Risks to Potash Mining posed by Droughts in Southeast Saskatchewan

Prepared for Watershed Security Agency, Saskatchewan, December 2013

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Summary

Potash mining and many other human activities are expected to face increasing risks from the effects of climate extremes. One of the most important extremes for the Canadian Prairies is drought and that hazard is thought to increase in frequency, intensity, duration and area in the future. This report is an overview exploration of the possible direct and indirect effects of drought to potash mining and the industry. It uses a case study of the Qu'Appelle River Watershed in southeast Saskatchewan. Methods used include a critical review of scientific literature supplemented by grey literature.

Drought can have positive and negative impacts for various aspects of potash mining, including impacts during establishment, operations, and effects on marketing and strategy. Both direct and several indirect effects are considered. The more knowledge about these relationships and early warnings of impacts can lead to improved adaptation to shifting climate patterns. This report provides one of the first overviews of the risks to potash mining of droughts. Research on this topic appears to be very sparse so many issues were covered.

Droughts are significant hazards in Saskatchewan and are expected to become worse in the future with continued warming. Questions addressed here by use of the case study are: 1) what are some of the direct and indirect impacts of droughts on potash mining? 2) what lessons arise for adaptation planning and implementation? Adaptation and vulnerability assessment require all three phases of assessment, including exposure (i.e., characteristics of the drought), sensitivity or impacts, and knowledge of adaptive capacity and its implementation. Research regarding drought was boosted, until recently. So that work appears to be ahead of research regarding the impacts of drought on the potash industry. The lack of knowledge of impacts is a large barrier to the understanding of the vulnerability of the industry to both droughts and climate change, and to the adaptation required to reduce vulnerabilities and gain from benefits.

The main direct effect is on the balance of water supply and demand. Indirect effects include the effects on water quality, health and safety (e.g., fire, heat stress, disease), waste management, emergency and risk management and marketing. Main points and recommendations regarding impacts and adaptation include:

1) Potash mining requires substantial and reliable water supplies, and therefore is sensitive to water scarcity. More frequent and severe droughts are expected than those of the past. Therefore, improved knowledge of impacts of drought water supplies and demand, as well as adaptation and adaptation planning are needed. Expansion plans for current mines and the development of new mines should consider climate change and drought adaptation planning such as for the possibility of water scarcity.
2) The main direct effect of future droughts appears to be water scarcity and corresponding possible water conflicts. Further understanding of this effect is needed. Research questions include: what effects would occur with a multi-year (e.g., 5-10y), severe and large-area drought? What deficits would occur with the water supplies? What increases in water demand would result? What types of drought is the potash industry prepared for? What are the chances of these types of drought occurring?
3) Further increases in water use efficiency, storage and exploration of alternate sources may be required sooner than previously considered. What is the

current adaptive capacity of the potash industry to deal with major droughts? How effective is this capacity?

4) Indirect effects of droughts may be numerous and perhaps as important as water quantity concerns. These would compound the direct effects and therefore, require further evaluation.
5) New lessons about past, present and future droughts are emerging due to past successful research programs. Risks of droughts are determined by the product of knowledge of these drought characteristics, including probabilities, and by knowledge of impacts. The latter is lagging and is a barrier to estimating risk. Therefore risk management is inadequate.
6) Impacts of other climate extremes, such as intense precipitation should also be considered. These other extremes may have effects that exacerbate drought effects. Their effects and corresponding adaptation are knowledge gaps.
7) Further development of tools and information is needed to aid industry, government and professionals to improve understanding of drought and climate change impacts on mining. Climate change and drought adaptation planning would be included as a main tool, perhaps as a part of enterprise risk management and strategic planning already being done by companies.
8) Much more and enhanced collaboration is needed among water, climate, government and industry people to address the task of decreasing vulnerability to climate extremes such as drought.

Overall, knowledge of the impacts of droughts on potash mining appears to be limited. This gap increases the risks of drought to the industry and therefore vulnerability to such climate extremes.

Introduction and Objectives

"A changing climate may pose significant physical risks for mining operations; it may also create indirect impacts for social, economic and environmental systems…Mining operations in the Prairies are more likely to be affected by flooding and drought, and to experience challenges related to competition for water… Globally mining companies are already experiencing a range of climate-related disruptions." (ICF Marbek 2012:7).

This section includes an overview of drought characteristics, describes the objectives and introduces potash mining in southeast Saskatchewan.

Drought Overview

Drought is defined as a prolonged period of abnormally dry weather that depletes water resources for human and environmental needs. An informal definition is that drought is a worrisome lack of water. Drought is more complex than the other natural hazards, so it has many definitions and no universal definition. Drought is determined by the interaction of water availability and the demands for water. The importance of drought is determined by its impacts. These drought definitions are conceptual definitions. Another type of definition is the operational (or objective) definition. They require measures of drought and information about drought impacts. Operational definitions can be suited to specific regions and times (Wilhite 2000).

Drought types are climatological, agricultural, hydrological and socio-economic. Climatological drought is determined by the degree of dryness compared to an average over a specified period. Agricultural drought expresses the effects of climatological drought on agriculture. This type considers soil moisture and vegetation growth, for example. Hydrological droughts associate the effects of water scarcity on surface and sub-surface water supplies. Climatological drought occurs first with sequences of dry and perhaps hot days. This dryness then affects agricultural activities. Water supplies then begin to dry up. These drought types then result in socio-economic drought, where water scarcity affects socio-economic sectors (Wilhite and Glantz 1985). All of these types may affect various aspects of the potash industry, including mining and marketing.

Drought measurement, monitoring, and modeling are accomplished with several indices. They range from simple approaches that only consider precipitation to more complex methods that incorporate a water balance approach. Two commonly used indices are representative of these types of indices. The Standardized Precipitation Index uses only precipitation and compares the degree of dryness (or wetness) to the climate stations' average precipitation. The Palmer Drought Severity Index uses several variables, including precipitation, potential evapotranspiration, antecedent soil moisture and runoff (Bonsal et al. 2012).

New findings about drought resulted from recent research programs, such as the Canada Drought Research Initiative of the Canadian Foundation for Climate and Atmospheric Sciences (Stewart et al. 2011). For example, Bonsal et al. (2011) found several new characteristics of past drought: 1) drought areas in the northern United States often migrate into the Canadian Prairies, 2) drought may begin in the winter (when they are less noticeable and less damaging), and persist into the summer, and 3) major droughts can have different sets of causes, and perhaps changing causes. These lessons are foundations for monitoring and early warning systems for adaptation to drought.

Future possible droughts are expected to be more frequent, intense, longer and larger. Wheaton et al. (2013) summarized the main characteristics of future possible droughts in southeast Saskatchewan:

- Have increased intensity of dryness, driven by increased evaporation potential. Drying likely overwhelms projected increases in average precipitation amounts.
- Droughts at least 6-10 months long increase in frequency by about an additional four events by the 2050s. The number of longer droughts doubles towards 2099.
- The number of droughts of at least five years doubles towards 2099.
- Decade-long droughts triple in frequency towards 2099.
- Storms with extreme precipitation are interspersed with droughts.
- Surprises result with the new combinations of climate variables.
- Worst-case scenarios of mega-droughts with even more intensity, frequency, duration and area are possible. These would have low probability, but high impact.

