

Incorporating climate change scenarios and water-balance approach to cumulative assessment models of solution potash Mining in the Canadian Prairies

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Abstract Changing hydroclimatic conditions on the Canadian Prairies include significant shifts in the intensity, duration, and frequency of precipitation events, as well as temperature and seasonal shifts that affect water availability and quality. Concurrently, high-water-use-intensity industrial development, such as solution potash mining, is also lessening availability of timely water resources in agricultural regions and southern Prairie watersheds. This study used a three-pronged approach to (1) incorporate climate change projections within CEA, (2) identify the impact of projected and trending population and industry growth to inform water-balance calculations and recommendations within the study area, and (3) calculate the net impact on water availability of changing hydroclimate on a specific industry (solution potash mining) using a case study methodology for application to the Qu’Appelle Watershed. The results indicate that an implemented process approach is a good option for incorporating climate change models and methods within cumulative effects monitoring and assessment programs, despite challenges associated with regional variance and lack of long-term data. The outcomes of case study development and review indicate a climate change impact (26% difference) on the available water resources anticipated within the area. And combining this with the water-balance approach, it is recommended that water and climate modeling be completed at the regional scale to account for assumptions and scenario/model-based projections.

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1 Introduction

The impacts of anthropogenic greenhouse gas production include a changing global climate and associated environmental impacts, whether positive or negative. Climate change, within the context of cumulative assessment models, serves as an additional mechanism for understanding and evaluating pressures on physical, economic, and social-cultural environments. Because global climate change models tend to be too granular for ready incorporation to more localized and regional cumulative assessment models, there are few examples of full consideration of changing climate in project-based environmental impact assessments (EIA). However, the improvement of downscaling methods and contextualization opportunities for incorporating general expectations for climate change in a region can be applied for enhanced cumulative effects assessment (CEA). In this way, and by focusing on a particular environmental compartment and parameter, such as water quantity, long-term impacts may be assessed with a reasonable expectation of accuracy. Intra-annual variability and localized impacts remain less certain and precise for such applications.

The benefits of including meaningful climate projections through CEA are centered on the provision of a more robust and defined expectation of the risks and opportunities likely to emerge from an industrial development or large-scale expansion. Through the process of determining the physical environment, economic, and social-cultural impacts of an industrial project and its components by means of CEA, project stakeholders and regulators are better able to predict how environments may respond.

In Canada, cumulative effects are enshrined in the *Canadian Environmental Assessment Act* (CEAA) 2012a, b. The CEAA outlines processes for EIA in the context of valued ecosystem components (VECs) and how a project may (positively or negatively) impact VECs and associated functions. The EIA process includes (1) scoping to set spatial and temporal boundaries, (2) analyzing baseline conditions, (3) identifying mitigation measures, (4) evaluating significance of impacts and mitigation, and (5) confirming that mitigation measures support continued functionality of VECs (CEAA 2012a, b).

Under CEAA (2012a, b), CEA considers the combined impacts of individual processes, accumulating these to determine the total contribution from all actions related to a specific project or development and interacting with existing or planned activities in a given area. For practitioners conducting CEAs, the challenges involve the regional extent of the assessment area, duration of impacts, and determination of methods for assessing complex interactions of processes and environmental compartments.

The results of the enclosed review note the benefits, challenges, and issues with incorporating climate change models into CEA and include projected impact on water availability related to both population and industrial growth within the study region (Qu'Appelle Watershed, Saskatchewan). The analysis provides information about the projected impacts of changing climate on water resources over the upcoming 15-year period and presents a case study focused on solution potash mining in the Qu'Appelle Watershed.

2 Methodology

2.1 Consideration of climate change projections in CEA

Climate change can be incorporated into CEA by means of a process approach following the five consecutive steps noted earlier. This process was adapted to determine, understand, and

analyze the effects of climate change on regional water availability in a specific watershed in the Canadian Prairies. The five-step process includes opportunities to both transition from EIA to CEA and to integrate changing climate conditions and projections through minor modifications and transformative revisions to the approach, intent, and description of boundary conditions, impacts, and interactions.

2.2 Site description

The Canadian Prairies comprise urban, rural, and agricultural watersheds that rely on spring melt runoff from the Rocky Mountains, as well as limited summer rainfall. Throughout the Prairies, these watersheds are more likely to be affected by drought than excess water (Wittrock 2012), thus the majority of water management strategies have been designed and implemented to store and convey water than to mitigate against flood. In these contexts, the implementation of CEA and analysis of potential climate change-relevant impacts of projects and development in the Canadian Prairies must take into consideration current land use and water demand, projected land use and water demand based on professional judgment and projects under review, and water availability under projected climate change.

