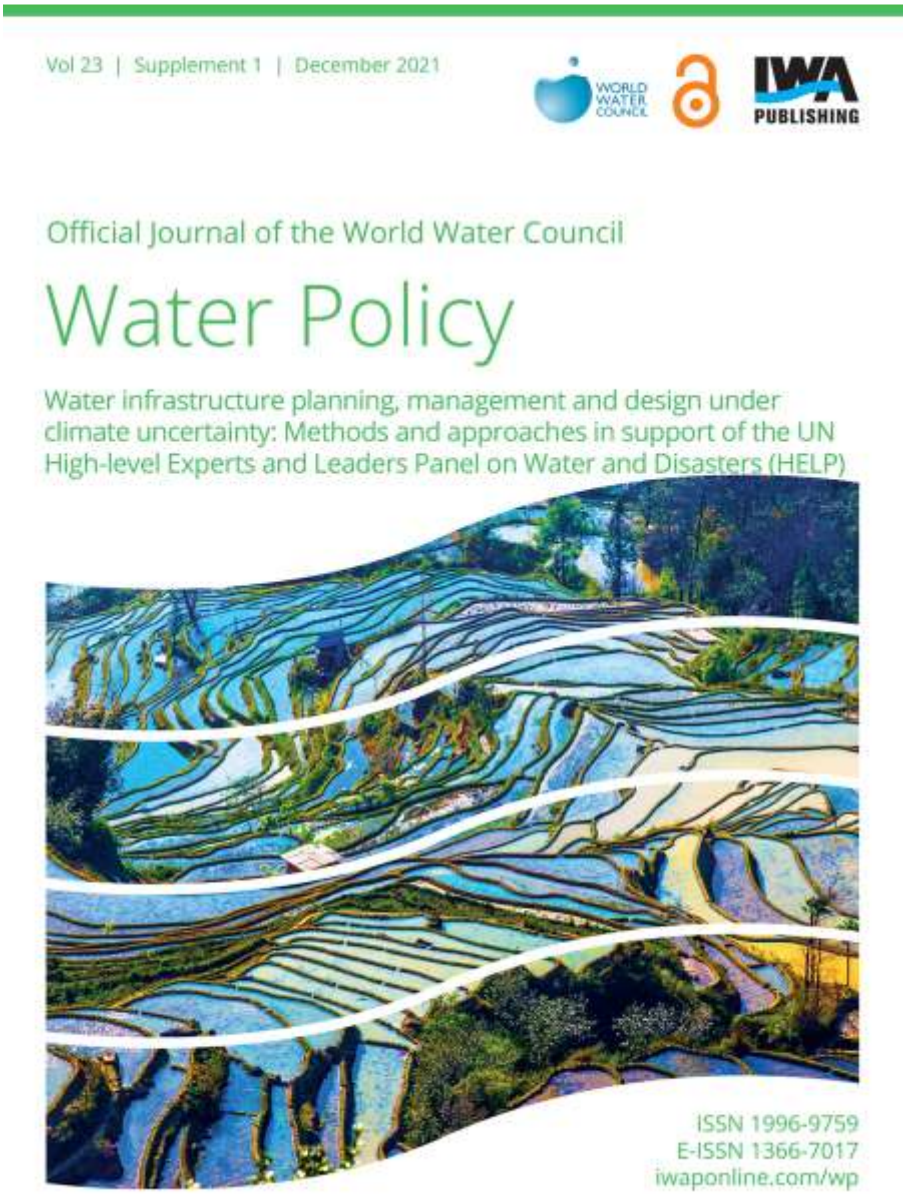

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On the need for streamflow drought frequency guidelines in the U.S.

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ABSTRACT

Extreme drought and resulting low streamflows occur throughout the U.S., causing billions of dollars in annual losses, detrimentally impacting ecosystems, as well as agricultural, hydropower, navigation, water supply, recreation, and a myriad of other water resource systems, leading to reductions in both the effectiveness and resiliency of our water resource infrastructure. Since 1966, with the introduction of Bulletin 13 titled 'Methods of Flow Frequency Analysis', the U.S. adopted uniform guidelines for performing flood flow frequency analysis to ensure and enable all federal agencies concerned with water resource design, planning, and management under flood conditions to obtain sensible, consistent, and reproducible estimators of flood flow statistics. Remarkably, over one-half century later, no uniform national U.S. guidelines for hydrologic drought streamflow frequency analysis exist, and the various assorted guidelines that do exist are not reliable because (1) they are based on methods developed for floods, which are distinctly different than low streamflows and (2) the methods do not take advantage of the myriad of advances in flood and low streamflow frequency analyses over the last 50 years. We provide a justification for the need for developing national guidelines for streamflow drought frequency analysis as an analog to the existing national guidelines for flood frequency analysis. Those guidelines should result in improved water resources design, planning, operations, and management under low streamflow conditions throughout the U.S. and could prove useful elsewhere.

Key words: 7Q10, Baseflow, Hydrologic design, Low flow frequency analysis, Low streamflow, Precipitation

HIGHLIGHTS

- Since 1966, the U.S. has adopted uniform guidelines for performing flood flow frequency analysis.
- Over one-half century later, no analogous uniform national guidelines exist for hydrologic drought streamflow frequency analysis.
- Existing low streamflow frequency methods are based mostly on flood frequency analysis and do not take advantage of the myriad of advances in both areas over the last 50 years.
- Numerous innovations in low flow frequency analysis are described, using analogies to recent advances in flood frequency analysis.
- A justification is provided for the need to develop national guidelines for streamflow drought frequency analysis.
- Such guidelines would enable agencies concerned with water resource design, planning, and management under drought conditions to obtain sensible, consistent, and reproducible estimators of low streamflow statistics.

1. INTRODUCTION AND BACKGROUND

Recently, the U.S. has undergone a series of extreme drought events, where losses to crops, livestock, and the overall gross domestic product are estimated to be in the billions of dollars (e.g., Fannin, 2012; Folger *et al.*, 2012; Howitt *et al.*, 2014; NOAA, 2019). For example, the 2012 drought/heatwave was the most extensive

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drought to affect the U.S. since the 1930s with over 33.9 billion dollars of damage and 123 deaths (NOAA, 2019). Of all weather-related disasters in the U.S., droughts alone accounted for $144 billion (41.2%) of the estimated $349 billion total cost of all weather-related disasters over the period 1980–2003 (Ross & Lott, 2003). In economic terms alone, droughts are the costliest natural disasters to strike the U.S. (Cook *et al.*, 2007). However, put in context, Stakhiv *et al.* (2016) argued that due to 'continuous adaptation by the various economic sectors associated with agriculture, as well as the growing suite of drought mitigation and compensation policies and programs of various governmental institutions', annual losses due to drought constitute only a miniscule percentage of the overall U.S. economy and only about 5% of agricultural sector production of the U.S. in 2015. Still, on a global scale, of all the 20th century natural hazards, droughts had the greatest detrimental impact (Bruce, 1994; Obasi, 1994), in part, due to the highly interrelated nature of water availability, agriculture, food supply, and the environment. Shifts in climate, water availability, and water demand make the estimation of low-flow statistics even more challenging.

As we describe here, there are many useful analogies between flood and low streamflow frequency analyses within the context of the design, planning, operations, and management of water resource systems. First and foremost, flood and low streamflows are both extreme events, and there may be considerable benefits from drawing upon analogies in flood frequency analysis (FFA) that are useful in drought streamflow frequency analysis. In a recent review article on drought, Brunner *et al.* (2021) suggest that 'droughts and floods should be studied in a joint framework' and that 'uniting droughts and floods in one framework requires stochastic continuous models and an improved joint representation of both types of extremes in hydrological models. This can be obtained by better representing processes important for both types of extremes in model structure and by developing calibration strategies specifically targeting both droughts and floods. Tackling these challenges will allow us to derive more reliable flood and drought predictions and ultimately help to minimize the negative impacts of extreme events.'

Unfortunately, to date, there has been little effort to integrate our knowledge of flood and drought streamflow frequency analyses. Since the introduction of the first U.S. federal guidelines for flood flow frequency analysis in 1966 (Bulletin 13, 'Methods of Flow Frequency Analysis'), there has been a relatively steady transfer and application of improvements and developments in flood flow frequency analysis resulting in subsequent Bulletins 15, 17, 17B, and 17C, so that the existing guidelines for flood frequency analysis in the U.S. (England *et al.*, 2018) represent the current state of the art. Remarkably during that same period of over a half century, there has been no effort analogous to those referenced national guidelines on flood frequency to ensure and enable coordination between all U.S. federal agencies concerned with water resource design, planning, and management under low streamflow conditions to obtain sensible, consistent, and reproducible estimators of low-flow statistics and indices.

