

Assessment of the hydrological drought risk in Calgary, Canada using weekly river flows of the past millennium

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ABSTRACT

Planning and management of water resource infrastructure requires a depth of knowledge on the characteristics of hydrological extremes, floods and droughts. Infrastructure design is traditionally based upon historically observed extreme events, assuming that they are independent and identically distributed (*i.i.d.*) and stationary, i.e. they fluctuate within a fixed envelope of variability. Information on historical hydroclimate provides a limited range of hydrological extremes, which rarely includes long-term worst droughts. This study demonstrates the application of a paleo-environmental dataset, 900 years of weekly streamflow stochastically derived from a tree-ring reconstruction of annual streamflow, to assess the hydrological drought risk. The historic and prehistoric hydrological drought characteristics, i.e. severity–duration–frequency (SDF) relationships, are evaluated. The results indicate that the severity and duration of hydrological drought with the same recurrence interval is substantially larger and longer than those observed over the 100-year historical period. Historic and prehistoric drought SDF relationships established in this study demonstrate the implications of non-stationary climate in the analysis of extreme droughts. Therefore, projected droughts of the 21st century may not exceed the drought severity found in the prehistoric record to the same extent that they exceed historical droughts in the instrumental record. This study emphasizes the importance of paleohydrology in comprehending the region's drought.

Key words: flow duration curves, hydrological drought, paleohydrology, prehistoric streamflow, severity–duration–frequency curves

HIGHLIGHTS

- The results from the study indicate that the drought characteristics over the past millennium differed substantially from those which occurred over the past century.
- Defining drought response triggers based on the historical data alone could underestimate the potential drought severity.
- Our results also indicate that it is irrational to assume stationary climate in determining the frequency of severe droughts.

INTRODUCTION

Droughts are among the most precarious natural disasters in Canada by virtue of their severity, duration and areal extent (Bonsal *et al.* 2011). They are characterized by a deficiency in precipitation over a specific region for a specific period of time (Mishra & Singh 2010). Although drought is regarded as a meteorological phenomenon, an appropriate definition of drought depends on the response of an environmental system to persistent moisture deficiency (Mishra & Singh 2010). Prolonged shortfall in precipitation (meteorological drought) would first impact the surface and groundwater storage in a watershed which, in turn, affects the magnitude of the streamflow and results in a hydrological drought. Hydrological drought is defined as a significant decrease in the availability of water in all its forms, appearing in the land phase of the hydrological cycle (Mishra & Singh 2010). Among all the processes in the land phase of the hydrological cycle, streamflow is the key component in describing hydrological drought, because it is the aggregate of runoff and baseflow received from the surface and subsurface storage, respectively. So, the water availability in a watershed or the watershed's vulnerability to hydrological drought can be easily assessed by constructing flow duration curves (FDCs). The flow threshold approach, a derivative of

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FDCs, is a widely adopted approach in the assessment of hydrological drought characteristics (e.g. Sung & Chung 2014; Rivera *et al.* 2017). A drought is said to occur if the streamflow is below a pre-defined threshold, which is generally considered to be a percentile of an FDC (e.g. Sung & Chung 2014).

Knowledge of severity, duration and frequency of droughts is vital to assess the impacts and to plan appropriate adaptation strategies for effective drought management (e.g. Spinoni *et al.* 2014). Decision-making in drought planning and management is based primarily on knowledge gained from the analysis of quantifiable droughts of the 20th century (e.g. Gan 2000; CDMP 2011). Although instrumental records provide some insights into the severity, duration and frequency of historically observed droughts, they fail to explain the extreme events that are outside the tails of the observational distribution. For example, droughts of 2001 and 2002 across much of the Canadian Prairies were unprecedented for the historical period of 100 years (Bonsal & Regier 2007); however, paleoclimate records for the region capture droughts of greater severity and duration than the observed droughts (e.g. Bonsal *et al.* 2013; Sauchyn *et al.* 2015). These studies in dendroclimatology tend to be limited to summer droughts (seasonal or July monthly), reproduced based on the correlations between tree-ring chronologies and historical droughts, quantified by the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI). A better understanding of variability in prehistoric droughts at higher resolution would help inform preparation for adaptation to anticipated severe droughts of the 21st century (e.g. PaiMazumdar *et al.* 2012). In this context, using methodologies of paleoclimatology and stochastic hydrology, Sauchyn & Ilich (2017) reproduced 900 years of weekly streamflow at various locations in the Saskatchewan River watershed. Taking advantage of research on the region's paleo-hydroclimate, the records of proxy streamflow for the past millennium are analysed in this study, with an emphasis on establishing the drought severity–duration–frequency (SDF) relationships of the historic and prehistoric droughts, applied to the City of Calgary, Canada as a case study.

In this study, the influence of the Pacific Decadal Oscillation (PDO) on the frequency and severity of drought over the historic and prehistoric periods is also evaluated. The PDO is a long-term ocean fluctuation (with the periodicity of approximately 20–30 years) along the equatorial Pacific Ocean. The significant influence of the PDO, and other low-frequency atmosphere–ocean oscillations, on the hydroclimate of Canadian Prairies is well established (e.g. St. Jacques *et al.* 2010; Gurrappu *et al.* 2016). Although these studies acknowledge that the negative phase of the PDO produces wet years and the positive phase is associated with relatively dry years, these inferences were made solely based on the historically observed climate. Moreover, the influence of low-frequency oscillations on drought severity is the topic of relatively few studies, with the exception of the recent research by Asong *et al.* (2018), who demonstrated that the periodicities in drought variability are associated with the El Niño–Southern Oscillation (ENSO) and Pacific North American (PNA) teleconnections.

This paper demonstrates the application of proxy streamflow records to better understand the variability in drought characteristics, i.e. severity, duration and frequency. To do so, the historic and prehistoric droughts are analysed and SDF relationships are established, as a tool to compare and contrast time series of hydrological drought. The first objective of the study is to analyse the gauge and proxy streamflow records of the study river basin, the combined watershed of the Bow and Elbow Rivers at Calgary, to determine the range of hydrological drought. The second objective is to evaluate the reliability of current water supply and management systems given the range of hydroclimatic variability and extremes, implicitly contained in this unique dataset of 900 years of weekly flows. The last objective is to evaluate the influence of the low-frequency PDO on the severity of hydrological droughts. The novel contribution of this study is the use of reconstructed weekly river flows for the past 900 years enabling the analysis of hydrological drought characteristics, namely frequency, severity and duration for both historic (1910–2015) and prehistoric (1110–1910) periods, to compare and contrast the region's hydrological drought risk.

Study region and data

The City of Calgary is located in southwestern Alberta in the eastern foothills of the Canadian Rockies. The major sources of water supply to the city are the Bow and Elbow Rivers (Figure 1), which mainly rely on the winter snowpack in the Rockies and rainfall during summer months (City of Calgary: Drought Management Plan, CDMP 2011). Recent studies have shown declines in the winter snowpack over the Canadian Rockies (e.g. Rood *et al.* 2005; Pederson *et al.* 2011; Fang & Pomeroy 2020). In contrast, the water demand is rising with increasing population and expanding economic activities in and around the city (Schindler & Donahue 2006). Moreover, climate models project increased frequency and severity of droughts over the region (e.g. PaiMazumdar *et al.* 2012).