Purpose and Objectives

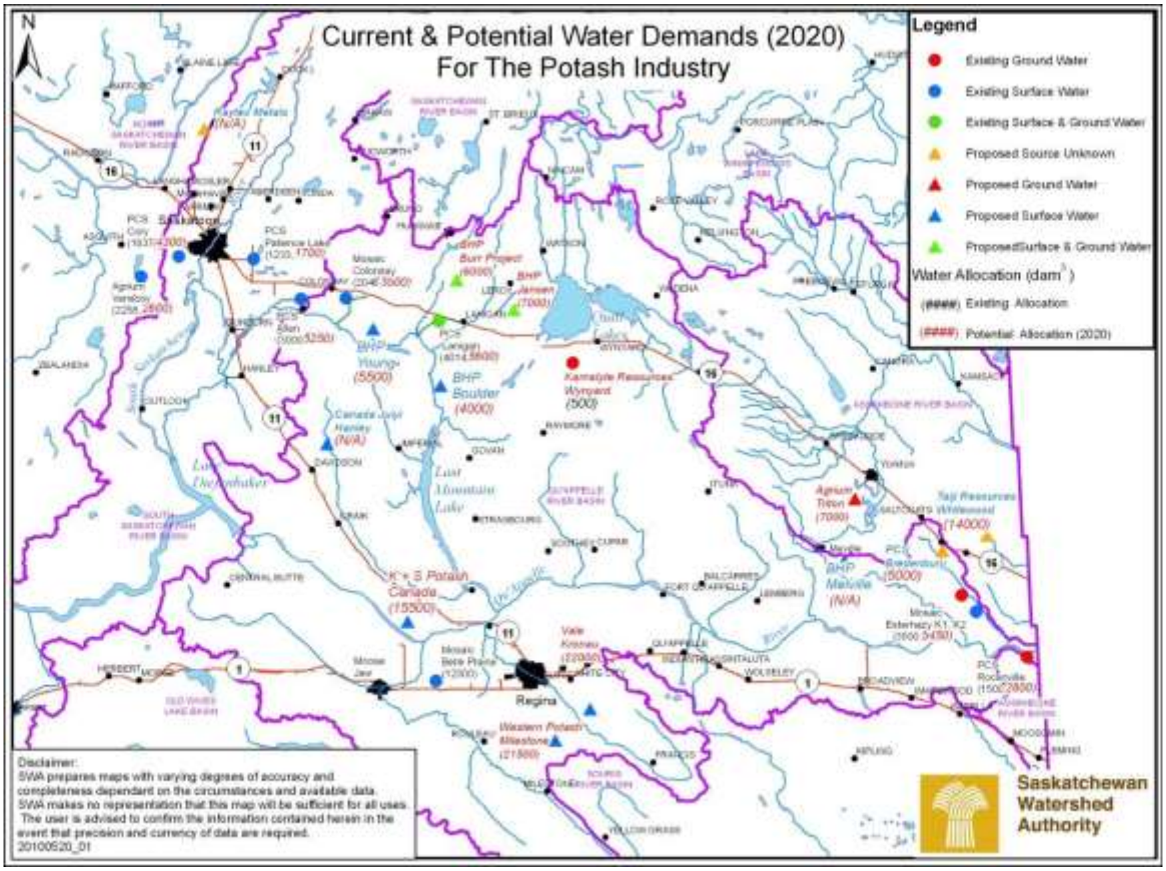
Droughts are significant hazards in Saskatchewan and are expected to become worse in the future with continued warming. Questions addressed here by use of a case study are: 1) what are some of the direct and indirect impacts of droughts on potash mining? 2) what lessons arise for adaptation planning and implementation? Risks are described as the product of the characteristics of drought (e.g., frequency) and impacts of the drought.

The purpose of this report is to provide an initial overview of the risks posed by droughts for the potash industry. The focus is on a case study of the Qu'Appelle River Watershed (QRW) in southeast Saskatchewan. The main impact areas considered for the potash mines are organized into direct and indirect effects. The main direct effect is the effect of drought on the balance of water supplies and demands. Indirect effects include those on water quality, safety (fire, heat stress, disease), management of waste, risk and emergency management, and markets/commodities. The effect of drought on water supplies is emphasized over the other possible indirect impacts. The scope of the report is an introduction to the topic in an exploratory manner.

The Natural Resources Canada (NRCan 2013) Adaptation Platform was established in April 2012 to encourage the mining industry and other sectors to examine potential climate change impacts and possible adaptation measures to manage these risks. This report provides initial work towards that goal. The process for understanding the risks and benefits of climate extremes, such as drought, consists of examining climate change and extremes, current impacts and adaptations, future possible impacts and adaptations, and vulnerabilities and opportunities. This report is a preliminary exploration of possible impacts of drought and adaptations to reduce negative effects and enhance benefits.

Potash Mining in the Qu'Appelle River Watershed

Much of the potash mining in Saskatchewan occurs in the QRW with five operating mines and eight proposed mines (Figure 1). These mines are PotashCorp at Lanigan and Rocanville, Mosaic at Esterhazy, Belle Plaine and Colonsay. The Colonsay mine is on the watershed's border and is included in order to use the data of Kulthreshtha et al. (2012). Only the Belle Plaine mine is a solution mine and the rest of the operating mines are underground mines. Expansion of currently operating mines and new mines are being planned (Kulthreshtha et al. 2012:18).



Map courtesy of Saskatchewan Watershed Authority.

Figure 1 Potash Mines in the Qu'Appelle River Watershed (SWA in Kulshreshtha et al. 20120)

The next section describes the methods. The following main section provides results of the literature review organized by topic areas of the impacts. This is followed by the discussion, conclusion, and recommendations to document the main points of the paper.

Methods

The main method used is a review of scientific journal articles regarding the risks of drought relevant to the Potash Industry in the study area. Literature regarding these topics appears sparse as it seems to be only an emerging area of research. Therefore, we also draw upon other types of publications for supplemental purposes. The range and numbers of scientific journals have been increasing considerably, so the review emphasized the climate impact, adaptation, and vulnerability literature.

The knowledge of the characteristics of past and future droughts is needed to estimate the main future possible impacts of droughts that would challenge the potash mining industry. That information is summarized in Wittrock (2013a) and Wheaton et al. (2013). Information about drought effects is then needed to determine risk and then suitable and effective adaptation options to reduce vulnerability.

The main effects of drought on the potash industry appear to be challenges to water supplies. Other work regarding impacts of major droughts on industry suggests that water supply is a main impact and risk (e.g., Wheaton et al, 2008, Wheaton et al. 1989). This direct effect is given priority here over the other indirect impact issues listed above.

An advisory committee was struck to provide initial direction, input and feedback. The committee consisted of people from the Water Security Agency, Saskatchewan, Ministry of Environment, Ministry of the Economy, the Saskatchewan Mining Association, Qu'Appelle Watershed Associations, Natural Resources Canada, Pittman Consulting, the University of Saskatchewan, and the Saskatchewan Research Council.

This work was coordinated with that of Pittman et al. (2013) and Wittrock (2013a and 2013b). Wittrock (2013a) characterized the historical drought and excessive moisture in the QRW. Wittrock (2013b) examines the historical risk of climate extremes to the potash industry, estimates future types of impacts and solutions, and gives a preliminary cost/benefit analysis of adaptation strategies. Pittman et al. (2013) used a case study and interviews with the potash industry in the QRW to examine climate change vulnerability and adaptation. The goal was to provide information regarding ways to enhance the competitiveness and adaptive capacity of the industry with a changing climate. They used interviews with key informants and document analysis to identify how climate change adaptation can enhance the competitiveness of the potash industry.

Results and Discussions

The main impact areas considered for the potash mines in the review of scientific journal articles and supplemental publications include the direct effect of drought on 1) water supplies and demands; and indirect effects on 2) water quality, 3) safety (fire, heat stress, travel), and 4) management of waste, 5) emergency and risk management and 6) markets and commodities management.