Temperatures across the Canadian Prairies study location average 18 °C in summer and –10 °C in winter. Temperature extremes range from –40 and +36 °C, making the Canadian Western Interior home to one of the globe's most extreme climates (Sauchyn et al. 2015). The Saskatchewan Water Security Agency (WSASK 2013) estimates that the mean annual precipitation varies between 360 and 470 mm (average of 415 mm/year) in the Qu'Appelle watershed. The Qu'Appelle watershed is approximately 41,222 km² and includes both surface and ground water resources to be considered in any water allocation and balance exercises (WSASK 2013; WUQWATR 2013).

2.3 Water-related climate change projections

As climate change impacts regional Canadian Prairie hydrologic regimes, the consumption of water for energy, industrial activity, and food production is likely to be a major issue. The projections for Canadian Prairies climate generally indicate trends toward a warmer future, while precipitation models are less conclusive and project both wetter and drier futures depending on the model (Barrow 2009; Lapp et al. 2009; Sauchyn and Kulshreshtha 2008). Because of the differing projections per precipitation and, thus, water availability within a changing climate, further research expertise is required to identify projections for application in the water balance and case study analyses completed herein.

Results from three extensive studies (Sauchyn et al. 2010; Sauchyn and Kulshreshtha 2008; Lemmen et al. 2008) into water management and resources availability are key to the completion of both water balance determination and impacts of expanding solution potash mining activities across the southern mid-Canadian Prairies region (specifically, the province of Saskatchewan) (Saskatchewan Watershed Authority 2012). The key implications of projected climate change on water availability, resources, and accessibility (including timeliness of precipitation events per agricultural production), within the contexts of increasing water demand due to population and industrial growth and longer, warmer summers (hence higher evaporation and evapotranspiration losses), indicate the likelihood of earlier spring runoff events and lessening summer water availability requiring more active, deliberate, and regional water supply management (Sauchyn et al. 2010).

The hydrology of the Canadian Prairies is dominated by cold weather processes, such as snow accumulation and melt, frozen soils and glacier runoff (Pomeroy et al. 2007). Snow comprises approximately one third of the annual precipitation, but snowmelt water represents about 80% of the runoff, soils and groundwater recharge, and surface water storage. Very little runoff is produced in summer, with the exception of precipitation received during intense summer convective storms. Within current hydrological regimes and understandings, it is well established that Canadian Prairie water resources are limited, highly sensitive to climate and land cover changes, and inadequate to support substantial water diversion.

As climate has changed in recent years, seasonal shifts toward earlier snowmelt runoff have produced declines in summer streamflow. Winter flows are moderately increasing, spring runoff and peak flows occur earlier, and summer and early autumn flows (July–October) are considerably lessened. A recent analysis (St. Jacques et al. 2014) of streamflow trends in the Canadian Prairies shows a distinct geographical pattern with significant declines in the west and significant increases in the east. These trends reflect climate projections that suggest a shift from snowmelt-driven hydrology to a mixed rain and snowmelt runoff regime and increasingly rainfall-dominated regime over time.

Driving physically based hydrological models with output from climate models, the results for the Rocky Mountains (for example, Kienzle et al. 2011) show an earlier onset of spring snowmelt, a tendency toward a more rainfall-dominated hydrograph, and reductions in the annual and summer flow volumes. Mid- through late-summer flows may decline by as much as 50%, with significantly higher runoff in winter.

The outputs from these climate change models and water availability trend analyses were incorporated into both the water balance approach and case study for solution potash mining activities and expansion.

2.4 Water balance approach

Data for the Canadian Prairie province of Saskatchewan were collected, compiled, and analyzed to identify potential impacts to water availability and needs for revisions to current and expected water resources management. These data were incorporated into water demand and water balance calculations to identify the net difference between anticipated water availability under climate change and anticipated water consumption (or diversion) under population and economic sector growth. Climate normals for 1981–2010 for each of the three solution potash mine regions were obtained from Environment and Climate Change Canada (2017a, b, c).

