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Past climate, future perspective: An exploratory analysis using climate proxies and drought risk assessment to inform water resources management and policy in Maine, USA

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ABSTRACT

In recent decades, significant progress has been made toward reconstructing the past climate record based on environmental proxies, such as tree rings and ice core records. However, limited examples of research that utilizes such data for water resources decision-making and policy exist. Here, we use the reconstructed record of Palmer Drought Severity Index (PDSI), dating back to 1138AD to understand the nature of drought occurrence (severity and duration) in the state of Maine. This work is motivated by the need to augment the scientific basis to support the water resources management and the emerging water allocation framework in Maine (Maine Department of Environmental Protection, Chapter 587). Through a joint analysis of the reconstructed PDSI and historical streamflow record for twelve streams in the state of Maine, we find that: (a) the uncertainties around the current definition of natural drought in the Chapter 587 (based on the 20th century instrumental record) can be better understood within the context of the nature and severity of past droughts in this region, and (b) a drought index provides limited information regarding at-site hydrologic variations. To fill this knowledge gap, a drought index-based risk assessment methodology for streams across the state is developed. Based on these results, the opportunities for learning and challenges facing water policies in a changing hydroclimate are discussed.

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1. Introduction

Located in the northeastern region of the United States, the state of Maine is known for its abundant water resources. In this "water-rich" state, the average annual precipitation (in its three climate divisions) ranges between 1016–1168 mm (40–46 inches). However, a prolonged drought at the turn of the 21st century (1999–2003) exemplified the widespread nature of the statewide socioeconomic impact of drought, including $32 million in crop losses (Maine Agricultural Water Management Advisory Committee, 2003; Schmitt, 2003). Detrimental impacts of the drought on Maine's natural resources and ecosystems were likely significant, but are not well understood. Focusing events (Pulwarty et al., 2007), such as the recent multi-year drought, provide a window in to the vulnerability of Maine's people, ecosystems, and economy to hydroclimatic extremes.

Proactive management and planning within a water allocation framework has been viewed as an important step toward the long-term sustainability of water resources in Maine. To this end, in 2006, the state of Maine completed a nearly decade-long rule-making process that culminated in the promulgation of a sustainable water use policy (MDEP, 2009). A major goal of this policy is to balance the human and ecological use of water by limiting withdrawals from the water bodies for agriculture and industrial purposes, and community use. A key tenet of this water allocation framework concerns the provision of seasonally varying aquatic base flows that mimic the natural flow regime and are likely to support ecosystem function and health. The limits on water withdrawals prevent repeated low-flow occurrences stemming from excessive withdrawals, thus supporting both ecosystem and water quality objectives. Maine Department of Environmental Protection (MDEP) Chapter 587 allows a variance from limits on water withdrawal from surface water bodies during droughts, when withdrawals may continue to occur despite unmet water quality and aquatic base flow thresholds. These variances aid Community Water Systems that rely on Maine's rivers and lakes. According to MDEP "*Natural drought condition means moisture conditions as measured by the Palmer Drought Severity Index with values of*

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negative 2.0 or less (MDEP, 2009)." While the PDSI threshold of −2 and more severe droughts have been rare in the 20th century, two aspects of drought occurrences motivate this study:

1. The range of variability seen in limited-length hydrologic and climate records provide a snapshot (depending on the length of the observational record) of the natural envelope of climate in a particular region; as a result, "hydroclimatic surprises" may occur, especially in cases where the observational record fails to represent the range of variability. Such events can prove to be major detriments to effective implementation of management and policy in water resources systems. In this context, to what extent is the 20th century record of Maine's PDSI consistent with the longer-term variability seen in a multi-century climatic reconstruction based on paleoclimatic data? To date, limited examples of use of hydroclimatic reconstructions to inform water policy and management exist (for example, Rice et al., 2009). In this study, we use the reconstructed record of Palmer Drought Severity Index (PDSI), dating back to 1138AD to understand the nature of drought occurrence (severity and duration) in the state of Maine (Cook et al., 2004).
2. Given that droughts exhibit substantial spatial and temporal variability, an analysis framework that allows translation of statewide PDSI index to watershed-scale estimates of hydrologic risk are likely to benefit water resources management and decision-making. In this study, we pursue a joint analysis of the historical record of the PDSI and streamflow across Maine and develop a probabilistic methodology to assess local hydrologic risk.

2. Background

This section describes the motivation and details regarding the water allocation framework, Chapter 587, in Maine. A limited discussion of the drought impacts on aquatic ecosystems and watershed management are also presented.