Water Supplies and Water Demand

"If water for processing and beneficiation is temporarily in short supply, operations can be disrupted and costs for post-use treatment can increase." (ICF Marbek 2012:8)

The balance between water supply and water demand determines the degree of water scarcity problems. Lack of water could result in challenges such as disruptions and increased costs or worse. Reliability of water supplies needs to be considered in all aspects of potash mining from establishment, expansion, and operations, through to decommissioning.

The threats to water availability in Canada, 2009, were mapped across Canada by Environment Canada (2013) (Figure 2). Southern Saskatchewan (including the QRW) was among the regions with a high threat, meaning that more than 40% of the water in rivers was withdrawn for human use. The indicator is the ratio of water demand and supply for each sub-drainage area. It does not include water withdrawn from lakes and groundwater.

The main source of water for the potash mines in the QRW is surface water. Many of the mines obtain their water through diversions from the South Saskatchewan River Basin. Most of the province's potash production is in the QRW. (Kulshreshtha et al. 2012:79). This section gives an overview of water demand for potash mining, water supplies during drought, and adaptation to water scarcity.

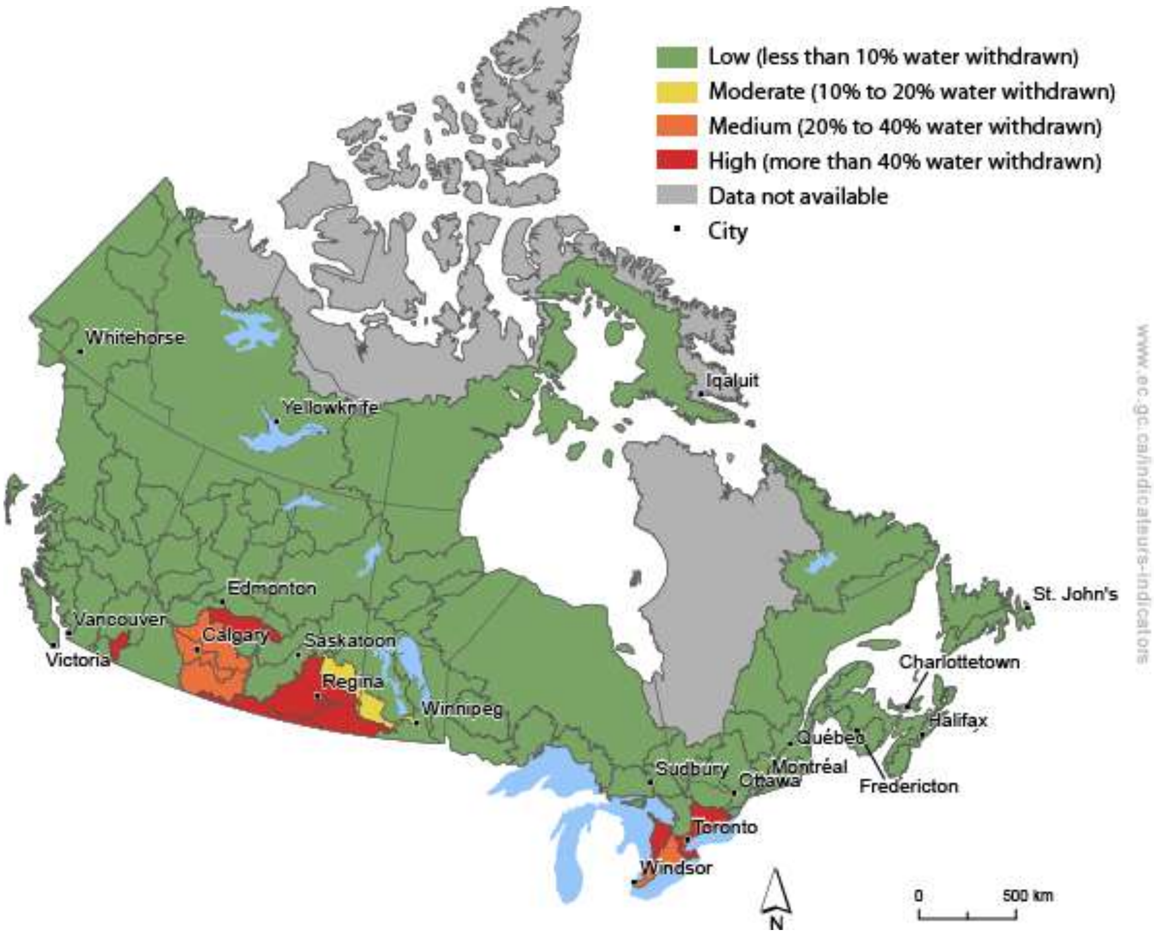


Figure 2 Threats to water availability in Canada, 2009
(Environment Canada 2013)

Water Demand for Potash Mining from Present to the Future

"The expansion of existing potash mines and development of new potash mines, especially solution mines, will have the biggest impact on water demand in the mining sector. Because of the nature of the potash extraction process, the water once used is unfit for other uses. Also, for some mines to be developed, significant amounts of water will have to be transferred from adjacent basins to fill the demand." (Kulshreshtha et al. 2012:29)

Water is used for many purposes at the mines. These include the extraction and milling of potash, domestic water, as well as waste disposal (Pittman et al. 2013). The water demand amounts vary with differences in technology of the milling process and the type of end product (Kulshreshtha et al. 2012:41). The need for water makes the potash industry sensitive to water scarcity. However, Pittman et al. (2013) reported no major stresses due to water shortage during 2002 to 2012. This finding could result from data restrictions and from lack of experience with the more severe droughts. Also, the mines could be able to cope with these shorter term periods of drought. A relatively short, but intense drought occurred during 2008 to 2010, however the core of this drought was in Alberta and western agricultural Saskatchewan (Wittrock et al. 2010). Therefore, signs of drought in the study area would have been slight.

Large expansions at currently operating mines and additional mines are planned for Saskatchewan and the QRW in the near future, and these would require even more water supplies. This need for additional water supplies may cause problems in times of decreased supplies due to droughts and increasing demands for water from other larger users, such as agriculture. The combination of worst droughts and increased demands will take the QRW and other watersheds in Saskatchewan into new territories of experience in terms of water supply, demand and availability.

Kulshreshtha et al. (2012) investigated the current (i.e., 2010) water demand levels in Saskatchewan, and provided estimates for three future periods, namely 2020, 2040 and 2060. Water demand was defined as an equivalent quantity of water intake or withdrawn from a source. The mining and industry components were combined in a mining/industrial sector. Three scenarios were developed for each period, namely a baseline, climate change and water conservation. For their climate change scenario estimates of water demand, they assumed future frequency of droughts to be 8% currently, 13% by 2040 and 18% by 2060.

Frequency of drought is not the only characteristic of concern. Other aspects such as severity, duration, timing and area of coverage have effects on water supply and demand and should be considered. The assumptions in the work by Kulshreshtha et al (2012) require comparisons against new findings emerging regarding future drought characteristics.

The water demand of the industry and mining sector in Saskatchewan was estimated at 106,647 dam^3 (2010), 202,807 (2020) and151,741 dam^3 in 2040. The industrial/mining sector demand is estimated to decline from the 2010 amount of 12% to 8% in 2060. Under the climate change scenario, no evidence was found to indicate that climate change would affect water demand. The reasons given were the nature of the production process and demand for water (p. 78). Under the water conservation scenario, the industry/mining sector's water demand is estimated to decrease by almost 8% by 2060 compared with the 2010 demand (Kulshreshtha et al. 2012:iii).

Water demand for potash production in Saskatchewan was estimated by Kulshreshtha et al. (2012:80) for each river watershed. For the QRW (baseline scenario) the demand is 2,082 dam^3 (transferred from the SSRW) and 13,999 dam^3 (from within the QRW); a total of 16,081 dam^3 for 2010. The amount increases to 9,209 plus 75,479 dam^3 by 2020, again for the baseline scenario. This is a total of 84,866 dam^3 is an increase of about 5.3 times the 2010 total. The demand tends to stabilize further into the future to a total of 103,958 dam^3 by 2060. The conservation scenario results in a lower increase to a total of 81,152 dam^3 by 2060.