Our goal is to document the need for guidelines for drought streamflow frequency analysis in the U.S., analogous to the Bulletin 13 effort, which at the time it was developed in 1966 was simply a description of the current state of the art of FFA within federal agencies, with evaluation and testing of those methods left to subsequent efforts resulting in Bulletins 15, 17, 17B, and 17C. Naturally, any such guidelines recommended here would also prove useful for other countries, regions, and even continents of the world, because as we describe below, the U.S. is not alone on this matter. We begin by providing the necessary introduction and background needed to describe the various aspects associated with the development of national guidelines for low-flow frequency analysis within the context of water resource system design, operations, planning, and management.

1.1. On the need for national standards for flood and drought streamflow frequency analyses

Engineering standards are documents that specify the characteristics and technical details that must be met by the procedures employed by an engineer within the domain that the standards cover. Engineering standards are normally published documents that establish specifications and procedures designed to ensure the reliability, consistency, and effectiveness of the methods applied by engineers. By developing and applying national standards for engineering methods, government agencies can help to ensure that the approaches to be employed are consistent, compatible, safe, and effective.

Many national programs are based on and consist of the accepted and uniform methods for deriving flood and drought streamflow frequencies. For example, the FEMA flood insurance program is based on standard and uniform methods of flood flow frequency analysis outlined in Bulletin 17C (England *et al*., 2018). Similarly, the U.S. Army Corps of Engineers and the U.S. Bureau of Reclamation employ standardized methods for project justification and selection based on the computation of expected annual damages to determine the design which maximizes net benefits. While some national standards, such as those for FFA (England *et al*., 2018), have undergone a steady evolution and development over the years in an effort to include the most up to date advances in associated research and technology, other national standards either do not exist, as in the case of low-flow frequency analysis, or are subject to considerable criticism, as in the case of federal water quality standards based on the geometric mean, which have been employed by the U.S. E.P.A. for decades and are subject to continued highly critical concerns (see Vogel (2020) for a summary).

Another important dimension associated with engineering standards relating to droughts involves the implementation of federal disaster assistance programs (U.S. Department of Agriculture, 2017) as well as numerous other federal financial assistance programs for drought emergencies. Numerous federal agencies offer loans or grants to assist with drought-related emergencies, and all such programs require uniform and reliable statistical approaches to evaluate damage costs associated with such drought emergencies. For example, programs for farming and ranching operations are administered by the U.S. Department of Agriculture through the USDA Farm Service Agency, the USDA Rural Development, and the USDA Natural Resources Conservation Service. Similarly, the U.S. Small Business Administration provides loans to businesses, including nonprofit organizations, and the U.S. Bureau of Reclamation offers grants for drought resiliency planning and project implementation.

The development and application of national standards for FFA has enabled federal agencies to adopt and apply consistent, reproducible, sensible, and state-of-the-art methods. Importantly, those same national guidelines and standards for FFA are also normally adopted by state agencies, as well as by engineering practitioners in private practice. Without such standards for either flood or drought streamflow frequency analysis, there is little assurance that results in project justifications, designs, and operations will perform as expected, or that applied standards will be reproducible in practice.

1.2. On the definition of drought

Interestingly, in spite of the extraordinary societal importance of drought impacts, there is no universal definition of drought. Dracup *et al*. (1980), Wilhite & Glantz (1985), Tallaksen & Van Lanen (2004), Mishra & Singh (2010), Sheffield & Wood (2011), Van Loon (2015), and the World Meteorological Organization and Global Water Partnership (2016) provided reviews of the wide variety of drought definitions. Lloyd-Hughes (2014) argued that due to the myriad views of droughts, corresponding to the disparate viewpoints of scientists, water managers, water users, and others, it is unlikely that any single method of assessing and describing drought severity will ever be suitable for all circumstances and users. Lloyd-Hughes (2014) argued that any suitable universal description of drought would require reference to water supply, demand, and management, in addition to the usual focus on meteorological and/or hydrologic conditions.

Mishra & Singh (2010) summarized the commonly employed four categories of drought: hydrological, meteorological, agricultural, and socio-economic, coined earlier by Wilhite & Glantz (1985). Lloyd-Hughes (2014) stressed that the influence of human intervention through water management is intrinsic to hydrological, agricultural, and socio-economic drought, and can only be ignored in the case of purely meteorological drought. We focus on the water management aspects of drought as related to the operations of water resource systems under drought conditions, and thus, our work does not attempt to classify, assess, or define drought. Rather, we are concerned with the development and application of methods for quantifying the frequency and magnitude of low streamflow conditions in rivers and water resource systems under drought conditions.

1.3. On the distinction between drought indices and low streamflow statistics

Mishra & Singh (2010), Heim (2012), Svoboda *et al.* (2015), Bachmair *et al.* (2016), the World Meteorological Organization and Global Water Partnership (2016), and Hasan *et al.* (2019) reviewed the myriad of hydroclimatic indices that have been introduced for classifying, monitoring, assessing, and managing various categories of drought. For example, the U.S. national drought atlas developed by Werick *et al.* (1994a, 1994b) summarized the Palmer Drought Severity Index, which is a meteorological drought index for characterizing the severity of drought. Svoboda *et al.* (2015) reviewed a number of more recent national drought studies. The U.S. Drought Monitor integrates streamflow, precipitation, and additional drought-related information, as well as expert knowledge, in generating maps across the U.S. to characterize current drought conditions (Svoboda *et al*., 2002). Elsewhere, large-scale national or even multinational drought monitoring and early warning systems are more commonly based on meteorological (precipitation-based) drought indicators (Bachmair *et al*., 2016).

On the one hand, the large number of available drought indices highlights both the challenge and the importance of developing an objective drought definition. On the other hand, rather than clarifying the definition of drought, the plethora of indices creates further confusion regarding the selection of an appropriate metric for a particular setting. While our discussions are closely related to previous work on drought indices for use in classification, monitoring, and management, our argument appears to be unique due to its focus on the characterization of hydrological drought within the context of low streamflow frequency analysis, for the sole purpose of improving water resource system design, operation, planning, and management activities. Thus, we do not focus on the myriad of hydroclimatic indices useful for describing meteorological, agricultural, and socio-economic drought, and instead focus on the probabilistic behavior of streamflow under drought conditions.

Our focus on drought is quite different from the previously mentioned studies, because we only concentrate upon drought-based statistics computed from low streamflows which are specifically useful for a wide range of water resource design, operations, planning, and management applications. Such streamflow drought statistics are distinct from many of the traditional meteorological drought statistics, because they are useful for evaluating river conditions during drought, and may not be useful for assessing, monitoring, and communicating the severity and duration of droughts, as is the case for other indices such as those reported by Werick *et al.* (1994a, 1994b), Svoboda *et al.* (2015), Bachmair *et al.* (2016), Tijdeman *et al.* (2018), and many others.

1.4. On the importance and need for drought and low-flow statistics

Low streamflow conditions have important societal impacts including, but not limited to, the need for municipal, industrial, agricultural, residential, recreational, and other water use restrictions; reductions in water quality, hydropower generation and power plant cooling efficiency; disruptions to navigation; agricultural/food system losses and stress; harm to drought sensitive species; ecological (instream) flow reductions; increased fire risk; and increased groundwater depletion.

Design, operations, planning, and management for the prevention of hydrologic drought is often accomplished via the computation of various low streamflow statistics, such as the 7-day, 10-year low streamflow (7Q10), or the daily streamflow with an annual exceedance probability of 95% (Q95). Such low-flow statistics are required in a wide range of water resource design, planning, operations, and management settings (Smakhtin, 2001; Ouarda *et al.*, 2008), as well as for the maintenance of environmental flows. Ensuring adequate streamflow under drought conditions is extremely important for protecting a wide range of aquatic species as evidenced from reviews by Dewson *et al.* (2007), Ouarda *et al.* (2008), Hulley *et al.* (2014), and Warren *et al.* (2015).

