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Probable maximum flood in a changing climate: An overview for Canadian basins

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A R T I C L E I N F O

Keywords:
Probable Maximum Precipitation (PMP)
Probable Maximum Flood (PMF)
Regional Climate Models (RCM)
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A B S T R A C T

Study Region: In Canada, dams which represent a high risk to human loss of life, along with important environmental and financial losses in case of failure, have to accommodate the Probable Maximum Flood (PMF). Five Canadian basins with different physiographic characteristics and geographic locations, and where the PMF is a relevant metric have been selected: Nelson, Mattagami, Kénogami, Saguenay and Manic-5.

Study Focus: One of the main drivers of the PMF is the Probable Maximum Precipitation (PMP). Traditionally, the computation of the PMP relies on moisture maximization of high efficiency observed storms without consideration for climate change. The current study attempts to develop a novel approach based on traditional methods to take into account the non-stationarity of the climate using an ensemble of 14 regional climate model (RCM) simulations. PMPs, the 100-year snowpack and resulting PMF changes were computed between the 1971-2000 and 2041-2070 periods.

New Hydrological Insights for the Region: The study reveals an overall increase in future spring PMP with the exception of the most northern basin Nelson. It showed a projected increase of the 100-year snowpack for the two northernmost basins, Nelson (8%) and Manic-5 (3%), and a decrease for the three more southern basins, Mattagami (-1%), Saguenay (-5%) and Kénogami (-9%). The future spring PMF is projected to increase with median values between -1.5% and 20%.

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1. Introduction

In Canada, there are over 15,000 dams owned by federal and provincial governments, hydropower utilities, industrial companies (including mining), municipalities and private individuals (Canadian Dam Association, n.d.). Some of the larger dams are used for hydropower with many of the medium to small sized ones used for irrigation, flood control, and water supply. Regardless of the size, all dams must be designed, operated and maintained to avoid unacceptable risk to inhabitants downstream. With the abundance of freshwater resources in Canada, about 63% of the electricity in the country is produced through large hydropower dams (Canadian Hydropower Association, 2017). Many of these hydropower dams have long life spans of up to 100 years which make them highly vulnerable to environmental change, especially the potential impacts of climate change.

In Canada, for most provinces, dam safety is legislated at the provincial level with regulations often inspired by the Canadian Dam Association's Safety Guidelines (Canadian Dam Association, 2013). Dams classified in the "extreme hazard" category are those that, in case of failure, have the potential to cause human loss of life and severe environmental and financial losses. Consequently, they have to meet strict design requirements regarding the maximum flow the dam must be able to pass based on the concept of Probable Maximum Flood (PMF). "Under disadvantageous conditions, PMP could be converted into PMF-the theoretical maximum flood" (WMO, 2009, p.1) that could occur "[…] at a particular geographical location in a given watershed […]" and at a particular time of year, "[…] with no allowance made for long-term climatic trends." (WMO, 2009 p.xxv). Many meteorological variables have an impact on the intensity of the PMF. One of the major drivers is the Probable Maximum Precipitation (PMP), which is the largest amount of precipitation that could accumulate in a given watershed, for a specific duration and for a particular time of year (WMO, 2009). Soil moisture, snowpack, temperature sequence, upstream regulation and reservoir capacity can also influence the impact of a PMP on runoff and increase the likelihood of a large flood event. Both recent historical observations and climate change simulations show increasing trends in the frequency and intensity of extreme precipitation events over Canada and most of the U.S.A. (IPCC, 2012). Since traditional methods for estimating PMPs and the resulting PMFs assume stationary conditions, there is a need to develop a methodology to account for changing climate conditions in the PMF calculations (Canadian Dam Association, 2013; WMO, 2009).

The approach suggested by the World Meteorological Organisation to estimate PMPs is based on observed meteorological data (WMO, 2009). It relies on the principle of moisture maximization of high-efficiency storms. The maximization technique finds the maximum amount of rainfall that each storm could have generated by assuming that all available moisture within an atmospheric column, commonly called the precipitable water, will indeed precipitate.

Recent studies have explored the use of climate models to compute PMPs in a future climate and their results clearly underline its sensitivity to climate change (Beauchamp et al., 2013; Kunkel et al., 2013; Rouhani, 2016; Rouhani and Leconte, 2016; Rousseau et al., 2014). Using global climate model (GCM) simulations from the CMIP5 ensemble with Representative Concentration Pathways 8.5 (RCP8.5), Kunkel et al. (2013) showed an increase in maximum precipitable water of 20–30% in the USA for the period 2071–2100 relative to 1971–2000. Since precipitable water is one of the key drivers in the calculation of PMP events, higher levels of atmospheric moisture will impact the PMFs.

In the province of Quebec (Canada), several studies have used outputs from the Canadian Regional Climate Model (CRCM4; De Elía and Côté, 2010; Music and Caya, 2007) to compute PMPs. Using two simulations over the Manic-5 basin, Beauchamp et al. (2013) found that summer-fall PMPs would increase by 0.5–6% over the 2071–2100 period. Using four simulations of the same regional climate model (RCM), Rousseau et al. (2014) showed an overall significant increase of summer-fall and spring PMPs for the Kénogami and Yamaska basins. Finally, Rouhani and Leconte (2016) used eight CRCM4 simulations for their PMP assessements over the Chaudière, Moisie and Great Whale basins. They found a significant increase for future summer-fall PMPs for the Great Whale, a small decrease for the Moisie and a significant decrease for the Chaudière.

Since there is no widely accepted method to either integrate the effect of a non-stationary climate in the determination of PMF magnitudes or to incorporate resulting adaptation changes into the design, operation, or maintenance of hydropower facilities, Manitoba Hydro, Ontario Power Generation, Hydro-Québec, Rio Tinto, and the Minister of Sustainable Development, the Environment and the Fight Against Climate Change[1] partnered with the Ouranos Consortium and the Water Earth Environment Centre of the National Institute of Scientific Research[2] to develop a robust method to evaluate future PMF values under climate change. The rationale behind this collaboration was to put together a team of climate experts and hydrologists to compute reference and future PMFs using operational hydrological models. This study considers multiple rainfall storm sizes, basins with different characteristics across Canada and covers some of the uncertainties related to climate model representation, and natural climate variability, by using an ensemble of simulations from the North American Regional Climate Change Assessment Program (NARCCAP; Mearns et al., 2009) and from multi-member CRCM4 simulations produced at Ouranos. As far as the authors are aware, the current study is the first to use an ensemble of RCMs to compute PMPs and PMFs and to address the uncertainty related to modelling through the use of different RCMs and driving GCMs. RCMs were used to take advantage of their fine spatial resolution (compared to GCM) which can better represent extreme precipitations and associated spatial variability over the study basins (Kopparla et al., 2013).

This paper is organized as follows: Section 2 presents the study domain, the climate data and the general methodology; Section 3 introduces the results of the simulated PMPs, the 100-year snowpack, and the PMFs. A discussion on the limitation of the approach is proposed in Section 4, followed by the main conclusions in Section 5.