Groundwater is used to supplement shortfalls in surface water, but the groundwater data are considered insufficient, for the most part. However, surface water demand is thought to increase at a faster rate than the demand for groundwater (Kulshreshtha et al. 20012). Surficial groundwater levels are sensitive to drought and supplies can be affected by drought (Wittrock 2003). Examples are provided in a subsequent section.

Kulshreshtha et al. (2012) note several data deficiencies, as well as those for groundwater, including the effect of water conservation and of climate change on water demand. They stress that identification of areas of water stress is needed. Several other recommendations include: the need for improved water use data, assessments of climate and water demand relationships, continued monitoring of drought effects, and development of many strategies to adapt to water scarcity. Kulshreshtha et al. (2012:51) found no study on the impact of climate change on water demand for Western Canada. However, they consider that important indirect linkages to water demand may be through water quality and availability.

Literature regarding climate relationships with water demand is lacking, but Chen et al. (2006) addressed this topic for the Calgary, Alberta region. They found a close relationship of climate and municipal water use. When weekly temperatures were greater than 10°C, municipal water consumption increased dramatically and created peak demands well above background. They estimate that water production may exceed licensed water withdrawal in hot summer days, especially during hot and dry times towards the 2060s. This would require water restrictions, water reuse and many other innovative and very effective adaptation strategies.

Water Supplies during Droughts

Water supplies during past major droughts indicate the type of water supply problems that may occur with future droughts. However, future droughts are projected to be more severe in several characteristics. Future droughts would also occur during a time with higher demands from increased population, agricultural irrigation, and expanded mining and other uses. Therefore, the likelihood of conflict and competition over water and the need for water sharing agreements would increase, unless adaptations such as water conservation and efficiency increase considerably.

The drought during 1999-2005 is a suitable example of a major drought as it brought some of the driest conditions in the Prairie Provinces in the historical record (Wheaton et al. 2008). Wittrock (2003) documented low flows, low water body levels, and groundwater levels across the Canadian Prairies during the 2001-2002 drought. For example, the mean annual flow of the South Saskatchewan River at Medicine Hat was the third lowest in the record since 1960, at 55 m^3/s. The drought in 1984-1985 and earlier produced lower flows. Water levels rebounded in June 2002 because of heavy rainfalls in southern Alberta and southwest Saskatchewan.

The 1999-2005 drought also affected the water levels of Lake Diefenbaker, a vital source of water for Saskatchewan. Monthly mean water levels of Lake Diefenbaker began to drop by 2000 and little recharge reached the reservoir until early summer 2002 (Figure 3). These rainfalls caused the levels to rebounded. The drought of 2001-2002 resulted in the lowest levels on Lake Diefenbaker since 1982.

Large area and intensive droughts affect water levels of Lake Diefenbaker. Lake Diefenbaker is a main source of water supplies for both the South Saskatchewan River and Qu'Appelle Watersheds. Therefore future effects of drought and resulting effects on stream flow are necessary to examine and consider in water supply planning. In terms of longer-term trends, spring inflows to Lake Diefenbaker have decreased by about 40 to 50% during the1970 to 2010 period. This trend is likely a result of a combination of the operation of the Oldman Dam, consumption, and climate change (Pomeroy and Shook 2012). Evaporation is a main consumptive use of water from the reservoir and is very high during droughts. The droughts of 1980, 1988, and 2001 pushed the calculated evaporation amounts to their highest levels for the record from 1972 to 2008 (Taylor p. comm. 2009).

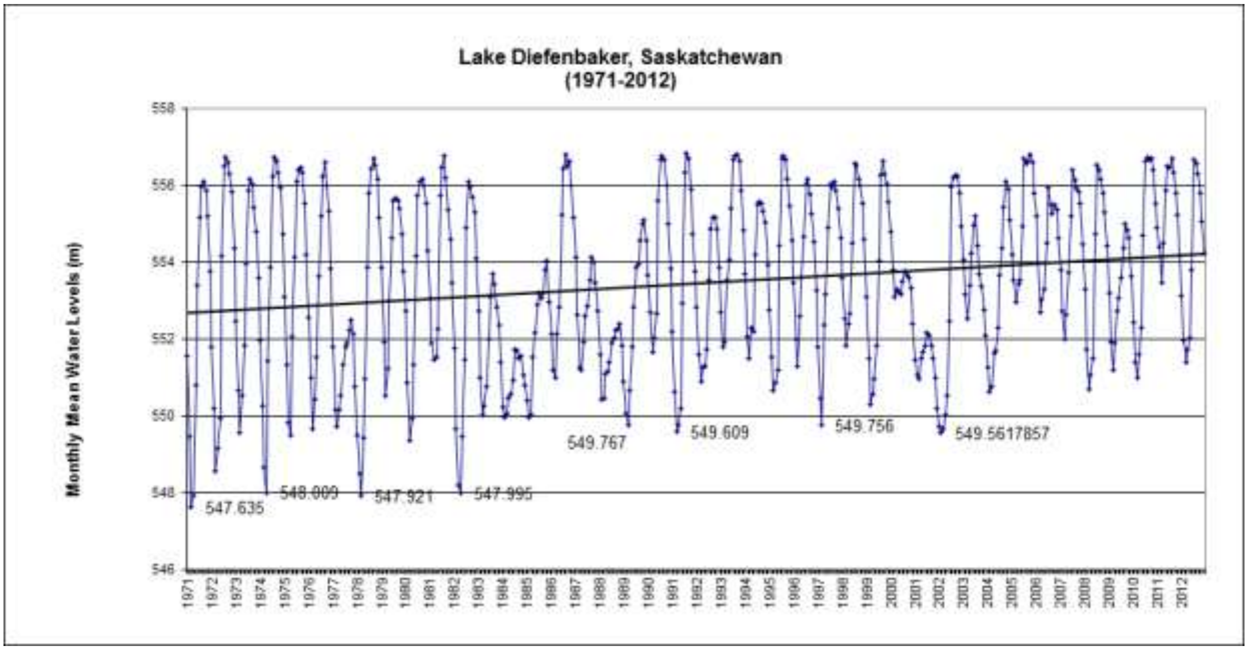


Figure 3 Lake Levels of Lake Diefenbaker, Saskatchewan, 1971 to 2012. Data: Environment Canada 2013b)

Wittrock (2013a) characterized many droughts specific to the study area of the QRW during 1901 to 2011. The worst five drought years were found to be 1961, 1988, 1949, 2001, and 1936-1937 using the Standardized Precipitation Evapotranspiration Index. Therefore, 2001 was found to be one of the worst recent droughts for this study area. Extreme wet periods rather than droughts have been causing trouble more recently, for example, during 2010-2011.

Projections for stream flow in the South Saskatchewan River (SSR) are for earlier spring runoff and average decreases of about 40% (Lapp et al. 2005). Martz et al. (2005) also projected decreased flows in the SSR in the future. These projections are averages, not considering the effect of drought, let alone multiple years of drought. St Jacques et al. (2010) examined trends of stream flows in Western Canada. They found that stream flows are declining at most gauged sites due to hydro-climatic changes of global warming and human impacts.

Groundwater is useful to augment surface water supplies. The drought of 2001-2002 caused large drops in the levels of observation wells in Saskatchewan (Wittrock 2003). Wells of shallow aquifers are most sensitive to droughts. Many observation wells of surficial aquifers showed declines especially during this drought period. An example is the Forget observation well in southeast Saskatchewan. The well levels had its second highest peak before 2000, then levels dropped considerably during the following dry period, and levels were still dropping in 2003. Wittrock et al. (2013c) are assessing the relationship of drought and extreme precipitation with groundwater in other watersheds in the prairies.

