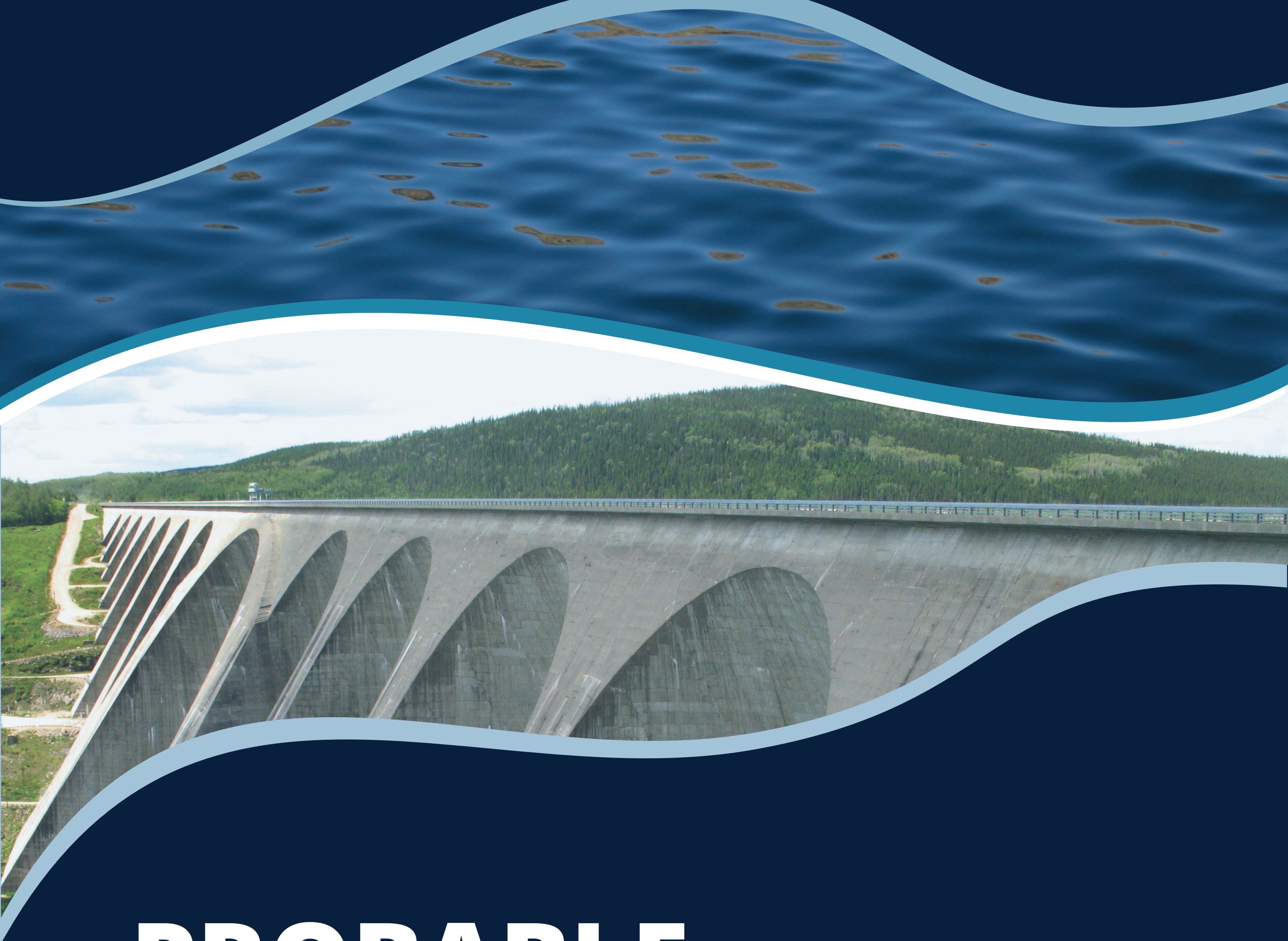

PROBABLE MAXIMUM FLOODS AND DAM SAFETY

IN THE 21ST CENTURY CLIMATE

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Centre d'expertise hydrique Québec

Participating Institutions

Ouranos
Located in Montréal, the Ouranos consortium conducts and funds research into regional climatology, climate change impacts and adaptation options.

Hydro-Québec
Québec's publicly-owned electric utility, Hydro-Québec is North America's largest hydroelectric producer, generating 99% of its electricity from renewables.

Ontario Power Generation
An Ontario crown corporation, OPG produces more than half the electricity used in the province, mainly from hydro- and nuclear-generating stations.

Rio Tinto
The aluminum-product group of Rio Tinto, RT is one of the largest producers of bauxite, alumina and aluminum, and owns hydroelectric facilities in Québec and British Columbia that power its smelting operations.

Manitoba Hydro
Manitoba Hydro, the province's public electric and natural-gas utility, produces approximately 98% percent of its electricity through hydropower.

Centre d'expertise hydrique du Québec
The CEHQ monitors dam-operator compliance with the *Dam Safety Act* and securely operates some 760 dams on behalf of the provincial government, working closely with other stakeholders to manage Québec's water regime based on safety, fairness and sustainable-development criteria.

Institut national de la recherche scientifique – Eau, Terre et Environnement
Located in Québec City, the Institut does applied and fundamental research in hydrology, biochemistry and geosciences.

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Executive Summary

Accommodating the shifts in precipitation and runoff associated with climate change represents a significant challenge for the owners and operators of dams. Most dams are designed to operate for many decades, so understanding how climate change may impact extreme-rainfall and flood events is essential to ensuring that current and future dams can operate safely and efficiently well into the future.

Executive Summary (Continued)

This study examines the methods used to estimate flood risk for dam design, and applies a method to incorporate projected climate change impacts to flood risk and identify potential adaptation options for five watersheds across Canada.

BACKGROUND

Dams provide multiple benefits to society including water security, energy production, river regulation and flood control. A trade-off for all of these benefits is the risk of dam failure and the ensuing, potentially large-scale human, environmental and financial losses. For this reason, safety is a critical issue for dam owners and operators, and it drives the continued development and implementation of safety-management systems to protect society against these risks.

In Canada, dam safety is regulated at the provincial level; however, most provinces have legislation that incorporates standards inspired by or mirroring the Canadian *Dam Association's Dam Safety Guidelines*. Among the many design criteria and inspection requirements identified by these guidelines, every dam must be able to accommodate an increase in water volume generated by upstream extreme-flood events; the amount of this increase varies based on a dam's hazard classification and the consequences of a breach or failure.

IN CANADA, DAM SAFETY IS REGULATED AT THE PROVINCIAL LEVEL; HOWEVER, MOST PROVINCES HAVE LEGISLATION THAT INCORPORATES STANDARDS INSPIRED BY OR MIRRORING THE CANADIAN DAM ASSOCIATION'S DAM SAFETY GUIDELINES.

Most dams in Canada are classified in the lesser-hazard categories, although many large and important structures are in the extreme-hazard category, because of the potential consequences of failure. Dams in the extreme classification are required to safely accommodate an inflow equivalent to the probable maximum flood (PMF). PMF is the largest reasonably plausible flood that could occur at some location and some time of the year, based on meteorological and hydrological considerations. The PMF is meant to be an objective design criterion; however, its magnitude will change as the scientific understanding of meteorology and hydrology evolves, and as the tools and technologies available to dam-safety practitioners advance.

STUDY MOTIVATION

Current climate change science suggests that the probable maximum precipitation (PMP)—the type of rainfall that often leads to PMFs—may increase in the next century. However, few studies have examined the potential regional impacts of PMP events and there is little guidance on how to incorporate potential climate change risks into the design and operation of dams. Dam owners and regulators currently face the challenge of determining a feasible and scientifically defensible method to quantify the climate change impacts on PMP/PMF, and to use this method to identify adaptation options to manage the associated risks over the lifetime of both existing and planned structures.

To address this need, the Ouranos Consortium partnered with academics, dam owners and regulators to better understand the risks climate change poses to Canadian dams. The main objective of this project was to review existing methods of PMP/PMF estimation, develop a credible methodology that owners and regulators can use to quantify potential climate change impacts on PMP/PMF estimates, and identify adaptation options available to manage the associated risks. Five Canadian watersheds with differing physiographic characteristics were included in this study to explore the variability of impacts across the country, with a focus on identifying climate change impacts for the 2050s future time horizon (2041-2070).

METHODOLOGY

The study included three phases. Phase 1 involved a literature review of how PMP/PMF has historically been calculated

Executive Summary (Continued)

in Canada, and of the research to date regarding the climate change impacts on these events. Discussions with each participating hydrologist identified and improved understanding of the similarities and differences in the methodologies employed to estimate the current PMP and PMF values for each targeted watershed. This helped identify the climate variables and types of experiments required to quantify climate change impacts on the resulting PMF. A literature review of methods used by the dam-safety community to accommodate a larger-than-design flood event was also conducted to inform discussions on future adaptation options.

Phase 2 focused on developing a methodology to incorporate climate change impacts into relevant meteorological variables. Using an ensemble of 14 Regional Climate Model (RCM) simulations, the projected changes for each watershed's spring PMP, 1/100 year maximum snowpack, and critical spring-temperature sequence were estimated for the 2050s. Changes in the summer/fall PMP in the 2050s were also estimated, but were not used in the subsequent PMF analysis, because they were not deemed to govern the calculated future PMF.

Phase 3 consisted of using the meteorological climate change factors estimated in Phase 2 to determine the resulting impacts on each watershed's spring PMF estimate. To support a meaningful comparison of the results obtained for the five study basins, a basic set of three standard experiments (and one additional optional experiment) was employed to understand the relative impacts of each meteorological input on the resulting PMF. Upon determining the magnitude and level of confidence in changes to PMF, each hydrologist provided commentary on potential adaptation options that could be considered to address these impacts, if required.

FINDINGS & CONCLUSIONS

Phase 1 results found that the largest historical PMF resulted from a spring-PMP event coinciding with the melt of a large (1/100 year) end-of-season snowpack for all five watersheds. For this reason, the remaining phases of the project focused on PMFs generated by this critical combination.

Phase 2 determined that the projected change in climate variables related to the spring PMF varies depending on the basin. Median change in the PMP for each watershed ranged from -10% to +20%, depending on the watershed and duration of storm. For most eastern watersheds, 2050s PMPs are likely to increase; for western study basins, no consensus was found. The 1/100-year maximum snowpack estimated from the RCM data showed a median change ranging from -9% to +8%, with decreases likely in southern watersheds, no consensus for more central basins, and an increase likely for the northernmost watershed. For all of the watersheds studied, spring thaw was found to occur earlier in the future, with a median change ranging from 5.5 to 9 days.