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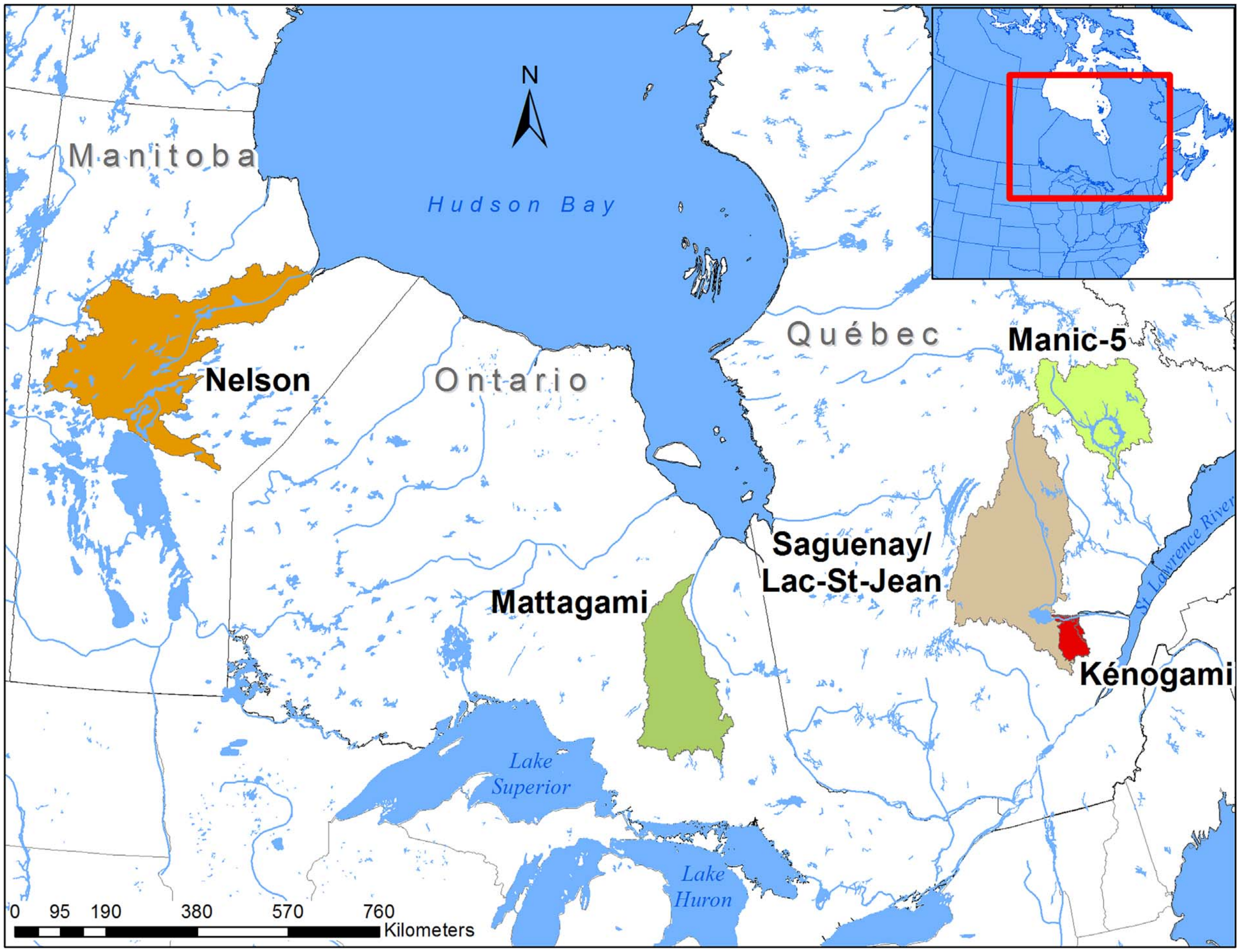

Fig. 1. The five basins included in the study: Lower Nelson, Mattagami, Kénogami, Saguenay Lac-St-Jean and Manic-5.

2. Methodology

2.1. Study domain, data and models

In this collaborative effort, five watersheds across Canada were selected where PMF studies had been performed using historical observations and traditional PMF methodologies. As shown in Fig. 1 and Table 1, those selected watersheds have different physiographic characteristics and geographic locations. Lower Nelson basin is characterized by a high mean annual runoff compared to the annual rainfall input to the basin. This can be explained because a significant portion of the average annual flow measured at the outlet of the Lower Nelson comes from the Lake Winnipeg/Churchill River Diversion located upstream.

Table 1
Characteristics of the five selected basins.

	Lower Nelson	Mattagami	Kénogami	Saguenay-Lac-St-Jean	Manic-5
Annual rainfall (mm)	315	517–621	1030	656	640
Annual snowfall (mm)	221	290–349	287	276	310
Mean annual temperature (°C)	−3.7	0.1–1.3	2	0.6	−1.8
Mean annual runoff (m^3/s)	3280	300–400	77.4	861	660
PMF timing	Spring	Spring	Spring	Spring	Spring
Drainage area (km^2)	91,000	36,800	3390	45,385	29,200
Storage (hm^3)	81,4	337	380	5083	35,000
Hydrological model	SSARR (USACE, 1991)	HEC-HMS (USACE, 2001, 2000)	HYDROTEL (Bouda et al., 2014, 2012; Turcotte et al., 2013, 2007; Fortin et al., 2001)	CEQUEAU (Morin and Paquet, 1995)	SSARR

Table 2
Details of the ensemble of 14 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. The different colors are linked to figures, allowing a specific analysis by group of simulations (green: CRCM4 simulations driven by different members of the CGCM3, pink: CRCM4 simulations driven by different members of the ECHAM5, orange: simulations from the NARCCAP ensemble).

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
RCM3	GFDL_CM2.5	1

In the current Canadian Dam Association guidelines, three main scenarios are identified as potentially generating the governing PMF: (i) a summer PMP event (Summer PMF); (ii) a spring PMP event combined with the melt of a 100-yr snowpack (Spring PMF-1); and (iii) a 100-yr spring rainstorm combined with the melt of a Probable Maximum Snow Accumulation (PMSA) (Spring PMF-2). From previous studies, based on the traditional method with observed data, we found that the spring PMF-1 (spring PMP and 100-yr snowpack) gives the highest values of PMF for all studied basins. Since the PMF is by definition the most intense flood, we focused our analysis on the scenario PMF-1. However, it is important to mention that the PMF is basin specific, so that different regions could lead to the selection of a different scenario.