Adaptation: Planning for Times of Water Scarcity

The great variability of precipitation and climate change factors combine to increase odds of drought for the Canadian Prairies. Some mines are considering climate plans (Pittman et al. 2013) and the effects of droughts are recommended to be a part of the planning. Droughts that are beyond the type documented in the instrumental record and perhaps even the paleo-record are expected (Bonsal et al. 2012). Drought scenarios of the future indicate that demand may exceed supply for watersheds, and water deficits would occur during some years. Planning and preparation needs to reflect the characteristics of the future possible droughts in order to be suitable, practical and effective.

Adaptation to increasing water scarcity includes several measures, such as increased storage of various types, conservation, efficiency of use, decreasing demand (e.g., by technology and conservation), diversions and other alternative sources such as groundwater, pipelines, and waste water use (recycling). Some of these options are being considered and/or applied by the mines (Pittman et al. 2013). They grouped adaptive strategies in four categories: 1) infrastructure investment, 2) water reuse and recycling, 3) innovative and alternative water sourcing, and 4) proactive planning.

The understanding of adaptation to drought is at an early stage and literature is sparse. Work by Wittrock and Wheaton (2007) began to fill this knowledge gap by examining the process and effectiveness of adaptation for the 2001-2002 drought in the agricultural and rural setting. The lessons from this research are useful for other sectors, such as mining. The main mechanisms of adaptation were classified as technological developments, government and community programs, production practices and financial management. Barriers to adaptation were documented and included lack of funds and research, lack of awareness, and difficulty in making changes. Many adaptation options were recommended and implemented through several media, including the websites and news items, but some of the recommended measures were not adopted because of the barriers. Innovations occurred at several levels. Examples included water sharing and equipment design.

Even with the considerable adaptation capacity applied during the 2001-2002 drought in Canada, several negative impacts occurred in agriculture and related sectors (Koshida et al. 2011). Several of the adaptations implemented were not only costly and disruptive, but they required new learning and processes. This finding indicates that this major drought resulted exceeded the threshold of adaptive capacity for agriculture. This is a lesson for mining to find out what types of drought would exceed their thresholds of adaptive capacity. It is also a warning that intense, massive and multi-year droughts can results in negative impacts even with considerable capacity.

Kulshreshtha et al. (2012: 78) included a scenario with adoption of conservation measures to deal with future water demans. These adaptations were considered to have the capacity to reduce the water demand for potash production in Saskatchewan by 25,000 dam^3 by 2060. The conservation scenario for the QRW decreases the water demand at 2060 from 5.3 times the 2010 amount to 5.0 times. The assumptions for the conservation scenario were that the province has developed a water conservation policy and that measures were adopted by the water use sectors to reduce demand. The authors selected the conservation potential for each type of water demand. They note the large uncertainty in the impact of water conservation programs and the rate of adoption. The urgency of the various approaches appears to depend on immediate supply side problems, including drought.

Water conservation and efficiency of use has several benefits besides being able to deal with times of water shortages. These benefits include: include decreased energy use, decreased waste, decreased product loss (e.g., Reid 1984), and other improvements that can decrease costs of several types. Water resources research and management would benefit by increasingly considering the effects of climate extremes such as droughts and floods. Both supply and demand management and several other innovations are required to deal with future droughts.

Water Quality and Drought

Water quality problems occur during drought related to factors such as decreased dilution, increased water temperatures, and water losses with increased evaporation at higher temperatures. These would affect aspects of the potash mining that require potable water for example. Poor water quality affects infrastructure such as pipes and plumbing. Increased and enhanced water treatment may be required.

A water quality indicator is used in Saskatchewan that is an assessment of the chemical, biological and physical constituents of water (Davies and Hanley 2010). This indicator estimates the current water quality status of the watersheds. The Upper QRW was rated as healthy and the Lower QRW was rated as stressed. The data were based upon the period from 1999 to 2008. The healthy rating indicates no apparent change in the function or services provided by the water. The system is estimated to be resistant and resilient to change. The stressed rating shows that the watershed has no degradation in function and/or services it provides.

Nelitz et al. (2013) give examples of indicators of water quality as affected by climate change. These include water temperature, suspended sediments, dissolved solids, nutrients, and contaminants. Metrics for the indicators include annual maximum stream temperature, spring freshet maximum suspended sediment concentration, and days per year with nutrients of contaminants exceeding a threshold. Vulnerability ratings were provided by infrastructure for several climate stressors including drought. They show medium vulnerability to drought of water treatment (pre-treatment, softening clarification), valves and pipes, and storage. Medium vulnerability is given for water distribution, including pipelines and valves and pipe materials. They also indicate medium vulnerability for reservoir and river systems related to drought.

The US Environmental Protection Agency (2013) has drafted a climate adaptation implementation plan for region eight (North Dakota and Montana). A portion of the plan is directed to protecting waters affected by decreasing precipitation days and increasing drought intensity. They state that the warmer air temperatures and high number of dry days of drought will result in warmer water. This may lead to low oxygen levels and hypoxia, harmful algal blooms and changes in the toxicity of some pollutants.

Klavier-Kibria (2010) discusses the possibilities of changed water-borne diseases with climate change. Extreme rainfall events can result in high concentrations of water-borne pathogens in surface waters. Therefore, drought with its low number of storms, can be beneficial in this regard.

Adaptation would include enhanced monitoring and awareness of possible problems related to water quality issues. Proactive planning would be required, as well as suitable, tested, and effective adaptation solutions.

Safety Issues and Drought

Safety and health issues related to drought include the direct effects of increased risk of heat stress and heat-related illnesses, accidents/injury for workers, and air quality deterioration from wind-blown dust. Some indirect effects are increased vector-borne, food-borne and water-borne diseases and wild fires. Water-borne diseases are discussed in the previous section on water quality.

Drought is often accompanied by high temperatures. The question should be asked: what are the effects of high temperatures on the mining operations? How would health and safety of workers be affected? The record high temperatures in Canada were recorded close to the QRW. The

Canadian record high temperature is 45°C at Yellowgrass and Midale in southeast Saskatchewan in 1937 (Phillips 1990). Klavier-Kibria (2010) reports that morbidity and mortality related to hot weather occurs both directly and indirectly. Heat-related illnesses include edema, brief losses of consciousness, cramps, exhaustion and heat stroke. Heat waves tend to increase the number of patients at hospitals and emergency departments and excess deaths.

Drought is also associated with increases in vector-borne diseases such as West Nile Virus, Lyme disease and hanta virus. The first two are considered here. West Nile Virus is a new disease to North America and the Canadian Prairies. The virus is dependent upon climate, habitat, and hosts for its survival. The effect of the virus on humans ranges from little effect to death. Saskatchewan was by far the hardest hit province in Canada during the 2003-2010 period with about 2,500 total human West Nile virus cases reported. The West Nile Fever occurs after humans are bit by virus-carrying mosquitoes (Culex tarsalis). Both the virus and the mosquitoes are much more active and therefore dangerous during warm to hot weather. The mosquito requires very little water to breed and does well in irrigated areas (Wittrock and Wheaton 2010a, Wittrock et al. 2011).

Lyme disease is carried by the tick Ixodes scapularis. Lyme disease does not seem to be a major issue in the Canadian Prairies yet and is a new entity, although a warming climate is bringing the tick and its diseases closer to the region (Koshida et al. 2011). A benefit of drought is that the nymphs die rapidly at relative humidity less than 100%. Potential expansion of the range of Lyme disease has been assessed as driven by climate change. By 2020-2049 a low risk of Lyme disease is projected to creep into southeast Saskatchewan (Wittrock and Wheaton 2010b).

