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Editorial

Special Issue: Hydrological Extremes in a Warming Climate: Nonstationarity, Uncertainties and Impacts

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1. Introduction

The intensification of global water cycle, associated with anthropogenic climate change, is affecting the characteristics of hydrologic extreme events throughout the world. With the increases in the intensity of extreme precipitation, persistent low precipitation and evaporative water demand at different spatial and temporal scales, hydrologic extremes (floods and droughts) have become more likely and more severe in many regions [1,2]. The changes in precipitation and evapotranspiration rates are projected to continue and intensify in a warmer future, and further exacerbate the risks associated with floods and droughts. In snow-dominated regions of the world, hydrologic extremes are further influenced by the transitions from snow towards rainfall-dominated regimes [3], along with exceptionally low snow conditions or snow drought [4] and changes in the frequency and severity of rain-on-snow conditions [5]. Additionally, the risks associated with the climate-induced changes in extremes could be exacerbated by the direct human impacts, such as floodplain development and land use change in some river basins. Thus, understanding the historical and future trajectories of hydrologic extremes is crucial for water resources and disaster risk management, such as reservoir storage management and flood and drought preparedness, as well as planning for adaptation measures.

In this context, the nonstationarity of hydrologic extremes is highly relevant, as it can significantly alter the magnitude and frequency of extreme events [6,7]. Furthermore, hydrologic extremes often result from a combination of interacting physical processes, referred to as compound events, and risk assessment methods that consider a single driver and/or hazard in isolation can potentially lead to an underestimation of the associated risks [8]. However, addressing nonstationarity and compound events pose a number of challenges, such as selecting an appropriate modelling strategy, handling uncertainties, and understanding and communicating the associated concepts and risks.

This Special Issue comprises a collection of 11 papers that provide advances in various aspects of climate change impacts on hydrologic extremes, including both drivers (temperature, precipitation and snow) and effects (peak flow, low flow, water temperature). The studies cover a broad range of topics on hydrologic extremes, including hydro-climatic controls, trends, homogeneity, nonstationarity, compound events and associated uncertainties, over both historical and future climates.

2. Summary of This Special Issue

Precipitation is a main driver of hydrologic extremes, and future changes in precipitation indices can be expected to have implications on both floods and droughts. In this respect, Khoi et al. [9] analyzed spatio-temporal changes in the intensity, duration and frequency of maximum and minimum precipitation over Ho Chi Minh City, Vietnam. The projections from statistically downscaled Global Climate Models (GCMs) from the Coupled

Model Intercomparison Project 5 (CMIP5) representative concentration pathways (RCP) 8.5 ensemble indicated generally increasing future trends in most extreme indices, with more statistically significant trends and higher rate of increases for the intermediate future period (2051–2080) compared to the near future period (2021–2050). They also found higher trends and more statistically significant increases in the extreme precipitation intensity and frequency indices than the duration indices.

Arctic and subarctic regions of the world have been experiencing enhanced hydrologic changes in response to the amplified warming and moisture transport to the region. In this respect, Shrestha et al. [10] analyzed historical trends in annual mean flow, minimum flow, maximum flow and its timing for stations across the permafrost region of Canada. The results revealed significant warming for the majority of stations over both cold and warm seasons, and precipitation increases for some of the stations. In response, nearly half of stations exhibited significant minimum flow increases, while the number stations with significant trends in mean flow, maximum flow and its timing were relatively smaller. Further, by using a multiple linear regression (MLR) framework, they showed the dominant controls of precipitation on mean and maximum flow, and temperature on minimum flow.

In snow-dominated regions, the change in volume, extent and duration of snowpack can be expected to have considerable effects on the streamflow extreme response. To this end, Wagner et al. [11] analyzed trends of temperature, snow water equivalent (SWE) and streamflow extremes for selected rivers in the Yakima River Basin in the Pacific Northwest US. They found increasing trends in winter air temperature, accompanied by decreasing trends in SWE accumulation and a shift to an earlier peak SWE. The implications of these changes were reflected in streamflow extremes in terms of increase in winter maximum streamflow and decrease in summer maximum and minimum streamflow. Future projections indicated a continuation of the historical patterns that lead to above freezing winter temperatures at most stations by 2060, and a transition of the basin to rain-dominant hydrologic regime. Furthermore, Dibike et al. [12] investigated the spatial variations and relative importance of precipitation, temperature and SWE drivers on annual maximum flow and mean spring flow across snow-dominated river basins of western Canada. By using a MLR framework, they found that the annual maximum SWE is the most important predictor of both flow variables. They also analyzed the ability of the MLR model to project future streamflow changes by comparing with the previous studies in the region that used process-based hydrological models. The results were both consistent and inconsistent, and they urged caution in using regression models for future hydrologic projections.

Studying a rainfall dominated basin in Malaysia, Tan et al. [13] quantified the projected impacts of climate change on hydrological extreme flows and environmental flow components using a large set of indicators. They showed increases in future projections of precipitation, streamflow, maximum and minimum temperature across the basin based on a hydrological model driven by bias-adjusted CMIP6 GCM simulations. Overall, extreme high flows showed more sensitivity to changes in climatic factors compared to the normal and low flows. Further, they highlighted the different behavior of simulated future hydroclimatic extremes based on high- and low-resolution model outputs.