2.1. In-stream flows and lake and pond water levels standards in Maine

The state of Maine, recognizing the value of its natural resources, has pursued environmental protection efforts in the past decades (UCS, 2007). Many of the statutes that have been enacted by the Department of Environmental Protection (DEP) over the last fifty years acknowledge the importance of natural ecosystem and maintaining water qualities of all its water bodies. Recently, DEP developed "*The In-stream Flows and Lake and Pond Water Levels rule*" which established river and streamflows and lake and pond water levels to protect natural aquatic life and other designated uses in Maine's waters (MDEP, 2009). Flow management seeks to provide natural variation of flow (seasonal aquatic base flows, or other seasonally variable flows), thus affording protection to aquatic life resources and maintaining water quality standards. Classified state waters, such as, rivers, streams, brooks, lakes and ponds are included. Important considerations such as, alteration of natural flow or water levels (non-tidal fresh surface water) through direct or indirect withdrawal, removal, diversion or other activity are included (MDEP, 2009). Knowledge concerning droughts is an important input in to the community water resources planning and in the allocation of available water supplies. The Chapter 587 (MDEP, 2009) notes, "*Whenever natural drought conditions, in combination with Community Water System use, cause the applicable instream flow or water level requirements of this chapter to not be maintained, the Community Water System may continue to withdraw water for public need subject to any conditions the Department may impose through the issuance of a variance pursuant to 40 CFR 131.13 (2006). Such variances may last for the duration of the drought condition and shall protect all water quality standards to the extent possible, recognizing the combined effects of a natural drought and the need to provide a safe, dependable public source of water.*" Thus, the recent promulgation of the water allocation rulemaking in the state of Maine seeks to incorporate adequate in-stream flow allocations to support ecosystem services, while meeting the allocation needs for agriculture, municipal and industrial sectors. While this is a significant step that will likely catalyze similar rulemaking in other states, the long-term prospects of desirable outcomes in some respect also hinge upon the hydroclimatic thresholds (for example, PDSI) and variances noted in the rulemaking/allocation framework.

2.2. Drought impacts on ecosystems

Natural droughts stem from lack of precipitation and result in surface runoff deficits and receding groundwater level (Lake, 2008); as a result, have a profound adverse effect on the natural ecosystems, such as loss of quality and quantity of native flora and fauna. From a riparian ecosystem health standpoint, the lower levels of runoff disrupt the lateral connectivity in streams. Shallow areas tend to become riffles and runs (Stanley et al., 1994) and become deep area pools. Thus the longitudinal fragmentation constrains the movement of nutrients, planktons, fishes, and other aquatic species. Species with sedentary lifestyles and limited capacity for movement suffer high mortality by getting trapped in riffles; however, pool dwellers survive with little mortality (Golladay et al., 2004; Lake, 2008). Mobile species, such as fish and other invertebrates may move into the pool (Magoulick, 2000; Lake, 2008) or as drought develops may emigrate into upstream or downstream of the river based on the landscape of drought progression. In pools, large populations reside in small amount of water. High concentration and density of different species may increase the intra- and interspecies interaction, such as predation and competition (Lake, 2003). Due to disruption of longitudinal flow, transport of nutrients and other organic matter deceases significantly (Dahm et al., 2003). Additionally, standing water in the pools may lead to algal blooms (Freeman et al., 1994; Dahm et al., 2003) with resulting stresses on oxygen availability in pools. In this manner, high density, crisis of food availability, warm temperature, low oxygen level creates unhealthy and inhospitable condition in the water and may lead to diminishing fish populations and those of other invertebrates (Lake, 2003). During extended droughts, due to the deficit of rainfall, many small streams and tributaries of large rivers dry up. In temperate climates, reproduction of fish that use small gravel streams for breeding decreases significantly (Lake, 2008). Overall, droughts can have a strong detrimental impact on the aquatic ecosystems; thus, a detailed characterization of their frequency and intensity is likely to aid improved management and policymaking to support ecosystem services.

2.3. Drought information for watershed management

Precipitation in Maine shows an almost equal distribution throughout the year. This lack of seasonality may lead to a short-term drought in any season. In the coastal regions of Maine, due to frequent storms, drought durations are generally shorter (Johnson and Kohne, 1993; Zielinski and Keim, 2003). The worst drought in Maine in over thirty years occurred during the summer 2001 period (Schmitt, 2003). Water withdrawal was higher than the safe yield in coastal areas, coupled with an increased water demand stemming from

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seasonal tourism and development (Schmitt et al., 2008). Tourism is increasingly important to Maine's economy. During the summer tourist season, water managers have expressed much concern about droughts have the potential to cause a decline in business, such as whitewater rafting (Fleming, 2002). Societal and ecosystems impacts from agricultural damage, forest fires, and river pollution resulting from droughts further complicate water resources planning and management (IWR, 2002; Wright and Agee, 2004).