Phase 3 indicated general increases in PMF estimates, although the amount of increase varies considerably depending on watershed, experiment and climate scenario. Median changes in PMF peak flows were found to range between -0.8% to +20%. The results varied substantially, however—overall changes in PMF-peak flows ranged from -25% to +90%, depending on basin and specific climate scenario. Changes in total PMF volume were generally less extreme than peak flows, and in many cases, projected reductions in snowpack partially offset the projected increases in PMP for the watershed.

Although results from this study indicate that climate change may increase future PMF values, it is less clear whether or not the investments required to accommodate these unlikely events are justified in all cases. Given the high level of uncertainty in individual PMF projections relative to the median projected changes, non-structural and regulatory adaptation-options were identified as the preferred way to manage potential impacts of climate change on PMF risk. Participants also noted the merit of performing a risk-based analysis to determine the maximum water volume a given structure should be required to accommodate.

Table of Contents

Dams: Built for Safety

Today's dams incorporate construction, design and maintenance experience spanning millennia. Indeed, the oldest dam still in operation dates from the reign of Egyptian Pharaoh Sethi more than 3,000 years ago in today's Syria. Dams have historically been built to store water for consumption, irrigation and navigation, as well as to control flooding. In more recent centuries, dams have also been used to generate mechanical power for milling and pumping, and eventually, electricity. The tradeoff for these benefits is a risk of dam failure and the ensuing large-scale, possibly even catastrophic, flooding. In a sense, dams are built when the recurring benefits outweigh the unlikely but wide-ranging potential damages.

The high cost of dam failures has inspired governing bodies to impose regulations on dam owners. In Canada, dam safety falls under provincial jurisdiction, and regulations are often inspired by or mirror the Canadian Dam Association's *Dam Safety Guidelines* (CDA, 2013). The guidelines classify dams by size and by the consequences of a breach on lives, the environment and the economy, with five hazard levels from low to extreme. Design, building criteria, inspection schedules and the frequency of reviews are set according to the dam's classification. For example, dams with high and very high hazard levels must be able to withstand the largest upstream river runoff occurring on average every 1,000 years. In practice, this usually means installing spill gates large enough to accommodate and direct incoming runoff safely downstream while maintaining reservoir levels below critical thresholds. Indeed, once water overtops a dike, seepage and overflow erode and weaken the crest in a chain reaction that eventually leads to a breach.

THE PROBABLE MAXIMUM FLOOD (PMF) IS THE LARGEST REASONABLY PLAUSIBLE FLOOD THAT COULD OCCUR AT A GIVEN LOCATION AND TIME OF YEAR, BASED ON METEOROLOGICAL AND HYDROLOGICAL CONSIDERATIONS.

Extreme hazard dams have to meet requirements based on the concept of probable maximum flood (PMF). PMF is the largest reasonably plausible flood that could occur at a given location and time of year, based on meteorological and hydrological considerations. The PMF is meant to be an upper limit to flooding, conveying the idea that the dam should be built to withstand the largest amount of rain and snowmelt that is compatible with our understanding of the physical world. While it is meant to be an objective criterion, PMF values ultimately depend on our evolving understanding of meteorology and hydrology. The challenge is that a PMF, by definition, is beyond anything previously observed—the concurrence of rare and extremely unlikely events that creates the so-called perfect storm.

The concept of PMF and the methodology to compute it dates from the 1930s (Tomlinson & Kappel, 2009), when high-quality meteorological data were much harder to come by and computations were done by hand. Today's satellite observations and computing capability create opportunities to modernize and possibly improve our estimation of PMFs. Also, our improved understanding of climate processes enables us to model and simulate what the climate might look like 50 to 100 years from now, and to infer the consequences for flood intensity. These climate simulations, consistent with the observed records, suggest an increase of 20-30% by 2070–2100 in the type of rainfalls that lead to PMFs (Kunkel et al., 2013). This is of concern to dam owners since many existing dams will still be standing at that time. Furthermore, population increases and development intensification are likely to increase our reliance on the benefits of dams and magnify our exposure and vulnerability to catastrophic failures.

To better understand the risks climate change poses to dams, the Ouranos Consortium partnered with INRS-ETE, Hydro-Québec, Ontario Power Generation, Rio Tinto, Manitoba Hydro and the Centre d'expertise hydrique du Québec to evaluate PMF values for the 2050 future time horizon (for the period 2041-2070). This report presents some results from the project and aims to contribute to a larger discussion about potential risks and adaptation actions.

Tipping the Climate Balance

The idea that climate conditions could radically change is anything but new. The Epic of Gilgamesh, a 4,000-year old poem, tells the story of a deluge flooding the earth. However, the concept gained acceptance as a credible scientific proposition only when keen observers recognized the presence of large erratic blocks and moraines carried by glaciers in temperate areas where no glaciers existed for hundreds of miles around. The quest for an explanation for these past ice ages—when glaciers flowed far to the south—became a popular endeavor, spawning a menagerie of theories. At the time these efforts started in the 19th century, the source of the sun's energy was still unknown, considerably limiting the breadth of explanations. The matter would be elucidated only with the discovery of atomic forces and quantum physics, which coincidentally would later prove essential to understanding what was coined, somewhat simplistically, the greenhouse effect.

A CONTESTED GREENHOUSE EFFECT

The greenhouse function of the atmosphere was hinted at in 1820 by Joseph Fourier, whose pioneering work on heat conduction led him to the conclusion that the heat coming from the depths of the earth was far too tenuous to warm the earth. Fourier also recognized that the amount of heat coming from the sun could not, on its own, account for the earth's temperature; the earth should be cooler. Either the stars provided enough light to warm the planet, or the atmosphere played some kind of insulating role by trapping radiated heat.

It would be John Tyndall in 1859 who, through a clever experimental apparatus, would systematically measure the opacity of various gases to infrared radiation, or dark heat as it was called at that time. Both water vapour and carbon dioxide (CO_2) appeared to be the major gases intercepting infrared, leading Swedish chemist Svante Arrhenius to propose in 1896 that increasing emissions of CO_2 through coal burning would eventually warm the earth. Far from being problematic, Arrhenius commented on the advantages for Sweden of such warmer climates (Arrhenius, 1896). This idea of CO_2 acting as a climate influencer was quickly challenged, however. In 1900, Knut Angstrom published results from a laboratory experiment showing that water vapour absorbed the same infrared frequencies as CO_2, and that 100% of infrareds were already blocked by current CO_2 concentrations. Together, these measurements suggested that CO_2 absorption was already at its maximum (saturated), and discredited Arrhenius' idea that rising CO_2 emissions would have any effect on climate.

The flaw in Angstrom' deductions would be identified only in 1931 by Edward Hulburt, a specialist in the upper atmosphere. In essence, Hulburt showed that temperatures in the lower part of the atmosphere depend on the optical properties of the upper atmosphere—12 kilometres above the earth—where the air is colder, drier and less dense. At such heights, it is CO_2, not water vapour, that dictates the radiative properties of the atmosphere. Hulburt also demonstrated that there is always a height at which air density is low enough to enable greater amounts of CO_2 to increase the absorption of infrared, thus debunking Angstrom's saturation theory (Hulburt, 1931).

Hulburt's work would go mostly unnoticed, however, and 25 years would go by before Gilbert Plass restored the credibility of the CO_2 hypothesis using a detailed numerical model describing the atmosphere as a series of superposed layers (Plass, 1956). His results suggested the earth would be warmer by about 3.6°C in a world with doubled atmospheric CO_2 concentrations. Just a few years later, in 1960, Charles David Keeling's maniacally precise measurement of CO_2 concentrations proved without doubt that the carbon emitted by burning coal, oil and gas was steadily accumulating in the atmosphere.

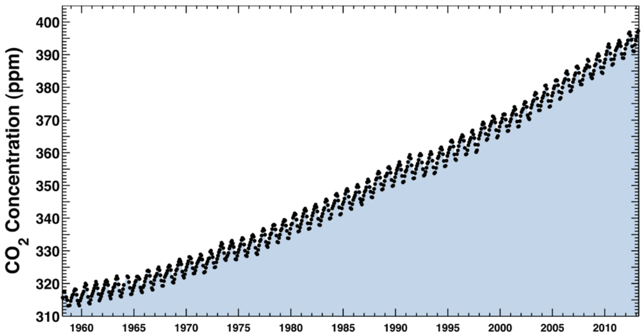


Figure 1 *Atmospheric CO_2 measured at the National Oceanic and Atmospheric Administration's Mauna Loa Observatory in Hawaii. Source: https://scripps.ucsd.edu/programs/keelingcurve/wp-content/uploads/sites/28/2013/04/mlo_full_record.jpg.*

ENERGY BUDGET AND FEEDBACK MECHANISMS

In 2015, CO_2 concentrations reached 400 ppm, far above the 320 ppm measured by Keeling in 1960 and well beyond the pre-industrial values of approximately 280 ppm inferred from ice cores. CO_2, along with other greenhouse gases, have tipped earth's radiative balance, with incoming energy exceeding outgoing infrared by 0.6±0.4 W/m^2 at the top of the atmosphere (Stephens et al., 2012). This small but positive energy input slowly adds heat to the planet, driving ocean and air temperatures upward. Some of this heat goes to melt land and sea ice, which in turn reduces the albedo (the reflectance) of the earth and causes more heat to be absorbed, inducing a positive feedback loop.

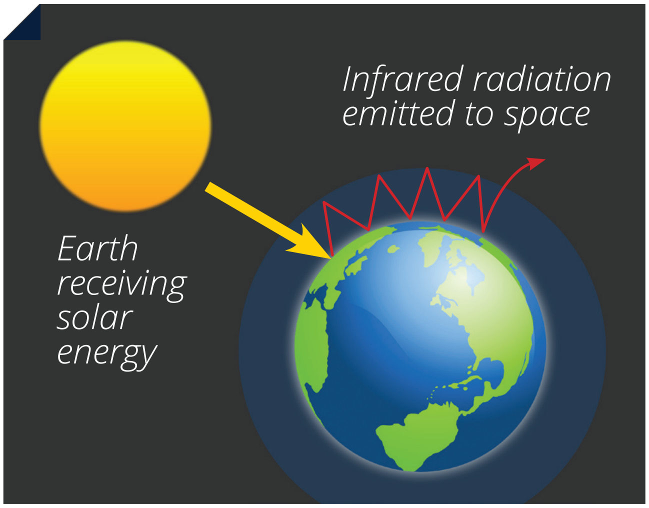


Figure 2 *Earth's recent radiative balance shows more incoming solar energy than outgoing infrared energy at the top of the atmosphere, slowly adding heat to the Earth system.*

Understanding feedback loops such as the ice-albedo effect are critical to appreciating the physics of the climate system. One of the most important positive feedbacks is due to water vapour. As anyone wearing glasses knows too well, water vapour condenses as it cools. Conversely, increasing temperatures cause water to evaporate; this is how dryers expel water from clothes. Based on the formula known as the Clausius-Clapeyron relation—developed by the 19th century German physicist Rudolf Clausius—scientists are able to calculate the relationship between atmospheric water vapour (at saturation) and temperature. From this relation, we find that at a constant pressure, 7% more water can remain in vapour phase before condensing for each one-degree Celsius increase in air temperature. Since water vapour is a potent greenhouse gas, more moisture raises temperature, driving a fast-response feedback loop that amplifies CO_2-caused warming.