Hydrologic drought streamflow statistics are used routinely for a wide range of water management activities. For example, low-flow statistics may be used to determine the quantity of water that can be safely withdrawn from a particular stream or reservoir without causing harm to aquatic species, to ensure adequate streamflow at downstream locations, and for preparing drought management plans. They may also be used for water quality purposes, such as to determine design discharges to rivers to ensure acceptable waste-load allocations from point sources (such as for National Pollution Discharge Elimination System permits) and for the development of total maximum daily loads for streams and watersheds.

Our focus on water availability and streamflow under drought conditions is quite different from the numerous previous and ongoing studies that have focused on drought monitoring, modeling, and assessment. Such studies have generally reported meteorological, hydrological, and agricultural drought indices to enable stakeholders to better understand and plan for the socio-economic consequences of drought. Instead, our primary goal is to encourage the exploitation of developments over the past half century in flood and low-flow frequency analysis for the purpose of developing standardized, consistent, and proven approaches for estimating low streamflow statistics for use in water resource design, operations, planning, and management activities across all federal, state, and local agencies within the U.S. It is our hope that such guidelines would find use in many other settings elsewhere around the world.

2. DEVELOPMENT OF GUIDELINES FOR DETERMINING DROUGHT AND LOW-FLOW FREQUENCY

The behavior of extreme low streamflows is governed by completely different processes than that of floods. The dominant processes that govern the behavior of low streamflows include watershed hydrogeology, long-term spatial and temporal climatic variability, the lack of precipitation, and anthropogenic influences relating to both ground and surface water withdrawals and return flows. One expects distinct differences between the frequency analysis of flood flows and low streamflows. Estimators of low streamflow statistics are known to have extremely high relative errors (even higher than for floods) due, in part, to a lack of data, measurement errors, complex hydrologic processes, the inadequate or improper characterization of watershed hydrogeology, and roundoff errors due to USGS reporting standards (Archfield & Vogel, 2009). The development of frequency analysis procedures that are specifically suited for low streamflows is not only needed but also long overdue. The following sections describe the various aspects, developments, and methodologies which form the basis of guidelines for performing streamflow drought frequency analysis (DFA) in the U.S. and elsewhere.

2.1. Existing reviews, guidelines, and software for low-flow frequency analysis in the U.S. and elsewhere at gauged sites

In comparison to guidelines for FFA, there is remarkably little guidance on how to perform low-flow frequency analysis in the U.S. and elsewhere. The only manuals or comprehensive studies we are aware of on low-flow frequency analysis in the U.S. are now largely outdated (Riggs, 1972; ASCE Committee, 1980), although the U.S. Geological Survey maintains an active website titled ‘Hydrologic Drought and Low-Flow Frequency’ (https://water.usgs.gov/osw/techniques/lowflow.html), which contains various valuable sources of information in the form of memos, training documents, software, and references. Another comprehensive, yet largely outdated manual of practice on hydrologic frequency analysis published by the U.S. Army Corps of Engineers (1993) contains only a single chapter of length 3 pages devoted to low-flow frequency analysis.

Perhaps, the greatest attention to the development of national guidelines for low-flow frequency analysis was developed for the U.K. by Gustard *et al.* (1992). This was a significant effort which began with the comprehensive study by the Institute of Hydrology (1980) along with seven other large low-flow studies summarized in Table 1.3 of Gustard *et al.* (1992) for various regions in the U.K. To date, the most comprehensive set of guidelines on low-flow frequency analysis that we are aware of is the report titled 'Manual on Low-Flow Estimation and Prediction' authored by Alan Gustard and Siegfried Demuth and published by the World Meteorological Organization in 2008. The purpose of that manual was 'to publish state-of-the-art analytical procedures for estimating, predicting and forecasting low river flows at all sites, regardless of the availability of observational data.' The intent of the manual by Gustard & Demuth (2008) was to enable agencies to 'predict and forecast low flows for a wide range of applications, including national and regional water resource planning, abstraction management, public water supply design, instream flow determination, effluent dilution estimates, navigation, the design of run of river hydropower schemes, the design of irrigation schemes, and water resources management during low-flow conditions.' Our goal is to emphasize the need for guidelines analogous to those reported by Gustard & Demuth (2008) which are suited to conditions in the U.S. There are several other manuals of low-flow frequency analysis which are not nearly as comprehensive as Gustard & Demuth (2008) as well as software for their implementation, as is described below in the section on regional methods. Another valuable source of research and guidance on methods for the estimation of low-flow statistics at gauged sites are the reviews by Smakhtin (2001) and Ouarda *et al.* (2008) as well as the summary articles by Burn *et al.* (2008) and Hulley *et al.* (2014) on the behavior and challenges associated with characterizing low flows in Canada.

2.2. Existing software for low-flow frequency analysis

Numerous software packages exist in the U.S. for the estimation of low streamflow statistics including the U.S. Geological Survey software packages known as STREAMSTATS, GLSNET, SWToolBox, SWSTAT, the U.S. E.P.A. program DFLOW, and the U.S. Army Corps of Engineers package HEC-SSP. In addition, numerous software packages exist for other regions of the world, such as the package LFSTAT that implements all of the methods outlined in the manual of practice by Gustard & Demuth (2008).

Regional methods of frequency analysis are now widely used in many regions of the world for both flood discharges and precipitation and are generally preferred over at-site methods (Ouarda, 2017). By comparison to FFA, the use of regional methods in low-flow frequency analysis is in its infancy (Ouarda *et al.*, 2008, 2018). Some examples of readily available software for the implementation of regional low-flow frequency analysis includes the Low Flows 2000 package (Young *et al.*, 2003), which has been adopted by the Scottish Environment Protection Agency for estimating low-flow statistics in ungauged catchments. Low Flows 2000 allows the user to estimate annual and monthly flow duration curves and to carry out a complete regional frequency analysis. Another software package known as REGIONS (Ouarda *et al.*, 2002) represents a general tool for the regional frequency analysis of extreme low and flood events. In the province of Quebec, the software package ARIDE (Ouarda *et al.*, 2005) combines hydrological, statistical, and GIS tools to enable a regional low-flow frequency analysis at any site in the region. Ouarda *et al.* (2018) recommend the use of readily available Generalized Additive Modeling (GAM) software for the implementation of regional low-flow frequency methods. An exhaustive review of the existing software for DFA is needed to determine common and promising features for use in developing guidelines for the U.S. and elsewhere.

While drought streamflow statistics are sorely needed, existing methods for their estimation in the U.S. are still based generally on recommendations for FFA. For instance, the U.S. EPA uses the software program DFLOW (Rossman, 1990; EPA, 2021) to estimate design streamflows for low-flow analysis and water quality standards. In DFLOW, the estimation of the 7Q10 is based on fitting a log Pearson Type III (LP3) distribution with parameters estimated using the at-site method of moments. The same method is used by the USGS software program SWSTAT (https://water.usgs.gov/software/SWSTAT/). Both of these estimation procedures use the LP3 distribution, a distribution recommended for FFA (Rossman, 1990), yet both approaches ignore advances in FFA (e.g., regional estimators of skew, regional hydrologic regression, outlier detection, etc.) that have been recommended in practice for FFA for over 35 years (IAC, 1982), as well as regional methods of FFA based on L-moments (Hosking & Wallis, 2005), which were used in the first national drought atlas (Werick *et al.*, 1994a, 1994b), and most importantly the four recent innovations associated with Bulletin 17C completed in 2018 (Griffis & Stedinger, 2007; England *et al.*, 2018). The four innovations include the adoption of a generalized representation of flood data that includes interval data and the recognition that floods can either be higher or lower than the level of certain infrastructure, such as bridge decks; the use of the expected moments algorithm, which incorporates historical and 'paleoflood' information (data from floods in the distant past); a generalized approach to the identification of low outliers in flood data; and an improved method for computing confidence intervals. A natural next step to Bulletin 17C (England *et al.*, 2018) would be to evaluate the suitability of the recent innovations in that Bulletin, with suitable revisions, for use in the estimation of low streamflow statistics.