The use of freshwater resources for agriculture is also an important consideration for a number of watersheds across Maine (refer to Supplementary Fig. 1). MDEP (2008) reports that dry periods during the potato cropping-season (March–September) caused a shortage of water-supply to bulk up potatoes before harvest in Aroostook County. In Washington County, dry conditions in late August stressed blueberry crops—the highest user of water in the Maine's agricultural sector. Predictive or long-term water shortfall information has the potential to improve planning in agricultural sector, for example, by identifying alternate water sources. One step in this direction is the statute requirement developed by Maine's Agricultural Water Management Board to assist farmers to develop water management plans, based on a prescribed format and procedures. In the nearby state of New Hampshire, PDSI is used as a metric for monitoring drought conditions and preparedness (NHDES, 2010).

The definition for natural drought at a location is complicated by the very nature of its severity and duration; at the same time, drought impacts are important for policy setting in water-sensitive sectors. PDSI is a widely used index for drought monitoring and characterization. Efforts to provide regular updates and forecasts for PDSI and other related variables appear to be a key priority for the National Integrated Drought Information System (www.drought.gov) in the United States, and have the potential to inform water allocation and use. An example of the use of PDSI information is that of the natural drought threshold used in Maine's Chapter 587. The analyses presented in the following sections explore the variations in the frequency of natural drought over the past centuries (based on the reconstructed PDSI), incidence of multi-year droughts, and how the 20th century record fits into the drought statistics based on an eight century-long record. Furthermore, we explore the relationship between the PDSI index for the entire state (or a sub-region) and the individual streams that both exhibit differing sensitivity to drought stress, and represent watershed units where community-scale water management and decision-making is pursued.

The reconstructed, multi-century PDSI records promise significant, new information to inform water resources management and policy. However, comparisons between reconstructed PDSI and the 20th century observations would be valid if the reconstructions were perfect. That is, the tree-ring width variations have a one-to-one correspondence with the PDSI variability. As is well known, that is never the case. Cook et al. (2004) provide extensive details regarding PDSI reconstructions with expanded spatial and temporal coverage using tree-ring records. Environmental proxies (in this case, tree rings) explain only a portion of variance of the historical data. This raises an important concern regarding careful interpretation and framing of the insights gained from various analyses in a manner that promotes appropriate use of the new information. Another important consideration is the reduction in the number of local chronologies for the pre-1610 period, which limits the confidence that can be placed on historical drought variability during the 12th to 16th century periods (Table 1 in the Supplementary information section provides detailed information regarding the available tree-ring chronologies for the state of Maine). Consequently, the use of such information may be limited to qualitative assessment and discussion regarding various management and policy options. To this end, the next section provides a detailed description and discussion of the reconstruction and the range of factors that influence these proxy records.

3. Data

3.1. Historical streamflow records

Daily streamflow data from twelve stream gauges in Maine, USA are analyzed in this study (see Table 1 for details). Stream gauging stations are selected based on the availability of a serially complete dataset spanning for the 1951–2003 period. Daily mean stream flow data were obtained from the U.S. Geological Survey Hydro-Climatic Data Network for the United States (U.S. Geological Survey, 2010). This network includes the gauges whose watersheds are relatively free of human influences such as regulation, diversion, land-use change, or excessive groundwater pumping.

3.2. Reconstructed Palmer Drought Severity Index (PDSI)

In this study, we used Cook et al. (2004) reconstructed record of PDSI for the state of Maine dating back to 1138AD. The Palmer Drought Severity Index (PDSI) has been the most commonly used and most effective drought index in the United States (Palmer, 1965). PDSI reflects variability in precipitation, air temperature, and local soil moisture, along with prior information of these measures, to determine the dryness or wetness of a particular region. PDSI value generally varies from −6 to +6. A normal or neutral value of 0 is used. Drought severity is represented as: moderate drought (−2), severe drought (−3), and extreme drought (−4).

Table 1
General characteristics of the selected USGS stream gauges in Maine.

