the Oldman River as of 2007. Water for new projects in the basin must be accessed through transfers of existing licenses or through the Oldman River Basin Water Allocation Order discussed in C.7.2. The AER has designated all of the Oldman River Basin as water short [49]. Figure 25 shows the hydrograph for the lower Oldman River, in which no water is available for allocation.

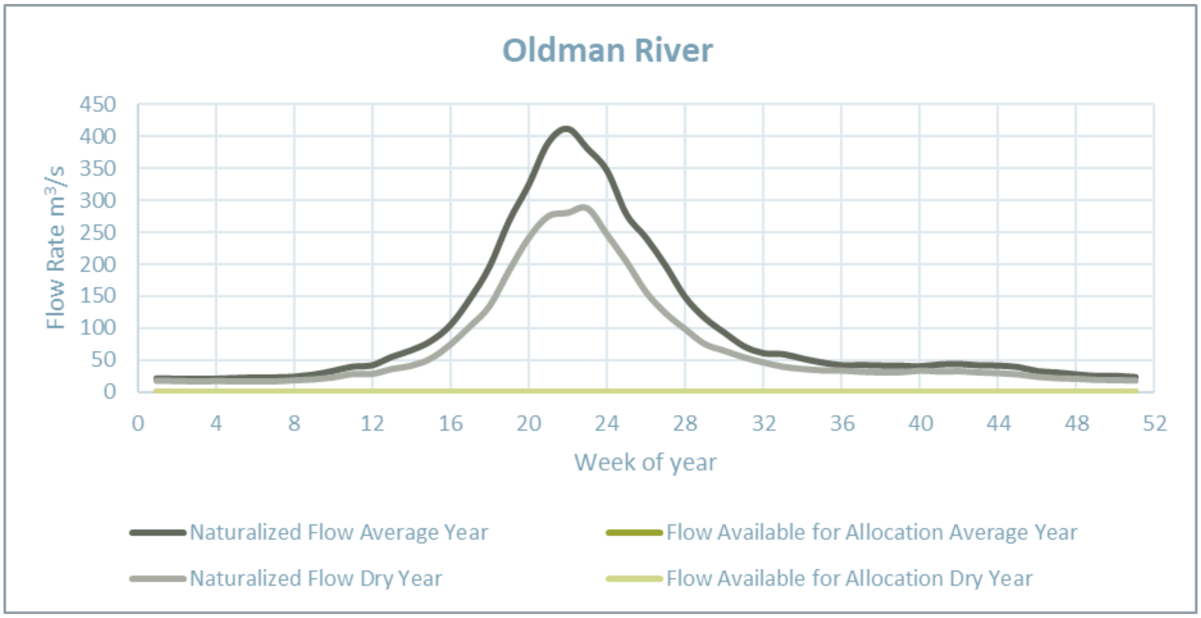


Figure 25. Comparison of water flow to water available in the Oldman River, in dry and average years.

C.8 South Saskatchewan River Sub-Basin

Primary Natural Ecoregions
Grassland [69]

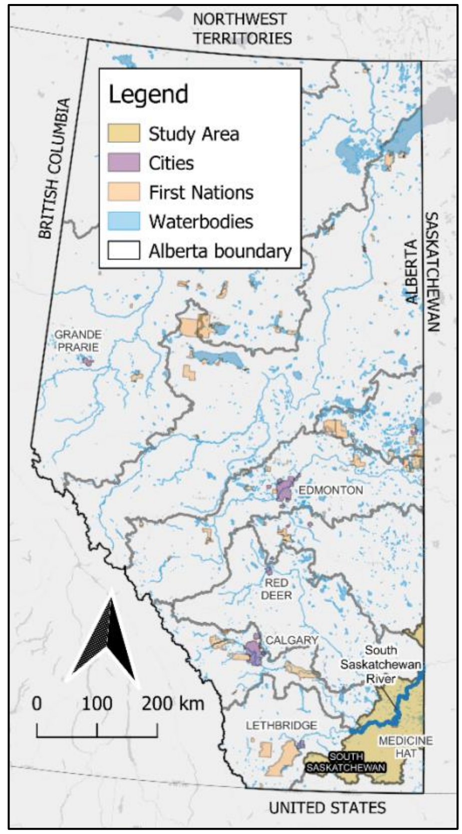
Headwater Source
Bow River, Oldman River [69]

