Journal of Hydrology 596 (2021) 125707

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: A review and analysis

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ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief

Keywords:
Drought
Flood
Wildfire
Water quality
Microbial communities

ABSTRACT

The increase in dynamic interactions between climate and human activities threatens water security in terms of water quantity and quality. Most water security studies have focused on water quantity compared to water quality, while both are equally important and vital for maintaining a healthy ecosystem and human well-being. The first part of the paper provides a review of the potential impacts of climate-related extreme events (i.e., drought, flood, and wildfires) on different water quality indicators and the potential impact of cascading extreme events (e.g., drought-flood regimes) on dynamics of water quality behavior. In the second part of the paper, we demonstrate the cascading impact of severe drought and an extreme historical flood event (October 1–4, 2015) in South Carolina (USA) on water quality variables. The effect of drought on water quality in contrasting land-use settings is investigated. Finally, water quality data was collected over a period of time in three types of land-use settings to study the dynamics of multiple flood and drought events on microbial communities. Flooding conditions result in high levels of bacteria associated with fecal contamination, especially in the stream setting, where large differences between drought and flooding occur in the microbial communities. The results highlight the significant impact of cascading events on water quality and microbial communities. The effect of drought on water quality indicators in different land-use settings can be different, highlighting the dominant role of watershed characteristics. Overall, it is essential to develop quantitative frameworks in the context of sustainability science to quantify the interaction between climate, watershed, and anthropogenic variables that control stream water quality. This study highlights the importance of understanding the relationships between extreme events and water quality indicators as an important step to improve ecosystem health and sustainability. Finally, some remarks are made on the knowledge gaps which need to be addressed in future studies.

1. Introduction

Climate, water, and human activities are tightly connected. Due to large scale variability in their coupling behavior, water security in terms of quantity and quality is a significant issue worldwide (Mishra and Singh, 2010; Veettil and Mishra, 2020). Although water quantity related problems get more attention, water quality is equally important and vital for maintaining a healthy ecosystem and human well-being. The projected climate change will further alter the precipitation and evaporation at a global scale (Konapala et al., 2020) that likely will increase climate extremes (e.g., floods and droughts) and result in higher streamflow dynamics that control the flow of nutrients and various water quality indicators. The surface water quality is controlled by multiple variables, including climatic, hydrological, and anthropogenic variables (Badruzzaman et al., 2012; Lintern et al., 2018; Abdul-Aziz and Ahmed, 2019). These variables can affect water quality at various temporal and spatial scales (Mosley, 2015; Lintern et al., 2018; Shoda et al., 2019).

Recent evidence indicates an increase in extreme precipitation events (Prein et al., 2017; Vu and Mishra, 2020), flooding, and droughts of greater intensity and duration (IPCC, 2014; Konapala et al., 2020), and these extremes impact water quality. Climate change is expected to bring more floods and droughts in the regions that are already witnessing these extremes on a global scale (Konapala et al., 2020). The frequency and intensity of extreme weather events are expected to increase in the future (IPCC, 2014). These extreme events can vary from wet (e.g., flood, extreme rainfall) to extreme dry (e.g., drought) events, which likely to impact water quantity, quality as well as the soil

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https://doi.org/10.1016/j.jhydrol.2020.125707

Available online 29 October 2020

physicochemical properties (Murdoch et al., 2000; Worrall et al., 2009; Senhorst and Zwolsman, 2005; Kundzewicz et al., 2008).

Drought, flood, and wildfires occur in a different part of the world, and they are more prominent in certain geographical regions (Fig. 1). According to the Colorado Flood Observatory data set, several locations worldwide have experienced flood inundation events with a duration of more than 30 days between 1985 to January 2015 (Fig. 1a). The extreme droughts are more common in semiarid locations, such as Northern and Southwestern Africa, Central Asia, Australia, western U.S., and the Iberian Peninsula (Fig. 1b). These Drought events may increase the likelihood of wildfires (Westerling and Swetnam, 2003; Murphy et al., 2015, 2020), flash floods (Whitehead et al., 2009), and dust storms (Hahnenberger and Nicoll, 2014; Reheis and Urban, 2011). Much of the western US has experienced severe droughts accompanied by an

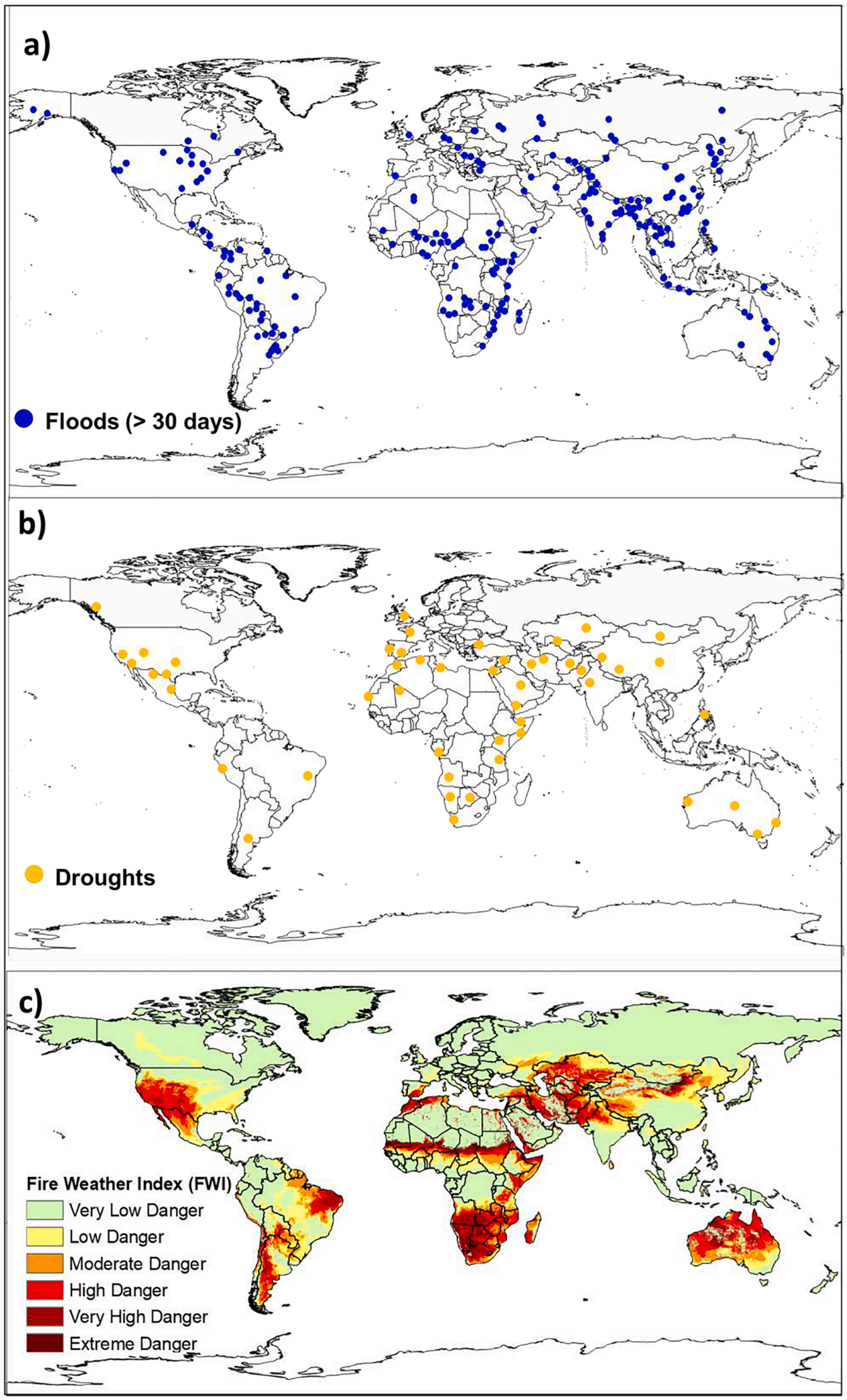

Fig. 1. a) Global map showing prominent geographical regions for the occurrence of extreme events: (a) Floods, (b) drought, and (c) Fire Weather Index (FWI) [Note: Flood information was collected from the Colorado Flood observatory from 1985 to 2015, drought hazard locations were adapted from Carrão et al. (2016), and FWI was obtained from the Global wildfire information system (GWIS)]