USGS gauge number	Gauge name	Drainage area (Sq. km)	Mean daily streamflow (m^3/sec)	Latitude (North)	Longitude (West)	Spearman rank correlation with PDSI
01010000	St. John River at Ninemile Bridge	3473.19	66.75	46°42′02″	69°42′56″	0.73
01010500	St. John River at Dickey	6941.2	134.93	47°06′47″	69°05′17″	0.71
01011000	Allagash River near Allagash	3828.02	55.10	47°04′11″	69°04′46″	0.66
01013500	Fish River near Fort Kent	2261.07	41.68	47°14′15″	68°34′58″	0.65
01014000	St. John River below Fish R, at Fort Kent	15317.26	275.69	47°15′29″	68°35′45″	0.69
01022500	Narraguagus River at Cherryfield	587.93	13.93	44°36′29″	67°56′07″	0.64
01030500	Mattawamkeag River near Mattawamkeag	3672.62	75.08	45°30′04″	68°18′21″	0.67
01031500	Piscataquis River near Dover-Foxcroft	771.82	17.72	45°10′30″	69°18′53″	0.67
01038000	Sheepscot River at North Whitefield	375.55	7.18	44°13′22″	69°35′38″	0.56
01047000	Carrabassett River near North Anson	914.27	21.41	44°52′09″	69°57′18″	0.60
01055000	Swift River near Roxbury	250.97	0.17	44°38′34″	70°35′20″	0.65
01057000	Little Androscoggin River near South Paris	190.37	3.92	44°18′14″	70°32′23″	0.61

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In the recent years, tree-ring based reconstructions of the streamflow in semi-arid regions have provided important details to support water resources management (for example, Woodhouse and Lukas, 2006). The availability of water in arid or semi-arid regions is well captured by tree-ring growth. In moist and wetter climates, tree rings are less sensitive and sometimes the growth is not limited by the moisture conditions; however, while calibrating, nearly half of the hydrologic variability of Maine's PDSI was explained by the tree ring for years 1928–1978 (data sources, description and quality are discussed in the next section). Normally, wide rings and narrow ring widths correspond to above and below average rainfall respectively. Cumulative precipitation shows high correlation with annual streamflow and also exerts a strong influence of tree-ring growth.

3.3. Performance statistics for the reconstructed PDSI

The reconstruction performance statistics for the grid over Maine are available separately. Fig. 1 shows the relationship between observed PDSI and reconstructed PDSI during the 1948–2003 period. The distribution of reconstructed PDSI is consistent with the instrumental PDSI (correlation, $\rho = 0.71$, p-value <0.01). For Maine's grid-point (Grid-point number: 270, Latitude: 45.0° N, longitude: 70.0° W), statistics such as: Calibration R^2, Verification R^2, RE, CE values is 0.474, 0.244, 0.211, and 0.165 respectively. In dendrochronology, calibrated variance of 0.474 is considered to be reasonably good (explaining almost half of the variation), however, this information must be discussed alongside any analysis and interpretation. Verification R^2 is 0.244 compared to a value of 0.474 in the calibration period. Verification $R^2 > 0.11$ is statistically significant at the 1-tailed 95% level using a 28-year verification period (Cook et al., 2004). Positive magnitudes of RE and CE imply meaningful reconstruction skill for the above-mentioned grid-point. Further details regarding the reconstruction and spatial pattern analyses are included in the Supplementary materials.

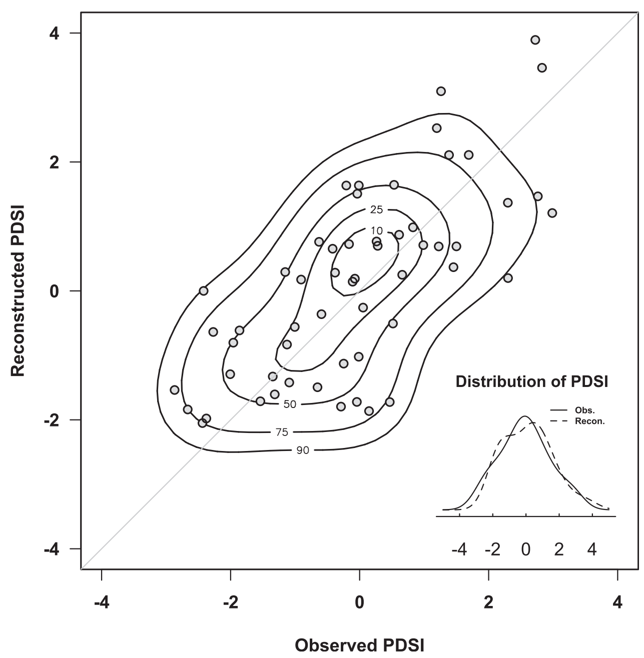

Fig. 1. Scatter plot of observed PDSI and reconstructed PDSI. The contour lines show a joint probability distribution using Kernel approach (Inset). Probability distribution functions for observed PDSI and reconstructed PDSI during the 1948–2003 period.