Gross Drainage Area
19,929 km^{2t}, ~2% of Alberta [69]

Major Tributaries
The majority of water in the South Saskatchewan River in this region is contributed by the Bow and Oldman Rivers

Population Centers
Medicine Hat, Redcliff, Bow Island

Major Water Uses
Municipal, irrigation, agricultural, industrial, commercial [70]



C.8.1 Hydrology

The South Saskatchewan River Sub-Basin originates at the confluence of the Bow and Oldman Rivers in southern Alberta and flows east and north into Saskatchewan. This region is semi-arid and fairly flat topographically, with only about 50% of the land area within the basin boundaries contributing runoff to the river [70]. Most of the water in the river comes from upstream basins, with very little from tributaries originating in the basin itself [70]. The period of highest streamflow is typically in the spring or early summer, and the lowest flow is typically in winter [70].

C.8.2 Licensing and regulation

As part of the greater South Saskatchewan River system, the South Saskatchewan River Sub-Basin is subject to the *Approved Water Management Plan for the South Saskatchewan River Basin*, which was implemented in 2006 [63]. The South Saskatchewan River Basin has been closed to new surface water licence applications since 2007 when the *Bow, Oldman and South Saskatchewan River Basin Water Allocation Order* was issued by the provincial government. This order enacted recommendations in the approved WMP specifically regarding limiting new surface water licenses in some basins. The order does not limit groundwater licenses that are not connected to surface water, and temporary diversion licenses can still be applied for. Existing surface water licenses can be transferred to a new licensee under specific circumstances, when approved by the regulator.

Approximately 290,000,000 m^3/yr are allocated from this basin, with municipal uses making up over half of the total volume of allocations [70].

C.8.3 Water availability in the South Saskatchewan River

The Approved WMP for the SSRB has created a moratorium on new licence allocations in the South Saskatchewan River as of 2007. Water in the basin for new projects must be accessed through transfers of existing licenses. The AER has designated all of the South Saskatchewan River Sub-Basin as water short [49]. The hydrograph is provided in Figure 26.