increase in massive wildfires (Rust et al., 2018; Murphy et al., 2020). The fire weather index, a key indicator of extreme fire behavior potential, is shown in Fig. 1c. The fire hazards are more common in the western USA, Australia, the southern and central parts of Africa, the southern-northeastern part of South America, and central Asia. It is essential to highlight that many regions dominated by fire hazards also witnessing more numerous drought and flood events (Fig. 1), which can result in cascading (compound) events. Therefore, understanding the extreme weather and climate events and their cascading effects, particularly on stream water quality, is essential to eliminate any potential impact on human health, reduce water treatment costs, and develop mitigation strategies in response to future extreme events.

The above discussion highlights the potential impact of climate and anthropogenic variables on water quality. However, it is difficult to pinpoint the role of climate due to a delicate and complex interplay of anthropogenic variables (e.g., variety of land use) across local to regional scale (Michalak, 2016). This challenge is compounded by the limited understanding of the potential impact of individual and cascading effects of climate extremes on water quality. The role of cascading events (e.g., drought-flood regimes) on water quality is often neglected. In this regard, the overall objective of this study are: (a) to provide a review on the potential impact of climate-related extreme events (i.e., drought, flood, and wildfires) as well as cascading events on different water quality indicators, (b) to investigate the potential impact of droughts on water quality indicators in different land use settings, (c) to demonstrate the potential impact of a severe drought and extreme flood cascading event on water quality, and (d) the potential impact of drought and flood regimes on microbial communities in different land use settings.

2. Review of the impact of land use and extreme events on stream water quality

2.1. Impact of land uses on water quality

The widespread change in land use patterns can have a significant impact on water quality and ecological integrity around the globe. Specifically, urbanization, agriculture, deforestation, and pasture conversion all pose a threat to biodiversity and lotic ecosystems (Miserendino et al., 2011). Numerous studies have shown that the high nutrient loads from agricultural and urban areas have dramatically reduced the water quality in rivers and streams (Foote et al., 2015). These studies highlighted the positive correlations between the anthropogenic variables such as grazing, agriculture, and urbanization with the concentration of total suspended sediments (TSS), nutrients (e.g., nitrogen and phosphorus), and dissolved oxygen in a watershed (Allan, 2004; Giri and Qiu, 2016; Lintern et al., 2018; Suarez and Puertas, 2005). More specifically, the TSS and nutrients concentrations were higher in urban watersheds than forest watersheds (Whitehead et al., 2009; Tu, 2011; Giri et al., 2018). There is also a clear positive correlation between the removal of vegetation in a watershed and water quality degradation (Meybeck and Helmer, 1989).

A smaller number of studies have acknowledged the role of other watershed characteristics and climatic variables on stream water quality (e.g., Tramblay et al., 2010; Young et al., 2005; Lintern et al., 2018; Alnahit et al., 2020). All these variables can potentially impact stream water quality as they can affect the source, mobilization process, and the delivery of constituents into the receiving streams (Granger et al., 2010). For example, steep watersheds were observed to impact water quality since steep slope facilitates the mobilization of pollutants into streams, leading to water quality degradation (Kang et al., 2010; Wan et al., 2014; Alnahit et al., 2020). Similarly, geological features and soil type in a watershed may also affect water quality (Biggs and Gerbeaux, 1993; Varanka et al., 2015; Lintern et al., 2018; Alnahit et al., 2020). For example, watersheds dominated by parent rock (e.g., Igneous rocks) showed low export of dissolved ions. In contrast, watersheds dominated by soft sedimentary rock (e.g., limestone) showed higher transfer of dissolved ions (Young et al., 2005). Moreover, higher Phosphorus concentrations in streams were reported in a watershed with high sediment deposition (Kirchner and Dillon, 1975). There are also strong links between geology and stream water temperature, in which groundwater interaction with streamflow may impact water temperature (Poole and Berman, 2001). In addition, groundwater levels may also alter stream water quality (Menció and Mas-Pla, 2008; Sprague, 2005). For example, groundwater was observed to control the concentration of dissolved nutrients and calcium bicarbonate in streams within the South Platte River Basin, Colorado, USA (Sprague, 2005).

2.2. Impact of drought on water quality

Hydrologic drought is defined as a period with inadequate surface and subsurface water availability (Mishra and Singh, 2010). Periods of drought may lead to significant consequences for water quality and quantity (Gámez et al., 2019; Jones and van Vliet, 2018; Li et al., 2017; Lehman et al., 2017; Djebou, 2017a, 2017b), waste load allocation (Golladay and Battle, 2002; Hernandez and Uddameri, 2014; Momblanch et al., 2015), aquatic ecosystems (Van Dijk et al., 2013; Gibson et al., 2020), and quality (quantity) of water for irrigation (Mosley, 2015). The impact of drought on the surface and groundwater resources may result in low flows and water availability, leading to deteriorated water quality (Mishra and Singh, 2010; Hrdinka et al., 2012; Mosley, 2015; Momblanch et al., 2015). For example, drought-induced low flow regimes increase the water detention period and contribute to an increase in algal blooms due to high nutrient concentrations (less dilution) (Van Vliet and Zwolsman, 2008; Mosley, 2015; Palmer and Montagna, 2015). Additionally, the drought–waterlogging cycles may affect the water quality by enhancing the decomposition of organic matter and sediments and flushing them into receiving streams (Hrdinka et al., 2012; Gámez et al., 2019; Jones and van Vliet, 2018). The higher temperatures during extreme droughts may also influence the stream respiration and reaeration rates in rivers and streams (Mosley, 2015). Table 1 summarizes the potential impact of drought on multiple water quality indicators across different parts of the world. In the following sections, we present an overview of droughts' possible effect on various water quality indicators in rivers and streams.

2.2.1. Algae and Turbidity

The combination of low flow and high temperature during drought events increase algal blooms and chlorophyll-a concentrations in streams (Table 1). For example, massive algae blooms during drought periods were documented in Darling–Barwon River (Australia), lower Nakdong River (South Korea), the River Murray (Australia) (Donnelly et al., 1997; Ha et al., 1999; Bowling et al., 2013). Many studies have reported high algal values during droughts in streams and rivers (Van Vliet and Zwolsman, 2008; Gilbert et al., 2012; García-Prieto et al., 2012; de Barroso et al., 2018). The observed algae values were mainly attributed to low flows, water column stratification and clarification, and sometimes high temperatures (Mosley, 2015). Conflicting opinions are observed related to the behavior of Turbidity during the drought period. Many studies observed low Turbidity values during droughts across many rivers and streams, which can be attributed to the lack of watershed runoff (Caruso, 2002a, 2002b; Mosley et al., 2012; Van Vliet and Zwolsman, 2008). However, the presence of point source pollutions that produce high suspended particles may increase Turbidity due to lack of dilation and low flows (Caruso, 2002a, 2002b).

