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Drought impacts on river salinity in the southern US: Implications for water scarcity

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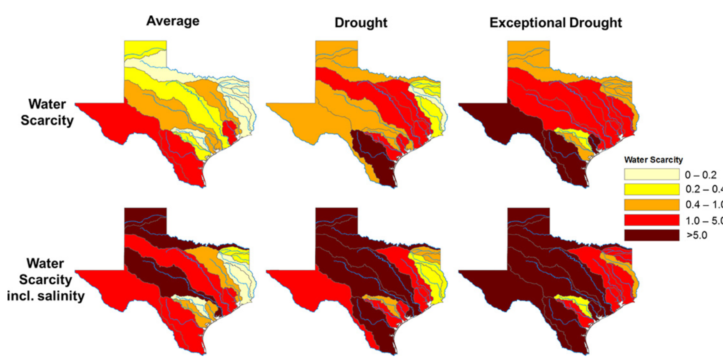
HIGHLIGHTS

- Impacts of droughts on river salinity were statistically analysed for southern US.
- Median increase in river salinity of 21% during droughts
- Impacts of salinity dimension on water scarcity levels were quantified for Texas
- Increasing water scarcity during droughts due to a combination of reduced water availability and increased river salinity
- Alleviating water scarcity should not only focus on water quantity aspects, but also on improving water quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrological droughts have a diverse range of effects on water resources. Whilst the impacts of drought on water quantity are well studied, the impacts on water quality have received far less attention. Similarly, quantifications of water scarcity have typically lacked water quality dimensions, whilst sectoral water uses are associated with both water quantity and quality requirements. Here we aim to combine these two elements, focussing on impacts of droughts on river salinity levels and including a salinity dimension in quantifications of water scarcity during drought and extreme drought conditions. The impact of historical droughts on river salinity (electrical conductivity (EC) was studied at 66 monitoring stations located across the Southern USA for 2000–2017. Salinity was found to increase strongly (median increase of 21%) and statistically significantly ($p \leq 0.05$) during drought conditions for 59/66 stations compared to non-drought conditions. In a next step, a salinity dimension was added to water scarcity quantifications for 15 river basins in Texas. Water scarcity was quantified using data of sector water uses, water availability, river salinity levels and salinity thresholds for sector water uses. Results showed that the dominant factor driving water scarcity highly differed per basin. Increases in water scarcity were further compounded by drought-induced decreases in water availability, increases in sectoral water demands and increases in river water salinity. This study demonstrates that droughts are associated with important increases in river salinity, in addition to reduced water availability, and that both of these aspects should be considered when quantifying water scarcity. Alleviating water scarcity should therefore not only focus on increasing water availability and reducing water demands (quantity aspects), but also on improving water quality.

1. Introduction

Increases in the frequency, magnitude and duration of droughts are expected in most regions worldwide due to climate change (Shabalova

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et al., 2003; Whitehead et al., 2009; IPCC, 2012) which may have widespread impacts on both water quantity and quality (eg. Nosrati, 2011). Whilst water quantity aspects have been studied extensively, the impacts of climate change and hydrological extremes upon river water quality are less well researched (Kundzewicz et al., 2008; Delpla et al., 2009; Whitehead et al., 2009; Nosrati, 2011). Few studies have assessed the impacts of drought and the induced low flow conditions on surface water quality (Caruso, 2002; Kundzewicz et al., 2008; Whitehead et al., 2009; Nosrati, 2011), despite the effects on water quality being equally as severe as the associated water quantity aspects (Wright et al., 2014). River water quality degradation predominantly occurs due to a reduced dilution capacity (van Vliet and Zwolsman, 2008; Whitehead et al., 2009), which increases the proportion of streamflow that originates from (polluted) point and groundwater sources (van Vliet and Zwolsman, 2008; Wright et al., 2014). Increased concentrations of several water quality indicators, nutrients (ammonium, dissolved phosphate), salinity (total dissolved solids, electrical conductivity) and major ions (e.g. chloride, sodium, fluoride, and sulphate) have been reported during previous droughts in various river basins and were mainly attributed to reduced dilution (Sprague, 2005; van Vliet and Zwolsman, 2008; Hrdinka et al., 2012; Hellwig et al., 2017).

In particular, salinity is an aspect of water quality that has previously been demonstrated to increase under drought conditions (e.g. van Vliet and Zwolsman, 2008; Hrdinka et al., 2012; Mosley et al., 2012; Mosley, 2015). However, few studies have comprehensively examined the effect of drought on river salinity levels, with the majority analysing a small number of monitoring sites obtained from a single (short) drought period to a single (short) reference period. Increases in salinity levels during drought periods, which are characterised by a reduction in streamflow, have been attributed to lowered dilution capacity (van Vliet and Zwolsman, 2008; Hrdinka et al., 2012) and an increase in the proportion of streamflow originating from (typically) more polluted point sources (Wright et al., 2014). Furthermore, reduced flushing (e.g. Mosley et al., 2012) and the increased penetration of salt wedges (e.g. Mosley et al., 2012) have been proposed. Increases in river salinity are of particular concern for the drinking water and food production sectors, which are associated with stringent salinity requirements (UNEP, 2016), Additionally, elevated river salinity levels can be extremely detrimental towards aquatic ecosystems (Cañedo-Argüelles et al., 2013; Cañedo-Argüelles et al., 2016).