2.4.1 Population growth projections

Based on current projections from both provincial and federal sources (Sask Trends Monitor 2016; Statistics Canada 2015), the province of Saskatchewan will continue to experience population growth based on natural rates of increase relative to the net of births and deaths, in-country migration patterns, and net international migration. For each components, the projections from present day to 2035 indicate slow population growth from the 2016 population of approximately 1,057,000 to a conservative estimate of nearly 1,118,000 or more aggressive estimate of 1,267,000 in the same time period (Statistics Canada 2015).

2.4.2 Forecasted provincial economic sector growth

Much of Saskatchewan's economy is resource- and agrarian-based as functions of geographic location, climate, and abundance of accessible natural resources and transportation routes. The province's uranium and potash reserves are some of the world's largest (NRCan 2012). Additional natural resources under development include oil and gas, gold, copper, diamonds, platinum, and zinc. The Fraser Institute recently rated Saskatchewan as one of the best places in the world for mining companies to invest as the province has created a balanced approach between incentivization and taxation (Fraser Institute 2017). Based on global markets and forecasted for demand, many sources (including Fraser Institute 2017 and Conference Board of Canada 2017) suggest that Saskatchewan's economy will continue to grow and diversify with additional opportunities becoming available for private investment in the next 15–20 years.

In agriculture, global food demand continues to increase steadily with directly correlated opportunities for Saskatchewan agricultural producers, particularly in high production niche and traditional crops such as mustard and canola, lentils, flax, and cereals. Commensurate increases are anticipated in agricultural-support sectors including implements engineering and dealers, commodities trading and wholesalers, seed, spray, and fertilizer sales companies, and custom seeding and harvesting operations. A UN DESA (2015) study forecasted that world population will reach a challenging 8.7 billion people by the end of 2035. This, in addition to Canadian commitments to meet free trade agreement quotas for world food production and sale, such as the Canada–Korea Free Trade Agreement and Trans-Pacific Partnership, will continue to fuel demand for Canadian agricultural products. Thus, it is anticipated that agricultural sector growth will continue to steadily increase to meet global food and crop yield optimization demands. Based on forecasting measures established by Statistics Canada (2015), Saskatchewan's agriculture sector is expected to expand at an annual compound rate of 1.2% (2014–2035).

Saskatchewan's well-established mining industry includes non-metallic, metal-ore, coal, oil and gas extraction, and quarrying. The province is the world's second largest uranium producer, accounting for approximately 22% of global uranium production (Statistics Canada 2015). Given continued and planned reliance on nuclear power in several Asian countries, in particular, this industry is expected to remain strong. Declining oil prices will continue push economic investment into other fuel industries and extraction methods, versus the generally heavy crude (south) and prohibitively deep oilsands (northwest) reservoirs. New growth industries are slow to emerge given the geopolitical stability of the Canadian Prairies; natural resources extraction companies have delayed development in Saskatchewan as a safety net should their existing bases of activity become inaccessible due to geopolitical unrest. The mining industry is challenging to predict as a single sector given the volatility of commodities, thus the projection methods provided by Statistics Canada (2015) lead to expectations for overall mining industry growth of 0.4% compounded annually over the forecasting period (2014–2035), while oil extraction and fuels industry projections suggest an annual average contraction of 1.5% between 2014 and 2035.

Manufacturing in Saskatchewan specializes in transportation, machinery and industrial equipment, and chemical manufacturing, as well as food, crop, and beverage processing. Among these industries, transportation, machinery, and industrial equipment have experienced the largest growth, aligned with growth in the resource development and agricultural sectors. Based on projections provided by Statistics Canada (2015), real manufacturing output is projected to increase at an annual compound rate of 2.4% between 2014 and 2020, with slightly slower growth of 1.9% annually from 2021 to 2035.

2.4.3 Groundwater calculations

To determine the impacts on site-specific groundwater resources through water levels, well logs were analyzed in areas close to the mine regions. The water level for the groundwater near the Esterhazy and Rocanville mine sites were observed by the Bangor A which represented the deepest and most water-rich regional aquifer formation found within Empress Group. The Bangor B well (drilled into a shallower Southerland formation above the empress formation) was determined to be too shallow for an aquifer formation (15.3 m) to provide sufficient water for potash production.

Based on bedrock formation and surface geology maps, the depth to the aquifer during drought events (lowest point on the hydrograph) was calculated as approximately 26 m. To simplify the calculation process, this groundwater level was assumed for the entire aquifer. In reality, this level would vary significantly due to changes in soil layers, sub-surface strigraphy, and water density.

