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Research papers

Drivers and trends of streamflow droughts in natural and human-impacted basins across the contiguous United States

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Highlights

- Human activities mostly affect drought trend magnitude but not direction.
- Regulation alleviates drought in California but worsens it in Colorado River Basin.
- Deficit is driven by precipitation- evapotranspiration timing and runoff ratios.
- Duration is influenced by vapor pressure deficit, temperature, and elevation.

Abstract

Climate change and human water demands are altering streamflow droughts. Most research focuses on natural basins due to challenges in distinguishing between climate and human effects. Moreover, the lack of consensus on how to separate these effects sometimes leads to conflicting results. To investigate the impacts of human activities on streamflow droughts, we conducted spatial and temporal analyses to assess differences in drought duration and deficit between natural and human-impacted watersheds across the contiguous United States. For the spatial analysis, we used random forest models adapted for spatial correlation to identify the drivers of streamflow drought duration and deficit from 42 climatic and landscape factors, including human activities. Our findings reveal that regional climate patterns account for most of the spatial variability in both natural and human-impacted basins. However, drought deficit and duration are driven by different factors, with spatial variations in deficit being more explainable (R^2=0.95) than those in duration (R^2=0.82). Deficit is primarily driven by precipitation-evapotranspiration synchronization and runoff ratios, while duration is influenced by vapor pressure deficits and elevation. The temporal analysis reveals that regulated watersheds experienced the greatest decreases and increases in drought duration and deficit over the last four decades, while natural watersheds showed the least change. Comparison of nearby basins demonstrates regional variation in human impacts: drought conditions were ameliorated in California but intensified in the southwest, including the Colorado River and Rio Grande basins. These findings can help water managers to understand streamflow drought changes and anticipate future trends based on shifts in climatic conditions and water needs.

Introduction

Severe streamflow drought is the costliest natural disaster and the second most deadly affecting the United States (U.S.) (Smith & Matthews, 2015). Between 1980 and 2025, the U.S. has experienced 32 droughts with associated costs exceeding $1 billion, resulting in a total financial toll of $367.5 billion (Smith, 2020). The costliest drought occurred in 2012–2013, with associated losses reaching $30 billion (Smith, 2020). In 2023, the Southern and Midwestern Drought and Heat Wave became the costliest event of that year, with damages amounting to $14.5 billion (Smith, 2020). Moreover, numerous studies project that by the end of the 21st century, several regions—including the Southwest (Balting et al., 2021, Zhuang et al., 2024), Central Plains (Cook et al., 2015, Gautam et al., 2023) and Northwest and Midwest (Gamelin et al., 2022)—are likely to experience higher temperatures and drier conditions, exacerbating threats to water security, economy, and ecosystem health.

Under natural conditions, precipitation deficits and abnormal temperatures are the primary factors driving streamflow droughts (Van Loon, 2015). This climatic signal is then modulated by watershed properties as it propagates into streamflow. In recent decades, growing freshwater demands for agriculture and urbanization have led to the construction of reservoirs and groundwater abstraction systems, along with land-use changes, altering watersheds' natural responses. These activities

influence droughts in complex ways, both mitigating and intensifying them through changes in flow timing and volume, modifications to land–atmosphere feedback, and impacts on groundwater recharge (Margariti et al., 2019, Pérez et al., 2024, Van Loon et al., 2016). Human-induced changes to drought have been observed in several regions of the contiguous U.S. (CONUS). In the Great Plains, agricultural land degradation has intensified drought conditions through increased wind erosion and higher atmospheric dust levels (Cook et al., 2008, Cook et al., 2009, Hu et al., 2018). Farming removes protective ground cover, making the soil more prone to erosion and dust formation, reducing soil moisture levels, decreasing evaporation, and lowering precipitation (Kandakji et al., 2021). In California, water extractions for irrigation have prolonged drought duration and increased deficits by diminishing water availability (He et al., 2017).