For this study, several meteorological variables (liquid precipitation, precipitable water, temperature, and snow water equivalent) were extracted from a subset of regional climate simulations from NARCCAP as well as CRCM4 simulations produced by the Ouranos Consortium (Table 2). These RCMs were driven at their boundaries by CMIP3 GCM simulations (Coupled Model Intercomparison Project Phase 3; Meehl et al., 2007), where NARCCAP RCM grid cells have dimensions of about 50 × 50 km^2 (2500 km^2) and CRCM4 about 45 × 45 km^2 (2025 km^2). With limited computing resources, the modelling groups participating in NARCCAP focused on the 2050 horizon (2041–2070) and considered a single greenhouse gases and aerosols (GHGA) future emissions scenario, the Special Report on Emissions Scenarios A2 (SRES-A2; Nakicenovic et al., 2000). The SRES-A2 describes a future where no significant efforts are made to curb emissions, and represented the track the world was currently on when this choice was made (Peters et al., 2012)The choice of the GHGA scenarios has a limited impact on the results since the study focuses on the 2050s.

Literature review and basic model evaluation were performed for all available NARCCAP RCMs in order to assess their capability of reproducing the historical climate and to generate meteorological variables that can be used to compute the PMP. For instance, from the ensemble of models available two models were not considered in this study, as some of their behavior were considered to be outliers: the WRFG model was found to produce a much too shallow snow cover (along with too short duration), while HadRM3 displayed a very noisy geographical precipitation pattern, which can be problematic for basin-scale extreme value analysis. In total, 14 simulations, coming from four individual RCMs were selected.

2.2. Computing PMPs from RCMs

The project timeline behind this study focused on PMP changes, without much time allocated to examine closely the ability of a model to simulate precipitation extremes. Fortunately, a number of recent analyses have focused on the evaluation of extreme precipitations generated from NARCCAP RCMs. Khaliq et al. (2015) looked at daily precipitation for 10-, 30- and 50-year return periods over Canadian Prairie basins, including the Nelson. For the Lower Nelson basin, they found that a large number of RCMs overestimated the 50-year return period precipitation, with an average ensemble mean overestimation around 30% when compared to gridded observations (10-km resolution). Monette et al. (2012) analyzed 1- to 10-day durations and 10-, 30- and 50-year return periods over several Quebec basins, including Manic-5 and Saguenay. For these two basins, they found that some RCMs underestimated these extremes, while the majority of RCMs overestimated them when compared to gridded observations (10-km resolution). The ensemble mean for 50-year events (7-day duration shown in Fig. 4) shows an overestimation around 5% for Saguenay and 15% for Manic-5. Mailhot et al. (2012) examined 2-, 5-, 10- and 20-year return periods and 24-, 72- and 120-h durations over Canada. Considering the multi-model mean, with grid tile results compared to collocated station observations, they found that biases decrease as duration increases, but the dispersion of values from the different RCMs of the ensemble increases. Inversely, for a given duration, biases increase with increasing return period. In general, they found a good agreement between models and observations, except over British Columbia where differences were the largest. In all these studies, sparseness of station density underlying the gridded observed datasets represented an important factor to consider in the analysis of extreme precipitation. Overall, the ensemble average showed better ability to simulate extreme precipitation compared to individual RCMs. This is why climate change studies must use an ensemble of multiple climate model outputs to help reduce the uncertainty associated with the use of a single model, and even more so when it comes to extremes over limited areas such as basins. In the case of the CRCM4, the model generally underestimates extreme precipitation (50-year annual maximum) over the province of Quebec (Monette et al., 2012) and overestimates them over the Lower Nelson (Khaliq et al., 2015).

Precipitable water simulated by RCMs must also be considered since it represents an important component in the PMP computation. Paquin et al. (2016) analyzed the skill of the CRCM4 to simulate precipitable water over the five study basins through comparison with recently released NVAP-MEaSUREs (National Aeronautics and Space Administation -NASA- Water Vapor Project -NVAP- Making Earth Science Data Records for use in Research Environments) surface and space-born observations (Vonder Haar et al., 2012). They found that the CRCM4 is able to reproduce the major characteristics of the observations (e.g., annual daily maximum and basin variability) and, can therefore serve to provide precipitable water data that could be used for PMP and PMF studies. We believe that this conclusion can be extrapolated to most RCMs in general, even though particular features of each RCM-GCM combination will remain an issue that must be considered in any study.

The guiding principle behind the development of this methodology to simulate future PMPs and PMFs under climate change is to stay as close as possible to the traditional method used by meteorologists and hydrologists (Chow and Jones, 1994; Debs et al., 1999; SNC- Lavalin, 2003; WMO, 2009) so that it can be understood and used by practitioners. In this proposed method, the observed records from the largest historical storms traditionally used were replaced by storms simulated by the ensemble of RCM simulations using an automated procedure.

Starting from the approach developed by Rousseau et al. (2014) and based on the concept of moisture maximization with RCM outputs, an enlarged region was first defined around each basin of interest. This extended area is considered meteorologically homogeneous with the basin of interest, and it is assumed that storms occurring over this extended region could have happened within the basin boundary. This technique increases the sample size of extreme rainfall events and allows extreme events to be captured more effectively.

Over the extended basin areas, three variables were computed from the ensemble of RCMs: liquid precipitation, precipitable water and snow on the ground (as snow water equivalent). Some pre-processing of the RCM data was necessary to generate standardized datasets that could then be processed identically for each RCM. Two NARCCAP simulations did not provide precipitable water outputs. In these cases, precipitable water was derived from the summation of the specific humidity available for 28 atmospheric pressure levels — from the surface to the top level (50 hPa), as described in Rousseau et al. (2014). For all NARCCAP runs, additional processing was required to obtain the rainfall portion from the total precipitation (liquid plus snowfall). Using mean daily temperature series, a temperature threshold of 0 °C was set to partition the liquid and solid precipitations.

The following subsections and Fig. 2 provide an overview of the steps leading to the computation of the PMPs. To name only a few, here is a list of some choices made based on preliminary sensitivity analyses: setting a threshold to select PMP events, choosing the best statistical distribution, defining an upper limit for the maximization ratio, defining a minimum threshold of SWE on the