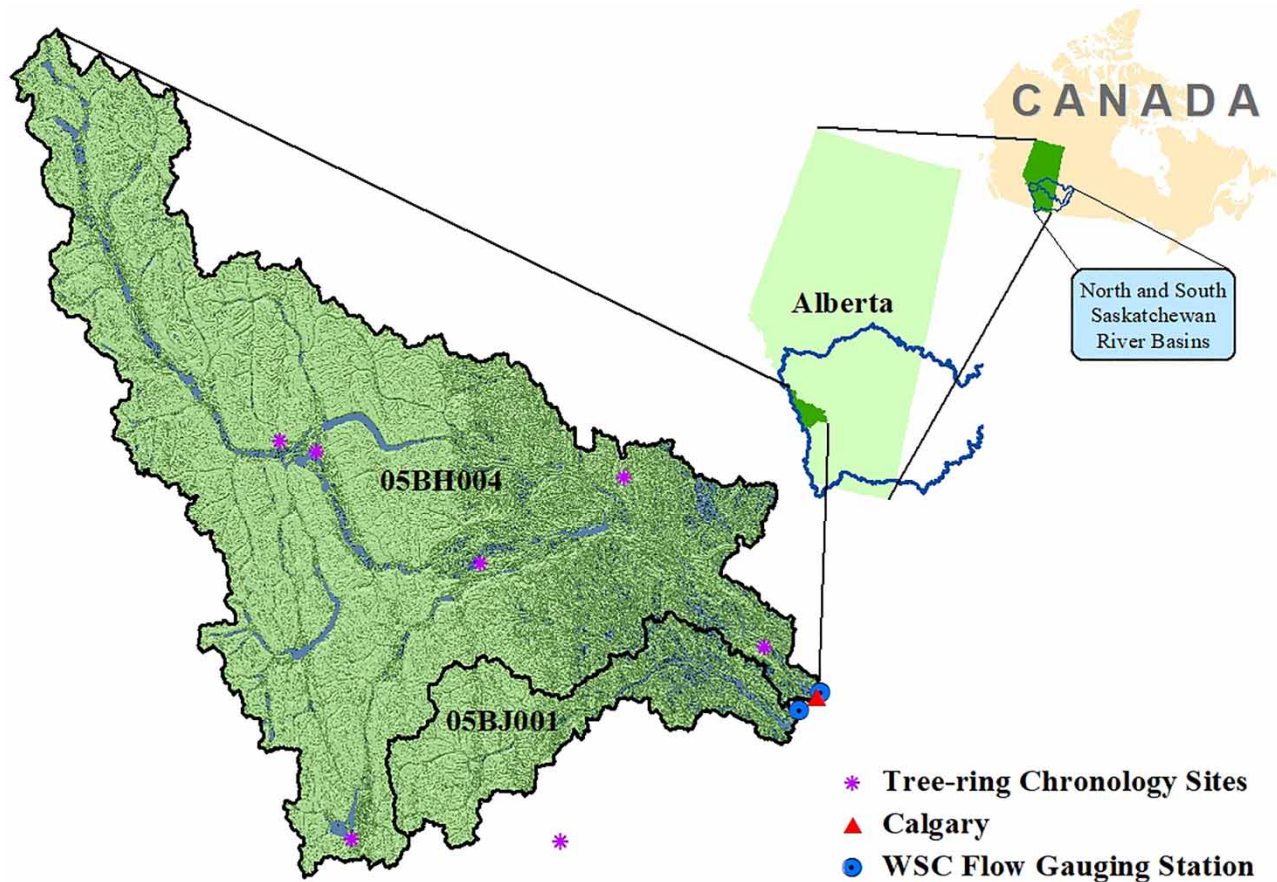


Figure 1 | Drainage areas of the Bow (WSC: 05BH004) and Elbow (WSC: 05BJ001) River watersheds. The asterisk symbols represent the tree-ring chronology sites used by Sauchyn & Ilich (2017) to reconstruct weekly streamflow, circles with dots represent the streamflow gauging stations operated by the WSC and a triangle represents the City of Calgary whose water demands are met by both the watersheds.

To compare and evaluate the historic and prehistoric hydrological droughts in these watersheds, streamflow datasets from two gauging stations located in and around the city, Bow River at Calgary (05BH004) and Elbow River below Glenmore Dam (05BJ001), are chosen. Several flow regulating structures are in operation on these rivers for domestic/industrial water supply, hydroelectric power generation, etc. (e.g. CDMP 2011). Therefore, to avoid the effects of human interventions on otherwise naturally flowing rivers, the naturalized records of instrumental streamflow produced by Alberta Environment (<http://esrd.alberta.ca/>) are used. Alberta Environment generated the naturalized streamflow datasets using the project depletion method, i.e. measured flows are adjusted to account for the effects of storage and diversions (e.g. NSW 2016). In this study, naturalized weekly records represent the instrumental or historical streamflow. Furthermore, the weekly streamflow of the past millennium, nearly 900 years of weekly data, is used to analyse the prehistoric droughts in these watersheds.

The streamflow dataset for the combined watershed (Figure 1) of the Bow and Elbow Rivers is generated by taking the algebraic sum of weekly streamflow in both the rivers for a common period (instrumental: 1912–2009; paleo: 1111–2010). To facilitate the identification of the combined watershed, it is called the ‘study watershed’ with a unique station code ‘05BHBJ0’. It is named using the similar convention followed by the Water Survey of Canada (WSC) in naming its streamflow gauging stations, ‘05’ represents the Bow River basin, ‘BH’ and ‘BJ’ represent Upper Bow and Elbow sub-basins, respectively, and ‘0’ represents the number of the common outlet, albeit imaginary, of these sub-basins. The time series of weekly streamflow in the study watershed (05BHBJ0) represents the total flow available for the City of Calgary. Any week with streamflow below a pre-defined threshold suggests the beginning of a longer duration drought; however, defining a threshold is crucial. So, to determine drought episodes and for effective drought management, the City of Calgary developed five critical flow rate triggers, also termed as drought response triggers, for each of the six seasons defined in the drought management plan (Table 1). Among these five critical flow rate triggers, the first-level trigger (Level 1) is used in addition to several other

Table 1 | Flow rate triggers for the study watershed 05BHB0 (Figure 1) proposed by the City of Calgary for implementations of restrictions and water management actions (refer Table 7 in the City of Calgary: Drought Management Plan, CDMP 2011)

Period	Flow rate trigger (m ³ /s)				
	Level 1 No impending storage; supply is 1.25 times demand plus instream flow needs (IFN)	Level 2 IFN and irrigation water demand (WID) met; city demand restricted	Level 3 IFN and WID demand cannot be met with city demand restricted	Level 4 IFN not met, WID compromised	Level 5 City demand cannot be met
Season 1 (January 1–May 1)	18.1	16.6	15.1	5.1	4.3
Season 2 (May 1–June 1)	44.0	40.4	36.7	26.7	4.7
Season 3 (June 1–August 20)	69.9	64.1	58.2	28.2	4.7
Season 4 (August 20–September 1)	58.8	53.9	79.0	19.0	4.7
Season 5 (September 1–October 1)	47.6	43.7	39.7	29.7	4.7
Season 6 (October 1–December 31)	18.1	16.6	15.1	5.1	4.5

thresholds derived from FDCs (discussed later) to determine the severity, duration and frequency of paleo and instrumental droughts.

The timescale of the streamflow datasets is weekly, whereas the seasons defined by the City of Calgary are in the number of days (Table 1). Therefore, using a simple conversion, the seasons are defined as the number of weeks for ease of analysis. Referring to the first and last days of a season defined in CDMP (2011), the first season S_i starts with the first week W_1 and if the last day of a season S_i is the fourth or later day in a week W_j , the week W_j is considered to be part of the season S_i . But if the last day of season S_i is the third or earlier day of the week W_j , the week W_j is considered to be part of the next season, S_{i+1} . Using these definitions of seasons, the seasonal flow datasets are extracted, all weekly flows in a season from each year, for further analysis.