The groundwater levels near the Belle Plaine mine sites were observed by analyzing the hydrograph produced by the Instow observation water well, depicting the Judith River Aquifer. Due to the overall depth of this water formation, available water resources, and highly saline water quality, it was assumed that this water source could not be practically utilized by the Belle Plaine Mine site and therefore was not accounted for within the calculations.

To determine the total groundwater resources available within the watershed region, the surface area available for recharge was multiplied by the low groundwater depth from observation well data and the specific yield of soils in the groundwater region.

2.4.4 Total water use estimates

To determine the total estimated water use for the mine sites, the current water use was multiplied for the cumulative growth forecast over the 15-year period. These values were then combined to determine the total water use for all industries in the Qu'Appelle watershed region. From these data, the percent water removed from the watershed per industrial sector over the 15-year period was calculated with the assumption of no transmittance of water to and from the watershed area.

The calculation of the available surface water was taken as the 15-year surface water contributions by means of the river sources to the industrial sites. This value was combined with that of the available 15-year groundwater resources to attain the total available water resources for all sites within the watershed.

The percent of industrial and municipal water removed from the watershed was determined by calculating the total available water resources (surface and groundwater) with estimated water use over the 15-year study period.

3 Results

The results focus on implementation of the forecasted models and projections relative to water availability and consumption patterns, as well as application of those outcomes to a specific industrial sub-sector, solution potash mining, in the province of Saskatchewan.

3.1 Impacts of projected population and economic sector growth

The protection of both the quantity and quality of source water is vital for communities and industries within Saskatchewan. Population, as well as sector growth within the province, will have profound impacts on the quality and quantity of water used. By incorporating the effects of climate change, these impacts become magnified as water sources become less available for human use. On a global scale, the costs associated with climate change on water resources could outweigh the benefits.

Within the prairies, the occurrence of extreme drought conditions and increased precipitation intensity (but less frequency) will likely require large investments in infrastructure, as well as changes in water and land management practices. Miller et al. (1997) predicted that substantial changes in the availability, seasonal timing, and quality of water would increase costs through all aspects of society (i.e., monetarily, societal, and ecologically). These predicted costs would be both positive and negative for some downstream water resource users. For example, both in-stream and out-of-stream water users may benefit from increased annual runoff through the utilization of the water resources for agriculture practices (WSASK 2013). Alternatively, annual runoff increases may affect shallow groundwater areas, disturbing agricultural use and urban foundations through oversaturated soils. Additionally, increased precipitation intensity has the potential to increase periods of turbidity, as well as nutrient and pathogen loading of surface water areas (WSASK 2013).

By incorporating the effects of climate change, these impacts become magnified as water sources become less available for human use. The magnitude of that magnification is dependent on the source in which the water is being drawn from (i.e., groundwater vs. surface water sources).

3.2 Climate change threats to groundwater quality and quantity

Based on a report published by Saskatchewan Water Security Agency (2008), 45% of the provincial population and 62% of the communities rely on groundwater as their sole water source. Any diversion of this groundwater system has a profound effect on the downstream environment that relies on its supply. While the effects of drought conditions become immediately apparent in surface water sources, typically groundwater source depletion is not noticed until extended periods of drought activity have occurred.

Current climate change models for the province predict longer, hotter summers with decreasing soil moisture, creating a significant effect on Saskatchewan's water supply. Through research conducted by Lemmen et al. (2008), the projected increase in rainfall due to climate change in the spring and fall will cause water to be retained in soils, which may result in increased crop productivity and the health of the ecosystem for a short period of time. However, due to the predicted increase in evapotranspiration, the province will likely experience drier soil conditions and a decrease in surface water supply and dependence on groundwater, with leading to a slow and steady decline in groundwater recharge rates overall. This decrease in soil moisture has the potential to decrease crop yields for large regions of the prairies. The increasing demand for crops will put pressure on farmers to maintain high yields, which will drive farms to innovate through increased irrigation practices. These practices will place further strains on groundwater resources though their increased depletion and hindrance on the recharge capacity of the system. Problems of this nature have previously occurred within the province of Alberta from 2001 to 2003 as described by Lemmen et al. (2008). The

projected increase in annual and seasonal temperatures will only intensify drought conditions and increase the likelihood of short, but extreme precipitation events as further climate change occurs.