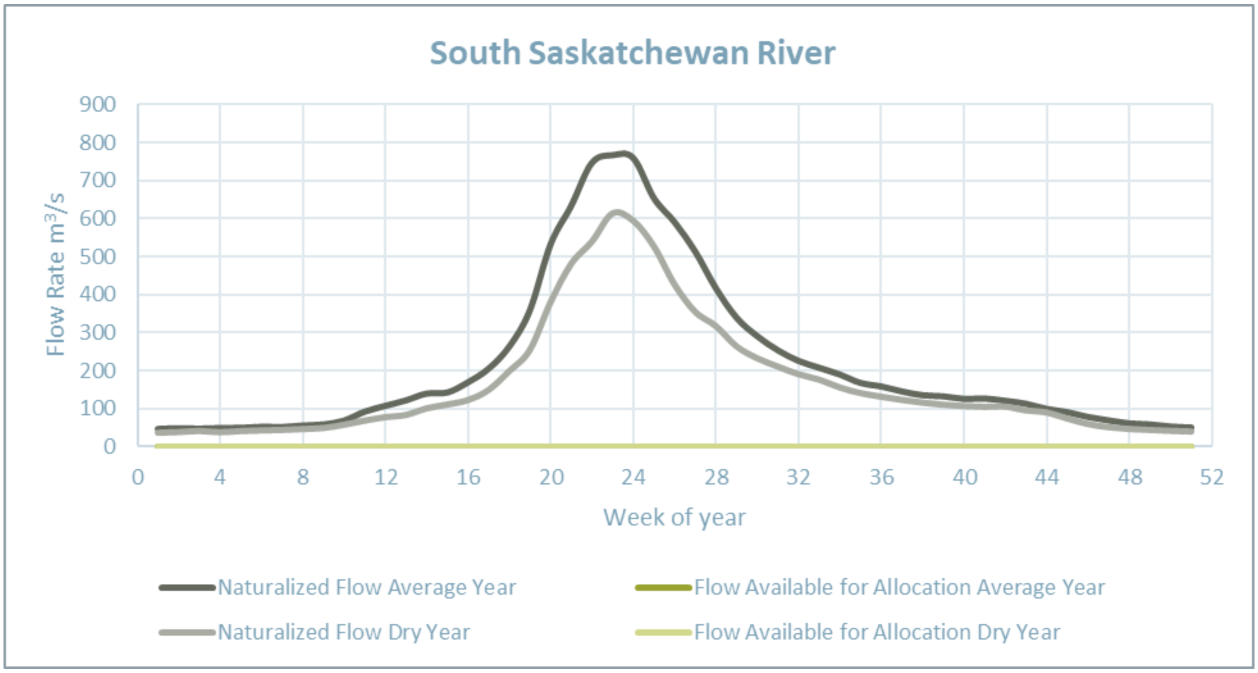


Figure 26. Comparison of water flow to water available in the South Saskatchewan River, in dry and average years.

C.9 Milk, Beaver, and Hay River Basins

Hydrographs of water availability for the Milk, Beaver and Hay River Basins (identified in Figure 27) are provided for context in Figure 28, Figure 29, and Figure 30, respectively. Less detail is provided for these rivers because they satisfy few of the criteria noted in 3.0, and in particular do not currently have planned hydrogen development in the region. Note that the Milk River has a moratorium on new licences in the Alberta portion of the watershed since 1986, except on a case by case basis to support small agricultural activities or municipal use [71]. For this reason, this analysis will assume there is no water available in this basin to support hydrogen development.