2.2.2. Nutrients and salinity

The impact of drought on nutrient concentrations in streams depends mainly on the land-use settings in a watershed (e.g., agriculture, urban, forest) as well as types of point source pollution. For example, lower Nitrogen and Phosphorus concentrations were observed during droughts in many rivers and streams (e.g., (Morecroft et al., 2000; Caruso, 2002a,

Table 1
The potential impact of drought on different water quality indicators in different parts of the world.

Author and Year of Publication	Study Area	Water Quality Indicators	Findings
Gámez et al., 2019	Two reservoirs in Central Texas, USA	Algal Bloom	An increase in both organic and inorganic Nitrogen amplify toxic algal blooms were observed
Jones and van Vliet, 2018	Rivers in Southern USA	Salinity	An increase in river salinity (21%) was observed during drought conditions.
Azevedo et al., 2018	Southeastern Brazil	The concentration of Mercury and its related compounds	An increase in bioaccumulation of Mercury and methyl mercury in fishes were observed during droughts
de Barroso et al., 2018	Castanhao river, Brazil	Algal bloom, Phosphorous, and Nitrogen	An increase in inorganic Phosphorous and Nitrogen along with algal bloom was observed drought conditions
Peña-Guerrero et al., 2020	Chile	Electrical conductivity and major ions	An increase in electrical conductivity and major ions were observed during drought conditions
Li et al., 2018	Alexandria Lake, Australia	Dissolved organic carbon, electrical conductivity, and sulphate concentration	An increase in dissolved organic carbon, electrical conductivity, and sulphate concentration during drought conditions
Li et al., 2017	Alexandria and Albert Lakes, Australia	Salinity and pH	An increase in salinity and acidification was observed during droughts.
Metre et al., 2016	Midwest USA	Nitrate Concentration	The increased in nitrate accumulation during drought may later lead to nitrate leaching
Shehane et al., 2005	St. John's river, Florida	Bacterial Content	An increase in the fecal coliform was observed due to drought conditions
Mosley, 2015	North America, Europe, Australia	Salinity, Stratification, Algal nature, and Dissolved Oxygen	During low flow, increase in salinity, stratification, algal bloom, and lowered dissolved oxygen (leading to deoxygenation)
Burt et al., 2015	Moorland Catchment, UK	Discharge-concentration relationship	An increase in Solute concentration along with the specific conductance of the streams was observed during drought, although the interaction characteristics have been observed to follow the hysteresis loop when streamflow is increased
Wright et al., 2014	Southeastern Australia	Taste, Odour, Bacterial content	Increased nutrient cycle during drought may cause algal bloom, which affects taste, odor along with an increase in bacterial contents
Lehman et al., 2017	San Francisco, California	Algal bloom/ toxicity	An increase in toxic algal bloom, including microcystic blooms was observed during droughts.
Mast, 2013	USGS watersheds, USA	Sulphate concentration	An increase in sulphate concentration was observed due to the increased pyrite oxidation
Bowling et al., 2013	Murray River, Australia	Bacterial content	An increase in cyanobacterial content was observed during low flow conditions
Baurès et al., 2013	France	Total Organic Carbon	An increase in Total organic carbon in streams was observed during prevalent drought condition
Mosley et al., 2012	Murray River, Australia	Total suspended solids and nutrient characteristics	An increase in Turbidity, salinity, nutrient content was observed during low flow condition
Hrdinka et al., 2012	Czech Republic	Dissolved Oxygen	The increase in Dissolved Oxygen in shallow lakes during drought condition is possibly due to increased aeration
García-Prieto et al., 2012	River Thomas, Iberian Peninsula	Algal bloom	During drought, increased algal bloom leads to a higher amount of bacterial contamination
Benotti et al., 2010	Lake Mead, Southern Nevada	Total dissolved solids and Nitrate	An increase in the water conductivity and nitrate content during low volumes of Lake Mead
Ylla et al., 2010	Mediterranean region	Dissolved Oxygen	The decrease in dissolved oxygen due to increased water temperature during drought conditions
Zieliński et al., 2009	Rivers in Poland	pH	A decrease in pH is observed in streams during drought condition
Van Vliet and Zwolsman, 2008	Meuse River, Europe	Dissolved solids and Sediments	A decrease in dissolved solids and Turbidity is observed during low flow condition
Caruso, 2002a, 2002b	Otago, New Zealand	Bacterial content	Widespread bacterial contamination is observed in streams during drought condition due to sustained livestock use and decreased dilution

2002b; Golladay and Battle, 2002; Oelsner et al., 2007; Hrdinka et al., 2012; Mosley et al., 2012; de Barroso et al., 2018). This may be due to the lack of watershed runoff and increased denitrification due to a longer water residence time (Andersen et al., 2004; Baurès et al., 2013; Mosley, 2015). On the other hand, the point source pollution facilities located in highly urbanized watersheds may result in increases in Nitrogen and Phosphorus concentrations in the streams (Andersen et al., 2004; Sprague, 2005; Van Vliet and Zwolsman, 2008; Macintosh et al., 2011; Hrdinka et al., 2012). This is especially true when the flow from these facilities remains relatively constant during droughts. A few other studies have also reported higher nitrate concentrations in agricultural watersheds during low flows (Baurès et al., 2013; Mosley, 2015). The higher nitrate concentrations may be due to the influence of sediment and Nitrogen fluxes during the drought (Mosley, 2015).

High salinities were positively correlated with increasing drought in most streams/rivers (Jones and van Vliet, 2018; Li et al., 2017; Mosley, 2015). This can be due to sustained evaporation of surface water and less dilution of more saline groundwater inputs (Caruso, 2002a, 2002b; Van Vliet and Zwolsman, 2008; Mosley et al., 2012; Mosley, 2015). Additionally, the increase in pyrite oxidation during droughts may increase the sulfate concentration in the stream (Mast, 2013). However, when the contribution of groundwater and saline point source facilities are small compared to the surface runoff, salinity did not increase during droughts (Wilbers et al., 2009).

2.2.3. Dissolved oxygen and pH

Drought has different levels of impact on dissolved oxygen concentrations (Table 1). In shallow streams, insignificant changes in dissolved oxygen during droughts were observed (Hudson et al., 1978; Caruso, 2002a, 2002b; Hrdinka et al., 2012). On the other hand, studies have reported an increase in the dissolved oxygen values during daytime in droughts (Ha et al., 1999; Sprague, 2005; Van Vliet and Zwolsman, 2008). This may be related to the enhanced primary production during the day. However, in watersheds with point source pollution facilities, a decrease in dissolved oxygen was observed (Anderson and Faust, 1972; Chessman and Robinson, 1987). This may be attributed to the fact that increases in nutrients lead to algal blooms. When the algae die or run out of nutrients, the bacteria start decomposing the organic matter (dead algae), and that leads to decreased oxygen concentrations to anoxic conditions if there is enough organic matter to degrade (Mosley, 2015; Ylla et al., 2010).