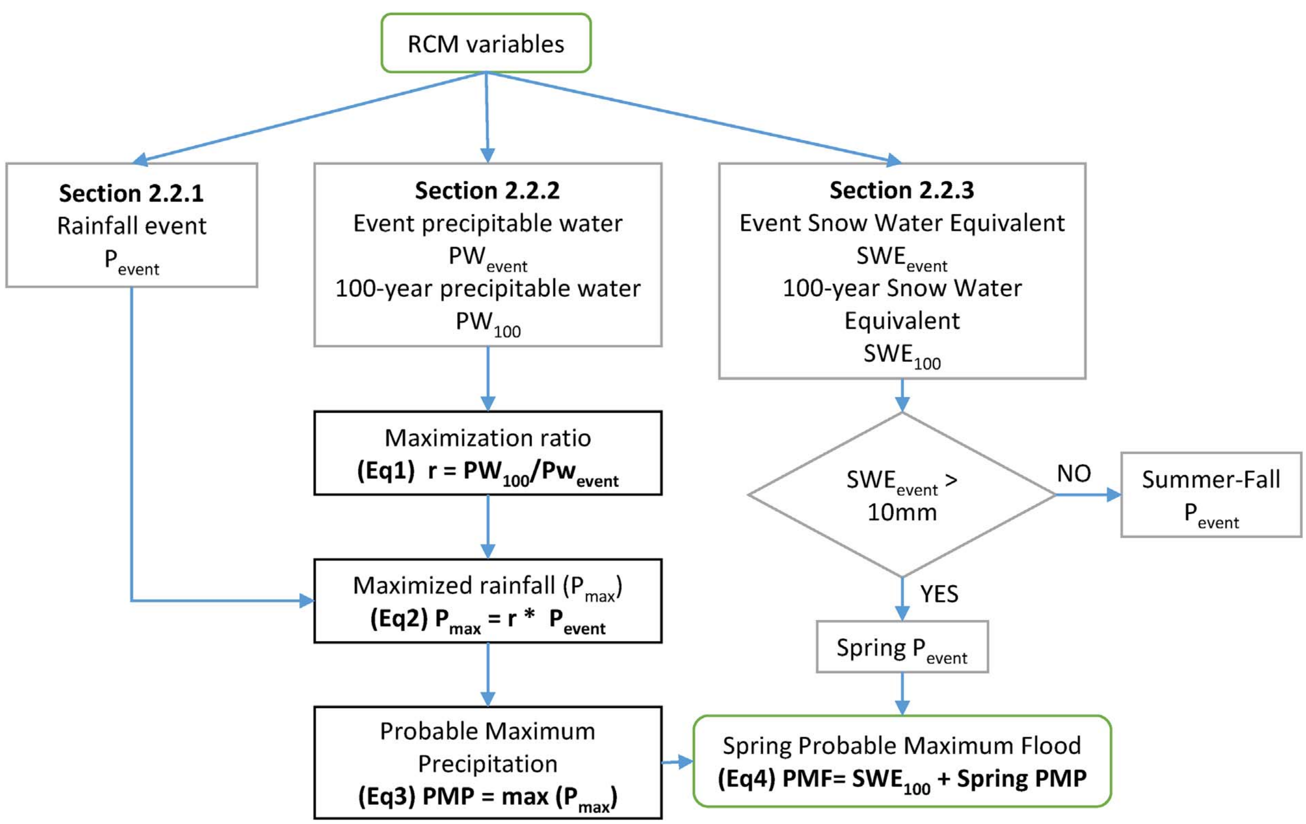

Fig. 2. Overview of the different climate variables and their role in the computation of the PMP and PMF.

ground to define the seasons. For all those steps, sensitivity analyses were performed to define the best approach with the objective of automating the procedure. The main purpose is to develop a general enough approach, easily reproducible by engineers with data coming from RCMs, while maintaining a physical coherence.

2.2.1. Storm definition

The traditional approach is typically interested in storms of 24-, 48- and 72-h durations. In the current study, the analysis was extended to 120-h storms to explore the impact of climate change on events of longer duration. Over each model grid-cell within the extended basin area, all rainfall events of 24-, 48-, 72- and 120-h durations were assessed for the current (1971–2000) and future periods (2041–2070). Precipitable water associated with each one of these events was also computed (see Section 2.2.2).

When using climate simulations, identifying major storms is not straightforward due to differences among RCMs. Some models systematically generate larger precipitation values than others. Setting a rainfall threshold to identify major storms could lead to few storms under one model, and to several storms under another. For this study, rainfall events were identified using a moving window technique that cumulates precipitation for different time durations accounting for all possible rainfall events (Rousseau et al., 2014). To avoid over-maximization of small events, only the 10% largest storms of each year, referred to as P_{event}, were kept for further calculation. It is noteworthy that another approach developed by Beauchamp (2010) defines rainfall events as consecutive rainfall days between dry days. However, this technique requires the use of a rainfall rate threshold to discriminate dry days and, as this threshold must be adapted to each RCM through a series of tests, it was not possible to perform such a task in the context of this project; it is worth mentioning that Beauchamp (2010) considered a single model in her study.

2.2.2. Maximization ratio

Each rainfall event (P_{event}) was maximized according to Equation 1 (see Fig. 2). The precipitable water of an event (PW_{event}) is defined as the maximum precipitable water found during the entire duration of P_{event} extending up to six hours prior to its start. In other words, it represents the amount of humidity associated with the event, generally coinciding with the arrival of a humid air mass in the vicinity of the basin. PW_{100} refers to the monthly 100-year return value of precipitable water and was calculated from the available 30-year sample of each RCM data fitted to a Generalized Extreme Value (GEV) distribution using the maximum likelihood approach. For the current and future periods, the PW_{100} value of each month of the year was calculated for each grid cell of the extended basin area. The maximization ratio used is thus defined for each extreme rainfall event and may vary in time and space. According to Equation 2, the maximization ratio was multiplied by each P_{event} and the resulting PMP was defined as the maximum of all the maximized rainfall (P_{max}) of each 30-year period (1971–2000 and 2041–2070).

Various studies have suggested imposing an upper limit to the maximization ratio on the basis that maximizing a storm by too large of a factor may render it physically implausible. Several values have been proposed for this limit, from 1.5 (USACE, 1978) to 2.0 (Dumas, 2006; WMO 2009) and even up to 2.5 (SNC-Lavalin, 2003). Other sources (Beauchamp et al., 2013; Chen, 2006) have considered that such a limit is arbitrary and have suggested a more physical approach where the PW_{100} may not exceed the value of precipitable water of a saturated atmosphere (PW_{Sat}), which is by definition the maximum possible moisture content. Tests performed with one simulation of the CRCM4 driven by one member of the CGCM3, showed a very small number of cases where a PW_{100} was greater than PW_{Sat} (less than 5%). Given that not all RCMs used in this study provide the data required to compute PW_{Sat}, the approach chosen was to limit the maximum value for PW_{100} to be less than 20% larger than the largest value found in the 30-year sample of the maximum PW values. Moreover, if it exceeds the latter value, we then use the maximum PW value in the sample. Given this criterion, we eliminate possible problems in the parameter-estimation process of the GEV and PW_{100} is kept within a more physically realistic range of values.

2.2.3. Definition of seasons

In traditional PMF studies, seasons are defined according to calendar dates, but here a flexible definition of seasons was chosen to account for both potential climate change (an earlier spring melt) and location (latitude) of each basin. For this study, snow water equivalent (SWE) was used as a proxy to distinguish the season in which the rainfall event and consequently the PMP occurs. Rainfall events taking place when there is a minimum accumulation of 10 mm of SWE on the ground (SWE_{event} on Fig. 2) were considered for the computation of spring PMP (following Rousseau et al., 2014), while other events were interpreted as summer-fall PMPs. Furthermore, to make sure that a possible spring PMP does not happen too early in the winter before the snowpack has matured, a check was made to assess that the event takes place between the months of January and August.