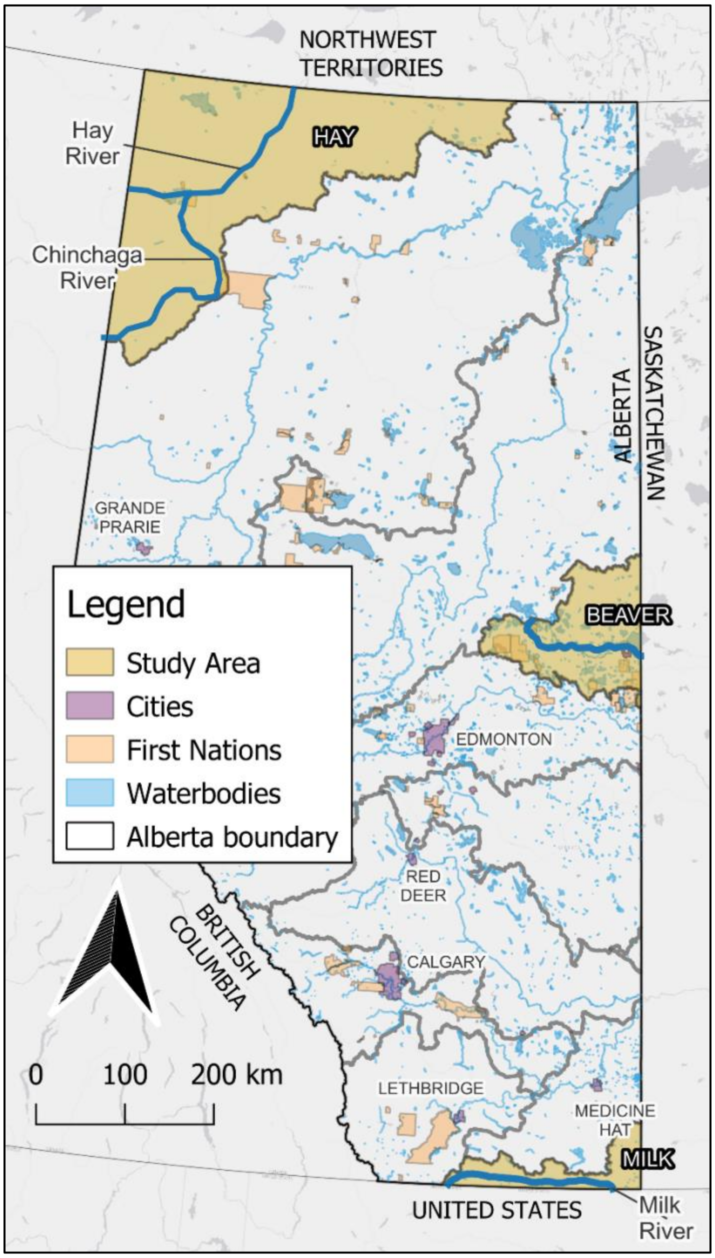


Figure 27. Locations of the Milk, Beaver, and Hay river basins.

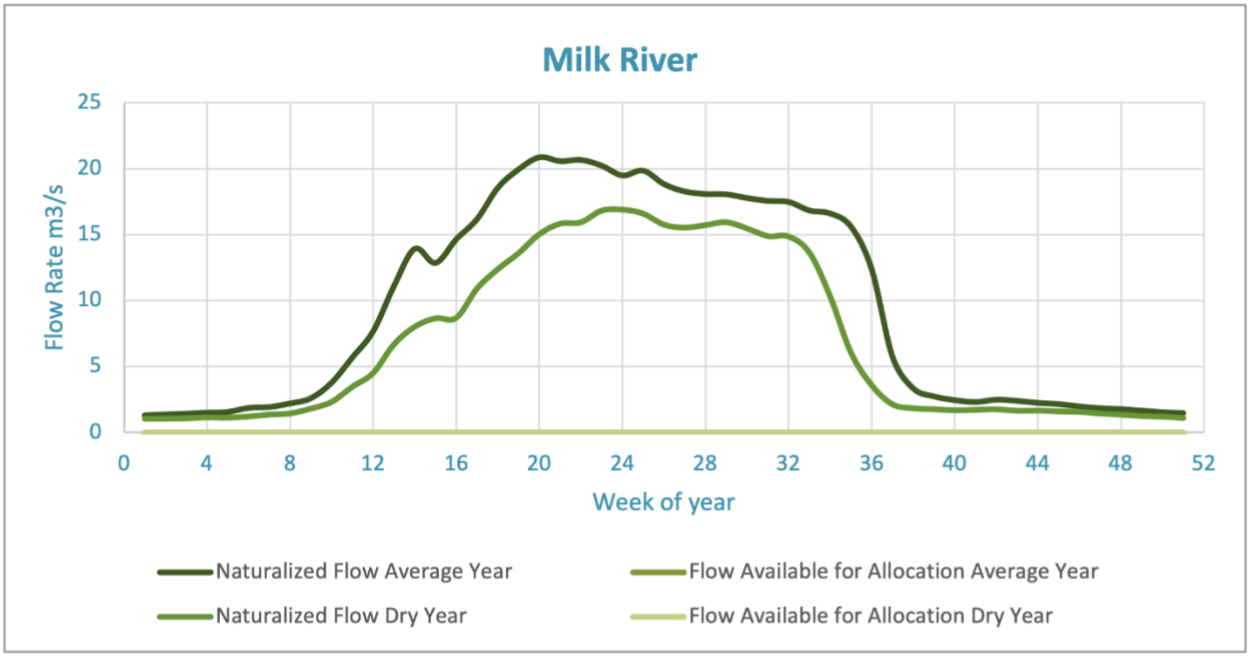


Figure 28. Comparison of water flow to water available in the Milk River, in dry and average years.