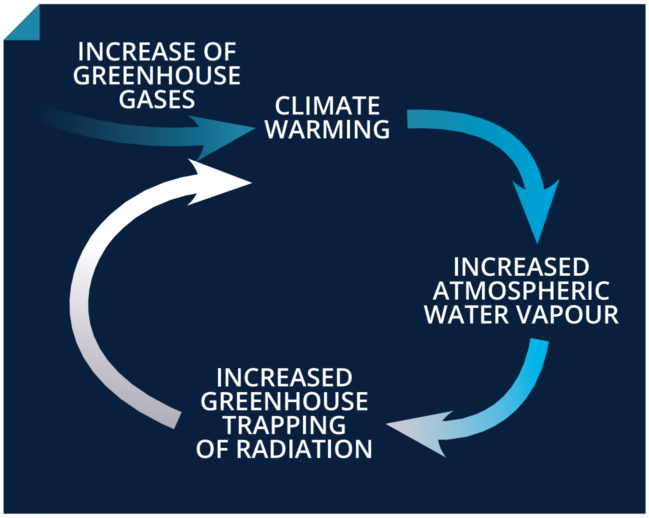


Figure 3 *The water-vapour feedback loop: higher concentrations of GHG increase the absorption of outgoing infrared radiation, leading to warmer air and more water vapour—itself a potent greenhouse gas—which will in turn amplify the warming caused by the initial increase in GHG.*

IMPACT ASSESSMENTS

Besides playing a positive feedback role, rises in evaporation rates and humidity levels also impact the water cycle. One might think that more moisture in the air would increase precipitation everywhere, but the reality is not so simple. Changes in pressure and wind patterns modify the trajectories of water vapour around the earth, leaving some areas with more or less precipitation, on average, than before. Although these changes in seasonal precipitation can be significant in terms of hydropower production, another concern is the evolving likelihood of intense rainfall events. Indeed, a higher moisture-holding capacity increases the potential for the atmosphere to release larger quantities of rainfall in short periods of time. As a matter of fact, historical observations and numerical climate simulations both show increasing trends in the frequency and intensity of extreme precipitation events over Canada and most of the U.S. (IPCC, 2012).

More intense and extreme precipitation does not, however, automatically mean that dams must accommodate more extreme streamflows. Many dams in Canada are designed for spring floods, where snowmelt plays a significant role. With warmer temperatures, most regions can expect less snowfall (although there are some exceptions), and thus less snowmelt during spring. An assessment of future extreme streamflow must thus proceed systematically, carefully weighting all of the various climatic factors playing a role in PMF calculations.

Many uncertainties must be considered to carry out a rigorous evaluation of the future risks to dam safety associated with climate change. First and foremost is model uncertainty. Climate models, for all their progress, remain relatively crude approximations of the real world with its complex processes that also interact with each other. As a consequence, models developed by independent teams using different representations yield future projections that can differ, significantly in some cases, and even more so when the horizon moves further in time. While these differences are sometimes due to refinements implemented in only some models, the range of model results is usually interpreted as a rough description of the overall scientific uncertainty about climate processes. For this reason, climate-impact studies incorporate dozens of different models in an attempt to capture, as fully as possible, the spectrum of potential futures.

Another important source of uncertainty is the greenhouse gases and aerosols (GHGA) scenario describing the future evolution of CO_2, methane and other atmospheric compounds emitted by human activities (known as the SRES and more recently as the RCP). Future levels of emissions hinge on the cost of renewable energy, proven fossil-fuel reserves, state- or industry-mandated regulations, demographics, etc. These factors lie squarely outside the realm of climate science and are studied by multidisciplinary teams including economists and systems analysts. While many emission scenarios have been published, climate scientists coordinate common experiments over a few scenarios bracketing a range of very-low to very-high emission levels. These scenarios all start with observed conditions then slowly diverge. The initial similarity of emission scenarios and the inertia of the climate system are such that the choice of emission scenario has little influence on climate outcomes before 2040.

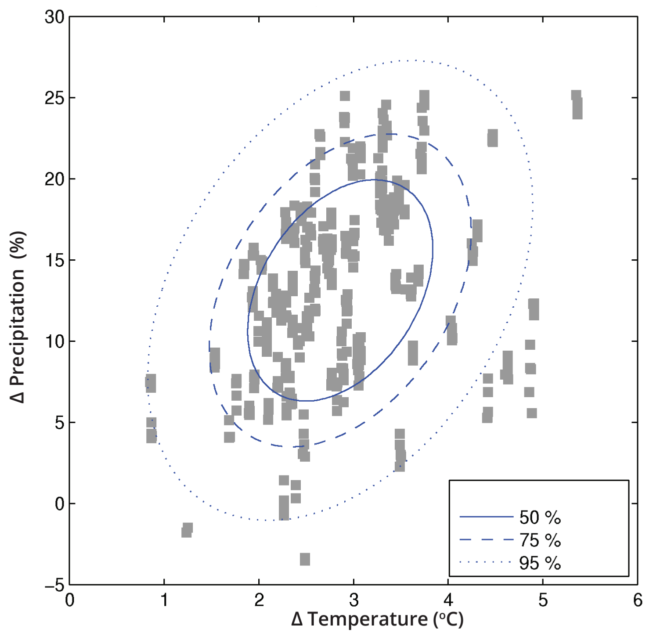


Figure 4 *Illustration of uncertainties through projected changes in annual precipitation and temperature for the 2050 horizon relative to the present climate over a study watershed, obtained from a large ensemble of global climate model simulations considering various future emission scenarios. Source: Braun, Ouranos, 2015.*

Finally, another critical source of uncertainty is natural, random climate variability. The climate system is in perpetual flux, swinging between states such as El-Niño and La-Niña phenomena, regularly shocked by volcanic eruptions emitting huge quantities of cooling aerosols, and constantly rocked by the dynamic interplay between ocean, atmospheric, land and ice processes around the globe. Even with a constant solar input and stable atmospheric composition, the earth would still experience warm and cold years, and wet and dry spells. This natural variability magnifies the challenge of accurately computing the likelihood of extreme

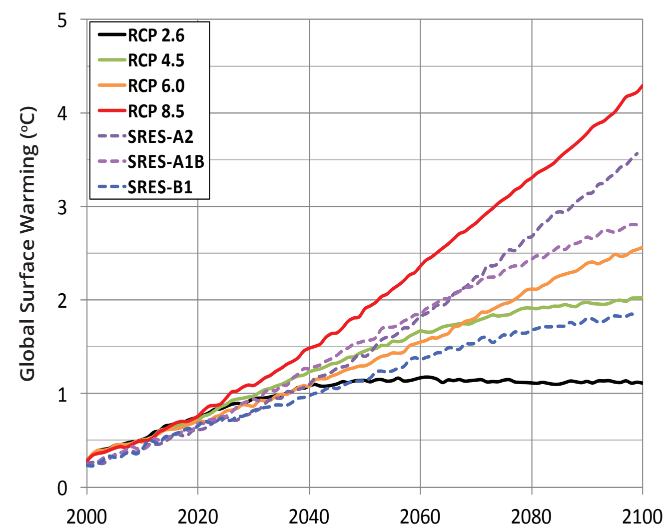


Figure 5 *Trajectories of modeled annual global surface warming, relative to the 1980-1999 period, associated with projected future GHGA emissions from various pathways. Source: Gervais, Manitoba Hydro, 2015.*

events. Indeed, the 30-year rainfall maximum could be very different from the maximum during another 30-year period in a similar climate, just by pure chance. This sampling uncertainty is why climate modelers run many simulations (members) using the same model and the same GHGA emission scenario: to have more years of simulation and better statistics related to rare events.

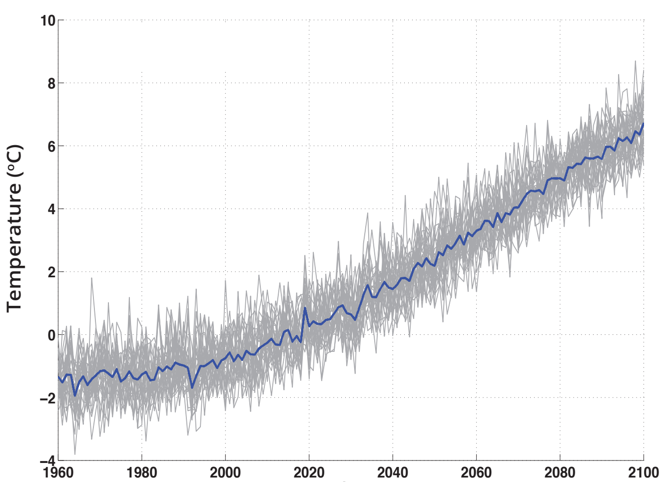


Figure 6 *Illustration of natural climate variability through the evolution of temperature over a study watershed from 30 members of the same Global Climate Model (CESM1 with RCP 8.5 post-2005). The blue line identifies the mean of the ensemble. Source: Willibald, Ouranos, 2015.*

Estimating the Largest Flood Ever

Flood risks are often evaluated from the point of view of probabilities. For instance, in some jurisdictions small dams are designed to handle the river runoff that is exceeded, on average, once every 100 years. This means that each year, there is a 1/100 probability that runoff will exceed this value. The computation of these 1/100 year events is relatively straigh forward, and involves fitting a statistical distribution to the historical record and then finding the value within that distribution that has an exceedance probability of 1%.

PROBABLE MAXIMUM PRECIPITATION

For dams posing extreme hazards, people usually wish them to be designed such that there is a near-zero probability of runoff exceeding designed capacity. This is somewhat outside the statistical realm and hydrometeorologists eventually came up with the concepts of probable maximum precipitation (PMP) and probable maximum flood (PMF) (Myers, 1967). Here, probable refers not to the rainfall or flood itself, but to the fact that various experts will come up with different values of PMPs and PMFs, suggesting an uncertainty around the numerical value. This PMP is defined, according to the World Meteorological Organization (WMO, 2009), as “the largest amount of precipitation that could accumulate in a given watershed, for a specific duration and for a particular time of year.” The challenge is to find PMP values with as much accuracy as possible, since underestimation increases risk of dam failure, and overestimation leads to unnecessary building and maintenance costs.

It’s worth reiterating that PMPs are specific to a region, a time of year, and duration of an event. As an illustration of the wide range of rainfall intensities that exist, the Indian town of Sohra (also known as Cherrapunjee), located on a high plateau overlooking the plains of Bangladesh, receives an average of only 11 mm of rain in January, but holds the world record for the largest amount of rain over 48 hours, namely 2,493 mm in June 1995. This is roughly the amount that Prince Rupert (BC), the wettest place in Canada, gets in an average year. Over a 24-hour period, the world record is held by Cilaos, on Réunion Island, where on January 8 1966, tropical cyclone Denise poured 1,825mm of rain. For comparison, the Canadian record over 24 hours is 490 mm at Ucluelet, BC, in 1967.