A statistically significant decrease in pH during drought was observed in many studies (e.g., Zieliński et al., 2009; Mosley et al., 2012). However, an increase in pH and alkalinity was observed due to less dilution of bicarbonate that dominated in groundwater (Sprague, 2005; Li et al., 2017). Furthermore, increased fecal coliform levels in some streams were observed during drought conditions (Table 1). This may be related to the lack of dilution and flushing processes (Caruso, 2002a, 2002b).

2.3. Impact of wildfire on water quality

Water from forest watersheds is widely used for water supply due to its high quality and lower treatment costs (Mast and Clow, 2008; Miller et al., 2013b; Murphy et al., 2015, 2020; Rust et al., 2018). However, forest wildfires can significantly alter watershed hydrology, stream water quality, and stream ecosystems (Mast and Clow, 2008; Shakesby and Doerr, 2006; Costa et al., 2014; Reale et al., 2015; Emelko et al., 2016; Rust et al., 2018). Due to changes in the climate, forest conditions, and land-use patterns, the frequency and severity of wildfires have increased significantly (Andela et al., 2017; Dennison et al., 2014; Westerling, 2016; Radeloff et al., 2018). Wildfires can increase the total suspended solids (Mast and Clow, 2008; Silins et al., 2009; Smith et al., 2011; Emmerton et al., 2020), nutrients (Burke et al., 2005; Mast and Clow, 2008; Writer et al., 2012; Son et al., 2015), and metal transferred to rivers and streams (Burton et al., 2016; Costa et al., 2014; Emmerton et al., 2020).

The loss of forest cover due to wildfires can lower evapotranspiration, interception, and soil degradation (Neary, 2011; Ebel and Moody, 2017). Wildfires can contribute to high ash and carbon particulates in watersheds due to combustion (Burton et al., 2016). As a result of these changes, a more significant proportion of rainfall with high ash and carbon particulates can be mobilized by overland runoff into streams leading to higher water quality degradation (Moody et al., 2013; Writer et al., 2012; Murphy et al., 2012; Writer and Murphy, 2012; Son et al., 2015). Besides, the changes in the flow paths along with the soil and organic matters can lead to impaired stream water quality and high costs for water treatment (Mataix-Solera et al., 2011; Emelko et al., 2011; Hallema et al., 2019, 2018; Martin and Hillen, 2016; Murphy et al., 2018; Robinne et al., 2018; Rust et al., 2018; Smith et al., 2011). In this section, we present post-wildfire effects on water quality indicators in rivers and streams. The potential impacts of wildfire on the water quality in different parts of the world are provided in Table 2.

Higher levels of Nitrogen, Phosphorus, dissolved organic carbon (DOC), and manganese (Mn), and Turbidity was reported in rivers and streams post-wildfire events (Table 2). For example, Emelko et al. (2011) observed higher Turbidity, dissolved organic carbon (DOC), and dissolved organic nitrogen (DON) in streams from burned watersheds based on four years of monitoring. Additionally, higher metal concentrations were reported either dissolved in water or attached to ash/suspended sediments (Burke et al., 2013; Burton et al., 2016; Gallaher et al., 2002; Rust et al., 2018, 2019; Smith et al., 2011). This high level of nutrients (e.g., organic carbon, Phosphorous, Nitrogen), metal concentrations, and dissolved organic matter in stream water may lead to excessive growth of algae and increased Turbidity (Bladon et al., 2014a, 2014b; Smith et al., 2011; Tsai et al., 2019; Rust et al., 2018). For example, Spencer et al. (2003) observed massive algae blooms post-wildfire.

The concentration of the suspended sediment in the streams post-wildfire is influenced by several factors such as rainfall patterns, watershed burn extent and severity, erosion processes, sediment sources, and scale effects (Smith et al., 2011). Overall, several studies highlighted that wildfires increase the concentration of suspended solids in the streams, especially in the years following the wildfire (Smith et al., 2011; Emelko et al., 2016; Rust et al., 2018; Emmerton et al., 2020). However, the suspended solids may decrease after a year of the wildfire as vegetation cover is re-established and fire impacts on soil and hillslope hydrological properties decline to the pre-wildfire levels (Smith et al., 2011; Reneau et al., 2007).

2.4. Impact of extreme rainfall and flooding on water quality

Extreme rainfall increases soil erosion, chemical leaching, urban waste, and nutrient discharge from watersheds into streams and coastal aquifers (Mishra and Singh, 2010). Heavy rainfall and subsequent stormwater runoff can mobilize pathogens and other microorganisms directly to streams, which increases bacterial concentrations that, in turn, spread waterborne disease (Curriero et al., 2001; Schuster et al., 2005; Patz et al., 2008). The Intergovernmental Panel on Climate Change (IPCC) highlighted a 90% chance of increased frequency of extreme rainfall events in the 21st century and a potential increase in the higher-latitude runoff by as much as 10–40% (Meehl et al., 2007). The interaction between climate, streamflow, and water quality are investigated during the last decade (Oh and Sankarasubramanian, 2012), as well as the impacts of extreme flooding events on water quality (Ascott et al., 2016; Paerl et al., 2019; Zoppini et al., 2019; Hutchins et al., 2020). In this section, we discuss the potential impact of extreme flooding on water quality indicators in rivers and streams. A summary of the potential impact of flooding on water quality worldwide is provided in Table 3.

The harmful algal blooms in lakes (e.g., Lake Erie, USA) can be attributed to a series of intense rainstorms that led to record springtime discharge from rivers with a record amount of nutrients (Michalak, 2016). On the other hand, due to the extreme rainfall, the high volume of water may dilute pollutants, and flooding may increase sediment loads in streams and rivers (Hrdinka et al., 2012). Besides changes in precipitation patterns, the time of occurrence along with the high frequency and intensity of extreme precipitation events can significantly impact the physical and chemical characteristics of the water body (Brunetti et al., 2001; Bates et al., 2008).

As higher flows and velocity occur during a heavy rainfall event,

Table 2
The potential impact of wildfires on different water quality indicators in different parts of the world.