The influence of the PDO on prehistorical (proxy) droughts is evaluated using the PDO index reconstructed by MacDonald & Case (2005). They produced this annual index using hydrologically sensitive tree-ring chronologies from California, USA and Alberta, Canada. This dataset was obtained from the repository of World Data Center for Paleoclimatology, Boulder (<ftp://ftp.ncdc.noaa.gov/pub/data/paleo/treering/reconstructions/pdo-macdonald2005.txt>). Figure 2 shows variability in the reconstructed PDO index over the past millennium (1004 years; 993–1196 AD). Although several reconstructions of the PDO exist, MacDonald & Case (2005) is used in this study because it covers the entire length of the reconstructed streamflow dataset (≈ 890 years) and is based in part on the tree-ring data from the study watershed. Based on the magnitude of the PDO index, PDO is classified into positive ($\text{PDO} \geq 0.5$), negative ($\text{PDO} \leq -0.5$) or neutral ($-0.5 < \text{PDO} < 0.5$) phases. So, the paleo-droughts were stratified accordingly based on the annual PDO index reconstructed by MacDonald & Case (2015). It is assumed that the paleo-drought events were least influenced by the PDO during neutral years ($-0.5 < \text{PDO} < 0.5$) and hence were ignored in the analysis. The influence of the PDO on the historical droughts is analysed using the November–March monthly averaged PDO index derived from sea surface temperature observations by the Joint Institute for the Study of Atmosphere and Ocean (JISAO), University of Washington (<http://jisao.washington.edu/pdo/>) (Mantua *et al.* 1997). The droughts are stratified based on the negative (cold: 1890–1924, 1947–1976 and 2009–2013) and positive (warm: 1925–1946 and 1977–2008) phases of PDO (e.g. Mantua *et al.* 1997).

Methods of analysis

Sauchyn & Ilich (2017) describe the methods used to generate 900 years of weekly streamflow datasets. To create these unique datasets, they combined the methodologies of paleohydrology, the variability of water levels over centuries and millennia (Meko & Woodhouse 2010; Meko *et al.* 2012) and stochastic hydrology, the use of statistical methods to generate

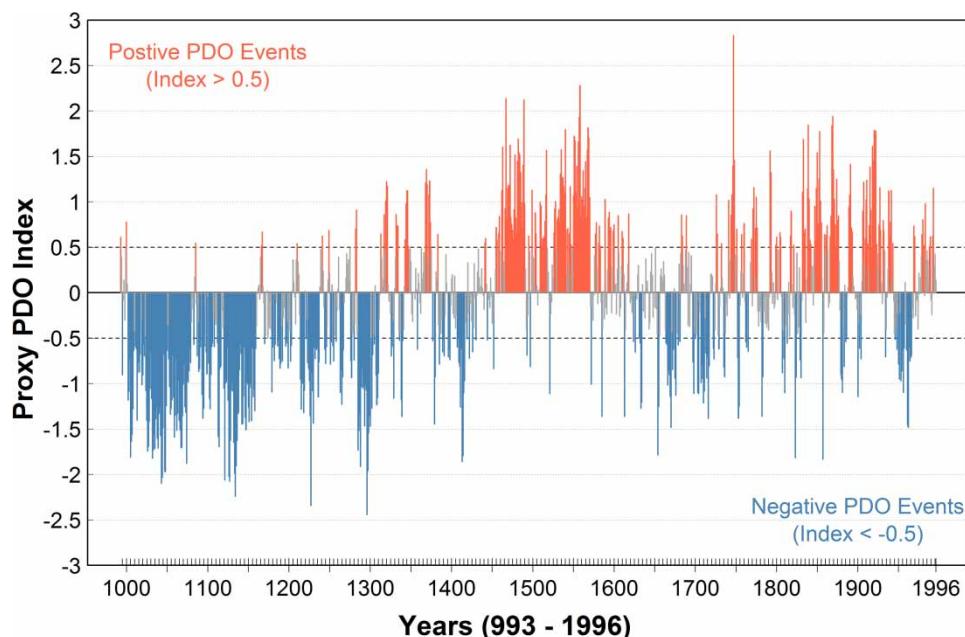


Figure 2 | Variability of millennial PDO reconstructed by MacDonald & Case (2005) using tree-ring chronologies. Red bars represent a positive year ($\text{PDO} \geq 0.5$), blue bars represent a negative year ($\text{PDO} \leq -0.5$) and grey bars represent a neutral year ($-0.5 < \text{PDO} < 0.5$). Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/wcc.2022.348>.

randomized hydrological time series that closely represent natural hydrologic processes (Ilich & Despotovic 2008; Ilich 2014). They used the tree-ring chronologies from several locations in the head waters of Bow and Elbow Rivers to first construct the paleohydrology (annual streamflow) of these watersheds and then stochastically downscaled them to produce 900 years of weekly streamflow datasets. To do so, they developed a new algorithm for generating stochastic time series of weekly flows constrained by the statistical properties of both the weekly historical recorded flow and annual proxy flow estimates, and also by the necessary condition that weekly flows correlate between the end of one year and start of the next. The weekly flows thus produced introduce hydrologic variability, and sequences of wet and dry years, not evident in the short historic flow record (Sauchyn & Ilich 2017).

The threshold level approach, introduced by Yevjevich (1967), is used to evaluate the characteristics of hydrological droughts in the study watershed. In this method, several threshold levels are defined below, which the flow is considered to be in deficit, i.e. low flow (e.g. Kjeldsen *et al.* 2000; Sung & Chung 2014; Rivera *et al.* 2017). Kjeldsen *et al.* (2000) suggest that the threshold levels in a perennial river can range between the 50th and 90th percentiles of the FDC, where the FDC relates the magnitude of flow to the percentage of time it is equalled or exceeded and summarizes the flow information (Searcy 1959). In this study, the drought characteristics are evaluated using four threshold levels (also referred to as truncation levels), i.e. 50th (Q_{50}), 70th (Q_{70}), 75th (Q_{75}) and 90th (Q_{90}) percentiles of the FDC. For instance, a week with a flow magnitude below Q_{70} is either an isolated drought event (flow deficit) or contributed to a longer duration drought. Therefore, to establish threshold levels, seasonal FDCs are constructed based on the weekly flows for each season for the entire period of record. Threshold levels can also be defined in two ways based on the time resolution of the data analysed, fixed or variable (Sung & Chung 2014). The threshold is considered fixed when a constant value is used for a definite period (season or year), and it is variable when the value changes over the course of a year based on the timescale specified, i.e. daily, weekly or monthly (Hisdal & Tallaksen 2003). A total of 24 fixed threshold levels (four each from six seasonal FDCs) and 208 variable threshold levels (four each from 52 weekly FDCs) are developed. All the threshold levels (fixed or variable) were established based on the FDCs of historical streamflow records. In addition, the use of first level (Level 1) drought response triggers suggested in CDMP (2011) is also explored as one of the threshold levels (Table 1).

Drought severity is computed as the ratio of flow deficit or surplus; that is, the difference between the actual flow and the flow threshold (fixed or variable), to the standard deviation (SD) of the dataset used for constructing the corresponding FDC (fixed or variable threshold). This standardized deficit is termed the low flow index (LFI). It is a non-dimensional number

used to identify individual flow deficit or surplus events; a week with a negative index ($LFI < 0$) indicates flow deficit or a hydrologic drought and a week with a positive index ($LFI \geq 0$) indicates flow surplus or adequate streamflow. The LFI defined either by the fixed or variable thresholds can be computed using the following equations:

$$LFI_{\text{fixed}} = \frac{Q_i - Q_{P,j}}{Q_{SD,j}} \quad (1)$$

$$LFI_{\text{variable}} = \frac{Q_i - Q_{P,i}}{Q_{SD,i}} \quad (2)$$

where Q_i is the i th weekly flow; $Q_{P,j}$ is the P th percentile of the j th seasonal FDC (historical); $Q_{P,i}$ is the P th percentile of the i th weekly FDC (historical); $Q_{SD,j}$ is the standard deviation of weekly flow series of the j th season for the entire period of record and $Q_{SD,i}$ is the standard deviation of the i th weekly flow series for the entire period of record.

The hydrological droughts are categorized based on their severity (LFI) using the drought classification derived by other indices such as the SPI (McKee *et al.* 1993) and the standardized precipitation evapotranspiration index (SPEI, Vicente-Serrano *et al.* 2010) (Table 2).