Droughts bring greater risks of dust storms. Dust storms are atmospheric disturbances with moderate to strong winds, blowing sediment and visibility reduced to 1.0 km or less at eye level. Dust storms are serious climatic hazards, resulting environmental, health and economic costs. As indicated by the definition, dust storms bring concentrated amounts of airborne particulates that can be hazardous to human health. The visibility reduction can also lead to transportation problems and accidents. During the severe drought of 2001-2002, at least 32 dust storms occurred, many traffic accidents were caused, along with two fatalities in Saskatchewan. Canada’s dust bowl is located in south-central Saskatchewan, just upwind of the study area (Wheaton 2005, Wheaton et al. 2008).

Wild fires in grasslands are a current risk and this risk increases during drought and higher temperatures. Two large grass fires burned occurred west of Saskatoon in October 2013. They burned more than 20 acres of land, but were brought under control within 1.5 h (CTV News 2013). Wildfires have affected large parts of other countries such as Australia and Russia in recent years (Bonsal 2013). Sectors such as health and transportation are adversely affected and damage to property can occur.

This is a reminder of the risk of grassland and cropland fires for communities and industry. The Government of Alberta has an industrial guidebook regarding wildfires (Alberta Government 2008). A first step is to assess the fire threat, than rank priorities, assess capabilities, and then identify mitigation options. Adaptive measures to deal with the increasing risk of wildfire during drought include keeping grass short, maintaining emergency water supplies and fire barriers, using fire-resistant materials and other “Fire-smart” ideas. The authors suggest updating company’s industrial wildfire control plan as required.

Management of Waste and Drought

"As part of a larger departmental program on Climate Change Impacts and Adaptation, CANMET-MMSL is assessing the current mine waste management and effluent treatment practices in the North with respect to their ability to accommodate the impacts of extreme climatic events. The work focuses on northern mining vulnerability, examining operations, development and reclamation projects, as well as researching potential adaptation options." (NRCan 2013). The results from this mine waste work of CANMET should be examined for information relevant to potash mining.

Waste management at potash mines may be subject to several effects of droughts. These would include the dust released from drying of brine ponds and possible wind erosion of tailings piles before they harden. . Fugitive dust is a reportable particulate to the National Pollutant Release Inventory of Environment Canada (2013c). Drying of brine ponds may be much easier to manage than dealing with extreme precipitation that can risk over-flowing of the ponds. Such problems can be managed using proactive options such as planning, close monitoring and contingency actions.

Markets and Commodity Management

Agriculture is the primary market for potash companies such as PotashCorp. The company also produces products for animal nutrition and industrial uses. PotashCorp is the world's largest crop nutrient company and has an important role in global food production (PotashCorp 2013). Droughts also affect regional and global food production and the use of agricultural inputs. Droughts are associated with reduced agricultural productivity in countries that purchase potash products for agricultural use. Depending on the timing of the drought, producers may choose to use less input, such as fertilizer. Potash from Saskatchewan is exported to more than 25 countries, with the main markets being the United States, China, Brazil, and India (Vigrass 2007).

Bonsal (2013) summarizes several climate extremes that have had serious effects on countries' food production and therefore, potential use of fertilizer. For example, during 2010 Russia experienced severe drought and shut down wheat exports because of limited supplies. In 2012 64% of the contiguous United States was in moderate drought or worse and 46% was in severe drought or worse. July 2012 was the hottest month ever recorded. A massive drought in 2010 in the United States also led to much reduced corn supplies and animal feed, for example. Southern China experienced a major drought during 2010 and 2011 that reduced food production.

Risk and Emergency Management for the Effects of Droughts

Potash companies provide forward-looking information in their news releases. Among the set of risks and uncertainties listed in the limitations on this information are those "associated with adverse weather patterns such as excess rainfall, fires, and floods" (PRN NewsWire 2013). However, no details for the explanation of the risks were found in a brief search of mining trade journals. The search of trade journals also found that the mining sector appears to be focusing on mitigation of greenhouse gases rather than impacts and adaptations. This focus would increase vulnerability to possible impacts, including those of droughts. One company is developing a climate change plan, as mentioned earlier (Pittman et al. 2013) however, no further details are provided.

Ford et al. (2010, 2011) surveyed the perception and responses of Canadian mine operations regarding climate change. Their results reinforce the requirement for research regarding the vulnerability of mining to climate change and the evaluation of adaptation options.

Nelitz et al. (2013) discuss risk assessment as one of the set of tools for climate change vulnerability analysis. The assessment is a method to prioritize aspects of the built and natural environment that are more sensitive to climate stressors. Risk assessment includes the processes of characterizing hazards, assessing impacts, and identifying adaptation to evaluate the vulnerability to climate risks. Risk ratings are given in terms of the magnitude of the consequence or impact and the probability of the hazard. Information regarding the probability of future droughts in southeastern Saskatchewan is provided in Wheaton et al. (2013). Other characteristics of drought, including duration and timing also are required. However, this review finds that information regarding impacts of drought and adaptation appears sparse and much more research of various types is required. This knowledge gap is a major barrier to the risk assessment process.

Insurers are raising the issues related to climate change. “Many major insurers, industry associations, and reinsurers, such as Swiss Re and Munich Re have been at the forefront of raising the profile of climate change as a business risk rather than an environmental issue. Left unmanaged, these risks may cause insurers to raise premiums or withdraw cover in particularly vulnerable locations.” (ICF Markek 2012: 11).

Additional Risks and Benefits posed by Droughts

Research regarding effects of droughts on potash mining is so sparse that several other effects may be possible as well as the ones mentioned here. This area is a knowledge gap. Questions include: what effects are possible for storage and shipment of product. This may be a benefit as drought often brings many dry days and reduced numbers of storms. This would make it easier to store and transport water sensitive products. Mild winters may mean less product used to treat roads (where applicable) and may lead to decreased sales (Business Wire News 2013). Compass Minerals, a supplier of salt and potash, reported a decline in sales by December 2012 due to the mild winter and continued mild weather.

The de-commissioning of potash mines is another area to examine for drought and other climate change effects. Plans should consider new dynamics of climate to ensure safety and security of many systems, including people, plants, animals and water supplies. Drought effects on water resources can be both integrated and cumulative threats (Cohen et al. 2004). Integrated threats to the water supplies are those that occur with combined stresses (e.g. increased agriculture, population, and mining demands for water). Cumulative threats include those that evolve over time and emerge slowly. These occur as climate change affects drought drivers, including increasing temperature and atmospheric patterns.

Risks of Other Climate Extremes besides Drought

Drought is not the only climate extreme that is changing as global warming continues. Other climate extremes can also pose risks to mining. These include extreme rainfall and snowfall events, multi-day rains, multiple wet years, extreme rain on snowpack, strong windstorms, lightning, and high humidity, as well as the risk of multiple extremes. Their impacts mean that adaptation planning and contingencies would be required. These would be for aspects such as travel, transport and communication, heat, and backup power.

The impacts from extreme precipitation and associated flooding may cause some of the most severe impacts. These extremes are expected to be beyond those recorded in the instrumental record (Wheaton et al. 2013) and may be well beyond those extremes planned for by industries and government. Wittrock (2013b) discusses a wider extent of risks to potash mining of climate extremes.

Conclusions and Recommendations

Droughts can have both positive and negative impacts for various aspects of potash mining, including impacts during establishment, operations, and on marketing and strategy. The more knowledge about these relationships and early warnings of impacts can lead to improved adaptation to shifting climate patterns. This report provides one of the first overviews of the risks to potash mining of droughts. Research on this topic appears to be very sparse so many issues were covered.

