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Analysis of meteorological droughts for the Saskatchewan River Basin using univariate and bivariate approaches

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SUMMARY

This study is focused on the Saskatchewan River Basin (SRB) that spans southern parts of Alberta, Saskatchewan and Manitoba, the three Prairie Provinces of Canada, where most of the country's agricultural activities are concentrated. The SRB is confronted with immense water-related challenges and is now one of the ten GEWEX (Global Energy and Water Exchanges) Regional Hydroclimate Projects in the world. In the past, various multi-year droughts have been observed in this part of Canada that impacted agriculture, energy and socio-economic sectors. Therefore, proper understanding of the spatial and temporal characteristics of historical droughts is important for many water resources planning and management related activities across the basin. In the study, observed gridded data of daily precipitation and temperature and conventional univariate and copula-based bivariate frequency analyses are used to characterize drought events in terms of drought severity and duration on the basis of two drought indices, the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). Within the framework of univariate and bivariate analyses, drought risk indicators are developed and mapped across the SRB to delineate the most vulnerable parts of the basin. Based on the results obtained, southern parts of the SRB (i.e., western part of the South Saskatchewan River, Seven Persons Creek and Bigstick Lake watersheds) are associated with a higher drought risk, while moderate risk is noted for the North Saskatchewan River (except its eastern parts), Red Deer River, Oldman River, Bow River, Sounding Creek, Carrot River and Battle River watersheds. Lower drought risk is found for the areas surrounding the Saskatchewan-Manitoba border (particularly, the Saskatchewan River watershed). It is also found that the areas characterized with higher drought severity are also associated with higher drought duration. A comparison of SPI- and SPEI-based analyses suggests only little effect of considering temperature, in the form of evapotranspiration, on identifying drought vulnerable areas. It is expected that the findings of the study will be helpful in the management and efficient utilization of the water resources of this important river basin in Canada.

1. Introduction

Droughts can be defined from various perspectives including meteorological, hydrological, agricultural, and socio-economical. In general, a drought is defined as a dry weather period that lasts over several weeks to months, with no or little accumulated rainfall. Such dry weather events have significant impacts on water resources, agriculture, forestry, hydro-power, health, and socio-economic activities. A reduced amount of accumulated rainfall leads to low soil moisture and river flows, reduced storage in reservoirs and less groundwater recharge (Tallaksen and van Lanen, 2004). According to Salinger (1995), drought-like conditions occur when the supply of moisture from precipitation or stored in the soil or hydrological reservoir is insufficient to fulfill the optimum water requirements of plants, water supply for urban dwellers, and inflows into hydro-power lakes. The start of a drought is not easy to ascertain, although its end may be. Droughts appear suddenly, spread in an unstructured manner, and can end in various ways (Wilhite, 2000).

Although many areas of Canada experience droughts from time to time, southern parts of Alberta, Saskatchewan and Manitoba Provinces of Canada, specifically the Prairies eco-region, are relatively more drought-prone, for reasons such as location in the lee of the western cordillera, distance from large water bodies and extremely high rainfall variability (Bonsal et al., 2012). Several multi-year droughts for the 1890s, 1910s, 1930s, late 1950s, early 1960s and 1980s have been reported for this region (e.g., Chipanshi et al., 2006; Bonsal et al., 2011; Stewart et al., 2011). Compared to

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these drought events, the drought experienced during eight consecutive seasons from September 2000 to August 2002 was the most severe drought on record (e.g., Evans et al., 2011; PaiMazumder et al., 2012). During this drought, Saskatchewan crop yields and harvested areas were below average in both 2001 and 2002, resulting in $3.6 billion drop in agricultural production. Nationally, the gross domestic product fell some $5.8 billion during 2001 and 2002 (Wheaton, 2011; Wheater and Gober, 2013). In the United States, economic losses of around US$6–8 billion are estimated annually due to droughts that are far beyond any other meteorological disasters (Wilhite, 2000).

Recently, Bonsal et al. (2012) analyzed Canadian Prairies' summer drought for pre-instrumental, instrumental and future periods until 2100 using the Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI). Their results revealed that the Prairies had observed drought-like conditions in the 1930s, 1958–1962, 1983–1989, and 2000–2004, and severe drought will be more perpetual in some areas of the southwestern Prairies in future. Sushama et al. (2010) also suggested that the southern Prairies might be a sensitive region with respect to droughts with projections showing less precipitation and a higher number of dry days during the growing season (April–September) in future.

Droughts are considered to be multi-faceted extreme events that can inflict considerable damage to the human society in many ways. Therefore, proper understanding of the spatial and temporal characteristics of historical droughts is needed for many water resources and agriculture planning and management related activities in order to mitigate their harmful effects on communities. This study is focused specifically on the Saskatchewan River Basin (SRB; Fig. 1) that is located in southern parts of the three rapidly developing Prairie Provinces of Canada (i.e., Alberta, Saskatchewan and Manitoba), where most of the country's agricultural activities are concentrated. The SRB is experiencing huge water demands and stresses due to increased usage of water for agriculture, industrial and domestic purposes. These demands and stresses require efficient water management strategies for the SRB. Recently, this river basin has drawn global attention due to challenging water related issues and it is now one of the ten GEWEX (Global Energy and Water Exchanges) Regional Hydroclimate Projects in the world.