The duration of a hydrological drought is defined by the number of consecutive weeks with a negative index ($LFI < 0$) as illustrated in Figure 3. However, if a weak-positive index ($0 \leq LFI \leq 0.5$) is preceded by a 12-week or longer duration drought and is succeeded by a negative index ($LFI < 0$), then the weak-positive LFI is assumed to contribute to a longer duration drought. Thus, the first drought event in Figure 3 (A_1 – A_3) is a 3-week duration drought, the second event (B_1 – B_{15}) is a 15-week drought with a weak surplus event in the 14th week and the last event (C_1) is an isolated 1-week drought. Although the severity of an isolated drought is defined by the magnitude of the LFI, the severity of a longer duration drought is represented by the average of the severities (LFI) of all individual events. For example, the average of the individual events A_1 – A_3 quantifies the severity of a 3-week duration drought, and similarly, the average of individual events B_1 – B_{15} quantifies the severity (inclusive of a weak surplus event B_{14}) of a 15-week duration drought, whereas the severity of an isolated drought C_1 is defined by the LFI.

SDF curves provide crucial information on the frequency and duration of severe droughts (e.g. Todisco *et al.* 2013; Sung & Chung 2014). To construct these curves, the LFIs are first computed using Equations (1) and (2) for the fixed and variable thresholds, respectively, and categorically separated droughts, $LFI < 0$. Then, droughts with the specified duration, i.e. 1, 2, 4, 6, ... 48, 50, 52 weeks, are extracted from both gauge and proxy streamflow records, as described above. In addition, it is assumed that a single longer duration drought consists of several shorter duration events, for example, the first drought in Figure 3 consists of three 1-week droughts (A_1 – A_3), two 2-week droughts (A_1A_2 and A_2A_3) and a one 3-week ($A_1A_2A_3$) drought. The severity of a >1 -week duration drought is quantified by taking the average of the severity of all individual events within the period of drought of specified duration.

The frequency of droughts was identified by fitting a suitable probability distribution to the extracted droughts of specified duration. The suitable distribution that best represents the distribution of droughts over the period of record is determined using a Kolmogorov–Smirnov goodness-of-fit test. Easyfit Professional version 5.6 is used to test the suitability of five distributions: the Generalized Extreme Value (GEV), 3 Parameter Lognormal (LN), 3 Parameter Log-Logistic (LL3), Gumbel Minimum (GMin) and 3 Parameter Weibull (W3). This analysis showed that the distribution of droughts is best represented by the GEV distribution, a special case of which is one of the generally recommended distributions for frequency analysis of

Table 2 | Classification of droughts based on their severity

Criterion	Description
$LFI \geq 0$	No drought or flow excess
$0 > LFI \geq -1$	Mild drought
$-1 > LFI \geq -1.5$	Moderate drought
$-1.5 > LFI \geq -2$	Severe drought
$LFI < -2$	Extreme drought

The LFI represents the number of SDs from the pre-defined thresholds.

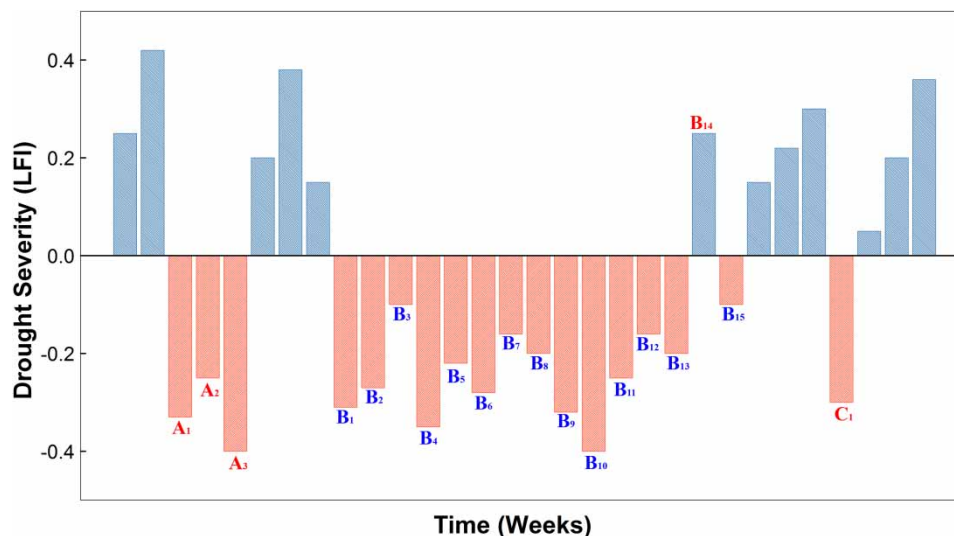


Figure 3 | Definition sketch of drought duration.

low flows in Canada, the W3 distribution (e.g. [Stedinger *et al.* 1993](#)). Therefore, the GEV distribution is fitted to the dataset of drought severity and the distribution parameters are estimated using the method of L-moments using the ‘lmom’ package ([Hosking 2019](#)) in the R statistical language ([R Core Team 2020](#)). Then, the quantiles of drought severity are extracted from the fitted curve (GEV fit) at several return periods, e.g. 500, 300, 200, 100, 50 and 10 years. This procedure is repeated to fit the droughts of other durations to the GEV distribution and extract quantiles of drought severity with the above-mentioned frequency. Later, SDF curves are constructed for both gauge and paleo datasets.

The other major aspect of this analysis was to examine the influence of the PDO on drought severity. First, the individual droughts ($LFI < 0$) are categorized according to the positive and negative phases of PDO using annual indices of the PDO reconstructed by [MacDonald & Case \(2005\)](#) for the prehistoric period and November–March monthly averaged PDO index by [Mantua *et al.* \(1997\)](#) for the historic period. Then, the quantile–quantile (Q–Q) plots are constructed to determine if the LFI series of both phases of the PDO came from the same population. The method of constructing Q–Q plots was earlier described and successfully adopted by [Gurrapu *et al.* \(2016\)](#) to identify the influence of PDO on annual peak flows in the watersheds of western Canada. The Q–Q plots are constructed by plotting the ranked droughts (quantiles) of the negative PDO phase (y -axis) against the ranked droughts (quantiles) of the positive PDO phase (x -axis). For an individual point (x_i, y_i) , x_i is the LFI of the i th ranked drought in the positive PDO phase and y_i is the LFI of the i th ranked drought in the negative PDO phase. The LFI series from both phases of the PDO can be assumed to be from the same population if the points fall along the 1:1 line. If the quantile ratio $r_i = (y_i/x_i)$ of the i th ranked drought is < 1 , then the i th ranked drought in the positive PDO phase is more severe than that in the negative PDO phase. Similarly, values of $r_i > 1$ indicate that the i th ranked drought in the negative PDO phase is more severe than that in the positive phase. If the PDO has no influence on the drought severity (LFI), then the mean of the quantile ratios (R) should be approximately 1. The significance of R is tested at a 0.1 level of significance using a two-sided permutation test with 10,000 iterations ([Manly 2007](#)).

RESULTS AND DISCUSSIONS

Despite considerable drought research in western Canada in recent decades, the focus of the majority of these studies was droughts observed over the last century (e.g. [Dey 1982](#); [Bonsal & Regier 2007](#)). The historical (instrumental) records of hydroclimate rarely include the long-term worst droughts and the knowledge of prehistorical (pre-instrumental) hydroclimate can assist in understanding the region’s vulnerability to extreme droughts. With the progress in paleo-environmental research, there has been a significant shift in the view of regional hydroclimatic variability, with extremes in climate and water variables that are outside the tails of the observational distribution ([Oldfield & Alverson 2003](#)). So, a product of paleo-environmental research is used in this study; that is, the reconstructed weekly streamflows are analysed and the results demonstrate the importance of prehistorical hydroclimate in assessing the hydrological drought characteristics in the study watershed, 05BHBj0.

Figure 4(a) and 4(b) are the annual hydrographs for the instrumental and proxy records of weekly streamflow. Figure 4 also shows the six seasons (S1–S6), and the corresponding first level (Level 1) drought response triggers defined in CDMP (2011), Table 1. While the black curves represent the averaged streamflow hydrographs, dotted blue and red curves are obtained by mapping the highest and lowest weekly flows, and represent the maximum and minimum hydrographs, respectively. Although the average hydrographs of both the periods match, the extreme (maximum and minimum) hydrographs are distinctively different with prehistoric hydrographs showing extremely high and low flows. There were several instances of flow being lower than the drought response trigger within the seasons of high water demand, i.e. S3–S5 (summer and early fall), Figure 4(a). The seasonal drought response triggers, Table 1, are defined based on the analysis of historical records of streamflow (CDMP 2011), and the minimum hydrograph from Figure 4(a) demonstrates the importance of updating the drought response triggers.