Droughts are significant hazards in Saskatchewan and are expected to become worse in the future with continued warming. Questions addressed here by use of a case study are: 1) what are some of the direct and indirect impacts of droughts on potash mining? 2) what lessons arise for adaptation planning and implementation? This section is organized into three standard parts of vulnerability assessment, with recommendations for each part: 1) characteristics of drought, the exposure, 2) sensitivity of the mining industry, the impacts, and 3) adaptation and vulnerability. Adaptation and vulnerability assessment require all three phases of information. Research regarding drought was boosted, until recently. So that work appears to be ahead of research regarding the impacts of drought on the potash industry. This is a large barrier to the understanding of the vulnerability of the industry to both droughts and climate change and to the adaptation required to reduce vulnerabilities and gain from benefits.

Characteristics of Droughts

Past droughts have been characterized and found to have some previously undocumented aspects, including their tendency to 1) migrate into the Canadian Prairies from the United States, 2) form during winter when they may not be as carefully monitored, and 3) have multiple causes that may be changing. Research is beginning to assess future possible droughts and concern is being expressed that the risk of larger, more intense and frequent droughts is emerging. These droughts are expected to be worse than those of the instrumental record and perhaps even of the paleo record that includes mega droughts.

Recently drought research has been boosted by projects such as the Canada DRI (Drought Research Initiative). However, this program and others have ended, and such research has slowed. Droughts are one of the worst hazards and new research programs are required. The types of droughts that cause particularly difficult impacts to the potash industry appear to be a knowledge gap. Communication of the new knowledge about droughts and their climate change drivers is also in its early stages. Much enhanced communication is crucial to effective adaptation to future droughts.

Exposure to Droughts and Adaptation

The main direct effects of drought to potash mining are thought to be through water scarcity. Several indirect effects include effects on water quality, safety and health, waste management, emergency and risk management and marketing. Main points include:

1) Potash mining requires substantial and reliable water supplies, and therefore is sensitive to water scarcity. More frequent and severe droughts are expected than those of the past. Therefore, improved knowledge of impacts of drought water supplies and demand, as well as adaptation and adaptation planning are needed. Expansion plans for current mines and the development of new mines should consider climate change and drought adaptation planning such as for the possibility of water scarcity.
2) The main direct effect of future droughts appears to be water scarcity and corresponding possible water conflicts. Further understanding of this effect is needed. Research questions include: what effects would occur with a multi-year (e.g., 5-10y), severe and large-area drought? What deficits would occur with the water supplies? What increases in water demand would result? What types of drought is the potash industry prepared for? What are the chances of these types of drought occurring?
3) Further increases in water use efficiency, storage and exploration of alternate sources may be required sooner than previously considered. What is the current adaptive capacity of the potash industry to deal with major droughts? How effective is this capacity?
4) Indirect effects of droughts may be numerous and perhaps as important as water quantity concerns. These would compound the direct effects and therefore, require further evaluation.
5) New lessons about past, present and future droughts are emerging due to past successful research programs. Risks of droughts are determined by the product of knowledge of these drought characteristics, including probabilities, and by knowledge of impacts. The latter is lagging and is a barrier to estimating risk. Therefore risk management is inadequate.
6) Impacts of other climate extremes, such as intense precipitation should also be considered. These other extremes may have effects that exacerbate drought effects. Their effects and corresponding adaptation are knowledge gaps.
7) Further development of tools and information is needed to aid industry, government and professionals to improve understanding of drought and climate change impacts on mining. Climate change and drought adaptation planning would be included as a main tool, perhaps as a part of enterprise risk management and strategic planning already being done by companies.
8) Much more and enhanced collaboration is needed among water, climate, government and industry people to address the task of decreasing vulnerability to climate extremes such as drought.

Overall, knowledge of the impacts of droughts on potash mining appears to be limited. This increases the risks of drought to the industry and therefore vulnerability to such climate extremes.

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References

Alberta Government .2008. FireSmart Guidebook for the Oil and Gas Industry. Provincial Forest Fire Center, Government of Alberta, Edmonton, AB. 40p.

Bonsal, B. 2013. Extreme weather and climate: is this the new norm? Presentation. Environment Canada, Saskatoon, SK. 57 slides.

Bonsal, B, R Aider, P Bachon, S Lapp. 2012. An assessment of Canadian prairie drought: past, present, and future. Climate Dynamics DOI 10.1007/s00382-012-1422-0

Bonsal, B, E Wheaton, A Meinert, E Siemens. 2011. Characterizing the surface features of the 1999-2005 Canadian Prairie Drought in relation to previous severe twentieth century events. Atmosphere-Ocean 49(40):320-338.

Business Wire News. 2013 January 10. Compass Minerals reports fourth-quarter highway deicing. Accessed 20 March 2013 at http://192.168.33.1/login.asp?www.northernminer.com/press-releases/story.aspx?id=1001979392

Chen, Z, S Grasby, K Osadetz and P Fesko. 2006. Historical climate and stream flow trends and future water demand analysis in the Calgary region, Canada. Water Science & Technology 53(10):1-11.

Cohen, S, R de Loe, A Hamlet, R Herrington, L Mortsch, D Shrubsole. 2004. Integrated and cumulative threats to water availability. Chapter 15 in Threats to Water Availability in Canada. National Water Research Institute, Burlington, ONT. NWRI Scientific Assessment Report Series No. 3 and ACSD Science Assessment Series 1. 128 p.

CTV News Saskatoon. 2013 October 1. Fire crews battle grass fires west of city. Accessed 24 December 2013 at http://saskatoon.ctvnews.ca/fire-crews-battle-grass-fires-west-of-city-1.1477985

Davies, H and P T Hanley. 2010. State of the watershed report. Saskatchewan Watershed Authority, Regina, SK. 39 p.

Environment Canada 2013a. Threats to water availability, 2009. Sources: Environment Canada (2012) Water Survey of Canada; Environment Canada (2011) Municipal Water and Wastewater Survey 2009; Statistics Canada (2012) Industrial Water Use Survey 2009; Statistics Canada (2011) Agricultural Water Use Survey 2010. Accessed 8 December 2013 at: http://www.ec.gc.ca/indicateurs-indicators/default.asp?lang=en&n=1B1433B4-1

Environment Canada, Water Survey of Canada. 2013b. Hydrometric Data. Accessed on 23 Dec 2013 at http://www.wsc.ec.gc.ca/applications/H2O/index-eng.cfm and graphed by V Wittrock, SRC.

Environment Canada, National Pollution Research Inventory. 2013c. Pollution and Waste, National Pollution and Waste Toolbox, Question and Answer. Accessed on 24 December 2013 at http://www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=A500F136-1

Ford J, T Pearce, J Prno, F Duerden, L Berrang-Ford L, M Beamier, T Smith, D Marshall. 2010. Perceptions of climate change risks in primary resource use industries: a survey of the Canadian mining sector. Reg Environmental Change 10:65–81.

Ford JD, T Pearce, J Prno J, F Duerden, L Berrang-Ford, T Smith, M Beamier. 2011. Canary in a coal mine: perceptions of climate change risks and response options among Canadian mine operations. Climate Change 109:399–415.

ICF Marbek. 2012. Adaptation Platform Mining Working Group: State of Play Report. Submitted to Adaptation Platform Mining Working Group, NRCan. Ottawa, ONT. 23pp.

Klavier-Kibria, J. 2010. Health. Chapter 11 in Sauchyn, D, H Diaz, S Kulshreshtha (editors). The New Normal: the Canadian Prairies in a Changing Climate. CPRC Press, University of Regina, Regina, SK. 380p.