2.3. Characterization of the probability distribution of low streamflow

Given the distinct differences in processes leading to extreme low and flood streamflows, one expects their probability distribution to behave differently. Matalas (1963), Vogel & Kroll (1989), Kroll & Vogel (2002), Bhatti *et al.* (2019), and others have provided recommendations for suitable probability distributions for low streamflow series (LSS) in the U.S. Kroll & Vogel (2002) and Bhatti *et al.* (2019) performed national assessments of the probability distribution of LSS across the conterminous U.S. Bhatti *et al.* (2019) found that the log Pearson Type III (LP3) distribution was generally favored for both intermittent and perennial sites, whereas the Pearson Type III (P3) and the 3-parameter lognormal distributions (LN3) also performed well at perennial sites. In addition, Bhatti *et al.* (2019) found that the generalized extreme value (GEV), LP3, and LN3 distributions all performed well for modeling the distribution of the inverse of LSS at perennial sites. Interestingly, using very different goodness-of-fit criteria than either Bhatti *et al.* (2019) or Kroll & Vogel (2002), Matalas (1963) also recommended the P3 distribution for use in models of LSS in the U.S. The findings of Kroll & Vogel (2002) and Bhatti *et al.* (2019) are also consistent with more recent assessments elsewhere. For example, in a national study for the U.K., Zaidman *et al.* (2002) recommended the use of the P3 distribution over all other alternative distributions considered. In a subsequent analysis, Zaidman *et al.* (2003) recommended the use of both the GEV and P3 distributions for low-flow frequency analysis in the U.K. In Canada, Yue & Pilon (2005) recommended the P3 distribution and also identified the GEV and LP3 as acceptable distributions. A thorough analysis of appropriate probability distributions for LSS using the most current data sets and methods is warranted. An alternative to assigning a particular probability distribution to the series of annual minimum d-day LSS is through the use of nonparametric empirical probability distributions. Takeuchi (1988) employed empirical distributions, termed flood and low-flow duration curves, for use in mapping the regional behavior and persistence of both floods and droughts, an alternative approach which may improve low-flow frequency analysis.

2.4. Regional methods of low-flow frequency analysis

Regional statistical methods introduced by Hosking & Wallis (2005) and many others are now in widespread use in flood and precipitation frequency analyses and should be useful for low-flow frequency analysis. This section summarizes numerous innovations in regional FFA, which should prove useful for developing guidelines for drought flow frequency analysis.

2.4.1. Regional estimators of skewness and GEV shape parameter

The use of regional estimators of skewness is commonplace in FFA (Griffis & Stedinger, 2009). While such regional estimators have been shown to improve FFA, their use in DFA has never been explored, and the simpler at-site skew estimators, which generally have poor statistical properties (Stedinger *et al.*, 1993; Ouarda, 2017; Stedinger, 2017), are commonly employed for DFA (Rossman, 1990). Procedures for estimating regional skewness for the LP3 distribution, which are now widely used in FFA, could be adapted for use in DFA for estimating regional skewness for the P3 or LP3 distributions at intermittent sites. Likewise, it is now common practice to employ regional estimators of the shape parameter of the GEV distribution (Hosking & Wallis, 2005), which has found an increasing application in FFA outside the U.S. (see, for example, Tables 3 and 4 in Vogel & Wilson, 1996; Salinas *et al.*, 2014). Regional estimators of the GEV model shape parameter are critical to obtain reliable estimators of flood quantiles (Lima *et al.*, 2016), and we anticipate that similar conclusions should apply to quantiles of LSS at perennial sites where the GEV model has been found to provide a good approximation to LSS (Kroll & Vogel, 2002; Zaidman *et al.*, 2003).

2.4.2. Innovations in the estimation of low-flow statistics at ungauged sites

Estimating low streamflow statistics at ungauged river sites continues to be a very challenging problem as evidenced by workshops and special issues on the subject (see Spence *et al.*, 2008, 2013). It is now common knowledge in FFA that regional methods are more attractive than at-site methods (Hosking & Wallis, 2005). Ouarda *et al.* (2008) provides a brief review of regional methods for low-flow frequency analysis. Regional regression models, perhaps the most common approach for the estimation of low streamflow statistics and flow duration curve quantiles at ungauged river sites, have been shown to perform much worse for low flows than for floods (e.g., Thomas & Benson, 1970; Smakhtin, 2001; Kroll *et al.*, 2004). Vogel & Kroll (1992) document that inclusion of hydrogeologic indices and physically based information in regional regression models for DFA could lead to considerable improvements. Recent advances in hydrologic regionalization for both FFA and DFA should prove useful for improving low streamflow prediction at ungauged sites, including ways to improve hydrogeologic characterization (Kroll *et al.*, 2004; Eng *et al.*, 2011; Stagnitta *et al.*, 2017), the use of the map correlation method (Archfield & Vogel, 2010), methods related to the region of influence (Tasker *et al.*, 1996), and most importantly recent advances in the application of both Generalized Additive Modeling (GAM) (Ouarda *et al.*, 2018) and Bayesian generalized least-squares hydrologic regression methods (Reis *et al.*, 2020).

2.4.3. Index drought analogy to the index flood method

There is a good deal of research that documents that the regional flood frequency method, termed the index flood method introduced by Dalrymple (1960), is one of the most efficient regional estimation methods (Cunnane, 1988; Potter & Lettenmaier, 1990). Stedinger (2017) and Ouarda (2017) review the background, advantages, and implementation of the index flood method based on the method of L-moments. Pilon (1990) extended the index flood method, used in regional FFA, to low-flow frequency analysis when the regional distribution is assumed to be a three-parameter Weibull. The performance of the approach was demonstrated by its application to the southern part of the province of Ontario in Canada. The extension of the index flood method using regional L-moments and the P3 and GEV models to the index drought problem is a natural and straightforward application and could be accomplished with minimal effort. There is clearly a great deal of value to extending the index flood method to create an index drought approach implemented using regional L-moments for use with both the P3 and GEV models for low-flow frequency analysis.

2.4.4. Estimation of low streamflow statistics at partially gauged sites

Previous research has introduced methods for the incorporation of short or spot measurements at the site of interest to improve estimators of low streamflow statistics. Stagnitta *et al.* (2017) indicated that baseflow correlation procedures (Stedinger & Thomas, 1985; Zhang & Kroll, 2007a) produce improved low-flow estimators compared with the use of regional regression when only four baseflow measurements were available. Stagnitta *et al.* (2017) also explored methods for estimating hydrogeologic indices (baseflow recession and aquifer time constants) from spot measurements and their use in regional regression. While this method was never superior to the use of baseflow correlation, it did show promise when compared with regional regression without hydrogeologic indices. Another use of spot measurements involves the estimation of flow duration curves at ungauged sites with the quantile–probability–probability–quantile (QPPQ) daily streamflow simulator (Archfield & Vogel, 2010). It is also possible to transfer information from multiple sites in a region (Zhang & Kroll, 2007b). A summary and evaluation of existing approaches for the integration of spot measurements into low-flow frequency analysis is sorely needed.

3. NONSTATIONARY LOW-FLOW FREQUENCY ANALYSIS

As evidenced from numerous recent review articles, research on approaches to nonstationary FFA is burgeoning due to the need to capture impacts of changes in climate, land-use, water-use, and other anthropogenic impacts on water management (Madsen *et al.*, 2013; Hall *et al.*, 2014; Bayazit, 2015; Salas *et al.*, 2018; Villarini *et al.*, 2018; Francois *et al.*, 2019). National trend studies have found widespread upward trends in annual minimum daily streamflows across broad regions of the U.S. (Lins & Slack, 1999, 2005; Douglas *et al.*, 2000). In fact, those studies found much greater and widespread evidence of increasing trends in annual minimum streamflows than in annual maximum flood flows. In spite of the widespread evidence of the nonstationary behavior of LSS, few U.S. studies exist (see recent discussions by Liu *et al.* (2015); Ahn & Palmer (2016); Kiem *et al.* (2021)). Nonstationary trends in LSS and associated DFA could have a critical impact on water resource management, yet most current low streamflow frequency analysis procedures assume that future conditions will be similar to those observed in the past, a very poor assumption.