2.2.4. Storms at different spatial scales

In standard PMF studies, meteorologists compute PMPs for different storm durations and for different storm sizes, ranging from 4000 to around 50,000 km^2. The proposed methodology determined PMPs at the scale of a RCM grid cell, which has dimensions of about 2500 km^2 (50 × 50 km^2). In order to establish areal relationships, the approach developed in this study consists in running the PMP analysis using different combinations of multiple grid cells, from 2 to 25, arranged in various spatial configurations (see Appendix A). First, spatial averaging of each climate variable is performed, as well as computation of the resulting PMP, by considering all possible combinations over the extended basin area. The maximum of all computed PMPs is identified as the final PMP that is associated to a particular combination. In some cases, multiple combinations are possible for the same area since the same number of grid cells can be aggregated differently. For those cases, the average of all computed PMPs is taken. For instance, the PMP corresponding to an area of three grid cells corresponds to the average of the four computed PMPs for combinations 3.1–3.4 (see Appendix A). The shapes of the different combinations were kept as much as possible to an elliptic form to represent realistic storms.

2.3. Spring probable maximum floods

As mentioned previously, a spring PMF can occur either from a combination of the spring PMP with the 100-year snowpack (SWE_{100}) or when a 100-year spring rainfall falls on a mature probable maximum snow accumulation. Over the study basins, the largest spring PMF values were originally obtained with the former and, so, the PMF methodology with climate model output was based on this particular association.

To support a meaningful comparison of spring PMFs over the five study basins, three experiments were performed. In the first experiment, the future spring PMF was computed using the projected change in spring PMP, everything else being equal. In the second experiment, the future spring PMF was computed using the projected change in spring PMP along with the projected change in SWE_{100}. For the third experiment, the future projected change in the critical temperature sequence was added to the analysis. However, the third experiment did not yield significant changes as the reference temperature sequences were originally selected to maximize flow conditions and, therefore, results from this experiment are not presented herein.

For each basin, a conventional PMF methodology, including the use of a calibrated hydrological model (see Table 1) was applied. Although each individual methodology used for the different basins was inspired by the same basic scientific principles, there is some professional judgment that has to take place (e.g., setting of antecedent soil moisture conditions in the hydrological model). For more information, the reader is invited to consult the Ouranos (2015) report.

3. Results

3.1. Probable maximum precipitation

Because the PMP is by definition the most extreme meteorological event among extremes, sampling errors were expected to generate a large spread in the projected spring PMP, as shown in Fig. 3. Other studies have examined projected changes of extreme precipitation with RCMs (Khaliq et al., 2015; Mailhot et al., 2012; Monette et al., 2012; Wehner, 2013) and indicated that, as return periods get larger, the spread in the results increases, leading to a weaker consensus between simulations. In the current study, we used as many RCM simulations as possible to cover climate-modelling uncertainties (considering different climate representations with RCMs and their driving GCMs) and found quite large spreads as expected. It is interesting to note that a large spread also occurred for simulations from the same RCM driven by different members of the same GCM (see in Fig. 3 CRCM4/CGCM3 in green, and CRCM4/ECHAM5 in purple). This particular spread represents the uncertainty related to natural climate variability, which is irreducible and would exist; such a large spread clearly points to an important sampling uncertainty and identifies the need for much larger natural variability ensembles to determine extremes with more confidence. A few groups have started to produce large ensembles providing datasets that can be pooled for extremes analyses, totalling 30–50 members in the case of GCMs (Deser et al., 2014; Fyfe et al., 2017) and 16–50 members with RCMs (Aalbers et al., 2017; Fyfe et al., 2017; Mizuta et al., 2016), representing equally probable futures.

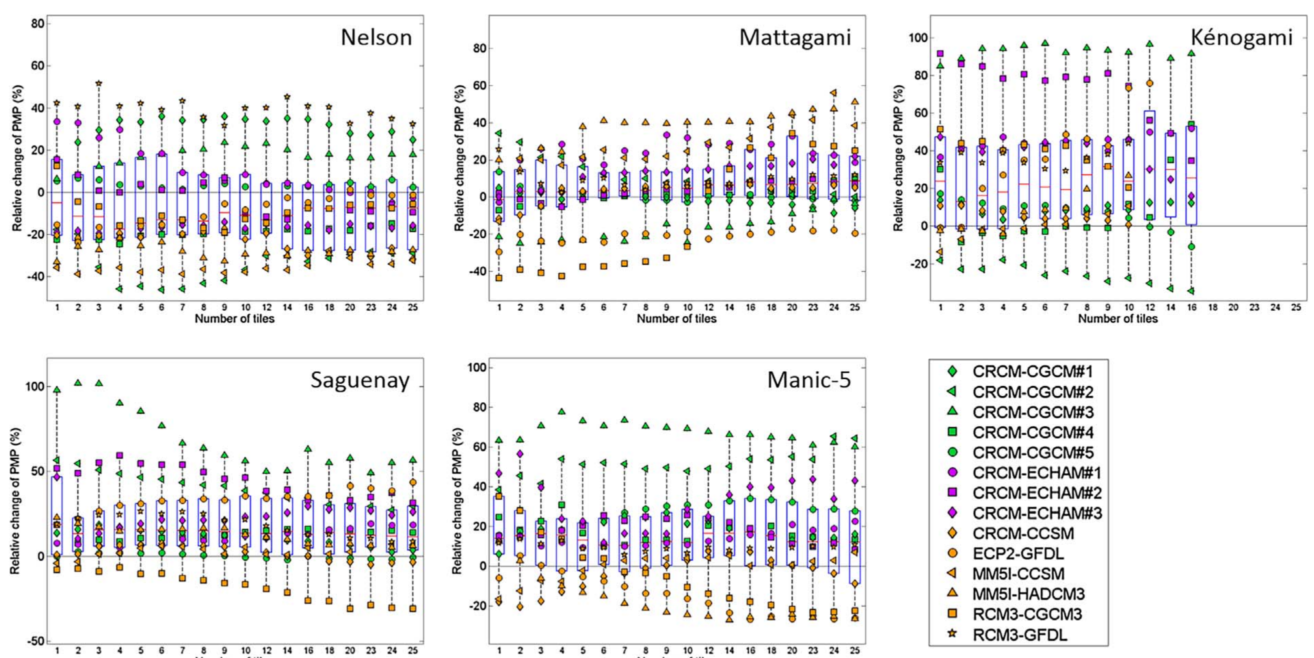

Fig. 3. Projected changes in the 72-h Spring PMP for the five study basins between 2041–2070 and 1971–2000 (%), for different storm sizes represented by the number of 2500 km^2 model tiles. The different colors represent the different groups of RCM simulations; green: CRCM4 simulations driven by different members of the CGCM3, pink: CRCM4 simulations driven by different members of the ECHAM5, orange: simulations from the NARCCAP ensemble.

Table 3
Median projected changes of the Spring PMP between 2041–2070 and 1971–2000 (%) for different durations.