Koshida, G, E Wheaton, V Wittrock. 2011 April. Assessing water adaptations and determining coping ranges to the 2001-2002 drought. Presentation and paper for the American Water Resources Association Conference, Baltimore, Maryland. Saskatchewan Research Council, Saskatoon, SK. 6p.

Kulshreshtha, S, A Bogdan, C Nagy. 2012. Present and Future Water Demand in Saskatchewan—A Summary by River Basins. Prepared for Saskatchewan Watershed Authority. University of Saskatchewan, Saskatoon, SK. 233 p.

Lapp, S, J Byrne, K Townshen, and S Kienale. 2005. Climate warming impacts on snowpack accumulation in an alpine watershed: a GIS based modeling approach. International Journal of Climatology 25(3):521-536.

Martz, L, T Rolfe, and R Armstrong. 2005. Climate change and water resources in the South Saskatchewan River Basin: an overview. Canadian Water Resources Association 58th Annual Conference. Reflections to our Future, Banff, AB. CWRA.

Natural Resources Canada (NRCan). 2013. Adaptation Platform. Accessed 27 December 2013 at http://www.nrcan.gc.ca/environment/impacts-adaptation/adaptation-platform/10027

Natural Resources Canada (NRCan). 2012. Minerals and Metals Sector (MMS) Project on Mine Waste Management in a Changing Climate, Enhancing Competitiveness in a Changing Climate Program. Accessed 1 December 2013 at http://www.nrcan.gc.ca/plans-performance-reports/17

Nelitz, M, S Boardley, R Smith. 2013.Tools for climate change vulnerability assessments for watersheds. Prepared for Canadian Council of Ministers of the Environment by ESSA Technologies Ltd. CCME. 135 p.

Pearce T, J Ford, J Prno, F Duerden. 2009. Climate change and Canadian mining: opportunities for adaptation. The David Suzuki Foundation, Vancouver

Pearce T, J Ford,J Prno, F Duerden, J Pittman, M Beamier, L Berrang-Ford, B Smit. 2011. Climate change and mining in Canada. Mitigation and Adaptation Strategies Global Change 16:347–368.

Phillips, D. 1990. The Climates of Canada. Canadian Government Publishing Centre, Ottawa.

Pittman, J, J Pearce and J Ford. 2013 DRAFT. Adaptation to climate change and potash mining in Saskatchewan: Case study from the Qu'Appelle River Watershed. Prepared for NRCan, Ottawa, ONT. 17pp.

Pomeroy, J and K Shook. 2012. Review of Lake Diefenbaker operations, 2010-2011. Presentation, Centre for Hydrology, University of Saskatchewan, Saskatoon, SK. 14 p.

PotashCorp. 2013. January 30. PotashCorp Increases Dividends by 33 Percent. PotashCorp web site accessed 20 March 2013 at www.potashcorp.com.

PRN NewsWire. 2013a Jan 30. The Mosaic Company announces settlement. Accessed 20 March 2013 at http://192.168.33.1/login.asp?www.northernminer.com/press-releases/story.aspx?id=1002026737

Reid, K. 1984. Water use in Saskatchewan's Potash Industry and opportunities for water recycling/conservation. Canadain Water Resources Journal 9:1:21-26. DOI:10.4296/cwrj0901021

St Jacques, J, D Sauchyn, Y Zhao. 2010. Northern Rocky Mountain streamflow records: global warming trends, human impacts or natural variability? Geophysical Research Letters 37, L0640 DOI 1029/2009lGL04045.

Stewart, R, J Pomeroy and R Lawford. 2011. The Drought Research Initiative: a comprehensive examination of drought over the Canadian Prairies. Atmosphere-Ocean 49(4): 297-302.

Taylor, N. 2009. Personal communication to E Wheaton. Neil Taylor, Environment Canada, Edmonton.

US Environmental Protection Agency. 2013. Draft Climate Adaptation Implementation Plan. Proection Agency Region 8. US EPA. 32 p.

Vigrass, L. 2007. Earth resources: energy and mining. Chapter 16 in Thraves, B, m Lewry, J Dale and H Schlichtmann. Saskatchewan: Geographic Perspectives. Canadian Plains Research Center, University of Regina, Regina, SK. 486p.

Wheaton, E. 2005. Dust Storms. In Envyclopedia of Sassskatchewan. Canadian Plains Research Center, Regina, SK. Saskatchwan Research Council #11182-3A05. P. 263-264.

Wheaton, E, S Kulshreshtha, V Wittrock, G Koshida. 2008 Dry times: lessons from the Canadian Drought of 2001 and 2002. The Canadian Geographer 52(2):241-262.

Wheaton, E, B Bonsal, V Wittrock. 2013. Future possible dry and wet extremes in Saskatchewan, Canada. Prepared for the Water Security Agency, Saskatchewan. Saskatchewan Research Council #13462-1E13. Wheaton, Saskatoon. 33p.

Wilhite, D, 2000. Drought as a natural hazard: concepts and definitions. In D Wilhite, ed, Drought, A Global Assessment. Routledge Press, New York, NY. Vol. I:3-18.

Wilhite, D. and M. Glantz. 1985. Understanding the drought phenomenon: the role of definitions. Water International 10:111-120.

Wittrock, V. 2013a DRAFT. Characterization of historic drought and excessive moisture in the Qu'Appelle River Watershed. Prepared for the Water Security Agency of Saskatchewan. Saskatchewan Research Council, Saskatoon, SK. 58p.

Wittrock, V 2013b DRAFT. Past, present and future vulnerability and risks of climate extremes for Potash Mines in the Qu'Appelle River Watershed: Literature review. Prepared for the Water Security Agency of Saskatchewan, Saskatchewan Research Council, Saskatoon, SK.

Wittrock, V. 2003. Canadian Droughts of 2001 and 2002. Water Resource Conditions in Western Canada: Impacts and Adaptations. Prepared for Agriculture and Agri-Food Canada. SRC #11602-4E03. Saskatchewan Research Council, Saskatoon, SK. 87p.

Wittrock, V, E Wheaton, B Bonsal. 2013c Draft. Implications of climate extremes for groundwater resources. Prepared for the Vulnerability and Adaptation to Climate Extremes in the Americans Project, Prairie Adaptation Research Collaborative, University of Regina, Regina, SK.

Wittrock, V and E Wheaton. 2010a. Climate hazards for disease risk: a case of West Nile Virus. Prepared for Environment Canada, Toronto, ONT. SRC #12624-8E09. Saskatchewan Research Council, Saskatoon, SK. 42 p.

Wittrock, V and E Wheaton 2010b. Climate connections with vector-borne diseases: a case study of the Ixodes Scapularis Tick and Lyme Disease in the Canadian Prairies. Prepared for Environment Canada, Toronto, Ont. SRC# 12829-15E10. Saskatchewan Research Council, Saskatoon, SK. 31 p.

Wittrock, V, E Wheaton, E Siemens. 2010 March. More than a close call: a preliminary assessment of the characteristics, impacts of, and adaptations to the drought of 2008-2010 in the Canadian Prairies. Prepared for Environment Canada. Saskatchewan Research Council, Saskatoon, SK. 157p.

Wittrock, V, E Wheaton and G Koshida. 2011 June. Climate connections to insects and diseases in the Canadian Prairies. Canadian Meteorological and Oceanographic Society Congress Presentation. Victoria, BC. Saskatchewan Research Council, Saskatoon, SK. #11228-1D11. 19 p.

Wittrock, V and E Wheaton. 2007. Towards understanding the adaptation process for drought in the Canadian Prairie Provinces: the case of the 2001 to 2002 drought and agriculture. Prepared for the Government of Canada's Climate Change Impacts and Adaptation Program. Saskatchewan Research Council, Saskatoon, SK. 154 p.