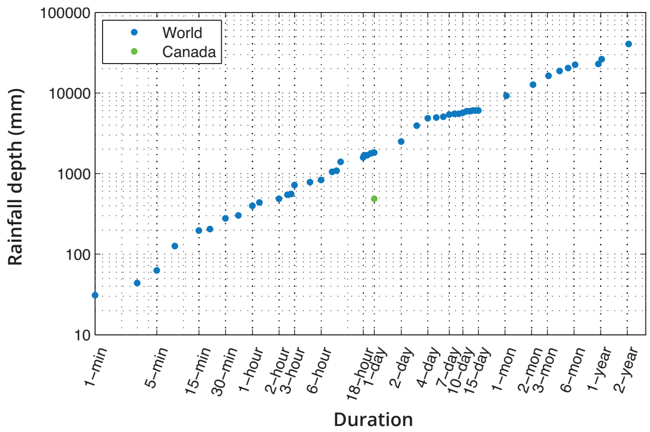


Figure 7 *World-record observed point rainfall (in mm) for various durations, including the Canadian 24-hour record at Ucluelet (green dot). Source: Gervais, Manitoba Hydro, 2015; based on data from http://www.nws.noaa.gov/oh/hdsc/record_precip/record_precip_world.html.*

An interesting question is whether we can use these records to tell us something about PMPs. In a sense, these record values suggest there is an upper limit to the amount of rainfall that can accumulate over a given period of time, which could lead us to constrain PMP values. However, the typhoons, cyclones or hurricanes that are behind these extreme events cannot be simply transposed to other regions without paying attention to the processes that generated them. This is why meteorologists define transposition areas, that is, regions within which weather systems can be shuffled around. This is, in fact, the basis of the estimation method for PMFs: for a given watershed, all major historical storms that occurred within its associated transposition area are positioned over the watershed and a hydrological model is run to convert rainfall amounts into runoff.

PRECIPITABLE WATER IS A CONCEPT THAT STRIVES TO REPRESENT ALL OF THE WATER IN AN ATMOSPHERIC COLUMN CONDENSED AT THE SURFACE. THIS MEASURE ESTIMATES THEORETICAL MAXIMUM PRECIPITATION.

To achieve this, Environment Canada published *Storm Rainfall in Canada,* a set of curves describing the depth-area-duration curves of major storms during the period 1912–1981. These historical storms generated nowhere near the theoretical maximum amount of rainfall, so the next step is the maximization of those historical storms. Here, maximization means finding the maximum amount of rainfall that each storm could have generated. The idea behind this maximization process is that each storm can be described by its efficiency in converting atmospheric water vapour into precipitation, measured by the ratio of precipitation over precipitable water. The hypothesis meteorologists make is that this efficiency would remain constant if more water vapour were available. By estimating the maximum amount of moisture that could have been held in the atmosphere over the watershed at the time of year when the storm occurred, and assuming the storm efficiency would be the same, we obtain the maximum precipitation that could have been left by each storm. The PMP is then calculated as the maximum rainfall left by the set of maximized storms within the transposition area associated with the watershed of interest.

PROBABLE MAXIMUM FLOOD

Once a meteorologist estimates PMP, a hydrologist converts it to a probable maximum flood (PMF). The concept is similar to PMP, but estimates the maximum flood that could reasonably occur in the watershed by considering many additional factors, such as:

SOIL MOISTURE

- For a flood to be the worst possible, the soil should have almost no available storage capacity. Hydrologists will often simulate a large rainfall a few days before they apply the PMP to make sure the soil is saturated, ensuring maximum runoff.

SNOWPACK

- In many Canadian watersheds, the spring flood is usually the largest one, triggered by the combination of rapid snowmelt and rainfall. Deep snowpacks increase the likelihood of large floods

TEMPERATURE SEQUENCE

- To melt precisely at the worst possible time, the snowpack must be primed by warm temperatures that bring it close to the melting point. Hydrologists simulate a temperature sequence over the weeks before PMP to bring the snowpack to a point where melting coincides with PMP.

RESERVOIR LEVEL

- Large reservoirs can store some runoff and reduce peak flow. However, hydroelectric dams tend to operate near maximum levels to increase the height of the fall and the energy generated. Hydrologists thus usually set the initial reservoir level near its maximum operational value.

Among these factors, snowpack can be the most difficult to handle: how much snow should we assume accumulates in the watershed to compute the PMF? It is possible to estimate a probable maximum snow accumulation (PMSA) describing the theoretical maximum amount of snow that could accumulate over the winter. The method used to compute this PMSA usually

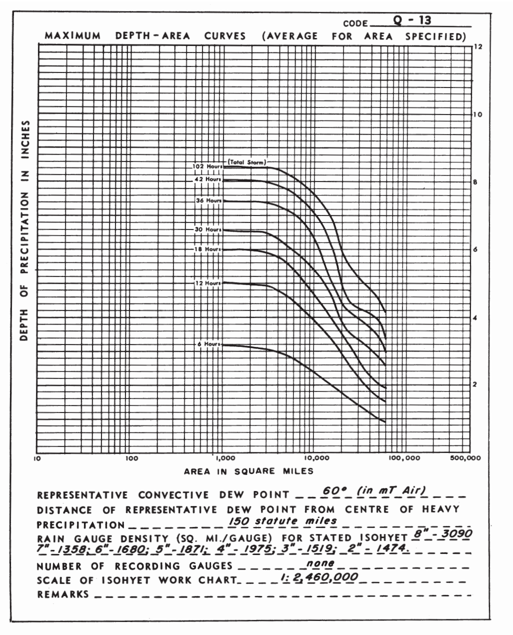


Figure 8 *Image of depth-area-duration curve taken from an Environment Canada analysis of a storm that affected the St-Lawrence valley from September 14 to 18, 1932. Source: Storm Rainfall in Canada.*

involves maximizing all snowstorms over many winters to calculate the largest amount of snow that could have been left on the ground during one season. In theory, hydrologists could combine PMP and PMSA, make sure the soil is saturated and the snowpack primed for melting, and compute the ensuing runoff. However, this leads to formidably large values and safety margins. Although the PMP and PMSA combination has been used in the past, the current consensus is to combine spring PMP with a 1/100 year snowpack, or a spring 1/100 year rainfall with a PMSA, and select the pair generating the largest runoff.

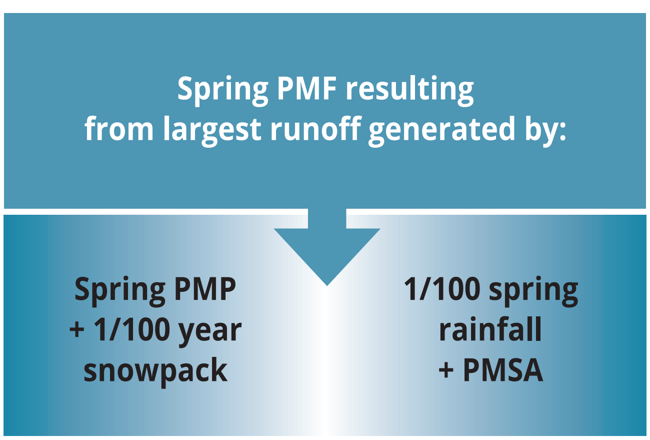


Figure 9 *Diagram of the two approaches used to select the largest spring PMF.*

Hydrologists enter these meteorological inputs into a hydrological model describing infiltration and runoff processes in the watershed drained by the dam. By moving the centre of the PMP-design storm over the watershed, tweaking the model parameters and temperature sequence, hydrologists evaluate the sensitivity of their results against their hypotheses and finally develop a hydrograph representing the worst physically plausible runoff scenario. Civil and mechanical engineers can use the hydrograph to design and construct appropriate dams, dikes and spill gates to safely accommodate the PMF.

Although designing a dam for a PMF might give the impression it can't possibly fail, the reality is not so simple. Historically, most dam failures are not the consequence of extreme events overwhelming under-designed structures, but are rather due to unstable foundations, poor-quality construction, lack of proper maintenance, inadequate management, communication failures or some combination of these factors. Indeed, the fact that a spillway and its gates are of adequate size does not guarantee that the dam operator will recognize exactly when they must be opened, that the gate motors will be powered and functional, that the gate will slide on its track without obstructions, and that the opening will be free of sediment. While these might seem trivial issues on a clear and sunny day, during a PMP-type storm access roads and power lines will likely be cut by swollen streams and fallen trees. As a result, employees may be unable or unwilling to reach the dam, and debris strewn by water and winds will jam spillways. Ultimately, there could be limited capacity to identify, diagnose and solve problems.

MAKING USE OF CLIMATE SIMULATIONS

The first global climate models became available in the 1960s. Known as general circulation models, they were limited to describing the circulation of the atmosphere, driven by solar radiation and heat-transfer mechanisms. The models were able to reproduce the atmospheric circulation around the globe even though they assumed the earth's surface was covered by still water, and ignored topography and the physics of cloud formation. Nonetheless, these simple models enabled researchers to test hypotheses and take great strides in improving our understanding of climate processes, notably the role that greenhouse gases play in the atmosphere's radiative properties.

With the rapid increase in computational power and numerical know-how, modelers gradually coupled atmospheric, ocean and later sea-ice models, included land topography and ocean bathymetry, and accounted for land-surface processes as well as clouds, atmospheric chemistry, oceanic biochemistry, vegetation, carbon cycle and glaciers. Given the breadth and complexity of these models—there are equations describing the CO_2 and vapour exchanges through stomatal cavities (microscopic leaf pores)—no single climatologist can claim to master an entire climate model. Instead, teams of researchers focus on specific topics. Climate models can thus be thought of as working embodiments of the scientific understanding of climate processes, and the differences among models illustrate the diversity of scientific viewpoints and of numerical algorithms.

Among the questions about climate models that scientists have tried to answer is the effect that an increase in greenhouse gases has on temperature and precipitation. For a doubling of CO_2 levels, the simple early models of the 1960s, as well as the most recent versions, simulate global warming of about 3°C, with estimates ranging from 1.5°C to 4.5°C. The fate of precipitation is not as clear. Warmer air means more potential for evaporation, which can lead to wetter or dryer conditions, depending on locations and wind patterns. Despite this, there is general agreement with the idea that more energy in the system leads to more intense maximum rainfalls, in part due to the higher levels of humidity made possible by warmer air temperatures.