Basin	Confidence level on sign of change	24-h	48-h	72-h	120-h
Nelson	No consensus	−2%	−9%	−11%	−6%
Mattagami	No consensus	8%	4%	5%	3%
Kénogami	Likely increase	18%	26%	23%	22%
Saguenay	Likely increase	19%	22%	14%	18%
Manic-5	Likely increase	17%	16%	14%	17%

Storm size, represented by the number of grid cells, has a limited impact on the relative projected change of the PMP. This observation holds for all storm durations and all five basins. Results for all storm sizes were combined to evaluate, for all storm durations, the overall projected PMP change, and the median of all projected changes are presented in Table 3. The median was selected as an estimator of the PMP change obtained with the 14 simulations. It was considered a more realistic estimator given the great dispersion of results projected by the simulations. As shown in Table 3, there is an overall increase in spring PMP for the three eastern basins: Manic-5, Saguenay and Kénogami, while the signal is not as clear for the Nelson and Mattagami basins. Our confidence in the results is based on the strength of a consensus evaluated as follows: (i) 'virtually certain' when at least 99% of the models give the same sign (14/14), (ii) 'very likely' when at least 90% of the models agree (13/14), (iii) 'likely' when at least 66% (9/14) agree, and (iv) 'about as likely as not' when between 33% and 66% (5–9/14) agree, which is equivalent to no consensus ((Cubasch et al., 2013), Table 1.2, p. 142).

For all durations, an overall likely increase is projected for Manic-5 (16%), for Saguenay (19%) and for Kénogami (22%), which means that at least 9 simulations out of 14, agreed on a positive change. For Mattagami (5%) and Nelson (-7%), no consensus was found.

3.2. The 100-year maximum snowpack

Snowpack and its maturity have a significant impact on whether the PMP will cause a PMF or not. That is why hydrologists apply a critical temperature sequence, inducing optimal melting of the snowpack at the time of occurrence of the PMP. Because the temperature sequence is constructed to optimize the thaw, the impact of implementing a future critical temperature sequence will be mostly on the timing of the PMF, not its intensity. Future climate simulations indicate an earlier melt period of around one week for the different basins (median values of 9 days for Manic-5; 8 days for Saguenay; 8.5 days for Kénogami; 7 days for Mattagami; and 5.5 days for Nelson).

As mentioned earlier, SWE_{100} refers to the 100-year return value of the annual maximum snow water equivalent calculated from the available data fitted to a Generalized Extreme Value (GEV) distribution using the maximum likelihood approach. It is noteworthy that extreme value analysis comes with uncertainties and when considering a 100-year recurrence with 30-year datasets, the uncertainty range can be quite large. Table 4 presents a comparison of SWE_{100} derived from observed data along with results obtained from the RCM simulations. For the Nelson, Mattagami and Saguenay basins, the observed 100-year snowpack was computed using several snow stations and therefore, results for mean and maximum basin values are presented. Overall, the observed 100-year maximum snowpack is captured within the RCMs' range showing some skill in the simulation of this variable. An exception is noted for the Nelson basin, where the estimated mean and maximum values derived from the ensemble of RCMs underestimate by about 25% the 100-year maximum snowpack derived from observed data. Besides model biases, the differences may be in part due to differences in the spatial representativeness of the observed data; the observation-based analysis of snowpack is based on a few snow-line measurements, while the RCM-based analysis was derived from simulated snow accumulation over a $50 \times 50\ km^2$ grid cell. Other potential differences include statistical fit uncertainty (for the 1/100-year value), as well as mismatches between the observation period, which varied depending on stations, while the RCMs uniformly cover the 1971–2000 period.

The relative changes in SWE_{100} are shown in Fig. 4. The results indicate a relatively large spread between the different climate

Table 4
Comparison of estimated SWE_{100} from observed data with those estimated from the ensemble of 14 RCM simulations over the five study basins. Note: parentheses include the number of snow course stations used to obtain the average and maximum values for each basin.

Basin	*SWE_{100} (mm)*			
	Observed data		From 14 RCM simulations	
	Mean	Max	Mean	Max
Nelson (16)	230	332	172	225
Mattagami (11)	290	306	253	311
Kénogami (1)	499		371	525
Saguenay (19)	373	431	346	428
Manic-5 (1)	415		354	474

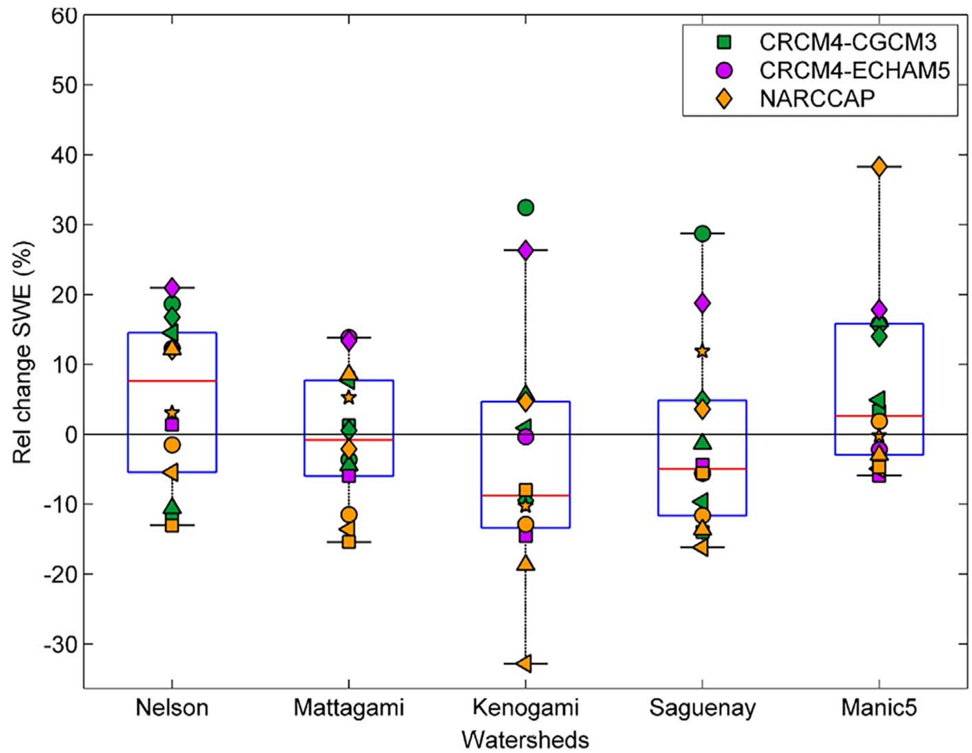

Fig. 4. Projected changes in SWE100 for the five study basins between 2041–2070 and 1971–2000 (%).The different colors represent the different groups of RCM simulations; green: CRCM4 simulations driven by different members of the CGCM3, pink: CRCM4 simulations driven by different members of the ECHAM5, orange: simulations from the NARCCAP ensemble.

simulations, showing both negative and positive changes for the same basin. The two northern basins, Nelson (8%) and Manic-5 (3%), are characterized by a positive median change, while the three southern basins, Mattagami (−1%), Saguenay (−5%) and Kénogami (−9%), are all characterized by a negative median change.