Numerous procedures summarized in the above review articles on nonstationary FFA are now available and easily adapted for performing nonstationary low-flow frequency analysis. Promising approaches include a nonparametric approach tested by Blum *et al.* (2019) on LSS and further analyzed by Vogel & Kroll (2020), and a parsimonious nonstationary approach introduced by Serago & Vogel (2018) for FFA, which could be easily adapted for use with LSS. Blum *et al.* (2019) tested a new approach to nonstationary low-flow frequency analysis that applies a stationary nonparametric quantile estimator to the most recent subset of the historical streamflow record, which is expected to exhibit stationary behavior. That approach was found to result in improvements in accuracy and reductions in bias over the standard approach of using the entire historical record. Vogel & Kroll (2020) generalized the results of Blum *et al.* (2019) and derived expressions for computing the optimal length of the recent subset record resulting in minimum variance estimators of the low-flow statistic. An alternative parametric yet parsimonious approach introduced by Serago & Vogel (2018) for nonstationary FFA could easily be adapted for use with LSS and a wide range of possible probability distributions. The approach introduced by Serago & Vogel (2018) is unique because it only requires a single additional model parameter, so that only three or four parameters are needed for a full nonstationary frequency analysis, compared with most of the methods summarized in the above review articles which often require five to eight parameters for nonstationary frequency analysis. Another attractive approach to handling nonstationary behavior is the seasonal stochastic streamflow modeling approach introduced by Kiem *et al.* (2021) for evaluating water supply reliability.

3.1. Impact of stochastic persistence on low-flow frequency analysis

A unique feature of LSS is that, unlike flood series, they tend to exhibit stochastic persistence resulting from groundwater and other storage processes, which have a critical impact on baseflow processes and thus LSS. For example, in a national assessment of the existence of stochastic persistence and deterministic trends on LSS, Douglas *et al.* (2000) found statistically significant serial correlation in annual minimum seven-day low flows at approximately 25% of the 1,474 river stations analyzed across the U.S. Douglas *et al.* (2002) and others have shown that the integration of the serial correlation of LSS is of critical importance when estimating the expected return period associated with streamflow drought events. The effect of stochastic persistence of LSS on engineering design quantiles should, therefore, be integrated into guidelines for low-flow frequency analysis.

Both stationary and nonstationary series of annual minimum low streamflows are likely to exhibit stochastic persistence, and it is very difficult to distinguish between trends and persistence as was so clearly demonstrated by Cohn & Lins (2005). For example, the existence of serial correlation is known to confound our ability to detect trends (Douglas *et al.*, 2000), though numerous procedures are available for removing the impact of serial correlation when performing trend detection. Since we expect LSS to exhibit both trends and persistence, an effort should be made to account for both of these factors in any resulting low streamflow frequency analysis.

3.2. Deterministic watershed models for estimating nonstationary hydrologic drought statistics

Deterministic watershed models (DWMs) provide tremendous promise for simulating future, possibly nonstationary, hydrologic conditions in a watershed due to their ability to account for the integrated impacts of future changes in climate, land use, water withdrawals, and other factors. DWMs provide a very useful tool for modeling future streamflow traces, which can then be subject to low-flow frequency analysis analogous to the way in which DWMs are increasingly being applied for FFA (Blazkova & Beven, 2009; Steinschneider *et al.*, 2014; Francois *et al.*, 2019).

There are dozens of DWMs to choose from as evidenced by the variety of textbooks which summarize numerous software packages for their implementation (Beven, 2000; Wagener *et al.*, 2004; Singh & Frevert, 2006; Singh, 2012) including the highly sophisticated recently released National Water Model (Maidment, 2017) that can provide near real-time, high spatial resolution streamflow forecasts for the entire U.S. Farmer & Vogel (2016) highlight that if a DWM is to be used for estimating either a low-flow statistic, such as the 7Q10 or Q95, or a flood flow statistic, such as the 100-year flood, it is necessary to implement the deterministic model in a stochastic mode to avoid bias in corresponding streamflow statistics. To enable the implementation of DWMs in a stochastic mode, Vogel (2017) advanced a new generation of DWMs, which he terms stochastic watershed models (SWMs), which are useful for generating streamflow ensembles as input to nearly all modern risk-based water resource decision-making approaches. SWMs are simply DWMs implemented using stochastic meteorological series, stochastic model parameters, and stochastic model errors to generate ensembles of streamflow traces that represent the variability in possible future streamflows (see Steinschneider *et al.* (2014) for a good example and Francois *et al.* (2019) for a recent review). Each SWM model trace or ensemble can be used to estimate a LSS that can then be used to obtain estimators of low-flow statistics such as the 7Q10 or Q95. Such an analysis results in an ensemble of estimates of 7Q10 and/or Q95, which can then be used to construct confidence intervals for the corresponding population value of those statistics.

While the use of DWMs for modeling average and high flows is now commonplace, there are fewer examples of studies that have evaluated the ability of DWMs for simulating low streamflow conditions. In a review of the use of DWMs for characterizing low streamflow, Davison & van der Kamp (2008) conclude that in spite of the plethora of DWMs available for simulating low streamflow, there are only a very limited number of studies that have evaluated the ability of DWMs to adequately characterize baseflow processes. Van Loon (2015) reviews numerous studies that have shown that low streamflows are usually poorly captured by DWM simulations, which is no surprise given the numerous challenges associated with modeling low flows summarized by Smakhtin (2001), Ouarda *et al.* (2008), and others.

Several authors have introduced new approaches to evaluate the goodness of fit of DWM simulations when one's primary interest is in the ability of such models to capture the behavior of LSS. For example, Pushpalatha *et al.* (2012) and Garcia *et al.* (2017) have suggested examining the efficiency of the inverse of LSS, rather than computing the efficiency of the streamflows or their natural logarithms as is common practice when evaluating the ability of DWMs for simulating average and flood flows. Farmer *et al.* (2015a) provides examples and reasoning for the importance of examining the goodness of fit of the inverse of daily streamflow when one's interest is in low streamflow. There is a need for more comparative assessments of the ability of various types of models for reproducing the behavior of low streamflows, analogous to the recent study by Farmer *et al.* (2015b).

4. SUMMARY AND CONCLUSIONS

On a global scale, of all the 20th century natural hazards, droughts had the greatest detrimental impact (Bruce, 1994; Obasi, 1994) in part due to the highly interrelated nature of water availability, agriculture, food supply, and the environment. In Section 1.4, we reviewed the myriad of societal consequences that stem from low streamflow conditions that occur during drought events. Shifts and changes in climate, water availability, and water demand will tend to aggravate societal consequences associated with drought and make planning for future low streamflow events even more challenging.

Since the introduction of the first U.S. federal guidelines for FFA in 1966 (Bulletin 13, 'Methods of Flow Frequency Analysis'), there has been a relatively steady transfer and application of improvements and developments in FFA resulting in subsequent Bulletins 15, 17, 17B and 17C, so that the existing guidelines for FFA in the U.S. represent the current state of the art (England *et al*., 2018). Remarkably during that same period of over a half century, there has been no analogous effort to ensure and enable all federal agencies concerned with water resource design, planning, and management under drought conditions to obtain sensible, consistent, and reproducible estimators of low streamflow statistics. Interestingly, this situation is remarkably similar to the European Union (EU) which has a detailed plan for flood risk management and improving societal resilience, but neglects drought risk management despite high drought damages (Priest *et al*., 2016). Clearly many of the issues raised in this commentary also pertain to the EU and elsewhere.

Our primary goal is to set the stage to exploit developments over the past half century in flood and low-flow frequency analysis for the purpose of developing standardized, consistent and proven approaches for estimating low streamflow statistics for use in water resource design, operations, planning, and management activities across all federal, state, and local agencies in the U.S. While our discussions are closely related to previous work on drought indices for use in classification, monitoring, and management of drought events, our recommendations distinguish themselves by their focus on the characterization of hydrological drought for the purpose of improving water resource system design, operations, planning, and management activities.

We have outlined numerous potentially fruitful areas of research related to the development of U.S. national guidelines for streamflow DFA including:

1. Review of environmental streamflow requirements and compilation of a list of estimators of low streamflow statistics and their use in ecological and water resource design, operations, planning, and management applications.
2. Review of the existing software for DFA and a gap analysis to identify needed features for use in developing national guidelines for the U.S.

3. Evaluating the suitability of the recent innovations in FFA outlined in Bulletin 17C, with revisions suited to LSS, for use in the estimation of low streamflow statistics at both gauged and ungauged sites.
4. Exploring the use of alternative probability distributions to describe LSS at intermittent and perennial sites with special attention given to modeling of inverse streamflows found to be quite attractive in low-flow frequency analysis; see, for example, Pushpalatha *et al.* (2012), Farmer *et al.* (2015a), Garcia *et al.* (2017), and Bhatti *et al.* (2019).
5. Investigating recent developments in the regional estimation of streamflow statistics and their application to gauged and ungauged sites, and partially gauged sites.
6. Research related to nonstationary low streamflow frequency analysis, with particular emphasis on the impact of changes in climatic, land-use, and water demand conditions.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Ahn, K.-H. & Palmer, R. N. (2016). Use of a nonstationary copula to predict future bivariate low flow frequency in the Connecticut River basin. *Hydrological Processes 30*, 3518–3532. doi:10.1002/hyp.10876.

