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Evaluation of probable maximum snow accumulation: Development of a methodology for climate change studies

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SUMMARY

Probable maximum snow accumulation (PMSA) is one of the key variables used to estimate the spring probable maximum flood (PMF). A robust methodology for evaluating the PMSA is imperative so the ensuing spring PMF is a reasonable estimation. This is of particular importance in times of climate change (CC) since it is known that solid precipitation in Nordic landscapes will in all likelihood change over the next century. In this paper, a PMSA methodology based on simulated data from regional climate models is developed. Moisture maximization represents the core concept of the proposed methodology; precipitable water being the key variable. Results of stationarity tests indicate that CC will affect the monthly maximum precipitable water and, thus, the ensuing ratio to maximize important snowfall events. Therefore, a non-stationary approach is used to describe the monthly maximum precipitable water.

Outputs from three simulations produced by the Canadian Regional Climate Model were used to give first estimates of potential PMSA changes for southern Quebec, Canada. A sensitivity analysis of the computed PMSA was performed with respect to the number of time-steps used (so-called snowstorm duration) and the threshold for a snowstorm to be maximized or not. The developed methodology is robust and a powerful tool to estimate the relative change of the PMSA. Absolute results are in the same order of magnitude as those obtained with the traditional method and observed data; but are also found to depend strongly on the climate projection used and show spatial variability.

1. Introduction

In northern regions, the probable maximum snow accumulation (PMSA) is one of the factors that can possibly lead to a probable maximum flood (PMF). Dams must be able to withstand earthquakes and floods (Dumas, 2006); and according to the Dam Safety Act and Regulation of Quebec, Canada, (Loi sur la sécurité des barrages, Gouvernement du Québec, 2000), dams that could have major consequences, should failure occur, have to be dimensioned with respect to the PMF. Also, current PMFs need to be periodically assessed using the best available information.

PMF has been defined in various ways. According to Dumas (2006): "The PMF is the flood that can reasonably be expected from the most severe combination of physically possible hydrometeorological conditions (rain, snow and temperature), and is estimated using maximized meteorological data and deterministic methods". Whereas, the World Meteorological Organization (WMO, 2009; in chapter 1.2.2) gives the following definition: "PMF is the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed. Such a flood could plausibly occur in a locality at a particular time of year under current meteorological conditions." In the same report, the definition of a probable maximum precipitation (PMP) contains the phrase "under modern meteorological conditions"; and furthermore "PMP and climate change" is discussed in chapter 1.8 (WMO, 2009). This indicates that climate change (CC) possibly affects PMFs, and neglecting this change is not a reasonable option when studying the variables that lead to these potential floods. Nowadays CC is widely accepted in the scientific community (e.g. Toprak et al., 2013). Moss et al. (2010) gives a good overview on the development in CC research, the work of the IPCC, different existing scenarios, and modeling techniques.

Abbreviations: CC, climate change; CRCM, Canadian Regional Climate Model; GEV, Generalized Extreme Value; PMF, probable maximum flood; PMP, probable maximum precipitation; PMSA, probable maximum snow accumulation; r, maximization ratio; RCM, regional climate model; SWE, snow water equivalent; w, precipitable water; w_{event}, precipitable water corresponding to a certain event; w_{max}, monthly maximum precipitable water; w_{100}, 100-year return value of the monthly maximum precipitable water; WMO, World Meteorological Organization.

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Indeed, nowadays the factor "climate change" is important to consider in hydrological studies; and the latest IPCC report (IPCC, 2014) provides a good insight in the most recent observations, projections and developments: Temperature observations show an overall clear trend toward a warmer climate, and this development is projected to continue. In our study region of Quebec, Canada, the projected change of the annual mean surface temperature is between 2% and 7% from 1986–2005 to 2081–2100, depending on the climate projections (all information of this paragraph is cited from IPCC, 2014). Snowfall amounts have diminished since 1950. It can be said with high confidence that the Northern Hemisphere spring snow cover has continued to decrease in extent; and this trend is further projected to continue. Observed total precipitation has increased significantly, and projections in our study area show an annual precipitation increase from 10 to up to 30%, which is large compared to natural variability. Extreme precipitation events will become more intense and frequent in many regions, but it must also be kept in mind that changes in precipitation will not be uniform. Extreme events of all kinds are influenced by CC as well: a decrease in cold temperature extremes, an increase in warm temperature extremes and an increase in the number of heavy precipitation events are only a few examples. The key drivers of global warming are cumulative emissions of greenhouse gases such as CO_2 and CH_4; those emissions largely determine global mean surface warming by the late 21st century and beyond. As it will be shown in this paper, several variables used for the estimation of the PMSA are influenced by CC. Given those findings and projections, it is crucial to evaluate the possible change of the PMSA (as part of the PMF subject) under CC conditions.