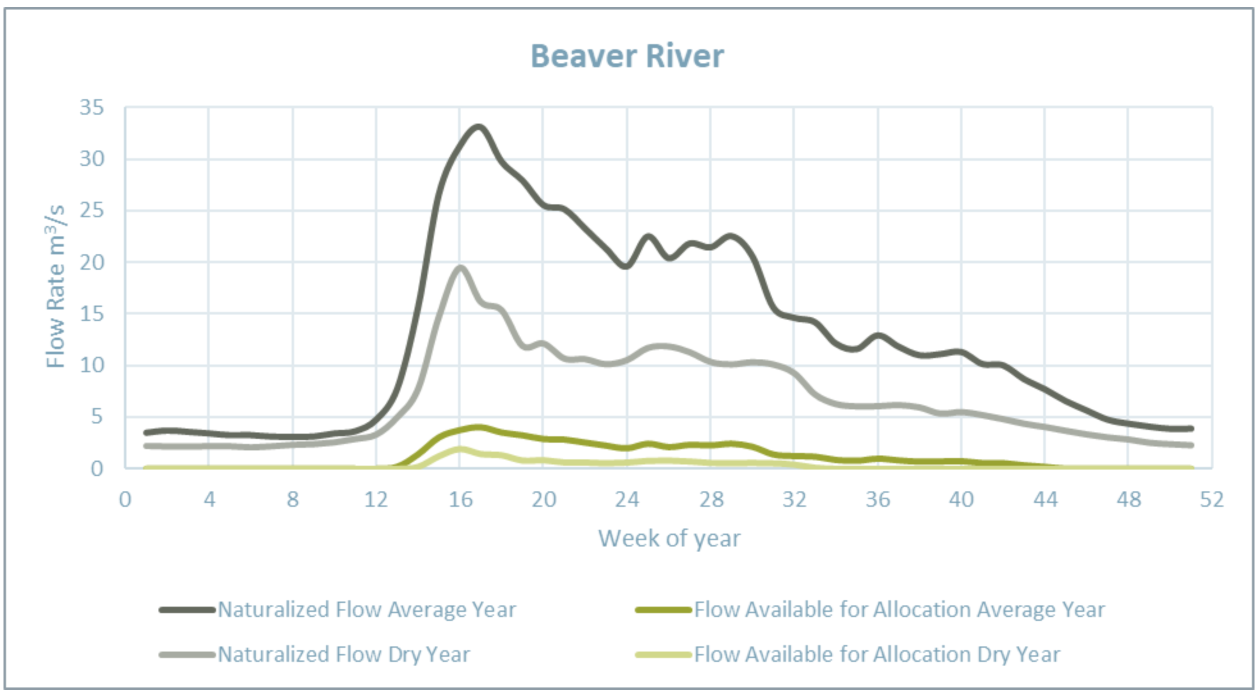


Figure 29. Comparison of water flow to water available in the Beaver River, in dry and average years.