Archfield, S. A. & Vogel, R. M. (2009). The implications of discretizing continuous random variables: an example using the U.S. Geological Survey reporting standards for streamflow data. In: *ASCE-EWRI, Environmental and Water Resources Congress, 2009*. Kansas City.

Archfield, S. A. & Vogel, R. M. (2010). Map correlation method: selection of a reference streamgage to estimate daily streamflow at ungauged catchments. *Water Resources Research 46*. doi: 10.1029/2009WR008481.

ASCE Task Committee on Low-Flow Evaluation, Methods, and Needs of the Committee on Surface-Water Hydrology of the Hydraulics Division (1980). Characteristics of low flows. *ASCE Journal of Hydraulics 106*(HY5), 7.

Bachmair, S., Stahl, K., Collins, K., Hannaford, J., Acreman, M., Svoboda, M., Knutson, C., Smith, K. H., Wall, N., Fuchs, B., Crossman, N. D. & Overton, I. C. (2016). Drought indicators revisited: the need for a wider consideration of environment and society. *Wiley Interdisciplinary Reviews: Water 3*(4), 516–536. https://doi.org/10.1002/wat2.1154.

Bayazit, M. (2015). Nonstationarity of hydrological records and recent trends in trend analysis: a state-of-the-art review. *Environmental Processes 2*, 527–542.

Beven, K. J. (2000). *Rainfall-Runoff Modeling: the Primer*. John Wiley and Sons Ltd, New York.

Bhatti, S. J., Kroll, C. N. & Vogel, R. M. (2019). Another look at the probability distribution of low streamflow series in the US. *Journal of Hydrologic Engineering 24*(10), 04019043.

Blazkova, J. S. & Beven, K. (2009). A limits of acceptability approach to model evaluation and uncertainty estimation in flood frequency estimation by continuous simulation: Skalka Catchment, Czech Republic. *Water Resources Research 45*, W00B16. http://dx.doi.org/10.1029/2007WR006726.

Blum, A. G., Archfield, S. A., Hirsch, R. M., Vogel, R. M, Kiang, J. E. & Dudley, R. W. (2019). Updating estimates of low streamflow statistics to account for possible trends. *Hydrological Sciences Journal*. doi.10.1080/02626667.2019.1655148.

Bruce, J. P. (1994). Natural disaster reduction and global change. *Bulletin of the American Meteorological Society 75*, 1831–1835.

Brunner, M. I., Slater, L., Tallaksen, L. M. & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: a review. *Wiley Interdisciplinary Reviews – Water*. doi: 10.1002/wat2.1520.

Burn, D. H., Buttle, J. M., Caissie, D., MacCulloch, G., Spence, C. & Stahl, K. (2008). The processes, patterns and impacts of low flows across Canada. *Canadian Water Resources Journal 33*(2), 107–124.

Cohn, T. A. & Lins, H. F. (2005). Nature's style: Naturally trendy. *Geophys. Res. Lett. 32*, L23402, doi:10.1029/2005GL024476.

Cook, E. R., Seager, R., Cane, M. A. & Stahle, D. W. (2007). North American drought: reconstructions, causes, and consequences. *Earth-Science Reviews 81*, 93–134.

Cunnane, C. (1988). Methods and merits of regional flood frequency analysis. *Journal of Hydrology 100*(1–3), 269–290.

Dalrymple, T. (1960). Flood frequency methods. *U.S. Geological Survey, WaterSupply Paper 1543A*, 11–51.

Davison, B. & van der Kamp, G. (2008). Low-flows in deterministic modelling: a brief review. *Canadian Water Resources Journal 33*(3), 181–193.

Dewson, Z. S., James, A. B. W. & Death, R. G. (2007). A review of the consequences of decreased flow for instream habitat and macroinvertebrates. *Journal of the North American Benthological Society 26*(3), 401–415.

Douglas, E. M., Vogel, R. M. & Kroll, C. N. (2000). Trends in flood and low flows in the United States. *Journal of Hydrology 240*(1–2), 90–105.

Douglas, E. M., Vogel, R. M. & Kroll, C. N. (2002). Impact of streamflow persistence on hydrologic design. *Journal of Hydrologic Engineering, ASCE 7*(3), 220–227.

Dracup, J. A., Seong, L. K. & Paulson Jr., E. G. (1980). On the definition of droughts. *Water Resources Research 16*, 297–302.

Eng, K., Kiang, J. E., Chen, Y. Y., Carlisle, D. M. & Granato, G. E. (2011). Causes of systematic over- or underestimation of low streamflows by use of index-streamgage approaches in the United States. *Hydrological Processes 25*, 2211–2220.

England Jr., J. F., Cohn, T. A., Faber, B. A., Stedinger, J. R., Thomas Jr., W. O., Veilleux, A. G., Kiang, J. E. & Mason Jr., R. R., (2018). *Guidelines for Determining Flood Flow Frequency – Bulletin 17C: U.S. Geological Survey Techniques and Methods, Book 4, Chap. B5*. p. 148. https://doi.org/10.3133/tm4B5.

Environmental Protection Agency (EPA) (2021). *Environmental Modeling Community of Practice: DFLOW*. Available at: https://www.epa.gov/ceam/dflow (accessed 23 April 2021).

Fannin, B. (2012). *Texas Agricultural Drought Losses Total $7.62 Billion, Texas A&M AgriLife Today*. Available at: http://today.agrilife.org/2012/03/21/updated-2011-texas-agricultural-drought-losses-total-7-62-billion/.

Farmer, W. H. & Vogel, R. M. (2016). On the deterministic and stochastic use of hydrologic models. *Water Resources Research 52*. doi:10.1002/2016WR019129.

Farmer, W. H., Over, T. M. & Vogel, R. M. (2015a). Multiple regression and inverse moments improve the characterization of the spatial scaling behavior of daily streamflows in the Southeast United States. *Water Resources Research 51*. doi:10.1002/2014WR015924.

Farmer, W. H., Archfield, S. A., Over, T. M., Hay, L. E., LaFontaine, J. H. & Kiang, J. E. (2015b). *A Comparison of Methods to Predict Historical Daily Streamflow Time Series in the Southeastern United States, USGS Scientific Investigations Report, 2014-5231*.

Folger, P., Cody, B. A. & Carter, N. T. (2012). Drought in the United States: causes and issues for congress. In: *Congressional Research Service, 7-5700, RL34580*.

Francois, B., Schlef, K. E., Wi, S. & Brown, C. M. (2019). Design considerations for riverine floods in a changing climate – a review. *Journal of Hydrology 574*(2019), 557–573.

Garcia, F., Folton, N. & Oudin, L. (2017). Which objective function to calibrate rainfall–runoff models for low-flow index simulations? *Hydrological Sciences Journal 2*(7), 1149–1166. doi.10.1080/02626667.2017.1308511.

Griffis, V. W. & Stedinger, J. R. (2007). Evolution of flood frequency analysis with Bulletin 17. *Journal of Hydrologic Engineering 12*(3), 283–297.

Griffis, V. W. & Stedinger, J. R. (2009). The log-Pearson type 3 distribution and its application in flood frequency analysis, 3. Sample Skew and Weighted Skew Estimators. *Journal of Hydrologic Engineering 14*(2), 209–212.

Gustard, A., Bullock, A. & Dixon, J. M. (1992). *Low Fow Estimation in the United Kingdom (IH Report No. 108)*. Institute of Hydrology, Wallingford, Oxon, p. 88.

Gustard, A. & Demuth, S. (2008). *Manual on Low-Flow Estimation and Prediction, Operational Hydrology Report No. 50*. WMO-No. 1029, World Meteorological Organization, Geneva, Switzerland, p. 136.

Hall, J., Arheimer, B., Borga, M., Brázdil, R., Claps, P., Kiss, A., Kjeldsen, T., Kriauciuniene, J., Kundzewicz, Z. & Lang, M. (2014). Understanding flood regime changes in Europe: a state of the art assessment. *Hydrology and Earth System Sciences 18*, 2735–2772.

Hasan, H. H., Razali, S. F. M., Muhammad, N. S. & Ahmad, A. (2019). Research trends of hydrological drought: a systematic review. *Water 11*(11), 2252. doi:10.3390/w11112252.