In northern regions, PMFs can either be induced by spring runoff due the extreme snow cover, melt conditions and rainfall occurring at the same time or by summer-fall runoff events produced by an extreme rainstorm. In the case of a PMF induced by the spring runoff, two scenarios are possible: a PMP event that occurs on a substantial snowpack or a substantial rainfall event on a PMSA. Existing studies agree on the substantial snowpack and the substantial rainfall event to be the 100-year return value of these variables (Debs et al., 1999; Dumas, 2006; CEHQ and SNC-Lavalin, 2004). It is neither recommended nor reasonable to combine a PMP and a PMSA, which are two independently maximized events (SNC-Shawinigan, 1992; in Debs et al., 1999).

The PMSA is defined in CEHQ and SNC-Lavalin (2004) as the maximum snow water equivalent (SWE) possibly accumulating over a year, should the strongest meteorological conditions occur. Since studies have shown that CC will affect water management (e.g., Milly et al., 2008), the development of a robust method for estimating the PMSA that accounts for CC becomes essential.

Chow and Jones (1994), Debs (1999) and CEHQ and SNC-Lavalin (2004) have provided good insights on the traditional method for estimating the PMSA. Observational data from severe past winters are used, where heavy snowfall events are maximized. This is done by multiplying the SWE of the event by the ratio of the highest probable air moisture content to the actual air moisture content of the event. Smaller snowfall events are not maximized (CEHQ and SNC Lavalin, 2004); and the maximized snow accumulation (MSA) is the sum of the maximized and non-maximized events throughout a winter. Several past winters that show a high amount of total snowfall are analyzed that way, because it is possible that the PMSA would correspond with a winter that is not the one with the highest total observed snowfall in terms of SWE. The PMSA is then the highest MSA of the analyzed winters. The method used to determine the PMSA can be summarized as "maximization of the most severe observed conditions". Recent studies have started addressing the subject of CC impact on the winter snowpack: MacDonald et al. (2011) analyzed potential future changes of the snowpack in a mountainous region of Montana, USA, due to CC. They found that an increase in greenhouse gas emissions leads to a decline in total accumulated SWE. Krenke et al. (2009) analyzed the change in the maximum future snowpack using outputs of a global climate model and also found a decrease in maximum snow storage in maritime regions of Russia during the present century.

Since the PMSA is expected to be sensitive to CC, the use of data from simulated regional climate models (RCMs) represents a valuable way to explore probable future evolutions of the snowpack. That being said, the non-stationarity due to CC should also be considered in the computational process. A purely empirical methodology is not useful when working with the very extreme of extreme events such as the PMSA. Empirical approaches are accompanied with high uncertainties when it comes to rare extreme events. Furthermore, in the aforementioned traditional method, the limited observational data, often available only over several decades, limits the accuracy of the PMSA estimation.

The objective of this study is to adapt the current approach used by engineers while using climate model projections as key inputs to assess the impact of CC on PMSAs. The specific objectives of this study are: (i) to develop a methodology for estimating the PMSA, while accounting for non-stationarity due to CC in both, the data and the computational method; (ii) to identify and resolve critical points in the calculation process; and (iii) to evaluate the evolution of the PMSA in the southern region of the province of Quebec, Canada, throughout the current century. To our knowledge there are no PMSA studies using new technological advancements like numerical models or simulated future climate data; neither are there PMSA studies taking into account the impact of CC. In a companion paper (Rousseau et al., 2014) on the issue of the PMF, we focused on the PMP while here the focus is entirely on the PMSA. More information on the subject of the PMF and PMP can be found in that paper. Meanwhile, the calculation of the PMF, which is a rainfall–runoff modeling problem,) will not be discussed in the present paper – the reader can consult Beauchamp et al. (2013).

The novelty in the present work, besides the use of RCM simulated data, resides in the use of a non-stationary statistical distribution to describe the maximum available humidity in the air. This way, the possible impact of CC is represented in the data and in the computational process. This might be challenging, since there is a physical limit to the possible available moisture content in the air at the moment of a snowstorm. Therefore, stationarity tests and break-point test of the moisture content series are carried out.

Results of studies that are based on simulated data often depend highly on the dataset (e.g. Papalexiou and Loutsoyiannis, 2006); and we therefore work with RCM data from three different CC projections. This allows us to have a first measure of variability of the results. Of course, a CC impact assessment of the PMSA cannot be limited to the use of only three simulations coming from the same RCM. However, the main goal of this work is to develop a methodology. The results of this work must therefore not be taken as a complete CC impact assessment study.

The paper is organized as follows: Section 2 introduces the datasets, study region and study watersheds; as well as the estimation method for the PMSA. In Section 3, PMSAs are estimated, analyzed and discussed. Conclusions and a brief summary follow in Section 4.

2. Methodology & data

2.1. Data

Three simulations of the Canadian Regional Climate Model (CRCM) are used in this study. Those simulations, called *afx*, *agr* and *aha*, were performed and supplied by Ouranos (Huard et al.,