3.3 Climate change threats to surface water quality and quantity

Based on a report issued by the South Saskatchewan River Watershed Stewards (2013), approximately 45% of the population within the province relies on the South Saskatchewan River. The quality and quantity of surface water is important for not only the human inhabitants but also for a wide range of aquatic life, providing diverse habitats for wildlife.

According to a study conducted by Dai et al. (2004), arid regions (classified as very dry—PSDI ~ 3.0) have more than doubled, from approximately 12–30% in “lack of moisture” since the 1970s. A large portion of this drying was due to El Niño-related precipitation decreases over land and increases through surface warming in the 1980s. A single model study conducted by Burke et al. (2006) indicated that by 2090, the proportion of land surfaces experiencing drought, mean drought duration, and the frequency of drought events was projected to increase by up to 30-fold, sixfold, and twofold, respectively.

Based on the close interaction between human factors (changes in land use, demand of water, and land cover) and surface water resources, economic, environmental, and social impacts related to drought conditions may arise. Through decreases in land precipitation and increases in temperatures, the enhancement of evapotranspiration, resulting in the reduction in soil moisture will be prevalent.

3.4 Solution potash mining case study: water balance under climate change

Both surface water and groundwater resources were examined using the water balance approach, since Canadian Prairie rural communities tend to rely heavily on groundwater for provision of both potable water and agricultural or other industrial water needs.

Since the volumes of both surface and groundwater account for precipitation (as runoff and infiltration) within the watershed region, these values have already been considered and therefore would not need to be considered a second time for the both non-climate and climate change scenarios.

3.4.1 Current surface water sources

Within the watershed study area lies the Qu’Appelle River, a major source of surface water for natural and anthropogenic operations. The Qu’Appelle River flow regime is a mix of a typical prairie river and lake drainage, modified by water contributions from the South Saskatchewan River system. For the purposes of this study, surface water consumption is assumed to be sourced primarily from the Qu’Appelle River. These estimates did not account for surface waters from prairie potholes, or smaller tributaries, as their useable volume is significantly smaller than that of the river. Based on a hydrometric station near Welby, Saskatchewan (Station 05JM001), during peak periods (March to April), the mean discharge of the river increases from 3.7 to 17 m³/s due to increased snowmelt and runoff. During low periods (February), the mean discharge in the river is approximately 2.6 m³/s (Pomeroy 2015).

For the determination of surface water resources available, the lowest value of surface water was used (2.6 m³/s) to ensure minimal water conditions for industrial use for both climate

change and non-climate change scenarios. For use in the water budget for the Qu'Appelle watershed, this value was assumed to be a constant average flow over the study period (signifying large reductions in surface water over a long period—i.e., worst case scenario). Over an annual basis, this value was determined to be 81,993,600 m³/year. As this water budget is used as a 15-year estimate, the annual value was multiplied by 15 years to determine the total available water resources (signifying a total volume of 1,229,904,000 m³ over the 15-year period). The value of 2.6 m³/s would be considered conservative in this case as the impacts of increased evaporation, water use, reduced snowpack, etc. can potentially decrease this value much further as the effects of climate change become more prevalent.

3.4.2 Current groundwater sources

With respect to available groundwater resources for the potash facilities, both the Rocanville and Esterhazy Mines have direct access to the Hatfield Valley Aquifer. The extent of the Hatfield Valley Aquifer is approximately 6090 km² (Maathuis and Schreiner 1982) with porous soil materials consisting mainly of interlaid silt and clay. Given these soil materials, the specific storage of the soil materials can be determined as 7–18% (average 12.5%) (Johnson 1966). This indicates that for every unit of this soil material, the volume of water that can be drained is 12.5% of total soil volume. The Belle Plaine Potash Mine lies on the Judith River Aquifer, a bedrock aquifer consisting of sediments deposited before glaciation. The extent of this aquifer is approximately 15,779 km² (Maathuis and Simpson 2007). Within the aquifer, the soil materials consist mainly of interlaid gray and greenish clay with “very fine” to “fine” sand. From these soil materials, the specific storage was determined to be 21–26% (average 23.5%) (Johnson 1966).

Groundwater in these sediments moves very slowly, creating a delay in recharge compared to immediate changes in surface hydrology. From the calculations described in Section 2, data for Table 1 were prepared for each of the mine site areas. It is important to note that groundwater resources are shared for Rocanville and Esterhazy mine sites.