To zoom in on climate change impacts at the watershed scale, regional climate models are often used due to their higher spatial and temporal resolutions. Regional climate models are very similar to global climate models in terms of their equations and their representation of climate processes, but the main difference is that instead of considering the entire planet, they focus on a limited area. For example, the CORDEX project (http://www.cordex.org) is a coordinated experiment where regional modelers contribute simulations over predefined domains covering Africa, Europe, Asia, the Arctic, North America, etc. The modeling process thus starts with future emissions scenarios describing evolving emissions and concentrations of greenhouse gases and aerosols, and different global climate models then simulate the climate over the entire globe using these scenarios. The results vary according to scenario, model and natural climate variability, whose influence makes weather almost unpredictable beyond two weeks. Wind, pressure, humidity and temperature values from these global simulations

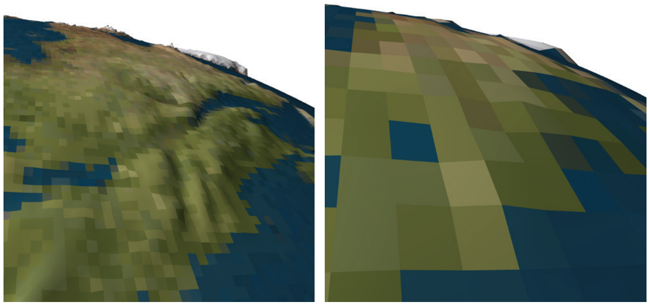


Figure 10 *Illustration of typical spatial resolutions of Regional Climate Models (left side, 40-km resolution) and Global Climate Models (right side, 200-km resolution) in Eastern Canada. James Bay is depicted in the top-left corner, Lake Ontario is centre-left and the St-Lawrence River is on the right side. Source: Braun, Ouranos, 2015.*

are then used to drive regional models, which themselves simulate the same climatic variables, but at higher resolutions. Nowadays, most global climate models run typically with grid tiles that have a horizontal resolution of 200 km, while regional climate models operate at a 25-50 km resolution.

The work and results presented in the next pages are based on an ensemble of climate simulations made by regional climate models over North America (Table 1), comprising of projections produced at Ouranos (CRCM4; de Elia and Côté, 2010) and available through the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009). These regional climate models are driven at their boundaries by global climate model simulations. Due to limited computing resources and an interest focused on the 2050 horizon (the 2041-2070 period), only one GHGA emission scenario was studied (SRES-A2), describing a future when no significant efforts are made to curb emissions. The results from over a dozen simulations from different models are stored in huge binary files containing the values of climate variables simulated by the model every six hours over each grid cell in the model. These grid cells have dimensions of about 50x50 km (2,500 km^2), meaning that small-scale processes, such as convective summer storms, are not generated by the model; climate modelers include specific parameterizations in their models to account for these small-scale processes. Climate analysts then select the grid cells that correspond with the area of interest—here specific watersheds—and compute the indicators they are interested in, such as the maximum summer precipitation over a 24-hour duration, from the raw values. Interpreting these results meaningfully—accounting for model limitations, natural climate variability and sampling uncertainty, especially in the context of extreme values—is a challenge.

To evaluate the potential effect of greenhouse gases on PMFs and dam safety, the outputs from this ensemble of regional climate model simulations were analyzed. The same approach used to estimate PMPs by maximizing storms was applied to climate model outputs (Rousseau et al., 2014). A transposition area was first defined around each basin of interest. Over each model grid-cell within this area and the periods simulated by the models (1971-2000 and 2041-2070), all rainfall events of 24- 48- 72- and 120-hour durations were recorded, as well as the precipitable water during those events. Then a

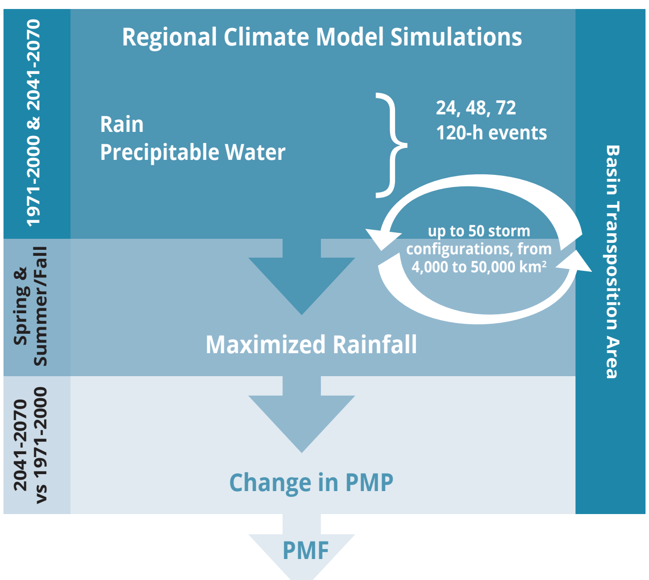


Figure 11 *Diagram of the methodology developed and applied in this project, using Regional Climate Model outputs to evaluate projected changes in PMF over the study basins. Source: Gervais, Manitoba Hydro, 2015.*

100-year return period precipitable water value was calculated and used to maximize the precipitation amounts from all recorded events. The largest maximized precipitation over the transposition area during spring as well as summer/fall were then labeled as the simulated PMP. By comparing the values for the future and historic periods, we get an estimate of the expected change in PMP from climate models. This analysis was performed about 50 times by aggregating model grid-cells into diverse configurations to cover storm areas ranging from 4,000 to around 50,000 km^2, which corresponds to the range used in many PMF studies. Snowpack time series from the regional climate model simulations were also analyzed to provide expected changes in snowpack depth, represented by the 100-year return period of the maximum annual values in snow water equivalent over each basin. Finally, the projected changes in the daily sequence of temperature were evaluated at the basin scale.

As a cautionary note, it's worth recalling that the impact of climate change on PMPs and PMFs has not been the focus of many independent studies. By closely following the traditional approach to calculating PMPs within the climate model realm, we've tried to make the methodology as familiar as possible to meteorologists and engineers. It's clear, however, that the available observations and modeling tools offer many other—possibly more fruitful—possibilities to understand and evaluate the physical limits of extreme precipitation.

REGIONAL MODEL	DRIVING GLOBAL MODEL	MEMBERS
CRCM4	CGCM3	5
CRCM4	ECHAM5	3
CRCM4	CCSM3	1
ECP2	GFDL_CM2.5	1
MM5I	CCSM3	1
MM5I	HadCM3	1
RCM3	CGCM3	1

Table 1 *Details of the ensemble of regional climate simulations used, including the name of the regional model, the driving global model and the number of different realizations from the same global climate model. All simulations use the SRES-A2 GHGA future emission scenario.*
Note: *the last five runs were part of the NARCCAP.*

PMFs Across Canada

Over the course of this project, the climate modeling approach to the estimation of PMPs, snowpack, 1/100 year rainfall and temperature sequence was applied to five different watersheds where dams have been designed with PMFs. An ensemble of 14 regional climate models at a spatial resolution of 45-50 km was used, covering 30-year present and future periods, enabling the evaluation of the uncertainty stemming from different model assumptions, as well as from sampling uncertainty. Indeed, the methodology calls for finding the maximum precipitation over a simulation period of 30 years. While this may seem long, there is a huge amount of variation between the 30-year maximums of various simulations, even when the same model is used. Comparing multiple simulations supports an initial assessment of the error made when computing the maximum during only 30-year periods.

The following sections describe the watersheds included in this project, and provide a broad overview of how the original PMF was computed and what changes can be expected to PMFs for the 2050 horizon (2041-2070 compared to 1971-2000). This analysis, based solely on the SRES-A2 future emission scenario, describes a future when no significant efforts are made to limit emissions, which represents the track the world is currently on.

Mattagami

Harmon Generating Station

Mattagami River basin is located within the Canadian Shield. Over the bedrock lies a thin layer of soil, composed primarily of silts and clays. Forests within the watershed are dominated by conifers, such as white and red pine, spruce and eastern hemlock, as well as deciduous trees including yellow birch, various maples, elm and oak. The Mattagami, meaning *meeting of the waters* in Ojibway, collects runoff from the Kapuskasing River and the Groundhog River and drains north towards James Bay via the Moose River. A diversion built around 1968 also diverts flow from the Opasatika River, while the Adam Creek diversion structure is used to divert the spring freshet.

RESERVOIR STORAGE

Reservoir storage is sometimes confused with reservoir volume. While the volume is the total amount of water sitting in the reservoir, storage refers to water that can be released downstream by the dam operator. More precisely, it is the amount of water that can be stored above the minimum operating level and below the maximum operating level.

In practice, some water can be stored for short periods above the maximum operating level without endangering the dam's structural integrity, but this is done only in exceptional circumstances. However, it is unlikely that water level would be near its minimum operating level before a PMF event. Indeed, operators usually keep levels high to maximize fall height and energy production, and a few days of advance notice would not be enough to draw the reservoir down. This is why PMF studies usually assume that the reservoir is near its maximum historical level at the time of the PMF event.

Kipling Generating Station

Storage dams along the Mattagami River include Mesomikenda, Minisinakwa, Mattagami and Peter Long, and feed eight generating stations: Wawaitin, Sandy Falls, Lower Sturgeon, Smooth Rock Falls, Little Long, Smoky Falls, Harmon and Kipling. Sandy Falls is the oldest station, in production from 1911 until it was decommissioned and rebuilt in 2008. Of all stations in the Mattagami watershed, Smoky Falls has the highest capacity: 268 MW since its 2015 re-development in partnership with the Moose Cree nation. In operation since the 1920s, Smoky Falls originally powered the Kapuskasing pulp-and-paper mill, which supplied newsprint to the New York Times (O'Kane, 2013).

The original PMP estimates for the basin were calculated in 1991 and used 10 major summer storms and four major spring storms over meteorologically similar areas in Ontario and the United States during the period 1878−1986. Also used was the August 1961 Timmins storm: torrential rain with hail that led to a flash flood, ripping roads apart and smashing houses. The potential maximum precipitable water was estimated using a 50-year return period from 12-hour dew-point temperatures. Depth-duration-area curves were calculated for durations of 6, 12, 24, 48, 72 and 96 hours and areas of 1,000, 2,000, 5,000 and 10,000 km^2. Storm centres were positioned over four different locations using the BOSS HMR52 software, which automatically centres, orientates and sizes the PMP storm for optimal results.

The spring PMF was timed during the first two weeks of May based on snow-course data and observed floods. The critical temperature sequence was a modified version of the record for a major spring melt flood in 1960. Two snowpack scenarios were used based on 100- and 500-year return period events. The summer PMF was set at the end of June, consistent with the large summer flood of summer 1957, and yielded a runoff that is only 60% of the spring PMF. Runoff was the result of simulations done with the Streamflow Synthesis and Reservoir Regulation (SSARR-8) computer model developed by the U.S. Army Corps of Engineers.