Authors & year of publication	Study area	Water quality parameters	Findings
Spencer et al., 2003	Glacier National Park, USA	Nutrients (e.g., Phosphorus, Nitrogen)	An increase in nutrient concentrations post-wildfire was observed
Townsend and Douglas, 2004	Kakadu National Park, Australia	Total suspended solids Phosphorous Nitrogen Manganese	No significant impact of wildfire on the volume of streamflow, mean concentrations, and the total mass transported into the stream.
Mast and Clow, 2008	Coal Creek and McDonald Creek, MT USA	Major constituents (e.g., Total phosphorus, Total Nitrogen, pH) Nutrients Suspended sediments.	An increase in nitrate concentrations suspended sediment concentrations post-wildfire. An increase in sulfate and chloride concentrations for two years post-wildfire A minor long-term effect on nutrients, dissolved organic carbon, and significant constituents except
Emelko et al., 2011	Lost Creek Wildfire, Canada	Turbidity dissolved organic carbon (DOC), and dissolved organic nitrogen (DON)	An increase in water quality concentrations was observed based on the four-year monitoring study.
Writer et al., 2012; Murphy et al., 2012; Writer and Murphy, 2012	Colorado Front Range, USA	Total suspended solids Dissolved organic carbon Nitrate	An increase in water quality concentrations in response to convective storms ten months post-wildfire
Miller et al., 2013b	Southeast of Lake Tahoe, NV USA	Ammonium Nitrogen (N) Phosphorus (P)	An increase in concentrations and loads of mineral N and P post-wildfire A wildfire followed by a high-runoff year had more impacts on Turbidity than a wildfire followed by low flows.
Costa et al., 2014	Marão River watershed, Portugal	Electrical conductivity Alkalinity, Ca, Ma, Zn, Mg, and Mn	An increase in the Mg and Mn in the stream post-wildfire
Reale et al., 2015	Jemez Mountains, NM USA	Specific conductance Turbidity Dissolved oxygen	The geochemistry of surface water was affected. A significant increase in Turbidity, Specific conductance post-wildfire
Son et al., 2015	Cache la Poudre River watershed, CO, USA	Major constituents (e.g., Total phosphorus, Total Nitrogen)	A significant increase in total Nitrogen and total phosphorus concentrations was observed as a response to convective storms ten months post-wildfire.
Emelko et al., 2016	Castle and Crowsnest River watersheds, Alberta, Canada	Total particulate phosphorus (TPP) Particulate phosphorus forms Equilibrium phosphorus concentration (EPC0) Suspended sediment	An increase in the TPP and EPC0 concentrations was observed post-wildfire. Sediments had higher levels of bioavailable particulate phosphorus post-wildfire.
Rust et al., 2018	Across the western, USA	Nitrogen Phosphorus Mn DOC	An increase in nutrient flux, major-ion flux, metal concentrations, and particulate matter within the first five years post-wildfire. Dissolved constituents of ions and metals tended to decrease in concentration within the five years post-wildfire.
Rhoades et al., 2019	Upper South Platte River, CO USA	Nitrogen carbon (C) export	An increase in Nitrate was observed post-wildfire.
Uzun et al., 2020	Northern California Coastal Ranges, CA, USA	Dissolved organic matter (DOM) Dissolved organic Nitrogen (DOM) Ammonium	An increase in Ammonium, DON, changes in DOM composition, post-wildfire generate more aromatic and more mobile DOC
Emmerton et al., 2020	Boreal Plains ecozone, Canada	Suspended sediment Dissolved material Nutrient Metal concentrations	An increase in suspended sediment, nutrients, and metals concentrations post-wildfire was observed.

massive levels of particulate matter can be carried either in dissolved or suspended forms in river and streams (Braga et al., 2017a, 2017b; Joshi et al., 2017; Du et al., 2018). The changes in stream water quality in terms of eutrophication and nutrient transport can be impacted by the changes in the flow level (Frisk et al., 1997; Kallio et al., 1997). Additionally, Alexander et al. (1998) highlighted that nutrient loading to coastal zones likely varies primarily with flow volume.

Extreme flooding can significantly alter stream water quality and stream ecosystems. For example, Peng et al. (2019) reported that flooding of restored wetlands has led to an increase in the Phosphorous levels in streams. However, other studies reported a decrease in Phosphorous content due to the absorption of Iron and Manganese oxides (Marrugo-Negrete et al., 2019; Hafeez et al., 2019). Furthermore, extreme flooding can have different levels of impact on dissolved oxygen concentrations (Table 3). For example, a few studies suggested a positive effect of flooding on dissolved oxygen (Ascott et al., 2016; Zoppini et al., 2019), while others reported a negative impact (e.g., Paerl et al., 2019) or a mixed response (Hutchins et al., 2020). The extreme flooding may result in a more significant impact on water quality compared to droughts (Hrdinka et al., 2012).

2.5. Impacts of climate extremes on microbial communities

Many environmental factors, such as hydrology, temperature, nutrient availability, land use and metal contamination, affect the diversity and structure of microbial communities in lotic ecosystems. Most of the differences in diversity and community structure are found in different compartments within a stream (e.g., benthic vs. surface water), driven by differences in organic matter (e.g., Zeglin, 2015). In most lotic

Table 3
The potential impact of the flood (low flows) on different water quality indicators in different parts of the world.

Author & year of publication	Study area	Water quality parameter	Findings
Hutchins et al., 2020	River Thames, United Kingdom	Dissolved Oxygen	Dissolved oxygen indicative of the summer low values, decreased. Some events also showed the opposite behavior.
Ascott et al., 2016	Thames catchment, United Kingdom	Dissolved Oxygen	Post-flood events a huge increase in DO levels are commonly notice, as flood water recedes the DO levels.
Paerl et al., 2019	North Carolina, United States	Dissolved Oxygen	Flood water brings in contaminants and runoff from the surface flow. This led to a decrease in DO values.
Zoppini et al., 2019	Po River, Italy	Dissolved Oxygen	A lower value of salinity and temperature can lead to higher concentrations of dissolved oxygen near coastal areas.
Hafeez et al., 2019	Rajanpur, Pakistan	Nitrates and Phosphorous	Floods could have varying effects of floods on soil heavy metals. Soil Phosphorous and nitrates were reduced after flood events.
Soto et al., 2019	Lake Winnipeg, Canada	Nitrate	Floodwaters have higher concentrations of Nitrate; this necessitates the adjustments in the amount of nitrate used in fertilizers for agriculture purposes.
Husic et al., 2019	Cane run watershed and Royal Spring basin, United States	Nitrate	After an initial lag, Nitrate concentration follows a flood hydrograph pattern in an increase. This can be noticed generally in rivers draining from karst topography.
Peng et al., 2019	Chaohu Lake, China	Phosphorous	Flooding leads to increased Phosphorous levels. It depends on the soil composition and land use of the watersheds involved.
Jeke and Zvomuya, 2018	Niverville, Manitoba, Canada	Phosphorous	Flooding duration needs consideration. More phosphate amounts are seen if the water is released from lagoons with increased residence time.
Marrugo-Negrete et al., 2019	Mojana region, Colombia	Phosphorous and Sulphides	Chemical reactions among various compounds involved during flood events can cause mixed behavior in constituents of water thereafter.
Braga et al., 2017	Po River, Italy	Turbidity	Even though there were some local variations in the amount of turbidity noticed in each tributary of the river. Flooding leads to an overall increase in all the tributaries.
Joshi et al., 2017	Apalachicola Bay, United States	Turbidity	Passage of low-pressure systems like storms and hurricanes, can result in higher flow velocity and thereby causing an increase in water turbidity.
Chen et al., 2018	Jiulong River, China	Nitrate, Ammonium, and Phosphate	Major increases in dissolved nutrients (nitrate, ammonium, and phosphate) in the Upper parts of the estuary during major Storms in 2013 and 2014 are noticed.
Gopal et al., 2017	Cooum and Adyar Rivers, India	Lead	An increase in lead content in the surface sediments is caused due to the migration of contaminated soil from an urban environment to coastal regions during flood events.
Peraza-Castro et al., 2016	Oka Hydrographic Unit, Spain	Suspended particulate matter (SPM)	Most of the suspended particulate matter can be carried by water during high flow events leading to higher amounts of concentrations in water during floods.
Rickenmann et al., 2016	Northern Alps and Prealps, Switzerland	Sediment load	Human activities such as buildings and other infrastructure had increased sediment loads during higher flow events in the Alps.

systems, there is also decreasing microbial diversity and increasing evolution to typical freshwater microbes within the Betaproteobacteria, Actinobacteria, and Bacteroidetes as streams turn into rivers (Read et al., 2015; Ruiz-González et al., 2015; Savio et al., 2015). However, few studies have examined changes in microbial communities regarding climate extremes, such as during or after a flood or drought. A disruption in typical microbial community structure, including increased diversity across two of five stream networks, was observed in a Georgia, USA study after increased precipitation and temperatures (Hassell et al., 2018). In another study investigating microbial communities in the Cache La Poudre River watershed, however, decreased phylogenetic diversity was observed three months post flood and return of diversity after ten months (Garner et al., 2016). Changes in benthic microbial community diversity were also observed in desert streams after flooding and were linked to increased nutrients (Abed et al., 2011).