To further examine the low flows in detail, seasonal FDCs using all the weekly streamflow records within a season for the entire record period are constructed. Figure 5 presents the lower half, exceedance probabilities larger than 50%, of the seasonal FDCs. FDCs for both gauge and proxy datasets are plotted together to enable comparison of the flow characteristics. Historical flow (blue dots) with 100% exceedance probability is as low as $5 \text{ m}^3/\text{s}$, indicating the perennial nature of the river. This low magnitude flow occurred during seasons 1 and 6, which includes winter months when the majority of the watershed is frozen with least precipitation as rainfall. Figure 5 also presents the Level 1 drought response trigger (red dotted line) for each season and the corresponding historical low flow (blue dashed line). It is apparent from Figure 5 that the seasonal historical low flows of seasons 1, 2 and 6 are lower than the corresponding drought response triggers, Figure 5(a), 5(b), and 5(f). In winter to early spring (i.e. seasons 1, 2 and 6), a critical period of water supply from the regional snowpack, the drought response triggers are generally conservative, i.e. within the range of historically observed streamflow. The margin between the water supply and demand is minimal during these seasons and hence the demand management, i.e. reduced per capita demand, is adopted for drought preparedness (CDMP 2011).

The historically observed low flows of seasons 3–5 are higher than the corresponding seasonal drought response triggers, Figure 5(c)–5(e). These seasons, summer and early fall, are periods of high water demand (Akuoko-Asibey *et al.* 1993), which necessitates the appropriate management of available water resources. The ‘study watershed’ responds quickly in translating melting snow and rainfall into streamflow because of steep headwater catchments and minimal storage as ground or surface waters. Thus, water management during the periods of high demand is critical in times of hydrological drought, i.e. deficit flow compared to a seasonal drought response trigger. In response to a hydrological drought, the water allocation to different sectors is as indicated in Table 1. Although the drought response developed by the City of Calgary seemed reasonable and relevant to the historical FDC (blue dots), the prehistoric FDC (red dots) reveals much lower magnitude flows during the high demand seasons, i.e. seasons 3–5. Therefore, to evaluate the characteristics of drought in this watershed, the

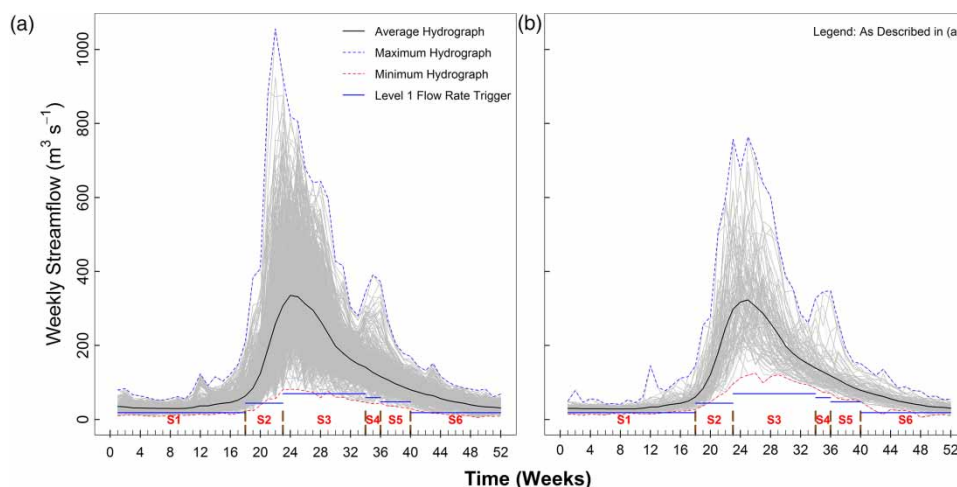


Figure 4 | Annual streamflow hydrographs for the (a) prehistoric and (b) historic periods in the study watershed 05BHBJO. Solid blue lines represent the seasonal (S1–S6) Level 1 drought response triggers defined in CDMP (2011). Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/wcc.2022.348>.

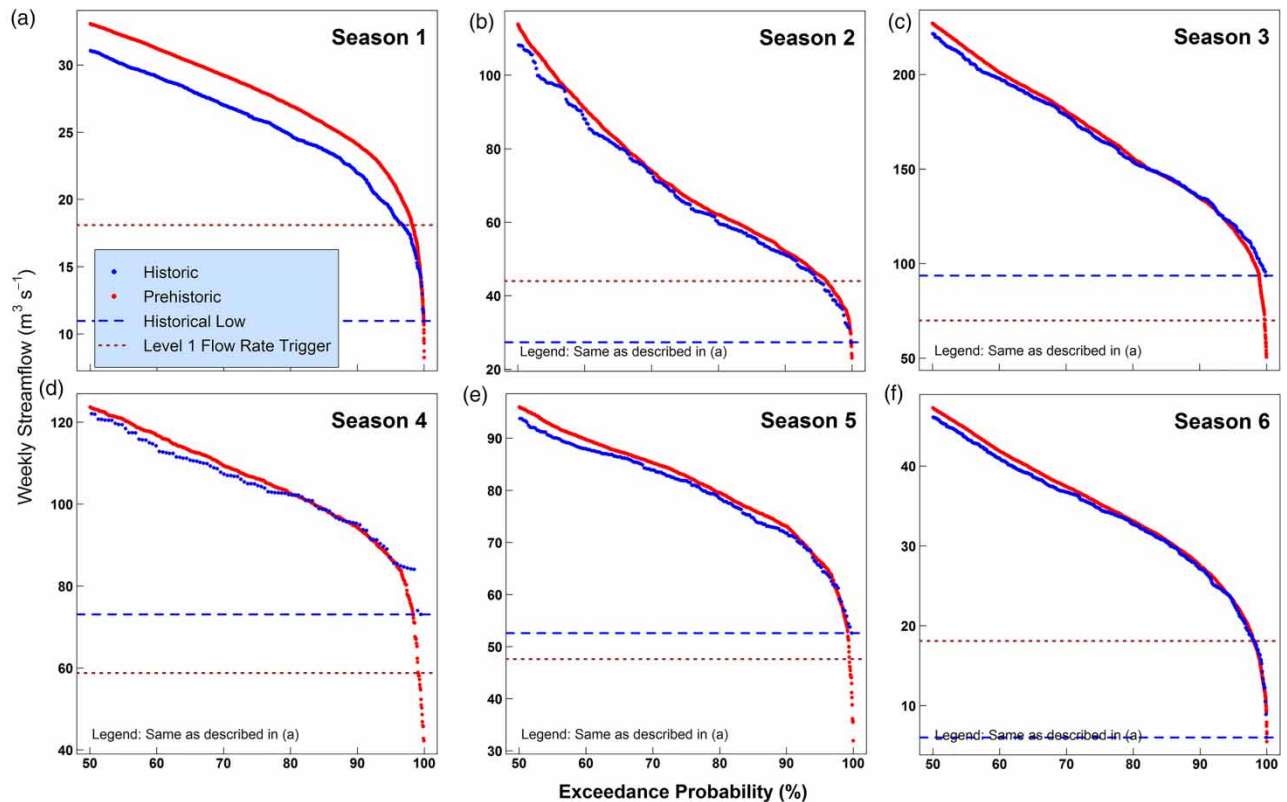


Figure 5 | Frequency distribution of seasonal low flows, i.e. flows equalled or exceeded at least 50% of the time, derived from the seasonal FDCs constructed for the study watershed 05BHBJO. Prehistorical low flows are represented by red dots and the historical low flows by the blue dots. Also shown are the historically observed low (absolute minimum) flow (blue dashed line) and the Level 1 drought response triggers (red dotted lines) defined in CDMP (2011), Table 1. Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/wcc.2022.348>.

flows that occurred at least 50% of the time (Q_{50}), i.e. low flows are analysed and evaluated in both gauge and proxy streamflow datasets from the study watershed.