4. Drought variability and hydrologic risk in Maine

4.1. Drought in the twentieth century

The four-year long drought of 1999–2002 was the most severe and damaging over the historical record (Lombard, 2004). The drought episode evolved from "widespread" during the four-year period and "severe" in 2001–2002. Lombard (2004) notes that the major impacts of the drought included: "*(1) thirty-five public-water suppliers, including 8 large community systems, were affected severely (Andrews Tolman, Maine Drinking Water Program, written commun, 2003); (2) approximately 17,000 private wells in Maine went dry in the 9 months prior to April 2002 (Maine Emergency Management Agency, 2002); (3) more than 32 million dollars was lost in crops in 2001 and 2002 and some growers of wild blueberries recorded crop losses of 80 to 100 percent (Maine Agricultural Water Management Advisory Committee, 2003).*" The 7-year long, 1963–1969 drought is the most severe case in the historical record in terms of its duration (Lombard, 2004). The 1978 drought in Maine was mild, however, the low-flow recurrence intervals reached the 35-year return period levels (Lombard, 2004). Observational records show that in each case of multi-year drought, only one or at most two years had a PDSI value below −2. However, consecutive dry years with negative PDSI less severe than the −2 threshold have the potential to cause significant damage to agriculture, forest life, mankind and ecosystem. Such droughts, mild yet prolonged, may have significant cumulative impact, however, do not meet the severity threshold of −2. Therefore, a detailed characterization of severity and duration of droughts is an important consideration for adaptive management and policy implementation for future droughts in the changing climate.

4.2. Long-term drought variability in Maine

Using a fifty-year moving window, we analyzed the frequency of dry (PDSI <-2) and wet (PDSI >2) years during the 1138–2003 period (Fig. 2). The Fourteenth century was a predominantly wet

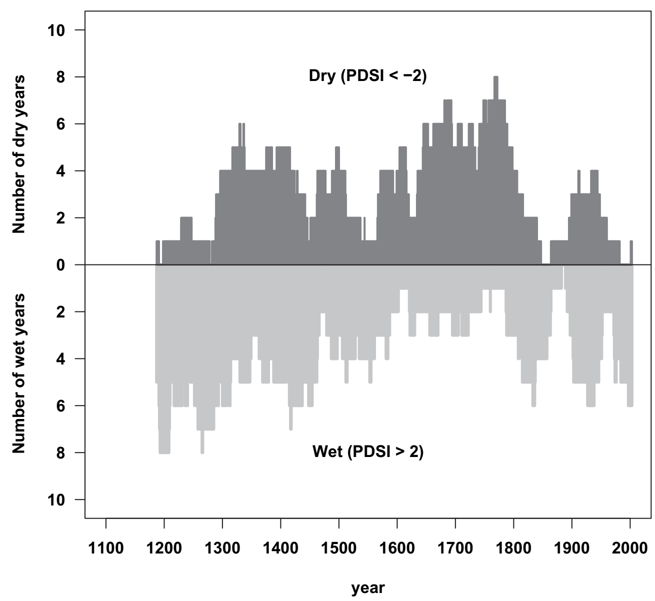

Fig. 2. Frequency of wet and dry years based on a 50-year moving window analysis for Maine's reconstructed PDSI index. This estimate highlights long-term variability in climate system and relative "wet" and "dry" conditions in this region. This also shows relative drought frequencies in different time periods in past millennium against a twentieth century (where instrumental data is available) record.

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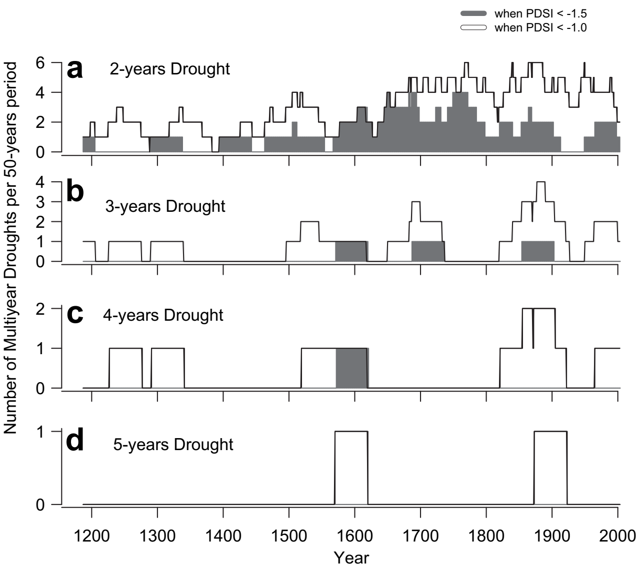