In the context of compound hydrologic extremes, Bennett et al. [14] investigated changes in concurrent extreme events (heat wave, drought, low flow and flood) in the Colorado River basin under historical-to-future (1970–1999, 2070–2099) RCP8.5 scenario. They projected increases in the future intensity and magnitude of concurrent events within critical regions of the basin, with temperature-driven extremes (heatwaves and drought) strongest and spatially coherent, and precipitation-driven extremes (flooding and low flows) less strong and more spatially variable across the basin. They also found an increase in the magnitude of all concurrent events from synoptic (5 days) to annual time scales, ranging from large increases for heatwaves and drought, to a smaller increase for low flows. Heatwave also affects glacier runoff and river water temperature, which was analyzed by Pelto et al. [15] using glacier runoff, discharge and water temperature records from the recent late summer heatwave events in the Nooksack river basin, located at the northwestern US–Canada border. The results indicated variable increases in discharge and water temperature across different areas of the basin in response to heatwave driven glacier runoff that account for about a third of total discharge. For the heavily glaciated northern sub-basin, discharge increase was relatively larger and water temperature increase was relatively smaller compared to the unglaciated southern sub-basin. With the ongoing glacier area loss and declining glacier runoff, the study suggested increased frequency of low flow extremes and high water temperatures that could exceed the tolerance levels of aquatic species.

Wang et al. [16] assessed the compounding effects of riverine and coastal flooding, the impacts of climate change on the corresponding drivers and the associated uncertainties, at Stephenville Crossing, a coastal-estuarine region in eastern Canada. They setup and calibrated a two-dimensional hydraulic model that combined with a hydrological model was applied to determine historical and projected flood characteristics (such as depths and extent) under various scenarios. The results suggested possible underestimations of future flood risks associated with projected intensity–duration–frequency curves generated based on statistically downscaled GCMs compared with the ones derived from convection-permitting regional climate model simulations. Temporal patterns of storm events had a major impact on flood characteristics and therefore design storm method can be considered a main source of uncertainty. Future increases in both drivers of flooding can further exacerbate the impacts of their concurrent occurrences. Besides, through a bivariate statistical analysis they showed the underestimations of compound flood risks when the interdependencies between driving mechanisms were not considered.

Nonstationarity of the hydroclimatic factors can lead to projected increases in the frequency and severity of floods and droughts, and subsequently challenge water resources management. In this respect, Xie et al. [17] developed a framework to consider different driving factors for nonstationary design flood volume estimation and represent the nonstationary spatial correlation of the flood events. Studying the cascade reservoirs in the Han River basin in China, they showed the long-term impacts of climate change and population growth on the regional hydrological characteristics, and subsequently the flood risks that can be misrepresented by the traditional design flood estimation methods base on stationarity assumption. They also found that the cascade reservoir regulation can reduce flow peaks and decrease flood volumes. Pasek and Marton [18] assessed the functional water volumes of a reservoir in Czech Republic during extreme hydrological conditions. They evaluated the uncertainties associated with the input variables including water inflows, hydrographs, bathymetric curves, and water losses due to evaporation and dam seepage. To design the functional volumes of multi-purpose reservoir and characterize the uncertainties, they linked a simulation-optimization model of the reservoir, to determine the optimal storage volume, with a simulation model that transforms the flood discharge and determines the retention volume of the reservoir. The study highlighted the significant effects of uncertainties in the storage volume and retention volume estimations, and the importance of considering climate change uncertainties and nonstationary flow conditions for reservoir management.

Regional flood frequency analysis (RFA) is a widely recognized approach to tackle the limitations associated with data availability at specific locations for flood quantile estimations for structure/infrastructure design. Identification of homogenous flood regions is a common RFA step prior to pooling flood information between similar catchments. Zhang and Stadnyk [19] evaluated multiple attributes, including geographic proximity, flood seasonality, physiographic variables, monthly precipitation and temperature patterns, to identify homogenous regions for RFA at 186 sites across Canada. They showed that the identification of homogenous regions relies on local hydrological complexities, representation of the primary flood mechanisms and geographic clustering of the sites. Catchments across eastern Canada form small geographic regions while areas in northern Canada, that are snowmelt dominated, are sensitive to temperature variations signifying the importance of monthly temperature pattern. They also found that the identification of homogenous regions can be a challenge across the Prairies and western Canada due the complex physiographic characteristics.

3. Conclusions

The intensification of global water cycle is affecting climate and hydrologic extreme in different regions of the world and this Special Issue provides critical information towards understanding the historical and projected future changes. The studies covered regions in Asia, Europe and North America, and included a range of precipitation, temperature, snow and streamflow extreme variables. The papers also demonstrated an intensification of the precipitation, temperature and streamflow extremes in the future climate, and as well as their relative controls and interactions. For snow-dominated regions, the studies highlighted the role of decreasing snowpack volume on both winter and spring maximum flow. The papers also emphasized the compounding effects of climate and hydrologic extremes, for example, temperature-driven (heatwaves, drought and elevated water temperature) and precipitation-driven (flooding) concurrent extremes, and their implications on water resources management. Additionally, the studies highlighted the importance of considering hydro-climatic nonstationarity and associated uncertainties in water resources risk assessment. Overall, the studies contributed to a growing body of knowledge on the changing hydro-climatic and hydrologic extremes, as well as methods to characterize and quantify the extremes and associated uncertainties. The advances in understanding and quantifying extremes is critical towards an effective water resources management, and planning adaptation strategies in a warming climate.

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