3.3. *Probable maximum flood*

The hydrologists involved in the study performed at least two sets of experiments on their basins using their own hydrological model and methodology. Table 5 presents for all storm sizes the relative changes in future spring PMFs from both experiments. For the first experiment considering changes in spring PMPs, results indicate an increase for four basins and a decrease for Lower Nelson. The magnitude of change varies between −1.5% and 21% and is strongly related to the magnitude of change in the PMP. For the second experiment considering the median changes in SWE_{100}, leads to similar results. Compared to the first experiment, basins with decreasing snow cover (Saguenay and Kénogami) show a decrease in the magnitude of the change in PMF, while the magnitude of the change in the PMF increases with increasing SWE_{100} (Nelson and Manic-5). There is almost no difference between the two experiments for Mattagami, where the relative change in SWE_{100} is almost zero.

For all basins, the projected changes in PMFs were all deemed manageable by the hydropower utilities given the existing infrastructures and operating rules.

Table 5
Results of the spring PMF for two sets of experiments considering first a projected change in the future spring PMP, and second this same change in spring PMP combined with the projected change in SWE_{100}.

	Projected changes in spring PMF	
Basins	Experiment 1 with: Future spring PMP	Experiment 2 with: Future spring PMP + Future SWE_{100}
Lower Nelson	−1.5%	0%
Mattagami	6.1%	5.6%
Kénogami	21%	18%
Saguenay	7.6%	3.8%
Manic-5	9.7%	11%

4. Discussion

The traditional method of estimating PMPs and PMFs from the observed meteorological record has a certain number of drawbacks. Creating detailed descriptions of observed large storms is a time consuming process and in Canada, has been largely discontinued since the late 1980s. Moreover, the method assumes stationary conditions without explicitly considering potential impacts of climate change on storm intensity, even if the WMO suggests that climate change should somehow be accounted for when estimating PMPs (WMO, 2009). Although the method proposed here is not a replacement for the traditional method, it was designed to be methodologically as close to it as possible to facilitate its use and interpretation by practitioners and spur discussions on how to effectively integrate climate change in dam safety assessments.

Regional Climate Models (RCMs) were considered in this study because they can generate a large numbers of physically plausible events leading to PMFs as well as include the effect of climate change. Using the current method, it appears that very large ensembles would be required to reduce the sampling uncertainty of extremes such as the PMP and make the results useful to decision-makers and regulators. The benefits of climate model-simulated events come at the cost of additional sources of uncertainties linked to climate-change analysis, including model representation of the climate system and future GHG emissions scenarios. Access to large ensembles recently produced might help in determining the PMP with more confidence, if the necessary variables are available. However, at the moment, these uncertainties make it challenging to integrate those results into engineers' practice.

The accuracy of PMP estimates under changing climate conditions is a key issue because underestimation would increase the risk of dam failure, and overestimation would lead to excessive building and maintenance costs. The validation of PMP values in the current climate is no less challenging as by definition it is not comparable with anything that has ever been observed in the past and is not related to any statistics. Evaluating the ability of RCMs to compute PMPs thus appears to be a theoretical exercise with little possibility for empirical validation, especially since PMP values often remain confidential.

While consideration of adaptation to increased flood risk from climate change is relatively new, methods to cope with floods in excess of a dam's inflow design flood is not a new topic. Due to the long lifespan of dams, progressive climatic change in many basins, and the relatively rapid developments in hydrologic sciences, it is not uncommon for the spillway capacity of older dams in operation to be deficient based on current best-practices (Dubler and Grigg, 1996; National Research Council, 1985). Cost-effective adaptation options to address the hydrologic deficiencies of aging dams have been widely studied by several agencies (ICOLD, 2014, 2010a, 2010b), and it is these same adaptation options that could be potentially used to address the potential risk of climate change increasing future floods. Generally speaking, adaptation options to accommodate a large flood event like the PMF can fall into one of three categories: (i) structural adaptation, ie. modifying the physical arrangement and/or dimensions of the dam and/or control structures, (ii) operational adaptation, ie. changing the way a plant is operated to improve flood risk management, and (iii) regulatory adaptation, ie. reducing the consequences of failure either through policy, or changing the way flood risk is considered in legislation. In this study dam owners found that their existing infrastructures and operations could accommodate these projected changes in future PMFs. Also, they found that, from a cost-benefit perspective, meeting design standards when climate uncertainties are large raises a lot of questions; costly infrastructure upgrades to accommodate possibly higher PMFs may provide no direct benefits to society, other than a theoretical decrease in an already unlikely catastrophic event. Finally, they acknowledged the need for the continuous development of early inflow forecasting/warning systems and increased operational flexibility to accommodate potential PMFs.

5. Conclusions

This project was unique as it brought together key experts from different fields from across Canada to develop a methodology to quantify the impacts of climate change on PMPs and PMFs. Inspired from the traditional approach and based on previous studies, an approach was developed to project future PMPs and PMFs under climate change. An ensemble of RCM simulations was used to evaluate the projected impacts of climate change on key meteorological variables required to derive the spring PMF in five Canadian basins.

Prior to the computation of the PMF, the results showed that the median change in the spring PMP for all duration and the five study basins ranged from -10% to $+20\%$. Overall the spring PMP was found to increase in the 2050s, with the exception of the Lower Nelson River, the most northern basin. The median change in the 100-year snowpack varied between -9% and $+8\%$, though there was a relatively large spread in the projections. The sign of change was dependent on the study basin's location with decreases likely in southern basins, while there was no consensus for more central basins and an increase likely for the northernmost basin. For all of the basins studied, spring freshet was found to occur earlier in the future, on the order of one week. Given changes in the spring PMP and 100-year snowpack changes, all five cases resulted in a projected median change in the PMF between -1.5% and 20%.

The economics of dam refurbishment in a changing climate raises a number of complex social and regulatory issues, compounded by the large uncertainties around future projections of PMFs. 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 magnitudes however, and only major structural upgrades—or decommissioning—could meet regulations based on such future extreme scenarios. Setting regulations—and design standards—on optimistic climate scenarios with lower PMF changes, of course, could create a false sense of security. Given the uncertainty in climate projections for these extremes, establishing appropriate regulations based on design standards represents a considerable challenge. Given the ultimate objective of protecting lives and maintaining the benefits afforded by dams, the focus of dam managers going forward should be on the overall risk profile, and not just on the risks associated with the most extreme of extreme floods. A system approach to assess overall risk profile and to determine inflow design flood requirements may be more appropriate to manage flood risk and intensity-duration-frequency (IDF) requirements.

Maintaining the public's trust in hydroelectric infrastructures 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.

Conflict of interest

None.