Regional climate model projections over the Mattagami basin for spring PMP future changes for the 2050 horizon (2041-2070 compared to 1971-2000) are distributed around a 10% increase for the 24-hour event, and a 5% increase for the 48-, 72- and 120-hour events. When converted into runoff, these lead to a 5-7% change in peak flow on the 12 different river sections. Future changes in the 100-year snowpack were centred around -1%, and had little effect on the peak flood. Keeping everything else equal, changes in the melt-temperature sequence tend to shuffle results considerably, some simulations yielding reductions of 10% in peak floods, while other reach increases of 15%. Usually, temperature sequences are precisely tuned to yield the highest flow possible, which was not done here and probably explains the large variability in the results. Overall, projections suggest PMF increases in the neighborhood of 5% on the Mattagami River.

Smoky Falls Generating Station

MATTAGAMI	
Annual rainfall	517−621 mm
Annual snowfall	290−349 mm
Mean annual temperature	0.1−1.3°C
Mean annual runoff	300−400 m^3/s
PMF timing	Spring
Drainage area	36,800 km^2
Storage	337 hm^3

Manic-5

Manicouagan Reservoir

The Manicouagan River, located in the Côte-Nord region, takes its source north of the Manicouagan crater and flows south into the St-Lawrence River. The crater is the largest visible on earth and is the result of an asteroid five kilometres in diameter impacting earth 215 million years ago; the collision released enough energy to melt Canadian Shield rock nine kilometres below the surface (O'Dale, 2015). The iconic round shape of the reservoir dates from the 1960s and the construction and filling of the Daniel-Johnson dam. The reservoir merged two crescent-shaped lakes located to the west (Mushalagun), and east (Manicouagan) of the impact ring. The current Manicouagan reservoir is an annular lake 70 km across with a total volume of 140 km^3: it is the fifth-largest in the world by capacity (ICOLD, 2015).

The Manic-5 watershed drains the upstream, northernmost section of the Manicouagan River and has its outlet at the Daniel-Johnson dam. Although the hydroelectric potential of the river was known since the 1920s, it was too remote at the time for such a major construction project. With the development of the iron and forest industries in the Côte-Nord region, along with a new road, improved electricity-transmission technologies and increasing demand for power, a feasibility study for the Manic-Outardes complex was commissioned in 1955. The project was launched in 1959 and the Manic-5 dam completed in 1964; it would take 13 years for the reservoir to fill and reach its operational level. Built during the so-called Quiet Revolution, the dam became an icon of Quebec nationalism, inspiring songs and now attracting more than 7,000 tourists per year.

The summer PMP was originally estimated based on eight storms during 1917−1996; the 1996 storm was the Saguenay deluge. Storms were maximized on the basis of maximum persisting 12-h dew-point temperatures. To compute the summer PMF, a 100-year return period rainfall was triggered four days before the 72-h PMP to ensure that the soil is close to saturation. The design storms were optimally located on the watershed and temporally distributed over the three days using the HMR52 software.

The spring PMF requires a comparison between two combinations: the 100-year snowpack with spring PMP and the PMSA with the 100-year rainfall. In both cases, no antecedent precipitations were applied since it is assumed that snowmelt will saturate the soil. However, the temperature sequence and the timing of the rainfall were carefully chosen to maximize peak flow: temperatures were set just above 0°C for two weeks prior to the design storm to prime the snow cover for rapid melting. During the PMP, it was assumed that the power plant is shut down and penstocks are closed, meaning that all runoff has to be evacuated through the spillway. These watershed and reservoir simulations were carried out using the SSARR model.

During the design phase of a dam, the PMF is used to size spillway capacity. However, once the infrastructure is built, PMF reviews and updates are still conducted, and given a new PMF, the question becomes: "What should the initial reservoir level be to ensure that the level during the PMF never exceeds a critical threshold?" The larger the PMF, the lower the reservoir level should be. At the Manic-5 dam, although the highest peak-flow is generated by the PMP+100-year snowpack event, the largest flood volume, and thus the lowest initial reservoir level required before the flood, is generated by the PMSA+100-year rainfall combination event.

Regional climate-model projections of future spring PMPs for the 2050 horizon (2041-2070 compared to 1971-2000) are centred on a 15% increase and lead to PMF peak flows increasing by about 10%; the total flood volume, however, increases by only 4%. When adding median projected changes to the snowpack (a 3% increase in snow water equivalent), the peak flow and flood volume increase by 11 and 6%, respectively. By routing projected inflows through the reservoir model, it is possible to find out how reservoir levels would fluctuate during such a future PMF, and results suggest the Manicouagan reservoir would reach a level 40 cm higher than under current PMF conditions, a value that can be managed by the current infrastructure.

MANIC-5

Annual rainfall	640 mm
Annual snowfall	310 mm
Mean annual temperature	-1.8 °C
Mean annual runoff	660 m^3/s
PMF timing	Spring
Drainage area	29,200 km^2
Storage	35,000 hm^3

Daniel-Johnson Dam at Manic-5

Kenogami

Chicoutimi Pulp on the Saguenay River, circa 1910
Source: Musée McCord, MP-0000.1101.7

Lake Dubuc Dam on the Chicoutimi River at Mill No. 2, circa 1980
Source: BAnQ, P90, P67405

Lake Kenogami, located near the Saguenay River, had been a hunting ground for Innu people for around 4,000 years before settlers built the small agricultural village of St-Cyriac on its shores at the end of the 19th century. Kenogami, meaning long lake in the Innu Montagnais language, is fed by three rivers: Pikauba, Cyriac and aux Écorces. It drains eastward through two rivers, Chicoutimi and Rivière aux Sables, flowing towards the boroughs of Chicoutimi and Jonquière, respectively, in the Saguenay region. At the beginning of the 20th century, wood-pulp mills located in Jonquière and Chicoutimi built two dams on the lake, Pibrac and Portage-des-Roches, to raise water levels and increase hydropower production.

Hydropower was used both to light the growing cities and to power the mechanical operations required to grind logs into pulp. By 1920, the Chicoutimi Pulp Company became the largest producer of mechanical wood-pulp in the world, competing against the Price family, owner of the Jonquière mills (Gagnon, 2007). Increasing demand for electricity would lead to court battles between Chicoutimi and Jonquière mill owners for water allocation, as well as to requests to further raise lake levels. In 1922, the Commission des Eaux Courantes du Québec would grant approval to raise the dams and build new dikes. The village of St-Cyriac, despite residents' legal appeal to the Commission, ended up under water by 1924 (Cantin, 1975).

Lake Kenogami has a small drainage area composed of rocky, uneven soils, with little water-storage capacity. It thus reacts very rapidly to rainfall, which is amplified by orographic effects. Indeed, during the 1996 Saguenay flood, the Kenogami watershed received almost twice as much rain as neighboring lowland areas. A rain gauge in the Réserve Faunique des Laurentides recorded 279 mm over 36 hours, an amount that led many private dams and dikes in the area to fail (Grescoe, 1997). This orographic effect makes it difficult to transpose storms from other areas to the Kenogami watershed. In a 1997 study, PMP values were thus estimated by maximizing local storms. The area is also among those receiving the most snow in the province, making the estimation of the 100-year snowpack and PMSA critical components of the PMF. The 100-year snowpack is estimated by frequency analysis of recording snow gauges, while the PMSA is based on the maximization of winter storms occurring during the three snowiest winters recorded.

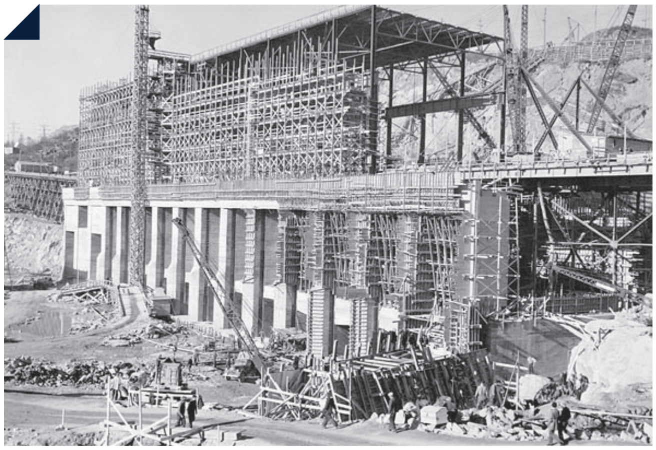
In the original 1997 study, the spring PMP+100-year snowpack proved to be the combination that lead to the largest PMF. Different daily hydrological models were tested (CEQUEAU, SSARR and HSAMI), and the one that simulated the highest peak flow—SSARR—was selected. A 2001 update used an hourly hydrological model to better account for the short response time of the watershed. This higher temporal resolution led to a 30% increase in spring peak flows, and switched the PMF to a summer/fall event. As a comparison, in terms of hourly peak flow, the PMF is close to three times as large as the 1996 deluge peak flow.

Future projections of the spring PMP from regional climate models for the 2050 horizon (2041-2070 compared to 1971-2000) suggest increases with a median value around 20%. The dispersion around that value is, however, extremely large, ranging from -25% to 90%, possibly due to the small dimension of the basin relative to the scale of the regional climate model's grid tile. The situation is similar for the 100-year snowpack, with projected changes ranging from -30% to 30%. In the HYDROTEL model used for the updated PMF study, additional water is routed into streamflow without significant temporal redistribution, leading to nearly identical increases in streamflow. Overall, median PMF changes centre around an increase of 20%, as was the case for the PMP. The median PMP change would be accommodated by current infrastructure with a slight overtopping of concrete dams; earth dikes have enough headroom to deal with the increase.

KENOGAMI	
Annual rainfall	1030 mm
Annual snowfall	287 mm
Mean annual temperature	2 °C
Mean annual runoff	77.4 m^3/s
PMF timing	Spring
Drainage area	3,390 km^2
Storage	380 hm^3

Portage-des-Roches Dam

Saguenay–Lac-St-Jean



Construction Work on Powerhouse No. 2 during the Shipshaw Power Development Project

Construction of Entrance to Tunnel C at the Shipshaw Power Development Plant

The Lac St-Jean and Saguenay fjord are located in a lowland area surrounded by mountains: the Laurentians to the south and the Monts-Valin to the north. The fjord is a graben (German for trench), created millions of years ago by forces in the earth's crust that created parallel fault lines. Glacial flow along the graben eroded and widened the flanks, left moraines and compressed the crust locally. At the end of the last ice age, the entire Lac-St-Jean area was connected to the ocean through the Saguenay, explaining the presence of marine species, such as salmon, living yearlong in what are now fresh water lakes. The receding sea also deposited clays and sediments, making some of the areas around Lac St-Jean prime land for agriculture, but leaving them susceptible to landslides such as the 1971 St-Jean-Vianney catastrophe.

Lac-St-Jean, called Piekouagami (flat lake) by the Innu, is fed by the Peribonka, Mistassini, Mistassibi and Ashuapmushuan, as well as by seven smaller rivers. The presence of so many rivers made the region an important hub for trade among Innu, and later with Europeans. Although the area was first colonized for its agricultural potential in the latter half of the 19th century, the presence of apparently limitless forest and tumultuous rivers spurred the development of lumber mills, followed by pulp-and-paper mills and eventually by aluminum smelters. The generating station built by the Aluminum Company of Canada (Alcoa) on the main lake outlet, called Grande Décharge, at Isle-Maligne in 1926 was at one time the most powerful in the world, and provided electricity to newly constructed aluminum smelter in Arvida.