Four threshold levels, i.e. Q_{50} , Q_{70} , Q_{75} and Q_{90} derived from the FDCs, are used to evaluate the hydrological drought characteristics in the study watershed. Although, the threshold level Q_{50} can be considered a low flow condition, the hydrological drought condition in perennial rivers is best characterized by threshold levels Q_{70} – Q_{90} , i.e. 70–90% exceedance on FDC (e.g. Kjeldsen *et al.* 2000; Smakhtin 2001). Q_{70} is the medium low-flow condition in a perennial river, i.e. a condition where the flow magnitude is least affected by the magnitude of annual precipitation and is positively influenced by the base flow contribution (Bardhan & Rao 2022), whereas Q_{75} in perennial flow regimes constitutes approximately 65–80% of the total annual base flow (Smakhtin & Toulouse 1998). Therefore, the flow thresholds Q_{75} – Q_{90} are technically considered as low-flow conditions and represent environmental flows in the majority of the river basins (Bardhan & Rao 2022).

The threshold levels are either fixed or variable over the course of a year. The fixed thresholds are derived from the FDC for the weekly flows in a season for the entire record period and the variable thresholds are derived from the FDC for the specified week's flow for the entire period of record. Figure 6 illustrates the range and distribution of fixed and variable thresholds corresponding to the (a) Q_{50} , (b) Q_{70} , (c) Q_{75} and (d) Q_{90} threshold levels, and the seasonal averaged values of these thresholds are presented in Table 3. The variable thresholds (blue dots) are larger than the fixed thresholds (red lines) because the variable threshold captures the variability of weekly flows in a season (Figure 6 and Table 3). For example, the seasonal averaged fixed threshold corresponding to Q_{75} is $\approx 80 \text{ m}^3/\text{s}$, whereas the corresponding variable threshold is $\approx 90 \text{ m}^3/\text{s}$. Moreover, the thresholds are larger during summer (season 3), a period of mountain snowmelt runoff and rainfall.

Drought severity was measured using the LFIs based on the pre-defined threshold levels. Figure 7(a) and 7(b) depicts the sensitivity of the LFI in identifying the prehistoric droughts based on various fixed and variable threshold levels, respectively. Indices 1–4 correspond to the low flows identified using the threshold levels Q_{50} , Q_{70} , Q_{75} and Q_{90} , respectively, and index 5

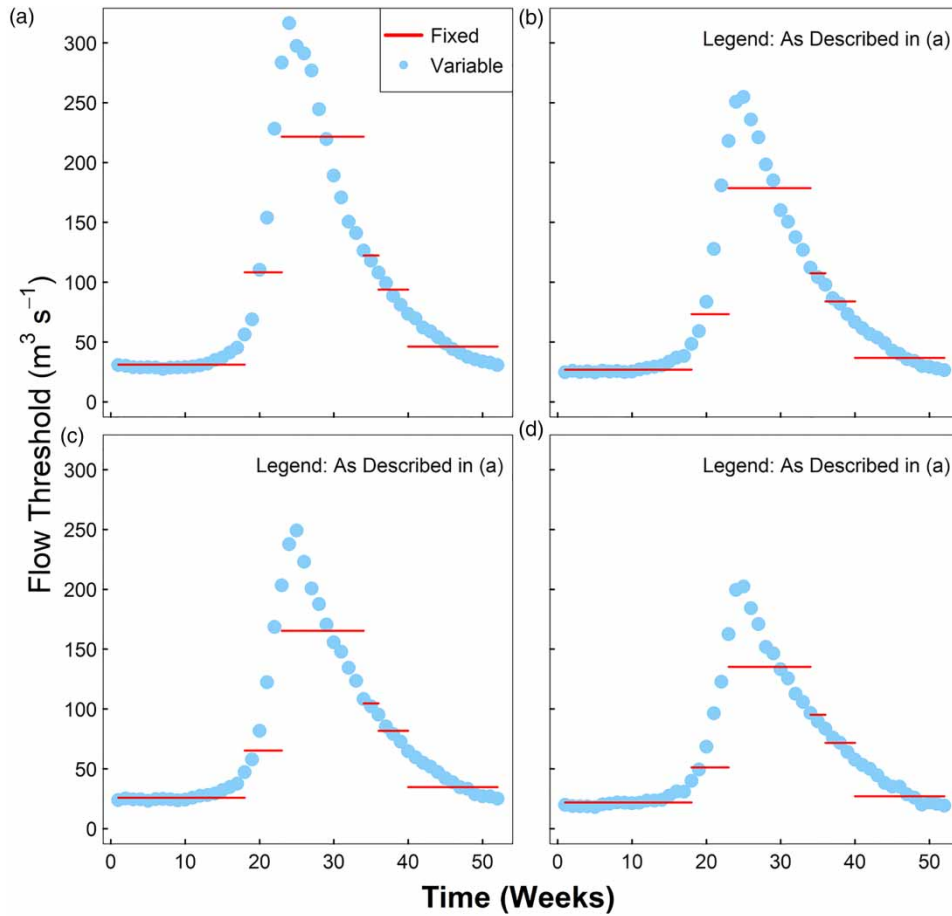


Figure 6 | Comparison of fixed (red lines) and variable (blue dots) threshold levels: (a) Q_{50} , (b) Q_{70} , (c) Q_{75} and (d) Q_{90} . Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/wcc.2022.348>.

Table 3 | Seasonal average of the fixed and variable thresholds at specified percentiles of the FDCs

Season	Threshold level (m^3/s)							
	Q_{50}		Q_{70}		Q_{75}		Q_{90}	
	Fixed	Variable	Fixed	Variable	Fixed	Variable	Fixed	Variable
1	31.08	31.75	26.99	28.02	25.96	26.96	21.95	22.51
2	108.32	123.51	73.39	99.86	65.30	95.51	51.20	75.40
3	221.58	234.61	178.57	194.46	165.37	184.89	135.14	154.14
4	122.38	122.18	107.39	108.18	104.62	105.33	95.22	93.16
5	93.81	94.31	83.90	84.92	81.84	83.10	71.81	73.89
6	46.12	47.85	36.72	42.59	34.67	41.12	27.14	34.65

corresponds to the low flows identified using the Level 1 drought response trigger, which is a fixed threshold for a season. Index 5 for a variable threshold is computed, assuming that the weekly flow threshold is fixed at the Level 1 drought response trigger of that season. Index 1 is based on the Q_{50} threshold level, which is the 50th percentile or quantile of the 50% exceedance probability from FDC. Since 50th percentile denotes the median of the dataset, the number of weeks with flow surplus ($\text{LFI} > 0$) and flow deficit ($\text{LFI} < 0$) should approximately be equal, although the intensities differ. It is apparent from Figure 7(a) and 7(b) that index 1 is distributed equally on either side of the $y=0$ line, irrespective of the severity. The drought severity