4 Results and discussion

4.1 Non-climate change scenario

The non-climate change scenario, in the context of available water resources, was assumed to attribute no climate related impacts to usable water sources. That is, the climate conditions

Table 1 Summary of available groundwater resources

Groundwater parameters	Rocanville and Esterhazy Mine sites	Belle Plaine Mine site
Extent of groundwater area (km ²)	6090	15,779
Lowest aquifer water depth (m)	26.16	170.06
Average specific storage of aquifer soil materials	0.125	0.235
Volume of available groundwater resources (m ³)	1.99×10^{10}	6.306×10^{11a}
Total available groundwater resources (m ³)	1.99×10^{10}	

^a This water resource is inaccessible for use due to aquifer depth, available water resources, and highly saline water quality

Table 2 Predicted future water use available water in watershed region

Industry parameters	Mining (potash)	Agriculture (irrigation)	Public (municipal)
Growth forecast comp/year	0.40%	1.20%	11.58%
Current water use within watershed (m ³)	45,937,000	6,000,000	37,500,000
Predicted future water use over 15 years (m ³)	732,000,000	108,000,000	2,910,000,000
Total predicted water usage over 15 years (m ³)	3.75×10^9		
Surface water available (m ³)	1.23×10^9		
Total groundwater available (m ³)	1.99×10^{10}		
Total available water resources (m ³)	2.11×10^{10}		
Water available after removal (m ³)	1.74×10^{10}		
% Removed	17.7%		

15 years from now would be the same as that of today, ensuring all water resources remain unchanged. Water use and industrial growth projections were used to determine predicted future water use and overall estimated water use for the large consumption industries in the Qu'Appelle Watershed. Estimates for total future water use over the next 15 years were created from 2035 projections data and the current combined industrial water consumption in the Qu'Appelle Watershed.

Total estimated water use for both the mine sites and for all industries in the Qu'Appelle Watershed over the 15-year period were calculated as described in Section 2 (Table 2). A removal of 17.7% represents the amount, with respect to total water resources available for the area, that current industries in the Qu'Appelle Watershed are expected to extract over 15 years.

For the purposes of this research, water use for each of the potash mines was also calculated and adjusted for future mine growth based on the predicted future water use equation by DePaul University (2009) that includes compounded growth forecasts over a set number of years (15). These projections account only for growth and expansion of existing mine facilities within the Qu'Appelle Watershed region, not for new mine developments. This key assumption may lead to an underestimation of the projected water demand for potash mining in the event of sector expansion. The data presented in Table 3 summarizes water use for each of the three potash mines currently operating in the Qu'Appelle Watershed.

The calculation of available surface water reflects the 15-year contributions from estimated precipitation as well as by means of river and lake resources proximate to the mine sites. This value was combined with that of the available 15-year groundwater resources to obtain the

Table 3 Predicted breakdown of available water and potash industry use

Potash mine parameters	Belle Plaine	Esterhazy	Rocanville
Growth forecast (%/year)	0.4	0.4	0.4
Current water use (m ³)	26,000,000	12,000,000	8,000,000
Predicted future water use (m ³)	414,000,000	192,000,000	125,000,000
Total estimated water usage (m ³)	732,000,000		
Precipitation in 15 years (m ³)	53,000,000	113,000,000	43,000,000
Surface water available (m ³)	1.238×10^9		
Groundwater available (m ³)	1.991×10^{10}		
Total available water resources (m ³)	2.119×10^{10}		
Total estimated water usage over 15 years (m ³)	7.316×10^8		
Water available after removal (m ³)	2.046×10^{10}		
% Removed (%)	3.5		

Table 4 Predicted climate change adjustments and water resource volumes

Groundwater resource parameters	
Surface water available (m ³)	1.23 × 10 ^{9a}
Climate change adjustment (% decrease)	35 ^b
Surface water available (adjusted) (m ³)	7.92 × 10 ⁸
Groundwater available (m ³)	1.99 × 10 ¹⁰
Climate change adjustment (% decrease)	20 ^c
Groundwater available (adjusted) (m ³)	1.59 × 10 ¹⁰
Total available water resources (adjusted) (m ³)	1.60 × 10 ¹⁰

^a Calculated by means of the mean surface flow (2.6 m³/s)

^b Interpolated from Bates et al. (2008) (maximum value) modeled by the SRES B1, A1B, and A1F scenarios

^c Originally incorporated from Bates et al. (2008) (maximum value) modeled by the SRES B1, A1B, and A1F scenarios

total available water resources for all sites within the Qu'Appelle Watershed. The calculations resulted in an estimated 3.5% water extraction volume required for current potash industries over 15 years. These calculations are based on existing information about consumption, although it is expected that some water will be recycled and recovered, meaning that the 3.5% extraction estimate is likely higher than actual.