During the following decades, a total of seven generating stations were built, as well as reservoirs on two lakes—Manouane and Passes-Dangereuses. These two reservoirs are the primary mechanism for regulating the watershed, with a storage capacity of 7,900 hm^3 compared to 5,083 hm^3 for the shallow Lac-St-Jean.

The PMF for this study was calculated for five locations within the Lac-St-Jean watershed. For PMPs, the estimation was based on meteorological records from the transposition area, including storm events dropping more than 50 mm of rain over three days at a minimum of two stations. For the PMSA, four winters with the highest snow accumulation were chosen, and the individual snowstorms during these winters were maximized. The temperature sequence assumes that the PMP occurs around mid-May and is composed of five parts that ensure the snowpack melts rapidly at the end of the sequence. The PMF is computed using the SSARR model and with the following assumptions: that lakes and reservoirs are at mean operating levels at that time of the year; that generating stations are offline during the 15 days starting with the PMP due to the failure of transmission lines; and that spillway gates are opened as soon as the risk of exceeding maximum reservoir levels becomes apparent. The results indicate that the PMF is twice as large as the 1928 flood and is the result of a spring PMP+100-year snowpack.

While the original PMF values were simulated using the SSARR model, for this project RT (Rio Tinto) relied on the CEQUEAU hydrological model it uses for day-to-day operations. The original spring PMP and 100-year snowpack values were run through CEQUEAU to establish the baseline flood volume and peak flow, before applying climate change factors to rainfall and snowpack. Regional climate model projections give a median change-factor for PMP of about +10% for the 2050 horizon (2041-2070 compared to 1971-2000), while the median change in 100-year snowpack is -5%. These counteracting changes compensate themselves in terms of flood volume, but lead to a slight increase in peak flow of 2%. These projected changes are comparable in magnitude to the differences in PMF values obtained from the SSARR and CEQUEAU models, suggesting that the climate change signal is within the hydrological uncertainty.

SAGUENAY–LAC-ST-JEAN

Annual rainfall	656 mm
Annual snowfall	276 mm
Mean annual temperature	0.6°C
Mean annual runoff	861 m³/s
PMF timing	Spring
Drainage area	45,385 km²
Storage	5,083 hm³

Chute-à-Caron Generating Station

Lower Nelson

Long Spruce Generating Station (located downstream of Kettle, work began in 1973, construction completed in 1979)

The Nelson River (known as Keche Sipi, or "Great River" in Cree) is located in northern Manitoba, originating at Lake Winnipeg and flowing 656 kilometres north into Hudson Bay. Lake Winnipeg, along with Lake Manitoba, are remnants of glacial Lake Agassiz, an ice-dammed lake larger than all Great Lakes combined and formed by the meltwaters of the Laurentian ice sheet approximately 10,000 years ago. Lake Agassiz outburst numerous times in the past: toward the Gulf of Mexico, scouring a valley 2 to 5 kilometres wide and 30 metres deep along the way; to the east through what is now Lake Superior; and to the west through the Mackenzie River into the Arctic (Thorleifson, 1966). These massive flood events are likely to have triggered significant climate change in the past, the last one causing a sudden sea-level rise possibly at the root of deluge myths.

The natural drainage area of the Nelson is more than a million square kilometres, but this grew by some 300,000 km² in 1977, when the Churchill River northwest of the Nelson basin was partially diverted into the Nelson through the Rat and Burntwood rivers system. This significantly increased the flow through the string of generating stations along the lower Nelson and brought the total drainage area to 1,400,000 km^2 - about 15% of Canada's total landmass. However, the flow from most of this drainage area is regulated before reaching the Nelson River. The uncontrolled drainage area flowing into the Nelson River, and the area of interest for PMF analysis, is 91,000 km^2.

The vast majority of water flowing through the Nelson River originates from the outlet of Lake Winnipeg. Among the world's biggest lakes, Lake Winnipeg has the largest drainage area relative to its lake area (40:1 ratio). More than a dozen rivers flow into the lake, from as far away as the Rocky Mountains, the Laurentian Divide in North Dakota and Minnesota, and nearly to the western shore of Lake Superior. With a surface area of 24,000 km^2, Lake Winnipeg provides a large amount of storage capacity and dampens flood peaks experienced on the Nelson River. Prior to the construction and operation of the Lake Winnipeg Regulation Project in the 1970s, settlements around the lake were at times subject to extreme floods due to the large variability of inflows and the limited capacity of its natural outlet.

The watershed's climate is continental subarctic, with cold winters and short, warm summers. For a watershed of this size, it has very little topographic relief. Forests and wetlands cover the watershed in the north, while the southern section is dominated by croplands and grasslands. Though its substantial hydroelectric potential was known as far back as 1913 (McClean et al., 1914), the harsh climate and remoteness of the Nelson River delayed hydroelectric development until the 1960s. Prior to this, electricity-transmission technology did not support the operation of generating stations so far away from consumers. In fact, the power line built in 1972 from Kettle station to Winnipeg was the world's longest high-voltage direct-current line at the time, measuring close to 900 kilometres.

For the original computation of the PMF, a number of conditions were considered based on recommendations from the Canadian Dam Association: a summer PMP, a spring PMP on a 100-year snowpack, a 100-year spring rainfall over a PMSA and a PMSA combined with an extreme temperature sequence. In all cases, outflow from Lake Winnipeg was set at the 100-year return period maximum, and maximum diversion of the Churchill River was assumed. Six storms among the 186 storms described in the Storm Rainfall Atlas of Canada and Warkentin's atlas of Prairie storms (Warkentin, 1987) were selected based on multiple criteria, including size, shape, orientation and the absence of orographic-enhancement effects. The summer PMP was based on July dew-point maximization, when moisture input is greatest. Since there are so few spring storms to analyze, spring PMPs were computed by seasonal adjustments of summer storms. This adjustment is done by looking at historical maximum storms on a month-by-month basis and comparing their rainfall to those of the July maximum. A SSARR model specifically calibrated to perform well during the wettest years on record was used for the computation of the PMF.

Future projections of spring PMP and 100-year snowpack from the ensemble of regional climate models for the 2050 horizon (2041-2070 compared to 1971-2000) are especially uncertain over the lower Nelson watershed, scattered from -35% to 30% for rainfall and -15% to 20% for snowpack. Although the median PMP change is around -10%, there is little confidence in this figure. To explore this range of possible futures, all future PMP scenarios were run through the hydrological model to better assess the spread of possible runoff outcomes. Results indicate a fairly robust linear relationship of 5:1 between changes in PMP volume and resulting changes in PMF peak flow, so that the median -10% PMP change translates into a PMF peak flow 2% lower than the current estimated value. Projected median changes to the 100-year snowpack and the 100-year outflow from Lake Winnipeg (the upstream watershed) counteract this projected reduction in PMP, resulting in a 1% increase in the PMF peak flow over the current value. Although this median increase in PMF peak flow is negligible, sensitivity to extreme future climate scenarios results in an uncertainty range of 23% of the baseline historical PMF peak flow.

LOWER NELSON	
Annual rainfall[1]	315 mm
Annual snowfall	221 mm
Mean annual temperature	-3.7°C
Mean annual runoff[2]	3,280 m^3/s
PMF timing	Spring
Drainage area	91,000 km^2
Storage[3]	81,4 hm^3

Artist's Rendering of Keeyask Generating Station (spillway in foreground, powerhouse in background)

Nelson River at Gull Rapids (site of Keeyask generating station)

[1] Climate normals from the Gillam Airport meteorological station from Environment Canada (1981-2010).
[2] Average annual flow at Kettle Generating Station (1981-2010).
[3] Storage between the minimum operating level and full supply level of Keeyask Generating Station.

Dams in the 21st Century – Adaptation Solutions

In Canada, dam construction reached its apogee during 1950-1980, and approximately half of the country's dams are now more than 50 years old. During their long lifetimes, dams around the world have witnessed considerable evolution in building techniques, materials, monitoring technology, geologic and hydrologic sciences, as well as in regulatory oversight. This evolution has been in part fueled by catastrophes and near misses. For instance, dam failures in Great Britain were long seen as accidental, caused by unpredictably intense rains, until the failure of two dams—Bilberry in 1852 and Dale Dyke in 1864—under clear-sky conditions. Inquiries into the cause of the catastrophes revealed gross and culpable negligence, and a lack of engineering skills. Lawmakers started to require dam owners to submit construction plans for approval and to permit inspections before filling began.

Population increases also played a role in the development of dams. Small village dams had to be periodically raised to increase storage for burgeoning cities. Upstream urbanization, deforestation and drainage increased peak flows into reservoirs. At the same time, natural sedimentation in reservoirs decreased effective volumes and required either dredging or raising crests. Scientific research also revealed previously unknown vulnerabilities, such as hydraulic uplift: the upward force created as water seeps into the soil beneath a dam structure. Not widely known to early dam builders, hydraulic uplift caused many dams to topple when their footings lifted. Another common problem is piping: water seeping under a dam carries fine sediments that scour channels or pipes and weaken dam foundations.

Dam engineering has progressed and a number of retrofit solutions were devised to adapt dams to changing requirements and environmental conditions. Tables 2, 3 and 4 present a partial list of structural, operational and regulatory adaptations designed to lower the risk of dam failure. The same adaptation options can help dams withstand the risks associated with climate change. Most operational options, such as better flood forecasting and lower operational reservoir levels, are widely applicable. The feasibility and cost-effectiveness of structural adaptations, however, vary based on the characteristics of each dam. It might be impossible to retrofit an existing dam with an additional bay without compromising its structural integrity, for example, or there might simply not be enough room to accommodate an auxiliary spillway.

The economics of dam refurbishment in a changing climate raise a number of complex social and regulatory issues, compounded by the large uncertainties around PMF future projections. For some watersheds, climate simulations project increases in PMF of more than 100%. While climate scientists put little confidence in the results of a single simulation—especially with regards to such extremes—a conservative approach to regulation would require dam owners to protect against worst-case future scenarios. No simple retrofit solutions can address changes of such magnitude, however, and only major structural upgrades—or decommissioning—could meet regulations based on such extreme future scenarios. Basing regulations—and design standards—on optimistic climate scenarios with lower PMF changes, of course, could create a false sense of security. Given the uncertainty of climate projections for these extremes, establishing appropriate regulations based on design standards represents a considerable challenge.

From a cost-benefit perspective, meeting design standards when climate uncertainties are large raises other questions. Upgrading dam infrastructure to accommodate a possibly higher PMF would provide no direct benefits to society other than a theoretical decrease in the already unlikely possibility of a catastrophic event. Indeed, the recent history of dams suggests that failures and near misses tend to result not from poor design, but from inadequate maintenance and monitoring, cavalier management or a string of relatively minor mistakes and failures.