Heim, R. R. (2012). A review of twentieth century drought indices used in the United States. *Bull. Am. Meteorol. Soc. 83*, 1149–1165. https://doi.org/10.1175/1520-0477-83.8.1149.

Hosking, J. R. M. & Wallis, J. R. (2005). *Regional Frequency Analysis: An Approach Based on L-Moments*. Cambridge University Press, Cambridge, UK.

Howitt, R. E., Medellin-Azuara, J., MacEwan, D., Lund, J. R. & Sumner, D. A. (2014). *Economic Analysis of the 2014 Drought for California Agriculture*. Center for Watershed Sciences, University of California, Davis, CA, p. 20. Available at: http://watershed.ucdavis.edu.

Hulley, M., Clarke, C. & Watt, E. (2014). Occurrence and magnitude of low flows for Canadian rivers: an ecozone approach. *Canadian Journal of Civil Engineering 41*(1), 1–8. doi:10.1139/cjce-2013-0300.

Institute of Hydrology (1980). *Low Flow Studies*. Institute of Hydrology, Wallingford, Oxon, UK. In four volumes.

Interagency Advisory Council (IAC) on Water Data (1982). *Guidelines for Determining Flood Flow Frequency, Bulletin 17B*. U.S. Department of the Interior Geological Survey Office of Water Data Coordination, Reston, VA, p. 194.

Kiem, A. S., Kuczera, G., Kozarovski, P., Zhang, L. & Willgoose, G. (2021). Stochastic generation of future hydroclimate using temperature as a climate change covariate. *Water Resources Research 56*, 2020WR027331. https://doi.org/10.1029/2020WR027331.

Kroll, C. N. & Vogel, R. M. (2002). The probability distribution of low streamflow series in the United States. *Journal of Hydrologic Engineering, ASCE 7*(2), 137–146.

Kroll, C., Luz, J., Allen, B. & Vogel, R. M. (2004). Developing a watershed characteristics database to improve low streamflow prediction. *Journal of Hydrologic Engineering 9*, 116–125.

Lima, C. H., Lall, R. U. & Troy, T. (2016). A hierarchical Bayesian GEV model for improving local and regional flood quantile estimates. *Journal of Hydrology 541*, 816–823.

Lins, H. F. & Slack, J. R. (1999). Streamflow trends in the United States. *Geophysical Research Letters 26*(2), 227–230.

Lins, H. F. & Slack, J. R. (2005). Seasonal and regional characteristics of US streamflow trends in the United States from 1940 to 1999. *Physical Geography 26*(6), 489–501.

Liu, D. D., Guo, S. L., Lian, Y. Q., Xiong, L. H. & Chen, X. H. (2015). Climate-informed low-flow frequency analysis using nonstationary modelling. *Hydrological Processes 29*(9), 2112–2124.

Lloyd-Hughes, B. (2014). The impracticality of a universal drought definition. *Theoretical and Applied Climatology 117*, 607–611. doi:10.1007/s00704-013-1025-7.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M. & Kjeldsen, T. (2013). *A review of applied methods in Europe for flood-frequency analysis in a changing environment*. NERC/Centre for Ecology & Hydrology, Edinburgh.

Maidment, D. R. (2017). Conceptual framework for the national flood interoperability experiment. *Journal of the American Water Resources Association (JAWRA) 53*(2), 245–257. doi: 10.1111/1752-1688.12474.

Matalas, N. C. (1963). *Probability Distribution of Low Flows*. Professional Paper 434-A, U.S. Geological Survey, Washington, DC.

Mishra, A. K. & Singh, V. P. (2010). A review of drought concepts. *Journal of Hydrology 391*, 202–216.

National Oceanic and Atmospheric Administration (2019). *Billion-Dollar Weather and Climate Disasters: Table of Events*. NOAA National centers for Environmental Information. Available at: https://www.ncdc.noaa.gov/billions/events/US/1980-2019.

Obasi, G. O. P. (1994). WMO's role in the international decade for natural disaster reduction. *Bulletin of the American Meteorological Society 75*(9), 1655–1661.

Ouarda, T. B. M. J., Gingras, H., Kouider, A., Rudolf, Z. R., Hache, M., Barbe, M. & Bobee, B. (2002). Regions, a general and automatic model for flood and drought regional estimation at ungauged basins. In: *1st Biennial Workshop of the Statistical Hydrology Committee of the CGU-HS, 2002 Annual Scientific Meeting of the CGU, Ban., AB, May 18–21, 2002.*

Ouarda, T. B. M. J., Jourdain, V., Gignac, N., Gingras, H., Herrera, H. & Bobee, B. (2005). *Development of a Low-Flow Regional Estimation Model for the Inhabited Part of Quebec, the ARIDE Model*. INRS-ETE, Research Report No. R-684-f1, p. 174 (in French).

Ouarda, T. B. M. J., Charron, C. & St-Hilaire, A. (2008). Statistical models and the estimation of low flows. *Canadian Water Resources Journal 33*(2), 195–206. doi:10.4296/cwrj3302195.

Ouarda, T. B. M. J. (2017). Regional flood frequency modeling. In: *Handbook of Applied Hydrology*, Chapter 77, 2nd edn. Singh, V. P. (ed.). McGraw Hill, New York.

Ouarda, T. B. M. J., Charron, C., Hundecha, Y., St-Hilairea, A. & Chebana, F. (2018). Introduction of the GAM model for regional low-flow frequency analysis at ungauged basins and comparison with commonly used approaches. *Environmental Modelling and Software 109*, 256–271.

Pilon, P. J. (1990). The Weibull Distribution applied to regional low flow frequency analysis. In: *Regionalisation in Hydrology*. (M.A. Beran, M. Brilly, A. Becker & O. Bonacci, eds). IAHS Publication No. 191, IAHS Press, Institute of Hydrology, Wallingford, UK., pp. 227–237.

Potter, K. W. & Lettenmaier, D. P. (1990). A comparison of regional flood frequency estimation methods using a resampling method. *Water Resources Research 26*(3), 415–424.

Priest, S. J., Suykens, C., Van Rijswick, H. F. M. W., Schellenberger, T., Goytia, S. B., Kundzewicz, Z. W., Van Doorn-Hoekveld, W. J., Beyers, J. -C. & Homewood, S. (2016). The European Union approach to flood risk management and improving societal resilience: lessons from the implementation of the Floods Directive in six European countries. *Ecology and Society 21*(4), 50. https://doi.org/10.5751/ES-08913-210450.

Pushpalatha, R., Perrin, C. & LeMoine, N. (2012). A review of efficiency criteria suitable for evaluating low-flow simulations. *Journal of Hydrology 420*, 171–182.

Reis Jr., D. S., Veilleux, A. G., Lamontagne, J. R., Stedinger, J. R. & Martins, E. S. (2020). Operational Bayesian GLS regression for regional hydrologic analyses. *Water Resources Research 56*, e2019WR026940. https://doi.org/10.1029/2019WR026940.

Riggs, H. C. (1972). Low-flow investigations, chapter B1. In: *Techniques of Water Resources Investigations of the United States Geological Survey, Book 4, Hydrologic Analysis and Interpretation*. U.S. Government Printing Office, Washington, DC.

Ross, T. & Lott, N. (2003). *A Climatology of 1980–2003 Extreme Weather and Climate Events, National Climatic Data Center Technical Report No. 2003-01*. NOAA/NESDIS, National Climatic Data Center, Asheville, NC.

Rossman, L. A. (1990). *DFLOW User's Manual, US EPA Risk Reduction Engineering Laboratory*. Office of Research and Development, Cincinnati, OH, p. 31.

Salas, J. D., Obeysekera, J. & Vogel, R. M. (2018). Techniques for assessing water infrastructure for nonstationary extreme events: a review. *Hydrological Sciences Journal*. https://doi.org/10.1080/02626667.2018.1426858.

Salinas, J. L., Castellarin, A., Viglione, A., Kohnova, S. & Kjeldsen, T. (2014). Regional parent flood frequency distributions in Europe – Part 1: is the GEV model suitable as a pan-European parent? *Hydrology and Earth Systems Science 18*, 4381–4389.

Serago, J. & Vogel, R. M. (2018). Parsimonious nonstationary flood frequency analysis. *Advances in Water Resources 112*, 1–16.