4.2 Climate change projections

To determine the potential effect of climate change on water resources in the Qu'Appelle Watershed, adjustment factors were applied to the non-climate change water-balance scenario to account for changes in water resource availability across the 15-year projection period. The climate change adjustment factors effectively decreased the original water volumes calculated, reflecting projected drought conditions (Bates et al. 2008) due to decreases in the Rocky Mountain snowpack. The total available water resources, adjusted for climate change, were determined by summing the projected surface and groundwater resources (Table 4), producing estimates of total available water available to industry over 15 years under climate change.

The climate change adjustment factor increases the amount of precipitation from the non-climate change prediction. Based on the total estimated water use calculated in Table 3, along with analysis of potential available water resources incorporating climate change, the percent water removed over the 15-year period was calculated (Table 5).

Table 5 Breakdown of available water and potash industry use (with climate adjustments)

Potash mines parameters	Belle Plaine	Esterhazy	Rocanville
Precipitation in 15 years (m ³)	53,000,000	113,000,000	43,000,000
Climate change adjustment (increase)	5% ^a	5% ^a	5% ^a
Precipitation available (adjusted) (m ³)	56,000,000	118,000,000	45,000,000
Surface water available (m ³) (adjusted)	7.92 × 10 ⁸		
Groundwater available (m ³) (adjusted)	1.59 × 10 ¹⁰		
Total available water resources (m ³)	1.67 × 10 ¹⁰		
Total estimated water usage over 15 years (m ³)	3.75 × 10 ⁹		
Water available after removal (m ³)	1.30 × 10 ¹⁰		
% Removed (%)	22.42		

^a Interpolated from NRCan (2008)

Table 6 Summary of 15-year industrial and potash growth scenario

Observed parameters	No climate change	Climate change
15-year industrial growth scenario		
Total estimated water usage (m ³)	3,749,000,000	3,749,000,000
Total available water resources (m ³)	21,140,000,000	16,720,000,000
% Removed (%)	17.7%	22.4%
% Difference in scenarios (%—as water removal)	26.4%	
15-year potash growth scenario		
Total estimated water usage (m ³)	732,000,000	732,000,000
Total available water resources (m ³)	21,193,000,000	16,776,000,000
% Removed (%)	3.5%	4.4%
% Difference in scenarios (%—as water removal)	26.3%	

Water use for each of the potash mines within the watershed was adjusted for mine growth using a compounding percentage over 15 years to attain realistic future water use data. Based on these calculations, water extraction of approximately 22% was projected, including climate change projections. Incorporating total estimated water use (Table 4), alongside previous analysis of available water resources, the percent water extraction over 15 years, was calculated while accounting for climate change. The analysis includes results of the water-balance approach with and without incorporating climate change projections, based on industrial growth and potash-specific growth (Table 6). Based on these analyses, more than 4% of the total water resources available will be extracted by current potash mines over the next 15 years.

Including climate change projections within the water-balance approach, a reduction of more than 4.4 billion m³ (>26%) of potential available water will be required to support and sustain industrial consumption. The impacts of climate change are projected to have significant impacts on the amount of water available for existing potash mines: a 26% reduction of water resources compared to the non-climate change scenario.

5 Conclusions

The results of this research demonstrate the capacity for including climate change scenarios in CEA processes and indicate significant benefits and opportunities thereto. Challenges with data quality and granularity introduce uncertainties to CEA in terms of scalability and applicability. However, using a process approach for implementation, it is possible to identify manageable data inputs that inform and strengthen the power of CEA-driven decision-making. In application to solution potash mining in the Qu'Appelle Watershed both climate change projections, as well as changes to population and industrial activity, were estimated and quantified. The key findings suggest that the incorporation of climate change projections using a water-balance approach over 15 years may result in a reduction of more than 4.4 billion m³ (>26%) in total water available for industrial consumption. While these results were significant in determining the potential impact of climate change on water resources in the Qu'Appelle Watershed, the calculated volumes may not reflect readily accessible water resources (particularly certain aquifers), which may result in higher real percent removal since there is less water available than estimated through this analysis. To improve the projection of net water availability, it is recommended that water and climate modeling be completed at the regional scale to account for the impacts of assumptions and scenario/model-based projections.

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