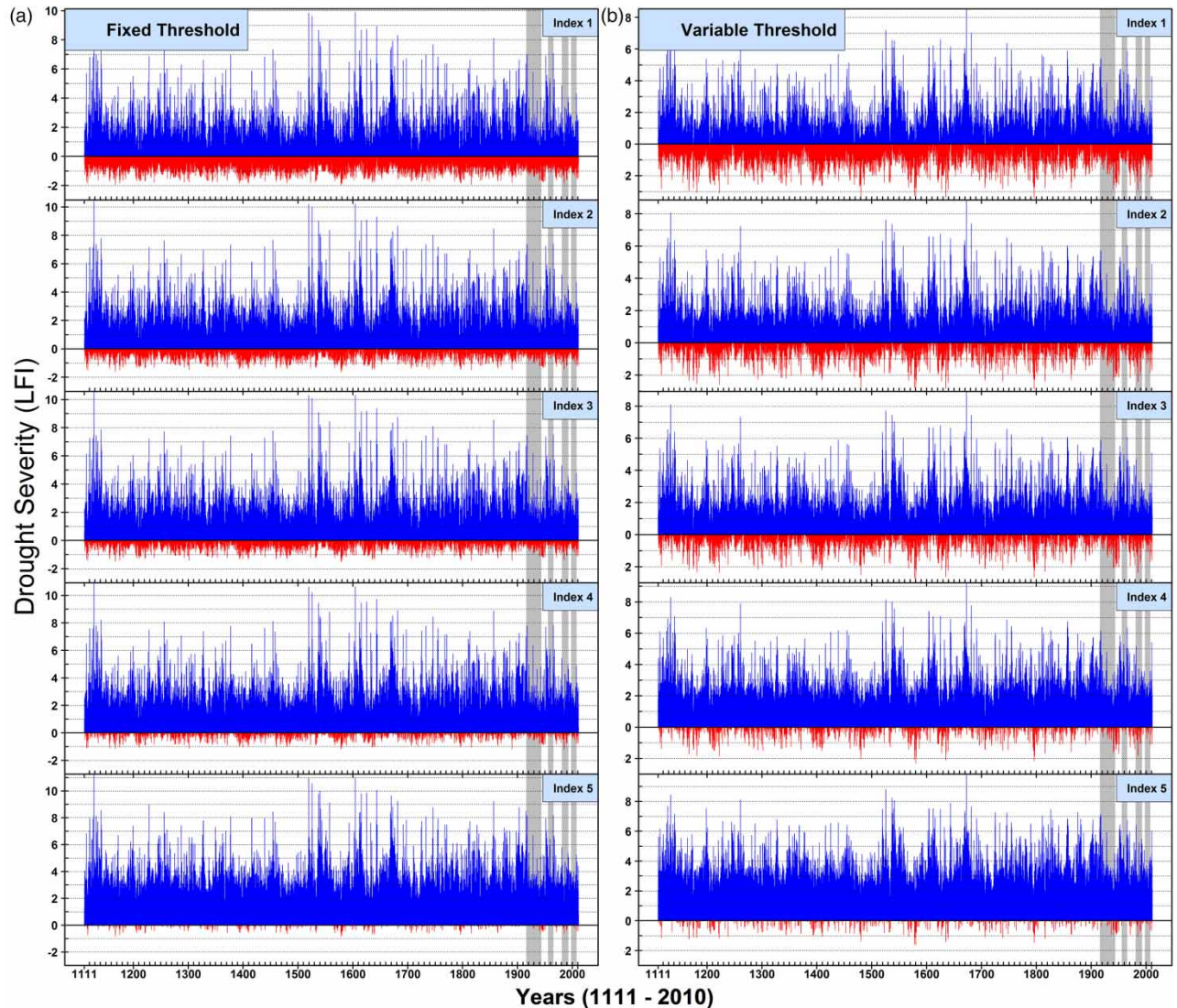


Figure 7 | Sensitivity of prehistoric droughts to several (a) fixed and (b) variable flow thresholds defined from the corresponding seasonal and weekly FDCs of the watershed 05BHBJO. Indices 1–4 are based on the thresholds from FDCs and index 5 is based on the Level 1 drought response trigger as defined in CDMP (2011). Grey bands represent the historical droughts of the region (e.g. Bonsal & Regier 2007; Bonsal *et al.* 2013). Please refer to the online version of this paper to see this figure in colour: <http://dx.doi.org/10.2166/wcc.2022.348>.

measured using a fixed threshold appears to be invariable (i.e. \approx constant) because the flow variability within a season is averaged (Figure 7(a)).

The indices based on the fixed thresholds fail to capture the seasonal variability and the severity of an event is compromised (Figure 7(a)), whereas those based on the variable thresholds capture the associated variability (Figure 7(b)), highlighting the region's earlier identified prehistoric severe and longer drought episodes, i.e. 1300s, 1480–1500, 1550–1575, 1620–1655, etc. (e.g. Bonsal *et al.* 2013; Sauchyn *et al.* 2015). For example, fixed threshold-based indices 3 and 4 classified these droughts as mild to moderate ($-1.5 < \text{LFI} \leq 0$), whereas the variable threshold-based indices 3 and 4 classified them as severe to extreme ($\text{LFI} \leq -1.5$). Kjeldsen *et al.* (2000) suggest that the variable threshold will reflect the expected flow in a river and therefore gives a more realistic drought pattern than a fixed threshold. Therefore, variable threshold levels are used to measure drought severity for further analysis of drought characteristics. Moreover, Figures 4 and 5 reveal the perennial nature of the studied rivers and henceforth, the drought severity is measured using the threshold level Q_{75} , generally adopted threshold for low flows (e.g. Dodangeh *et al.* 2017).

Frequency curves of prehistoric and historic droughts are constructed by fitting the droughts severities ($LFI < 0$) to a GEV distribution. The plots indicate that these curves are not much different for shorter duration droughts; that is, 1 week and 2 weeks (results not shown) but are substantially different for longer duration (≥ 3 weeks) droughts. Figure 8 shows the frequencies of a 12-week (≈ 3 months) drought from the historic and prehistoric periods. These curves indicate that the frequency of droughts with the same severity was much higher than what has been observed over the past century. For example, based on the historically observed droughts, a 12-week drought A_H (severity ≈ -0.85) has a frequency of 10 years (Figure 8(b)), whereas prehistoric 12-week droughts (A_{PH}) had a frequency of 3–4 years (Figure 8(a)). Similarly, the prehistoric drought frequency curve implies that a 100-year historical drought (B_H) had a chance of occurring every 8 years (B_{PH}). Moreover, the majority of the historical droughts were mild to moderate (i.e. $-1.25 < LFI \leq 0$), whereas the droughts over the past millennium were more severe ($LFI \leq -1.5$).

To summarize drought frequency, SDF curves are developed for both historic and prehistoric periods. In Figure 9, the SDF curves for the study watershed 05BHB0, drought severity (LFI) is based on the Q_{75} threshold level or 75th percentile of the FDC. It is apparent from these figures that the prehistoric droughts of any specified duration are more severe than the historic droughts. For example, historically observed 12-week duration drought (A_H) with a 100-year return period is moderate ($LFI \approx -1.1$), whereas its prehistoric counterpart (A_{PH}) is a severe drought ($LFI \approx -1.6$). Otherwise, a 100-year 12-week duration severe drought, A_{PH} ($LFI \approx -1.6$) of the prehistoric period has no counterpart in the historic period. These curves demonstrate that the occurrence of severe and longer duration droughts is not uncommon in this region.

Finally, the influence of the PDO on drought severity in the watershed is analysed. The $Q-Q$ plot, Figure 10, presents evidence that the severity of hydrological droughts ($LFI < 0$) is influenced by the phase of PDO. Figure 10 shows the $Q-Q$ plots for the prehistorical and historical droughts quantified by the LFI s based on the variable threshold defined by the 75th percentile of the corresponding FDCs. Prehistorical droughts are stratified into PDO phases using the annual indices reconstructed by MacDonald & Case (2005), whereas the historical (gauge) droughts are stratified according to the previously identified phases of PDO (e.g. Mantua *et al.* 1997). The $Q-Q$ plots demonstrate that severe droughts are typically more common in the positive phase of PDO, since the quantiles of drought severity largely appear below the 1:1 line. The permutation tests show that this is a significant result ($p < 0.1$) in both prehistoric and historic periods. Although the mild droughts ($LFI \geq -1$) are equally likely to occur in either of the PDO phases, moderate to extreme droughts ($LFI < -1$) are more likely to occur in the positive phase of PDO (Figure 10).