Untangling the interactions among climate, watershed properties, and human activities presents challenges. While climate patterns operate on global to regional scales, human influence is often more localized and difficult to isolate (Tijdeman et al., 2018). The impacts of human activities are variable in magnitude, timing, and intensity, influenced by factors such as the location of the water abstraction, the volume and use of the water extracted, and the climate (Apurv et al., 2017). Among these activities, land-use changes pose particularly complex analytical challenges. Many hydrological models rely on broad land-use classifications and crude parameter values to represent them. However, such changes are quite complex; they disrupt hydrological functional landscapes, alter soil properties, and influence meteorological forcings (Auerswald et al., 2024, Mahmood et al., 2014). Moreover, both climatic and human influences are dynamic, evolving over time in response to temperature trends, shifts in precipitation, and evolving human water needs (Singh & Basu, 2022). Due to these complexities, most studies have focused on natural basins, where human action is minimal, to better distinguish the effects of climate and watershed properties from those driven by water management practices and land-use changes (Konapala and Mishra, 2020, Peña-Gallardo et al., 2019).

Research on how human activities may influence streamflow droughts has largely been limited to case studies, with a few exceptions of larger regional or national-scale studies using observational data or integrated modelling. These exceptions typically focus on specific human activities, such as regulation (Brunner, 2021, Simeone et al., 2024a) or agricultural practices (Adelsperger et al., 2024), and have sometimes yielded conflicting results. For instance, in large-case studies, reservoirs have been found to decrease the number of catchments experiencing simultaneous drought (Brunner, 2021), while other studies have found the opposite effect (Wan et al., 2017). Additionally, previous work has identified similar drought propagation patterns from precipitation to streamflow in both natural and human-impacted basins, indicating a comparable response to the climate signal (Tijdeman et al., 2018). However, this similarity does not necessarily imply that streamflow droughts are unaffected by human-induced changes. Despite the important results of these previous studies, it remains unclear how various human activities have impacted droughts on a large scale and whether these impacts are uniform. For these reasons, this study aims to uncover how streamflow droughts differ spatially and temporally between natural and human-impacted

basins across various regions of the CONUS. Using observational data, we show how human activities, including agriculture, reservoir regulation, and urbanization, have influenced streamflow droughts over recent decades. Specifically, this study addresses the following questions.

(1) What are the factors driving spatial variability in streamflow droughts, and how do they differ between natural and human-impacted basins?

(2) How do streamflow drought trends vary, and what distinctions exist between these trends in natural versus human-impacted basins?

To answer these questions, we classified watersheds according to the primary human interventions, such as urbanization, agriculture, or regulation. We then calculated streamflow drought duration and deficit from 1980 to 2020. Subsequently, we developed random forest (RF) models that account for spatial correlation using a range of climatic, landscape, and anthropogenic factors to identify drivers of streamflow drought. Finally, we computed temporal trends and assessed differences between natural and human-impacted basins by comparing nearby basins experiencing similar climatological conditions. Additionally, we investigated the relationships between observed drought trends and trends in climate variables.

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Section snippets

Methods

We conducted a spatial and temporal analysis to compare streamflow drought characteristics between natural and human-impacted basins over recent decades. Fig. 1 illustrates the methodological steps for this comparison, which are detailed in the subsequent subsections. …

Drivers of spatial variability in streamflow droughts

Drought patterns exhibit distinct regional variations. The Southwest and Southern Great Plains experience the longest droughts, lasting an average of 100 days annually (Fig. 3a). The Southeast and Northwest face moderate droughts of approximately 86 days per year, while the Northeast, Northern Great Plains, and Midwest experience shorter droughts, averaging 74 days annually (Fig. 3a). The longest droughts, surpassing 160 days, occur in the Great Plains, specifically in the red region where the …

Drivers of spatial variability in streamflow droughts

Drought patterns of duration and deficit exhibit distinct regional variations (Fig. 3). Southern regions, particularly the Colorado Plateau in the Southwest and some areas of the Great Plains, experience the longest droughts (Fig. 3a). In contrast, northern regions, especially the mountainous areas of the Coast Ranges and Cascade Range in the Northwest, experience the largest water deficits (Fig. 3b). Our RF-GLS models effectively captured these spatial patterns, though they were more …

Conclusions

We conducted a continental-scale study of droughts in the U.S., examining how interactions between streamflow, climate, watershed characteristics, and human activities influence drought properties, using observational data to analyze these relationships. Specifically, we examined the role of human activities in modifying droughts and how their impacts vary across regions. Below, we present the key findings that address our two research questions:

1. Drought patterns show distinct regional …

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CRediT authorship contribution statement

Sara Alonso Vicario: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **George M. Hornberger:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Maurizio Mazzoleni:** Writing – review & editing, Supervision, Conceptualization. **Margaret Garcia:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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