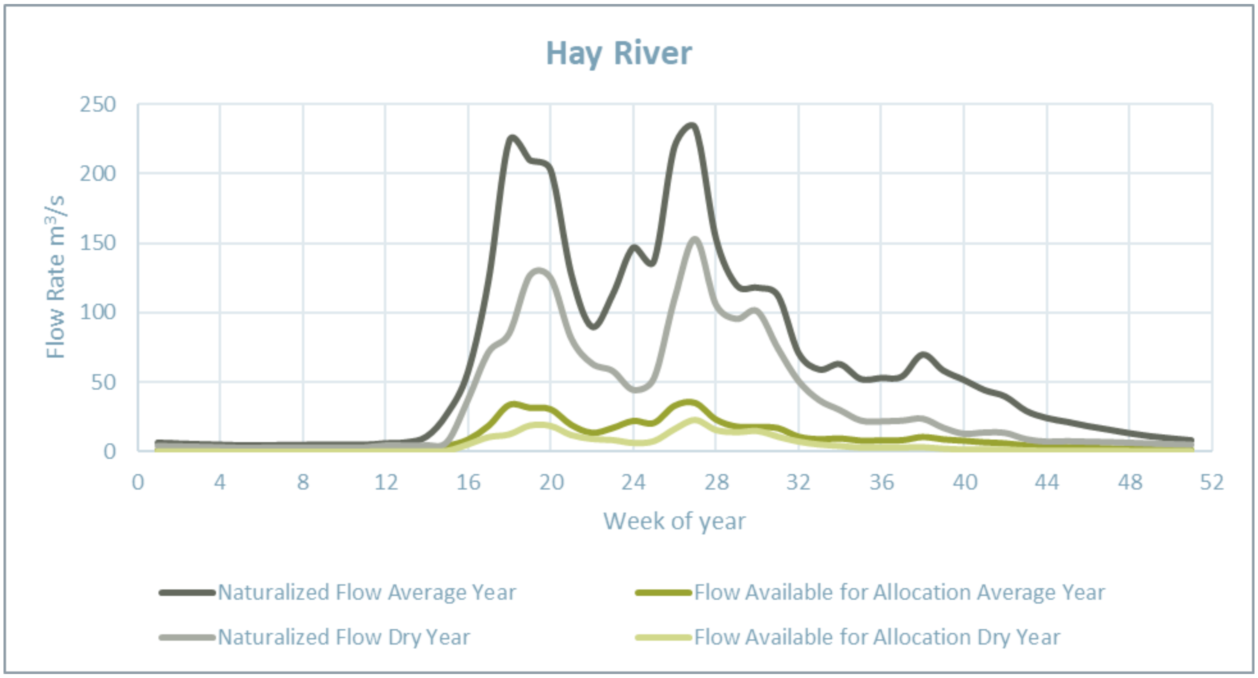


Figure 30. Comparison of water flow to water available in the Hay River, in dry and average years.

Appendix D Water Availability Analysis Methodology Details

This appendix contains additional explanation of the methodology for calculating water availability, described in Section 3.0.

Naturalized flow is a term used in Alberta's regulatory framework, which the SWAD and WCO are enforced against. It describes what the flow of the river would be without any anthropogenic impacts. It cannot be measured directly and must be calculated by subtracting anthropogenic impacts from flow recorded at gauge stations.

For some rivers, the AEPA maintains naturalized flow datasets which have the real-world operational restrictions (e.g., dam operation, ice cover, etc.) as well as diversions subtracted from the recorded flow, at the times of year when licensees actually take water [72]. This is a complex task that is nuanced for each basin. For rivers which the AEPA does not maintain this dataset, the analysis used historical data recorded flow from Water Survey of Canada gauge stations and estimated naturalized flow [73]. WaterSMART's experience indicates that licence holders across the province generally consume approximately 40% of the volume they have an allocation for. Therefore, to estimate naturalized flow, it was assumed that 40% of the total licence volume in the river should be added to the publicly available recorded flow to account for anthropomorphic impacts [14]. Note that this assumes users are diverting at constant rate throughout the year, which is recognized to be an approximation.

After the naturalized flow dataset is obtained by either method, the analysis uses a consistent set of steps to determine the water available for new allocations. First, the relevant regulation is applied (e.g., the SWAD dictates that 15% of the naturalized flow must remain in the river at all times) to determine what volume can be allocated for all purposes. Next, future water use is accounted for by subtracting from the available volume 60% of existing licenses. This accounts for an increase in water use from 40% to 60% of licensed volume over time. In future analysis, additional work should be considered to determine a more accurate scaling factor.