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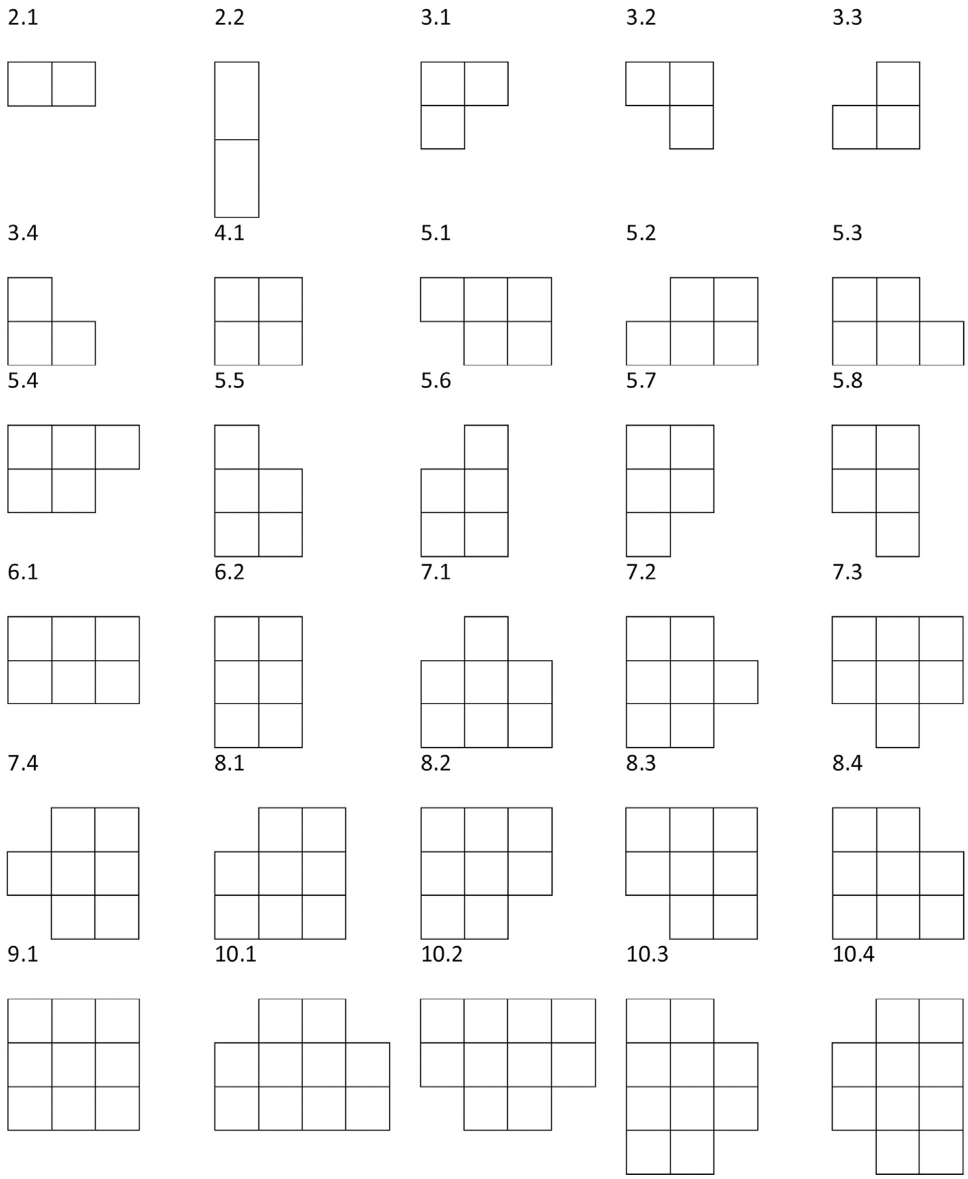
Appendix A. Combinations of multiple grid cells

In the following combinations, the first digit refers to number of grid cells, while the second refers to the order number of the spatial configuration.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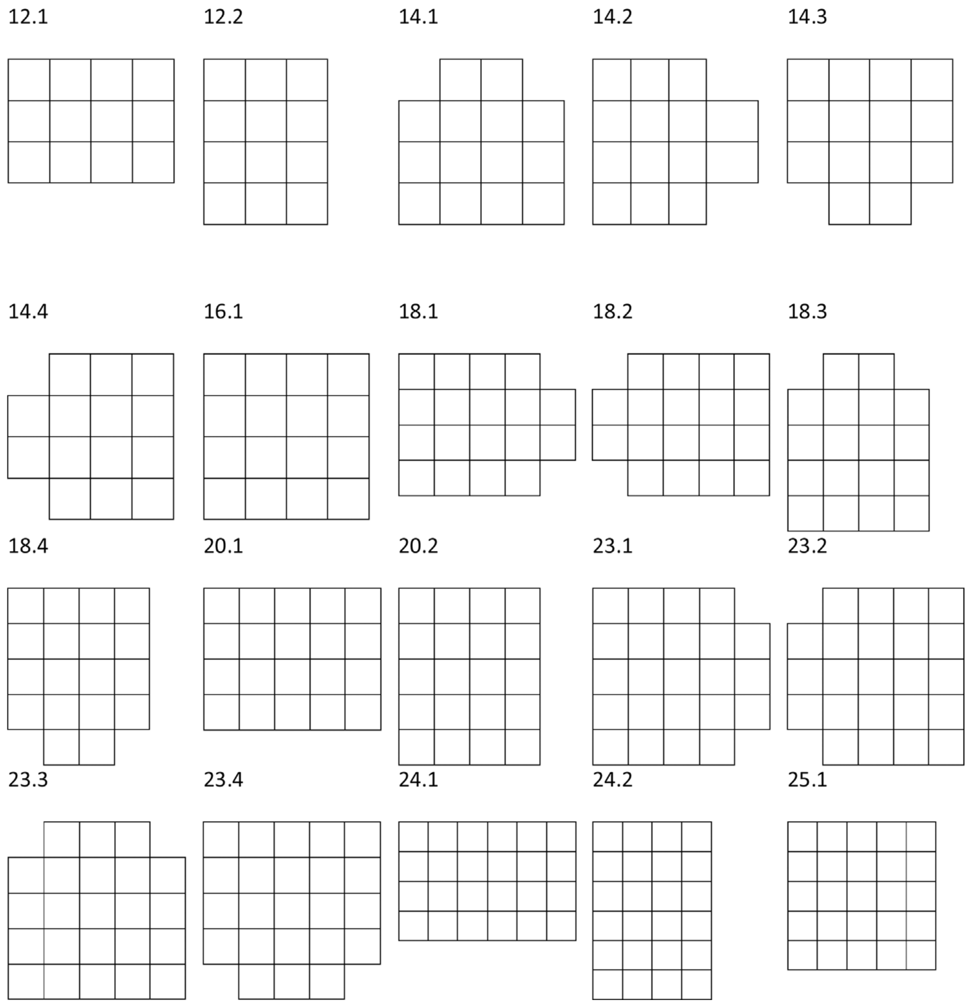

Appendix B. List of Acronyms

CCSM3	Community Climate System Model
CGCM3	Canadian Global Climate Model, version 3
CRCM4	Canadian Regional Climate Model, version 4
ECHAM5	European Centre Hamburg Model
ECP2	Experimental Climate Prediction Center
GCM	Global climate model
GFDL_CM2.5	Geophysical Fluid Dynamics Laboratory
HadCM3	Hadley Centre Coupled Model, version 3
MM5I	PSU/NCAR mesoscale model
PMP	Probable maximum precipitation
PMF	Probable maximum Flood
PW	Precipitable water
RCM3	Regional Climate Model, version 3
RCM	Regional climate model
SWE	Snow water equivalent

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