Fig. 3. Multi-year drought occurrence using a threshold of PDSI below −1.00 and below −1.50 for the paleoclimatic PDSI (1138–2003) and relative change in the multi-year drought frequencies at two abovementioned thresholds. Drought magnitude is defined as the ratio of severity (consecutive years when PDSI was <−1.0 or <−1.50) and duration. a. Number of multi-year drought with duration of 2 years, b. Number of multi-year drought with duration of 3 years, c. Number of multi-year drought with duration of 4 years, d. Number of multi-year drought with a duration of 5 years or more.

period. There were only one or two dry years and up to eight wet years were found in every fifty-year period during that time window. But at the end of thirteenth and in 14th century, frequency of dry years gradually increased and fluctuated between four and six throughout the century. Number of dry years rose during the 17th and 18th century and number of wet years decreased during that time period. Six to eight dry years were observed while one to three wet years occurred during the seventeenth and eighteenth century period. Subsequent periods show fluctuations consistent with a variable hydroclimate. Based on the unusually wet and dry year counts, the 20th century PDSI fluctuations in Maine appear to be among the wettest (PDSI >2) and least dry (PDSI <−2) compared to the remainder of the multi-century record. This analysis provides an illustrative example of the temporal fluctuations and the dynamic range of drought variability in Maine. Dramatically different wet and dry period frequency in the paleoclimatic record as contrasted with the 20th century instrumental record, illuminate unique historical periods that were either dry, wet, variable, or persistent. These hydrologic regime scenarios capture a representative set of drought severity and duration statistics. Within the context of droughts in Maine, the prospect of using historical drought statistics, appropriately incorporating the uncertainty, and pursuing adaptive management and options analyses (with water allocation and ecosystems services as the key objectives) can provide valuable insights in to the vulnerabilities and also promote proactive exploration of strategies for coping and adaptation.

MDEP recommends negative two or below as the threshold of natural drought condition. Considering this definition, multi-year

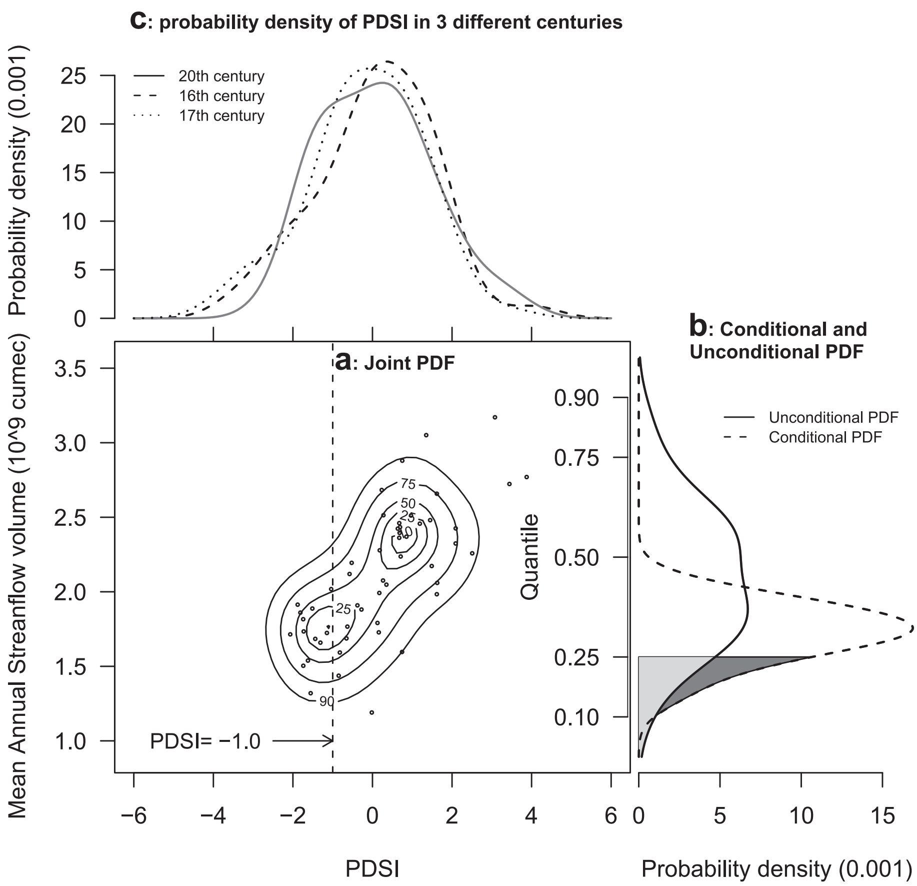

Fig. 4. a. Scatter plot of PDSI and mean annual streamflow (Q) and contour lines in joint probability distribution using Kernel approach, b. Probability distribution functions (PDF) for unconditional estimate and also the conditional distribution of mean annual streamflow (Q) given PDSI ≤−1, c. Probability distribution of PDSI values in three different time periods 1601–1700, 1501–1600 and 1901–2000.