Prolonged drought also may affect microbial communities, although there are few studies that examined the entire microbial community. A severe drought in the San Francisco estuary dramatically increased Microcystis and related toxin-producing Cyanobacteria, likely due to increased residence time and temperature (Lehman et al., 2017). In other stream environments during intermittent drought events, microbial community diversity decreased in hyporheic habitats compared to surface water environments (Febria et al., 2012). Interestingly, benthic biofilms changed from cyanobacterial to a diatom-dominated community after a prolonged drought in a small-scale experimental study, likely due to changes in nutrients (Barthès et al., 2015).

3. Analysis of impact of drought on water quality in different land use settings

In this section, we investigated the potential impact of droughts on water quality in two different types of watersheds. These two watersheds were selected due to the long-term availability of water quality data as well as they represent two different land-use settings. The first gauge (USGS- 03512000) (Lat 35°27′41″, Lon 83°21′13″) is located in the Oconaluftee River, North Carolina, where forest lands dominate the watershed. The second station (USGS-02203873) (Lat 33°42′33.9″, Lon 84°14′21.0″) is situated in Cobbs Creek, Georgia, where urban lands dominate the watershed. The data obtained from the two stations are daily streamflow, Turbidity (TUR), Dissolved Oxygen (DO), pH, and Specific conductance (SC). The Standardized Precipitation Evapotranspiration Index (SPEI) was used (Vicente-Serrano et al., 2010) to identify drought events.

The monthly time series (2015 to 2020) of SPEI, streamflow, and water quality indicators for forest and urban watersheds are shown in Fig. 2 and Fig. 3, respectively. Both stations witnessed low flow during a drought period that continued through 2016 and 2017, which resulted in low TUR and DO values. On the other hand, an increase in TUR and DO values were observed during the wet periods. The correlation between SPEI and flow, TUR, and DO were statistically significant at the two stations, except for DO values at Oconaluftee River station, which is dominated by forest lands. On the other hand, an increase in pH and SC values during droughts was observed at the watershed dominated by forest lands (Fig. 2). However, SC and pH showed an insignificant correlation with the droughts at the watershed dominated by urban lands (Fig. 3).

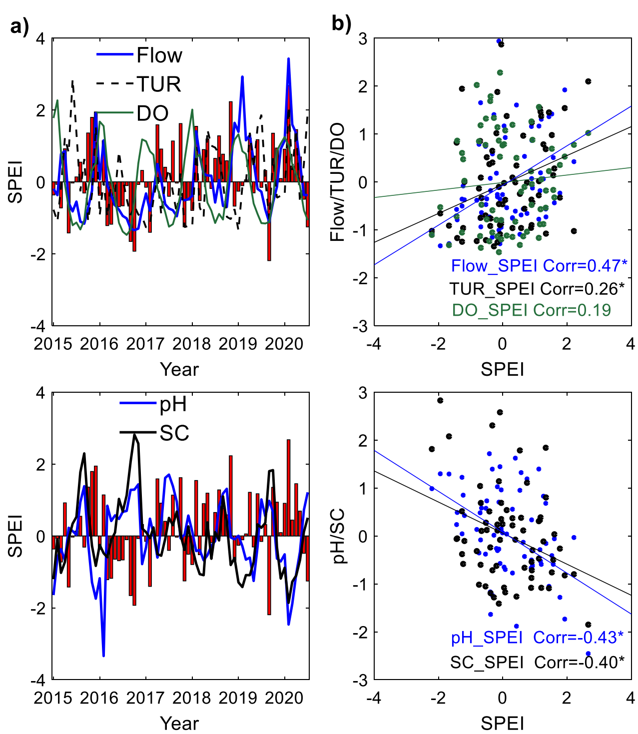

Fig. 2. a) Monthly time series of SPEI and the observed streamflow, Turbidity, Dissolved Oxygen, pH, and Specific Conductance at the gauge station located in Oconaluftee River, North Carolina (USGS- 03512000). b) Correlation between SPEI and the selected water quality variables. [Note: "*" indicates a statistically significant ($p < 0.05$) correlation between SPEI and the selected water quality variables].

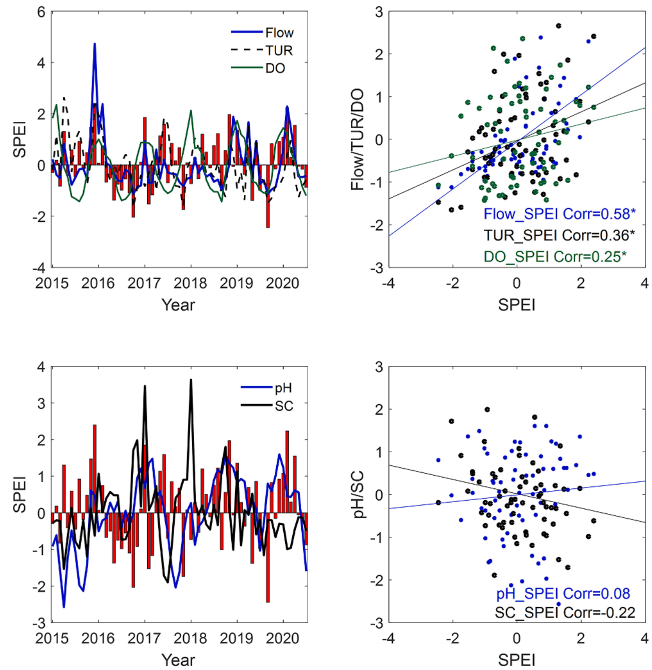

Fig. 3. a) Monthly time series of SPEI and the observed streamflow, Turbidity, Dissolved Oxygen, pH, and Specific Conductance at the gauge station located in Cobbs Creek in Georgia (USGS-02203873). b) Correlation between the monthly SPEI and the selected water quality variables. [Note: "*" indicates statistically significant ($p < 0.05$) correlation between SPEI and the selected water quality variables].

4. Impact of cascading (compound) extreme events on water quality

Although the impacts of climate extremes on water quality indicators have been investigated, the studies involving cascading (compound) events are limited. These issues are highlighted in our recent projects (Mishra, 2015; Mishra and Campbell, 2017). In climate science, compound events are characterized by two or more extreme events occurring simultaneously or successively (Seneviratne et al., 2012). The compound event can also be a combination of human and natural related disasters (Mishra et al., 2021). In simple terms, a cascading (compound) event occurs due to the combination of two or more individual extreme events occurring successively (simultaneously). Examples of cascading events are: (a) a severe drought event followed by an extreme flood (drought-flood regime), and (b) extreme drought followed by wildfire (drought-wildfire regimes), which can be further compounded by flooding events.