The results from this study will inform drought management by enabling water managers to redefine the threshold levels for effective allocation of the available water resources in the City of Calgary. The methodology used in this study is transferable to other municipalities and river basins, with application to drought mitigation, reservoir operation, design of hydraulic structures, analysing performance of rural water management systems, assessing climate change impacts, predicting flow in

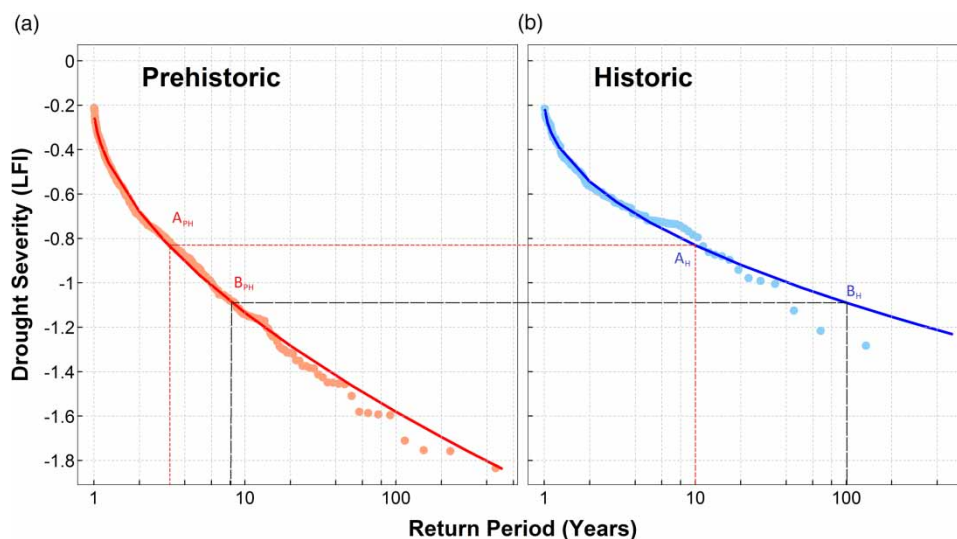


Figure 8 | Frequency of 12-week duration droughts in the study watershed 05BHB0 for the (a) prehistoric and (b) historic periods. Drought severity is based on the variable threshold defined by the 75th percentile of weekly FDCs (index 3).

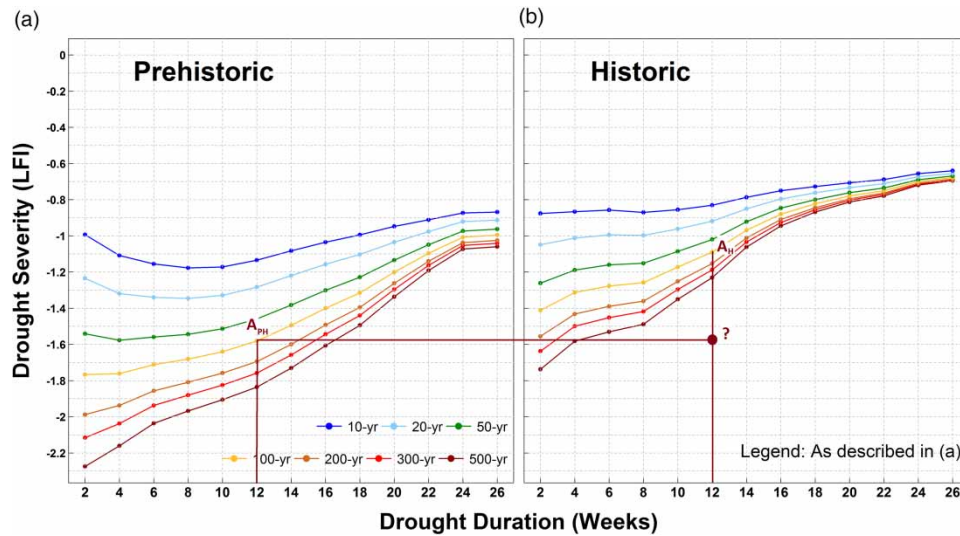


Figure 9 | Drought SDF curves for the (a) prehistoric and (b) historic periods for the study watershed 05BHBJ0. Drought severity (LFI) is based on the variable threshold defined by the 75th percentile of weekly FDCs.

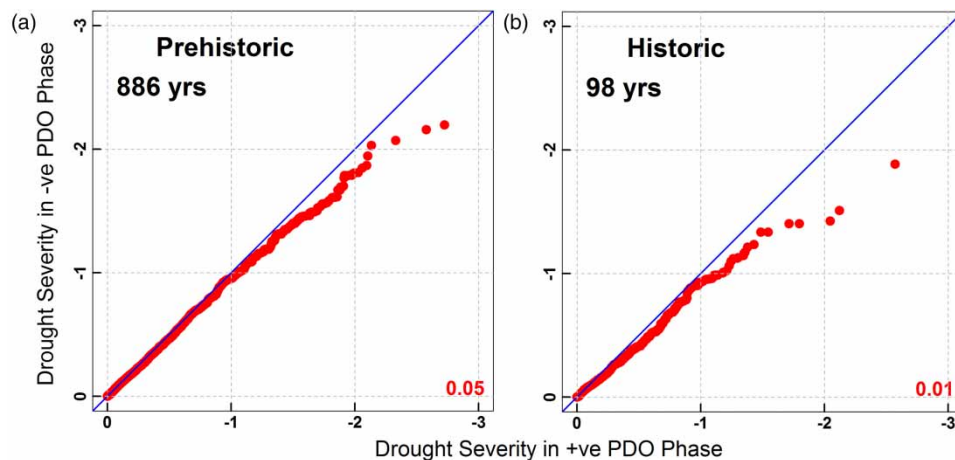


Figure 10 | Quantile-quantile (Q-Q) plots of (a) prehistoric and (b) historic periods based on the drought severity (LFI<0) in the study watershed 05BHBJ0, stratified according to the phases of PDO. Drought severity is based on the variable threshold defined by the 75th percentiles of the historical FDCs. Shown in the lower right-hand corner are the significance levels of the permutation test.

ungauged watersheds and long-term watershed protection plans. There are policy implications for water protection, water conveyance and storage, and drought preparedness and mitigation strategies. The most relevant potential strategic impacts relate to adaptation to climate change: adjustments to design codes and standards, management practice and policy in response to recent and anticipated climate changes. Despite these advantages, the major challenge in application of this methodology in other municipalities comes from the data availability for the prehistoric period. However, with advances in paleo-environmental research, such data; that is, prehistoric hydroclimate, can be reconstructed or generated using chronologies of tree-rings, ice-cores, lake sediments, and so on (e.g. Hodder *et al.* 2007; St. George *et al.* 2009; Cook *et al.* 2010; Sauchyn *et al.* 2015).

SUMMARY AND CONCLUSIONS

Planning and management of water resource infrastructure requires a depth of knowledge on the frequency of extreme hydrological events, floods and droughts. Traditionally, these frequencies are derived from the analysis of historically observed

extreme events, assuming they are independent and identically distributed (*i.i.d.*) and the system fluctuates within a fixed envelope of variability (e.g. Milly *et al.* 2008). However, the validity of these assumptions has been questioned globally (e.g. Milly *et al.* 2008; Stedinger & Griffis 2008; Gurrapu *et al.* 2016). Despite these challenges, the City of Calgary proposed, in their drought management plan, several drought response triggers with the assumption of stationary climate. Streamflow below these triggers is considered deficit flow, and appropriate drought response action will be taken for effective water management (e.g. Steinemann & Cavalcanti 2006; CDMP 2011). In this study, the instrumental and pre-instrumental streamflow records of the Bow and Elbow River basins are analysed to compare and contrast the drought characteristics of historic and prehistoric periods. The results indicate that there were several pre-instrumental droughts of significantly greater severity and/or duration than the instrumental droughts of record in the 1930s–1940s, late 1970s, 1980s and early 2000s (Figure 7(b)). The results also provide evidence for the teleconnection between the PDO, a recurring pattern of ocean–atmosphere climatic variability, and drought severity, with a greater tendency for severe to extreme droughts in the positive phase of the PDO. Results from this study augment the earlier findings that the droughts of the 20th century were relatively mild compared to the pre-instrumental period (e.g. Bonsal *et al.* 2013; Sauchyn *et al.* 2015) by providing more information on the region’s exposure to severe drought. The results also demonstrate the implications of non-stationary climate in the analysis of extreme droughts, and the study emphasizes the importance of paleohydrology in comprehending the region’s drought characteristics. Overall, the results indicate that the potential severity of hydrological drought at Calgary (Alberta, Canada) has been underestimated by the City of Calgary in their Drought Management Plan.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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