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droughts are rare in the 20th century observational record (Fig. 3). However, if we consider a less severe PDSI threshold (such as −1.50, −1.00 or below), a number of multi-year dry periods are evident. Taking the −1.50 or below as a threshold, we identified one 4-year, three 3-year and a number of 2-year droughts in this area during the 20th century. Considering −1.00 or below as a threshold, we find two drought events of five years or longer duration, six 4-year drought and large numbers of 3-year and 2-year droughts in Maine. The analysis of frequency and duration discussed above points to the importance of identifying and developing triggers in drought plans that recognize and respond to prolonged moderate droughts (less severe than the natural drought threshold) in a timely manner. In some respect, the above discussion underscores the need to broaden the definition and metrics for drought monitoring and response. Drought monitoring and forecast products (for example, PDSI or Standardized Precipitation Index) are generally available as area averaged (state or climate division) indices. A related challenge is that of understanding the relationship between the drought indices and the watershed-scale hydrologic variability. The following discussion considers this need and develops an empirical framework that relates PDSI to the streamflow.

4.3. *Ascertaining local hydrologic risk conditioned on the statewide drought condition*

Localized estimates of hydrologic risk, conditioned upon the statewide PDSI observation or forecast, provide usable information to water managers and policy makers. Fig. 4a shows the empirical probability distribution for PDSI during three century-long periods. To the extent that PDSI and watershed hydrologic variations are linked, the attendant variability in the PDSI statistics capture the nonstationarity in historical records, also evident in the results from a moving window analysis (Fig. 2). We used a non-parametric probability density estimation approach to determine the joint probability density of the annual instrumental PDSI and mean annual streamflow (1951–2003 period) for the aforesaid twelve stream gauges in Maine. Kernel density estimators represent the non-parametric density estimators that are widely used in theoretical and applied statistics (Bowman and Azzalini, 1997). In comparison to parametric estimators, non-parametric estimators are not restricted to have a specified function form, so as to allow adaptive estimation from data, including departures from linearity. The joint non-parametric probability density estimate (instrumental PDSI index and the annual streamflow for the St. John River at Ninemile Bridge, Maine stream gauge) for the 1951–2003 period is shown in Fig. 4b. The strong linear relationship (correlation = 0.73) highlights that the PDSI index is indeed a useful metric to assess broad-scale hydroclimatic variability. However, the joint relationship also highlights a weakly bimodal nature of the probability distribution, thus providing additional information regarding a flatter probability density distribution for streamflow (Fig. 4c, in this case, we plotted unconditional estimates for the reconstructed PDSI data). The correlation of PDSI index with all the stream gauges in Maine is reported in Table 1.

Based on the 20th century hydrologic data, we further develop conditional probability density function between the instrumental PDSI and annual mean streamflows in different gauges. These relationships are used to develop a watershed-specific characterization of the risk for low flows. We plotted probability distribution function (PDF) for all streamflow data of aforementioned gauge with a solid line, Fig. 4b. Then the conditional distribution of mean annual streamflow (Q) given PDSI ≤ -1 is obtained by an appropriate consideration of the joint probability distribution rescaled by the PDSI probability distribution. Finally, a hydrologic risk estimate is obtained by considering the ratio of exceedance probability based