The combination of drought and extreme rainfall can modulate water quality in which the deficit in precipitation and subsequent runoffs may lead to the deposition of pollutants within the soil. During extreme rain events and subsequent flooding, these pollutants are discharged into waterways, with the result that stagnant water in urban areas can lead to severe issues of water quality. A drought-flood regime will affect water quality differently based on rural, agriculture, and urban landscape patterns. The combination of extreme events is expected only to increase (Konapala et al., 2020); therefore, there is a need to advance our understanding of how these extreme rain and flooding events affect the dynamics of water quality. The combined impact of drought and flood extremes on water quality is currently poorly understood, and it is important to quantify how these combinations of climate extremes affect water quality in different types of landscape.

Cascading of extreme events (drought to wildfires) is expected to change hydrology, water quality, and dynamics of microbial communities in watersheds. It is essential to explore the change in water quality indicators within a watershed following the fire, and the watershed conditions control them (e.g., altered landscape and changing hydrology) and changes in stream internal processes. The consequences of drought - wildfire regime also destroys the vegetation cover, alters spatial soil properties (e.g., infiltration), and geomorphic features. The results discussed in the following section are related to our research on drought-flood regimes (Mishra, 2015).

4.1. Analysis of drought-flood cascading event on water quality

South Carolina (USA) experienced a severe drought followed by a historical extreme flooding event caused by Hurricane Joaquin during the 1st week of October 2015. This is a classic example of a cascading event where both types of hydrologic extremes (extreme low and high flows) were distinctly observed. This section presents a synoptic overview of how historic rainfall and flooding have impacted the streamflow and water quality indicators. The USGS station (USGS 02110704) (Lat 33°49′58″, Lon 79°02′38″) located in Waccamaw River at Conway Marina in South Carolina was selected to analyze the potential impact of cascading events on water quality indicators, such as Turbidity, Dissolved Oxygen, pH, and specific conductance (SC).

The timeline of the drought-flood cascading event and its impact on water quality indicators are provided in Figs. 4 and 5. The daily streamflow due to severe drought was 12 m^3/s (October 1), which significantly changed to 525 m^3/s (October 7) during the extreme flooding event. The extreme flooding event led to very high TUR values in the streams of up to 40 FNU (400% higher) than its values during droughts. The DO values also increased to 6.4 mg/l during this extreme event (October 4, 2015), and then decreased to 3 mg/l during the normal period (November 18). Both pH and SC values were reduced during the extreme flood event (Fig. 4). Higher amounts of SC were observed during the drought periods (16 µS/mm) compared to the flooding events (4.6 µS/mm), as shown in Fig. 4.

Fig. 5 shows the cascading effects of the significant droughts and floods on the selected water quality indicators. The highest TUR values (40 FNU) occurred during the rising limb before reaching the peak flow.

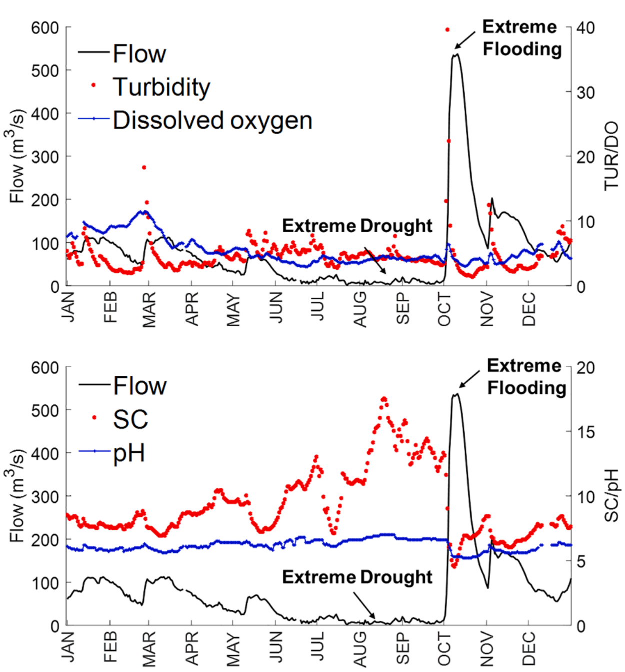

Fig. 4. Cascading effect of extreme droughts and flooding on flow and water quality indicators at Waccamaw River at the Conway Marina in South Carolina (USGS 02110704) for the year of 2015. TUR = Turbidity (FNU); DO = Dissolved Oxygen (mg/l); pH; SC = Specific Conductance (µS/mm).

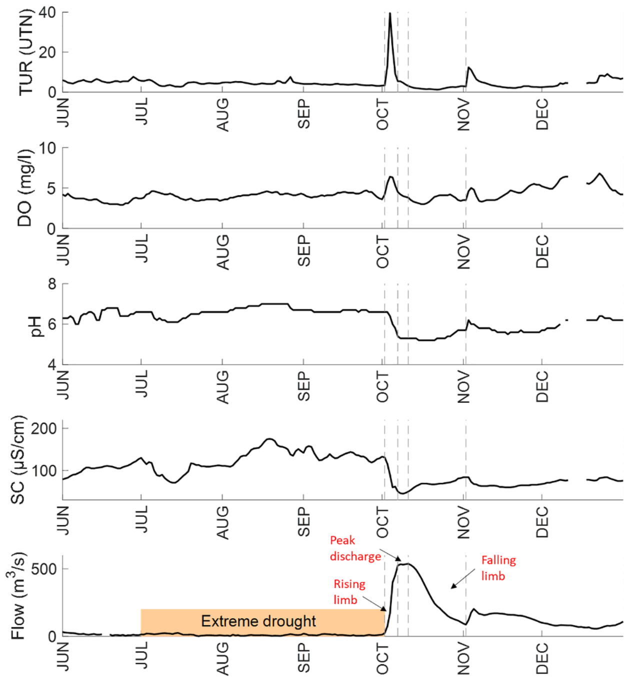

Fig. 5. Cascading impact of extreme drought to extreme flood events on the water quality indicators at Waccamaw River at the Conway Marina in South Carolina (USGS 02110704) from June to December 2015.

During the rising limb of the hydrograph, TUR and DO values reached their peak values (Fig. 5). The pH and SC values decreased significantly during the rising limb and remained constant at the peak discharge. In the falling limb, both pH and SC values increased slightly, while TUR and DO mostly remained constant.

5. Analysis of drought and flood on microbial communities in different land use settings

Here, we aim to assess the changes in microbial community structure from three different water sites in the Congaree watershed near Columbia, South Carolina under different water flow conditions. The three were: 1) pre-urbanized Congaree River site (Broad River Bridge); 2) post-urbanized Congaree River site (Congaree Boat Ramp); and an urbanized small river site (Smith Branch). Samples were collected in the spring and early summer (April to June) of 2016. Changes in community structure in relation to water type (river, stream) and flow rate were assessed by various indices of microbial diversity, both alpha diversity (richness and diversity) and beta diversity (similarities in communities between samples). The flow rate is classified into three groups, the standard flow is the mean of the daily mean discharges. The low flow (drought) is the minimum 30-day mean of the daily mean discharges, and the high flow (flood) is the maximum 30-day mean of the daily mean discharges. We also assessed the impact of flow rate on microbial community composition within a water type.