In this study, the behavior of so called meteorological droughts is investigated at the level of 13 watersheds that represent natural subdivisions of the SRB (Fig. 1). Observed gridded data of daily precipitation and temperature and conventional univariate and newly emerging copula-based bivariate frequency analyses are used to characterize historical drought events in terms of drought severity, duration and maximum severity on the basis of SPI (McKee et al., 1993), a purely precipitation-based index, and Standardized Precipitation Evapotranspiration Index (SPEI; Vicente-Serrano et al., 2010), a temperature and precipitation-based index. The SPEI is relatively a new drought index and it has the advantage of being multiscaler than the PDSI, which was used in some of the previous studies (e.g., Bonsal et al., 2012). The PDSI is not generally suitable for mountainous regions with frequent climatic extremes and it is unable to capture emerging droughts compared to the SPI (Zargar et al., 2011). Other drought indices that have been used in some parts of the study area include the Z-Index (Quiring and Papakryiakou, 2003), Multi-Index Drought Index (Sun et al., 2011), and Drought Severity Index (PaiMazumder et al., 2012). It must be noted that several studies have been done across the world to study droughts using just the precipitation based drought index, the SPI, which has also been recommended by the World Meteorological Organization (WMO, 2009) for analyzing periods of moisture deficit. In addition, it is important to point out that no clear guidelines are available in the literature on the choice of a drought index. In most cases, availability of relevant data drove the choice of a drought index (Mishra and Singh, 2010).

The use of both SPI and SPEI for characterizing drought events for the SRB will furnish an opportunity to directly evaluate the influence of temperature and hence of evapotranspiration in defining drought events. This is an important research question for drought risk analysis. In addition, none of the previous studies on droughts in this region has examined the frequency-magnitude relationships of drought characteristics and their probabilistic behavior, particularly in both univariate and multivariate settings. Also, investigation of spatial patterns of drought risk indicators for identifying drought-sensitive geographic regions has not been attempted until now. These are some of the main objectives of the present study, in addition to developing various methodological guidelines for probabilistic drought risk analysis.

This paper is organized as follows: description of the study area and observed gridded dataset used in the study is given in Section 2. Detailed description of the methodology for characterizing drought events and for performing univariate and copula-based bivariate frequency analyses is provided in Section 3, followed by results of the study and their discussion in Section 4. Finally, main conclusions of the study are provided in Section 5.

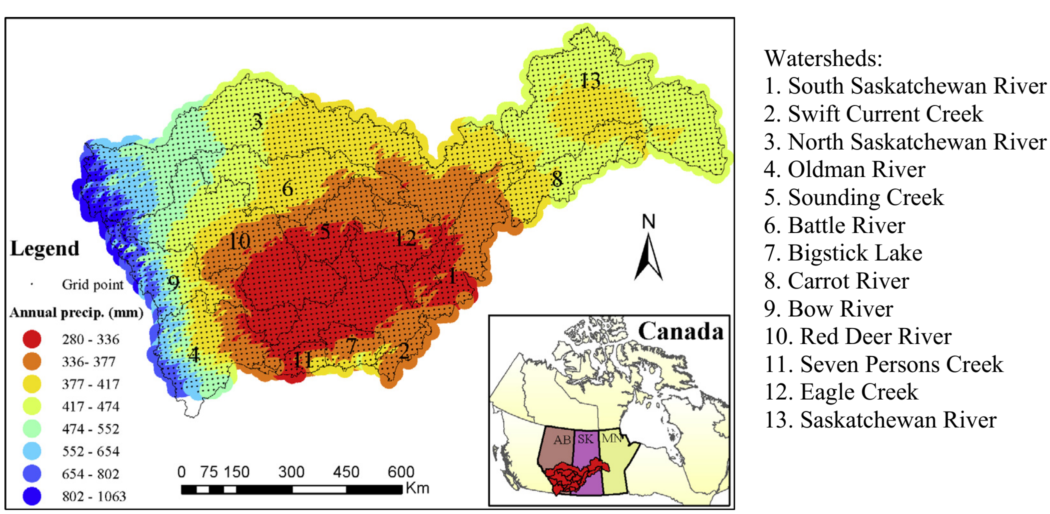

Fig. 1. The Saskatchewan River Basin (405,864 km^2 drainage area) with its 13 watersheds and spatial distribution of annual precipitation developed from 10 km × 10 km gridded observed dataset for the 1961–2003 period. Inset shows location of the study area in Canada. The abbreviations AB, SK and MN mean Alberta, Saskatchewan and Manitoba, respectively.