Sheffield, J. & Wood, E. F. (2011). *Drought: Past Problems and Future Scenarios*. Earthscan, London and Washington, DC.

Singh, V. P. (2012). *Computer Models of Watershed Hydrology*. Water Resources Publications, Golden, Co. ISBN-13: 978-1887201742.

Singh, V. P. & Frevert, D. K. (2006). *Watershed Models*. CRC Press, Boca Raton, FL.

Smakhtin, V. U. (2001). Low-flow hydrology: a review. *Journal of Hydrology 240*(3–4), 147–186.

Spence, C., Whitfield, P. H. & Ouarda, T. B. M. J. (2008). Introduction to the special issue on low-flow Prediction in Ungauged Basins (PUB) In Canada. *Canadian Water Resources Journal 33*(2), 103–106. doi:10.4296/cwrj3302103.

Spence, C., Whitfield, P. H., Pomeroy, J. W., Pietroniro, A., Burn, D. H., Peters, D. L. & St-Hilaire, A. (2013). A review of the Prediction in Ungauged Basins (PUB) decade in Canada. *Canadian Water Resources Journal 38*(4), 253–262. doi:10.1080/07011784.2013.843867.

Stagnitta, T. J., Kroll, C. N. & Zhang, Z. (2017). A comparison of methods for low streamflow estimation from spot measurements. *Hydrological Processes*. doi:10.1002/hyp.11426.

Stakhiv, E. Z., Werick, W. & Brumbaugh, R. W. (2016). Evolution of drought management policies and practices in the United States. *Water Policy 18*, 122–152.

Stedinger, J. R. (2017). Flood frequency analysis. In: *Handbook of Applied Hydrology*, Chapter 76, 2nd edn. Singh, V. P. (ed.). McGraw Hill, New York.

Stedinger, J. R. & Thomas, W. (1985). Low-flow frequency estimation using base-flow measurements. U.S. Geological Survey Open-File Report 85-95, U.S. Geological Survey, 22 pp, doi:10.3133/ofr8595.

Stedinger, J. R., Vogel, R. M. & Foufoula-Georgiou, E. (1993). Frequency analysis of extreme events, chapter 18. In: *Handbook of Hydrology*. Maidment, D. R. (Editor-in-Chief). McGraw-Hill Book Company, New York, NY.

Steinschneider, S., Wi, S. & Brown, C. (2014). The integrated effects of climate and hydrologic uncertainty on future flood risk assessments. *Hydrological Processes*. http://dx.doi.org/10.1002/hyp.10409.

Svoboda, M. D., LeComte, D., Hayes, M., Heim, R., Gleason, K., Angel, J., Rippey, B., Tinker, R., Palecki, M., Stooksbury, D., Miskus, D. & Stephens, S. (2002). The drought monitor. *Bulletin of the American Meteorology Society 83*, 1181–1190.

Svoboda, M. D., Fuchs, B. A., Poulsen, C. C. & Nothwehr, J. R. (2015). The drought risk atlas: enhancing decision support for drought risk management in the United States. *Journal of Hydrology 526*, 274–286.

Takeuchi, K. (1988). Hydrological persistence characteristics of floods and droughts. *Interregional comparisons. Journal of Hydrology 102*, 49–67.

Tallaksen, L. M. & Van Lanen, H. A. J. (eds) (2004). Hydrological drought: processes and estimation methods for streamflow and groundwater. In: *Developments in Water Science*, Vol. 48, Elsevier Science B.V., Amsterdam, The Netherlands..

Tasker, G. D., Hodge, S. A. & Barks, C. S. (1996). Region of influence regression for estimating the 50-year flood at ungauged sites. *Water Resources Bulletin 32*(1), 163–170.

Thomas, D. M. & Benson, M. A. (1970). Generalization of streamflow characteristics from drainage-basin characteristics. U.S. Geological Survey Water-Supply Paper 1975, U.S. Geological Survey, Reston, VA.

Tijdeman, E., Barker, L. J., Svoboda, M. D. & Stahl, K. (2018). Natural and human influences on the link between meteorological and hydrological drought indices for a large set of catchments in the contiguous United States. *Water Resources Research 54*, 6005–6023. https://doi.org/10.1029/ 2017WR022412.

U.S. Army Corps of Engineers (1993) Hydrologic Frequency Analysis, EM 1110-2-1415, see chapter 4 titled: Low Flow Frequency Analysis.

U.S. Department of Agriculture (2017). *Farm Service Agency Disaster Assistance Programs at a Glance, Fact Sheet*. p. 2.

Van Loon, A. F. (2015). Hydrological drought explained. *Wiley Interdisciplinary Reviews – Water 2*(4), 359–392.

Villarini, G., Taylor, S., Wobus, C., Vogel, R. M., Hecht, J., White, K. D., Baker, B., Gilroy, K., Olsen, J. R. & Raff, D. (2018). *Floods and Nonstationarity: A Review, CWTS 2018-01*. U.S. Army Corps of Engineers, Washington, DC.

Vogel, R. M. & Kroll, C. N. (1989). Low-flow frequency analysis using probability plot correlation coefficients. *Journal of Water Resources Planning and Management, ASCE 115*(3), 338–357.

Vogel, R. M. & Kroll, C. N. (1992). Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics. *Water Resources Research 38*(9), 2451–2458.

Vogel, R. M. & Wilson, I. (1996). The probability distribution of annual maximum, minimum and average streamflow in the United States. *Journal of Hydrologic Engineering, ASCE 1*(2), 69–76.

Vogel, R. M. (2017). Stochastic watershed models for hydrologic risk management. *Water Security*. http://dx.doi.org/10.1016/j.wasec.2017.06.001.

Vogel, R. M. (2020). The geometric mean? *Communications in Statistics: Theory and Methods*. doi:10.1080/03610926.2020.1743313.

Vogel, R. M. & Kroll, C. N. (2020). A comparison of estimators of the conditional mean under non-stationary conditions. *Advances in Water Resources*. https://doi.org/10.1016/j.advwatres.2020.103672, 2020.

Wagener, T., Wheater, H. S. & Gupta, H. V. (2004). *Rainfall-Runoff Modelling in Gauged and Ungauged Catchments*. Imperial College Press, London, p. 332.

Warren, M., Dunbar, M. J. & Smith, C. (2015). River flow as a determinant of salmonid distribution and abundance: a review. *Environmental Biology of Fishes 98*(6), 1695–1717.

Werick, W. J., Willeke, G. E., Guttman, N. B., Hosking, J. R. M. & Wallis, J. R. (1994a). National Drought Atlas Developed, EOS, AGU, Vol. 75, p. 89–90. doi:10.1029/94EO00706.

Werick, W. J., Willeke, G. E., Guttman, N. B., Hosking, J. R. M. & Wallis, J. R. (1994b). The National Drought Atlas, Geophysics News 1993, p. 8–10.

Wilhite, D. A. & Glantz, M. H. (1985). Understanding the drought phenomenon: the role of definitions. *Water International 10*(3), 111–120.

World Meteorological Organization and Global Water Partnership (2016). Handbook of drought indicators and indices. In: *Integrated Drought Management Programme, Integrated Drought Management Tools and Guidelines Series 2*. Svoboda, M. & Fuchs, B. A., (eds). World Meteorological Organization, Geneva, Switzerland, p. 45.

Young, A. R., Grew, R. & Holmes, M. G. R. (2003). Low flows 2000: a national water resources assessment and decision support tool. *Water Science & Technology 48*(10), 119–126.

Yue, S. & Pilon, P. (2005). Probability distribution type of Canadian annual minimum streamflow. *Hydrological Sciences Journal 50*(3), 438. doi:10.1623/hysj.50.3.427.65021.

Zaidman, M. D., Keller, V. & Young, A. R. (2002). *Low Flow Frequency Analysis: Guidelines for Best Practice*. Centre for Ecology & Hydrology, Environment Agency, UK, p. 33.

Zaidman, M. D., Keller, V., Young, A. R. & Cadman, D. (2003). Flow-duration-frequency behavior of British rivers based on annual minimum data. *Journal of Hydrology 277*, 195–213.

Zhang, Z. & Kroll, C. (2007a). Closer look at the baseflow correlation method. *Journal of Hydrologic Engineering 12*, 190–196.

Zhang, Z. & Kroll, C. (2007b). The baseflow correlation method with multiple gauged sites. *Journal of Hydrology 347*, 371–380.

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