The greater consideration of river salinity, and water quality aspects in general, for sectorial uses (in both non-drought and drought conditions) would help to improve upon concepts that have traditionally neglected an explicit water quality dimension, such as the concept of water scarcity. The term 'water scarcity' has most commonly been assessed as the ratio of water use to the overall water availability ('criticality ratio') (Falkenmark, 1997; Raskin et al., 1997; Alcamo et al., 2003; Vörösmarty et al., 2000; Oki and Kanae, 2006). Other water scarcity indicators have also been developed, such as the IWMI indicator, the water poverty index (Mlote et al., 2002) and the water footprint-based assessment (Hoekstra, 2017) (for a synthesis see Liu et al., 2017). Regardless of the indicator used, several studies have demonstrated that water scarcity is expected to worsen due to climate change, population growth and increasing demands for food and energy (e.g. Seckler, 1998; Rockström et al., 2009). However, with a few exceptions (Liu et al., 2016; van Vliet et al., 2017), these current quantifications of water scarcity are made solely based on water quantity aspects. As water quality aspects also pose important constraints on usability, estimations of water scarcity that include relevant water quality requirements per sector are more appropriate (van Vliet et al., 2017). Therefore, 'water scarcity' is defined in this paper as "the condition wherein demand for water by all sectors, including the environment, cannot be satisfied fully due to the impact of water use on supply or quality of water" (Liu et al., 2017).

Hence, the objectives of this study are as follows: (1) to investigate the influence of hydro-meteorological drought on salinity levels in Southern US rivers; and (2) to assess the impact of drought-induced changes in river salinity levels on water scarcity, including both water quantity and water quality impacts. With 66 monitoring stations examined over a 17-year time period in the Southern US, this study investigates the relationship between drought and river salinity at a large spatial scale whilst also accounting for multiple drought events. In addition, this study represents a first attempt to quantify water scarcity including a salinity dimension, and to investigate the effect of drought conditions on salinity-driven water scarcity.

Four main steps were taken to address these objectives. Firstly, the relationship between two drought indicators and river salinity are statistically analysed and river salinity levels measured in identified drought periods are statistically compared to salinity levels measured during non-drought periods (Sections 2.4 and 3.1). In a next step, drought-induced changes in river salinity are explicitly included in quantifications of water scarcity, allowing for comparison of salinity-driven scarcity under 'average, 'drought' and 'exceptional drought' conditions (Sections 2.5 and 3.2). Lastly, the main uncertainties and implications of the presented results for water management are discussed (Section 4).

2. Methodology

2.1. Study regions

To analyse the impact of drought on river water salinity levels, we focused our analysis on the 'Southern US States' (Fig. 1a), defined as contiguous states within Federal Emergency Regions IV, VI and IX (Supplementary Fig. S1). The southern US states were chosen as they are highly vulnerable to hydro-meteorological droughts, with many of the worst recent droughts being located in the Southern US (e.g. 2010–2013 Southern Drought, 2012–2016 Californian Drought). Furthermore, droughts are expected to increase in frequency, intensity and duration in Southern US states as a result of climate change (Dai, 2013). Lastly, there is a high reliance on surface water withdrawals for meeting sectoral water demands, especially for the public sector in the southern US, making this region particularly vulnerable to changes in surface water quality (salinity) and hence surface water scarcity.

Of the Southern US states, Texas was selected as a focus region for analysing the impact of drought-induced changes in river water salinity levels on water scarcity (Fig. 1b). Texas faces particularly prevalent water management issues, whereby large demands are coupled with already stretched supplies (TWDB, 2017). These issues will be exacerbated further by climate change and population growth, whereby water demands are expected to rise by 87% in the next 50 years (TWDB, 2017).

2.2. Monitoring data

The study period for the analysis of the effect of drought on river water salinity was from 1 January 2000 to 1 October 2017. Electrical conductivity (EC) was selected as the salinity parameter due to the widespread availability of this data. EC data (specific conductance in $\mu S\ cm^{-1}$ at 25 °C) was downloaded from the USGS National Water Information System (NWIS) website (https://waterdata.usgs.gov/nwis/qw). The following data requirements were set. For investigating the effect of drought on river water salinity, the USGS water quality monitoring site had to have at least 3650 (daily) measurements of EC within the study period. This represents a minimum time period of 10 years of data in order to allow for identification of monitoring sites with sufficiently long time series to observe changes in river EC levels with drought. In total, 66 sites were selected as having sufficient data availability for this study, with a mean average of 8446 measurements per site (Fig. 1a). Hence, daily mean EC was downloaded at each site for the study period. Daily mean discharge data, where available, was also