Given the ultimate objective of protecting lives and maintaining the benefits afforded by dams, the focus of dam managers is on the overall risk profile, and not only on risks associated with the structural design of the dam itself. Maintaining the public's trust in hydroelectric infrastructure will require proactive measures, including research into current and emerging risks, development of better future PMF estimates, and implementing a credible and diverse portfolio of initiatives to mitigate risk.

ASSESSING OVERALL RISK

Taking a broader view of reducing loss of life raises a number of challenges. Indeed, a watershed is a complex system comprised of interdependent natural and operated components. Design is only one of the many factors that can contribute to dam failure. Others include the failure of spillway equipment to operate properly, generating capacity hampered by forced unit outages, transmission-system-failures, staffing limitations, the inability of staff to access dam sites during crises, and operational and forecasting errors. All factors must be considered, both independently and holistically.

To understand how a dam system behaves following accidents, failures and intense periods of rainfall and snowmelt, a multi-faceted system model can be developed. The model includes: software that generates a large variety of weather scenarios; a rainfall-runoff model that translates meteorological inputs into flow into reservoirs and powerhouses; a model that simulates power-generation operations, reservoir management, transmission constraints and cascading impacts of potential equipment failure; a hydrodynamic model that describes water flow in the event of dam or dike failure; and a safety model that estimates the potential loss of life given expected flood patterns and population distribution in the floodplain.

The system model estimates the likelihood of failure events and the potential for loss of life expressed as a recurrence interval (every 10, 100, 1,000 years). This type of risk analysis not only supports comparisons with other industries, but may also help identify vulnerabilities that could be fixed, emergency plans that would reduce fatalities in the event of a failure, and development policies that would limit the impacts of floods.

Table 2 *Structural adaptation options.*

TYPE	OPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES
SPILLWAY IMPROVEMENTS	Service Spillway Modification	Lowering of spillway crest invert	- Increased spill capacity with minimal impact on general arrangements and operation	- Possible redesign of gates required - Structural considerations - Loss of spill capacity during construction - Potential loss of storage for overflow spillways or removal of flashboards during flood season - Potential upgrade in energy dissipation structures
		Rollway/ sluiceway/ chute conversion/ modifications	- Increased spill capacity with minimal impact on general arrangements/ operation	- Structural considerations - Loss of spill capacity during construction
		Bay addition/ increase crest length	- Increased spill capacity with minimal impact on existing works - Minimized loss of existing capacity during construction	- May be complicated to retrofit at existing facility
	Service Spillway Replacement	Replacement of existing spillway with new structure	- Complete redesign. - Minimal performance/ reliability risks - Opportunity to replace aging works near end of service life	- Expensive - Potential loss of spill capacity during construction

Table 2 *Structural adaptation options (continued)*

TYPE	OPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES
SPILLWAY IMPROVEMENTS	Auxiliary Spillway Modification	Modification of existing auxiliary spillways	- Retrofit structure to increase capacity without requiring additional space (e.g. piano key/ labyrinth weir, rubber pneumatic gate weir)	- Loss of auxiliary spill capacity during construction - Some modification options may reduce active storage and operational flexibility.
	Auxiliary Spillway Construction	Addition of ungated/gated spillway	- Increased additional spill capacity - No loss of existing spillway capacity	- Requires construction/ operation/maintenance of independent structures - May not be feasible due to space limitations
		Addition of fuse plug /hydro-fuse gate	- Relatively easy to install/retrofit	- Environmental implications of sedimentation/scour from erosion of plug - Costs/time to repair fuse plug after use - Maintenance/upkeep costs if used frequently - Design requires suitable location to minimize risk of triggering dam failure - Some concerns over reliability/ performance of erodible fuse plugs if not properly maintained - Fuse-plug performance may be jeopardized if required to operate during freezing conditions - Discharge during fuse-plug operation is largely uncontrollable
EARTHWORKS / CHANNEL IMPROVEMENTS	Dam Embankment Modification	Raising embankment height/ addition of flash boards to increase reservoir surcharge capacity/ conveyance of spillway	- Relative ease of construction and low cost - Localized slope steepening or parapet wall construction along the crest may be feasible to increase embankment height elevations within the freeboard region of the dam that is only subject to wave action	- Structural modifications to spillway/ energy-dissipation structures may be required to manage increased surcharge levels due to increased velocities - May not be effective if flood capacity governed by height of other principal structures (e.g. PH deck elevation)
	Addition of upstream storage capacity	Construction of upstream reservoir to attenuate flood wave	- No modification to existing site required	- Requires construction/operation/ maintenance of independent facility - May increase flood hazard risk in case of cascade-failure mode

Table 2 *Structural adaptation options (continued)*

TYPE	OPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES
EARTHWORKS / CHANNEL IMPROVEMENTS	Channel Improvements	Upstream/downstream channel improvements to increase outlet capacity of dam/ reduce downstream flood risk	- Allows for passage of higher flows for given forebay/tailrace levels - Downstream channel improvements may reduce dam-failure consequences for nearby communities	- Environmental considerations
		Earthcut spillway/ diversion channel creation	- Creates a safe channel defined for passage of floods around principal dam structure	- Must be properly located and designed to protect against channel erosion and triggering of dam failure - May require riprap armouring or lining to prevent excessive scour during operation - Careful design and ongoing maintenance of channel is required to ensure reliable performance
	Overtopping Protection System	Reinforce/stabilize embankments to allow for safe flood passage during overtopping	- Increasingly viewed as a viable alternative to address hydrologic deficiencies when other options not feasible - Allows for no change in dam operations	- May not be feasible for high-head structures - Typically only suitable for lower-head dams, where overtopping would be of short duration and of limited magnitude - Not accepted as an option by some regulatory agencies - Requires careful analysis of dam-failure modes, as there is a high risk of structural failure during embankment overtopping
POWERHOUSE IMPROVEMENTS	Unit Addition/ Re-Runnering	Increase SNL capacity of powerhouse units can pass during PMF	- No modifications to spillway required - Improved station energy production	- Increased flow capacity may be minimal - Loss of power production during construction - Requires increase in average flows to be justified (capacity factor)
DECOMMISSIONING	Removal of Structures	Remove structure	- Risk of failure is eliminated - May be advantageous if facility is at end of service life	- Loss of asset/source of energy production - May cause significant changes to water regime - Remedial measures may be required for habitat restoration/adaptation

Table 3 *Operational adaptation options.*

TYPE	OPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES
PLANT OPERATIONS	Reduced Forebay Level	Lowering normal operating level to increase available storage to attenuate flood wave	No changes to facility structures/operations required	- Reduced head/unit efficiency/ power production - Consideration of structural/ mechanical limitations to minimum operating level - Environmental/community considerations to change in water regime
		Use of forecasting/ warning systems knowledge to pre-draw forebay prior to flood event	No modification to structure required	- Requires forecasting abilities to predict flood events ahead of time - May not be effective if reservoir size is small
SYSTEM OPERATIONS	Modification to Upstream Regulation	Reduction in diversion flows	No structural modifications required	- Potential requirement to modify operating licenses - Requires reliable forecast of inflows
		Change in upstream operations (pre-ventive lowering of operating level) to reduce flood-peak inflow	No structural modifications required	- Potential requirement to modify operating licenses - Requires reliable forecast of inflows/coordination between multiple stations - May not be feasible in situations governed by cascade-failure mode of multiple stations

Table 4 *Regulatory adaptation options.*

TYPE	OPTION	DESCRIPTION	ADVANTAGES	DISADVANTAGES
DAM HAZARD ASSESSMENT/ RECLASSIFICATION	Review options available to reduce IDF requirement by reducing consequences of failure/ dam-hazard classification	Changes to emergency preparedness plan, improved redundancies and warning systems, expropriation of land in inundation to reduce LOL/consequence of failure	No changes to facility structures/operations required	- May not reduce consequences of dam failure - Dam reclassification does not reduce hydrologic risk to structure, only changes consequences of failure
ADOPTION OF RISK-INFORMED APPROACH FOR INFLOW DESIGN FLOOD (IDF) SELECTION/ SPILLWAY SIZING	Risk-informed approach for selecting IDF over traditional prescriptive standards-based approach	Evaluate probability-weighted consequences of dam failure due to extreme floods against costs of increased discharge capacity to handle the event. Sizing of spillway is based upon probabilistic flood hazard, consequences of failure, definition/understanding of tolerable risk, and application of the ALARP principle.	Provides justification for the amount spillway capacity required for a structure given the probabilistic flood hazard and consequences of failure, rather than adopting a prescribed IDF based on broadly-defined dam classifications in standards-based approaches. Gives owners/ practitioners a better understanding of site-specific flood risk and enables prioritization of measures to address any deficiencies. Risk-informed dam-safety programs are emerging in the dam safety community, and are increasingly being seen as an option to address deficiencies.	Requires significantly more detailed analysis/expertise regarding flood risk over standards-based approach: - Identification of all modes of failure required - Quantifying probabilities and consequences of each failure mode - Developing a continuous probability-distribution of flood risk (up to PMF) - Some consideration of joint probability-distributions required for non-independent events may be necessary - Definition of tolerable risk required - Demonstration of As Low As Reasonably Practicable (ALARP) principle is required when sizing spillway - Most regulatory bodies still employ a standards-based approach to flood hazard. Several associations (ege.g. CDA) recognize risk-based approaches, but provide limited guidance on scoping and requirements. - Might not be acceptable to some regulators

Abbreviations

CCSM3	National Center for Atmospheric Research (NCAR) Community Climate System Model version 3
CDA	Canadian Dam Association
CGCM3	Canadian Climate Centre Coupled General Circulation Model version 3
CO_2	Carbon Dioxide
CORDEX	COordinated Regional Climate Downscaling EXperiment
CRCM4	Canadian Regional Climate Model version 4
ECHAM5	European Centre Hamburg Model version 5
ECP2	Scripps Experimental Climate Prediction Center Regional Spectral Model
GFDL_CM2.5	Geophysical Fluid Dynamics Laboratory Climate Model version 2.5
GHGA	Greenhouse Gases and Aerosols
HadCM3	Met Office Hadley Centre's regional climate model version 3
MM5I	Pennsylvania State University/National Center for Atmospheric Research (NCAR) Mesoscale Model
NARCCAP	North American Regional Climate Change Assessment Program
PMF	Probable Maximum Flood
PMP	Probable Maximum Precipitation
ppm	parts per million
PMSA	Probable Maximum Snow Accumulation
RCM3	Regional Climate Model version 3
RCP	Representative Concentration Pathways
RT	Rio Tinto
SRES	Special Report on Emissions Scenarios
SSARR	Streamflow Synthesis and Reservoir Regulation
WMO	World Meteorological Organization

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