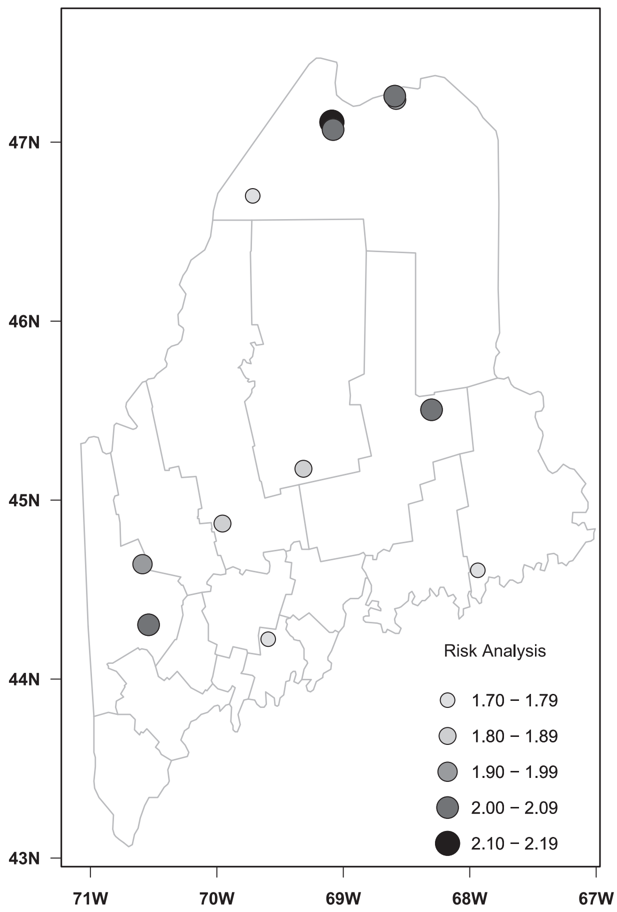

Fig. 5. Conditional hydrologic risk is defined as the ratio of the probability for a low flow (lower that the 25th quantile) when PDSI information is included to the unconditional flow estimate.

on the conditional distribution to that of the unconditional streamflow distribution. Mathematically,

$$\text{Risk} = \frac{P[(Q \leq Q_{25})|\text{PDSI} \leq -1]}{P(Q \leq Q_{25})}$$

Here, Q is annual stream flow and Q_{25} the 25th percentile based on the historical record. For a number of stream gauges in Maine, the hydrologic risk associated with flow occurrences below the 25th percentile of the mean annual flow undergoes a nearly two-fold increase upon the inclusion of the conditional PDSI information (Fig. 5). The results presented in Fig. 5 indicate the conditional hydrologic risk for low flows vary from watershed-to-watershed. Based on the conditional hydrologic risk assessment, specific vulnerabilities can be diagnosed. The drought index-based risk assessment methodology for streams across the state allows tailoring of information for watershed-specific water allocation and management through comprehensive analysis with some measures such as human occupancy, and water uses characteristics. An important factor in determining vulnerability is the water use. As noted in Section 2.3, agricultural sector is an important user of freshwater resources. In the Supplementary section, we provide a county-wise map for agricultural water withdrawals.

5. Summary and conclusions

The paleoclimatic reconstructed PDSI record offers the opportunity to analyze the fluctuations in the frequency of wet and dry periods over a multi-century period. A motivating factor for this

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study is the use of PDSI threshold of −2 in the definition of natural drought for the state of Maine. In this study, we pursued an exploratory analysis of the PDSI index for Maine. We found that the 20th century instrumental record provides important information regarding contemporary drought statistics, including drought events where moderate, yet prolonged droughts have occurred. A multi-century record of PDSI provides an assessment of the broader envelope of hydroclimatic variability in this region, one that is not readily evident in the instrumental record. The historical record provides a number of century-long periods with varying wet and dry period statistics that can be used for scenario analyses and planning. In this study, while exploring the utility of paleoclimatic data we also emphasize the need for a careful consideration of uncertainties regarding use of hydroclimatic reconstructions.

Runoff volumes across watersheds show moderate-to-strong correlation with PDSI. Based on the 20th century hydrologic data we developed joint relationships between the statewide PDSI and water year runoff volume. These relationships are used to develop a watershed-specific characterization of the risk for low flows. These joint probabilistic relationships highlight that the inclusion of PDSI information can benefit local hydrologic risk assessment. Our results suggest the vulnerability of drought (based on statewide PDSI) is not uniform throughout the state, and local characterization methodology shows that elevated hydrologic risk can be quantified for each stream and emergency management agencies can prepare for droughts based on the higher or lower risk values. From the standpoint of incorporating long-term PDSI information in to watershed planning and management contexts, the historical records provide a number of "hydrologic analogs" for a range of dry and wet periods over a given planning horizon (for example, 30 years). Consequently, scenario-based planning can utilize these past drought records to estimate risk and vulnerability. Our ongoing work focuses on developing quantitative methods to develop watershed-specific drought risk assessments based on reconstructed data.

Finally, in a changing climate, adaptive management approaches stand to benefit from a careful scrutiny of various aspects of a rule or policy that lends itself to a "set of decisions" to guide the management of natural waters. In increasingly complex and often over-allocated systems, decisions have cascading effects that persist and often have the potential for unintended consequences—consequently, a continual review and, perhaps, inclusion of scientific information is likely to ensure the long-term, intended outcomes for watershed systems.

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Appendix. Supplementary information

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2010.10.054.

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