5.1. Site descriptions and sample collection

The Congaree River Basin is located in Lexington, Richland, and Calhoun Counties, and covers 690 square miles. The four watersheds are predominately within the “Sandhills” region of the State, but also are within the “Upper Coastal Plain” near its convergence with the Wateree River of the Catawba River Basin. The urban land is comprised of the City of Columbia. Of the 441,000 acres in the Congaree River Basin, 34.6% is forested land, 26.6% is agricultural land, 19.0% is forested wetland, 17.9% is urban land, 0.3% is barren land, 1.3% is water, and 0.3% is non-forested wetland (Meitzen and SCDNR 2008). The urbanization percentage is encompassed mainly by the Greater Columbia Metropolitan area. The Broad River and Saluda River merge to form the Congaree River, which flows southeasterly for 50 miles and merges with the Wateree River to form the Santee River Basin. There are a total of 1,165 stream miles and 5,350 acres of lake waters in the Congaree River Basin (Meitzen and SCDNR 2008).

Approximately 600 mL of Congaree River Basin water was collected within 1 L white high density polyethylene plastic bottles at upstream (Broad River Bridge, BR, 34.025929, −81.070472, n = 24) and downstream (Congaree River Bridge, CRB, 33.96491, −81.036192, n = 20) locations, as well as at a tributary, Smith Brank (SB, 34.038117, −81.060088, n = 20), from March-June in 2016, for a total of 64 samples. The bottles were stored in a cooler and driven to the Life Sciences Facility at Clemson University for analysis.

5.2. Sequencing

Prior to DNA extraction, 500 mL of each water sample was filtered through 0.22 µm and/or 0.8 µm filters to collect the free living and particle attached bacterial communities, respectively. Samples were stored at −80̊C before nucleic acid extraction from the filters. Total DNA was extracted from all samples using the Qiagen AllPrep Kit and was quantified with Qubit™ fluorometric quantitation (Invitrogen). Using universal 16S rRNA gene primers, the V4 region of 16S rRNA genes was amplified following previously published methods (Kozich et al., 2013). The PCR conditions used consisted of 2 min at 95 °C, followed by 30 cycles of 95 °C for 20 s, 55 °C for 15 s, and 72 °C for 5 min, followed by 72 °C for 10 min. Each PCR reaction was normalized using the SequalPrep Normalization Plate Kit (Thermo Fisher Scientific). The concentrations of the extracted nucleic acid and PCR products were determined using Qubit 2.0. After the cleanup process and normalization of the library pool, sequencing was performed on the Illumina MiSeq 4000 (Illumina, San Diego, CA) at Clemson University using the 500 cycle MiSeq V2 Reagent kit following the manufacturer's instructions with custom forward, reverse, and index primers added to the reagent cartridge.

5.3. Sequencing and statistical analyses

The raw Illumina fastq files were demultiplexed and the barcodes were removed on Illumina BaseSpace® (basespace.illumina.com). Preliminary screening of the raw sequence data resulted in trimming approximately 15 bp from the 5′ and 20–50 bp from the 3′ end of the sequence in order to remove low quality bases prior to joining. The sequences were then analyzed using the latest Qiime2 workflow (Bokulich et al., 2018). Briefly, amplicon sequence variants (ASVs) were determined in Qiime2 via the DADA2 pipeline using an open reference picking mode, based on no more than 1% difference between sequences; and likely represents strain to species level variation (Callahan et al., 2016). Taxonomic classification of the bacterial non-chimeric, denoised, joined reads was performed using a Qiime2 classifier (sk-learn, (Pedregosa et al., 2011)) pre-trained on Silva v123 at 99% identity (Quast et al., 2013). Sequences that occurred <10 times in the entire dataset were removed using the filter table option. Additionally, all taxa associated with chloroplast and mitochondria, as well as unassigned taxa were removed. Representative bacterial ASV sequences were further analyzed by multiple-sequence alignment via MAFFT and FastTree to reconstruct the phylogenetic tree prior to beta diversity analyses (Katoh, Misawa et al. 2002).

The number of sequences in each sample were rarefied to 9900 prior to diversity analyses. A comprehensive diversity analysis was performed using the diversity core-metrics-phylogenetic script in Qiime2 (Bokulich et al., 2018). Data tables and Shannon diversity index analysis (Shannon and Weaver, 1949)data were exported from Qiime2 and further analyzed. Shannon diversity index estimates alpha diversity via a combination of the richness (number of taxa, in this case, ASVs) and evenness of the ASVs within a sample (Shannon and Weaver, 1949).

To visualize the differences in ASVs between samples and measure their significances, Principal coordinate analysis (PCoA) were performed in the "vegan" package (Oksanen et al., 2015) on the R platform (R Core Team, 2017) and plotted with ggplot2. A significance test (PERMANOVA test, Adonis tool) with 999 permutations based on Bray-Curtis distance was performed in Qiime2 (Bokulich et al., 2018). Principle coordinate analyses takes the similarity or distance matrix generated from the ASV/taxa vs. sample table and plots the relationships between the samples as an ordination in a lower dimensional space, in this case in two dimensions (Legendre and Legendre, 2012). PERMANOVA (permutational multivariate anova) tests to see if the difference in the centroids of sample or treatment groups in an ordination plot are significantly different (Anderson, 2005).

Linear discriminant analysis (LDA) effect size (LEfSe) (Segata et al., 2011) was used to identify bacterial taxa that were significantly different between sites and flow regimes within a site. LDA is similar to regression analysis or ANOVA, but the extent of difference is determined between two or more groups based on a linear relationship between continuous independent variables and a dependent variable that is categorical (LDA, 2009). The Kruskal-Wallis (KW) sum-rank test ($P < 0.05$) was used in the LEfSe analysis to detect features with significantly different abundances between the specified categories, and this was followed by an LDA to estimate the effect size of each differentially abundant feature (logarithmic LDA score >3.0) through the online Galaxy platform (http://huttenhower.sph.harvard.edu/galaxy).

5.4. Microbial alpha diversity

To visualize within sample diversity (richness and evenness), Shannon diversity index was used as a nonparametric estimator of alpha diversity (Shannon and Weaver, 1949). Overall, samples from Smith Branch were more diverse than the Broad River and Congaree Boat Ramp and the highest diversity samples were at the Smith Branch and Broad River Bridge sites with high flow rates (Fig. 6). The highest diversity values at all sites were in samples identified with high flow rates, and these were significantly more diverse than the samples from the same site with either standard flow rates (Broad River Bridge, Smith Branch) or low flow rates (Congaree Boat Ramp).

5.5. Microbial beta diversity

We next wanted to determine if there were differences in microbial communities between samples, and what was likely responsible for those differences. Samples collected from Smith Branch are distinct from those collected from Broad River Bridge and Congaree Boat Ramp as assessed by Bray-Curtis similarity with PCoA (Fig. 7). Additionally, PERMANOVA analysis with Bray-Curtis distances between locations indicated that microbial communities from the Smith Branch samples were significantly different than communities from the river sites (F-value of 18.6405 with $p = 0.001$). The majority of explained variation (43%) separated the communities by river type (river vs. stream) along the x-axis. The second axis only explained 14% of the variation and was likely due to slight seasonal variations. The effect of current flow intensity is subtler and more irregular than location or date. However, separate clustering occurred with microbial communities associated with low flow current, compared to all other states of flow rate. Microbial communities associated with either standard flow or high flow also formed clusters more easily distinguishable from other groups.

5.6. Microbial composition

The taxonomic makeup of the microbial communities from the Broad River Bridge and Congaree Boat Ramp were generally consistent with each other, and the dominant phyla were the Bacteroidetes (average relative abundance = 29.2%), Actinobacteria (21.9%), Proteobacteria

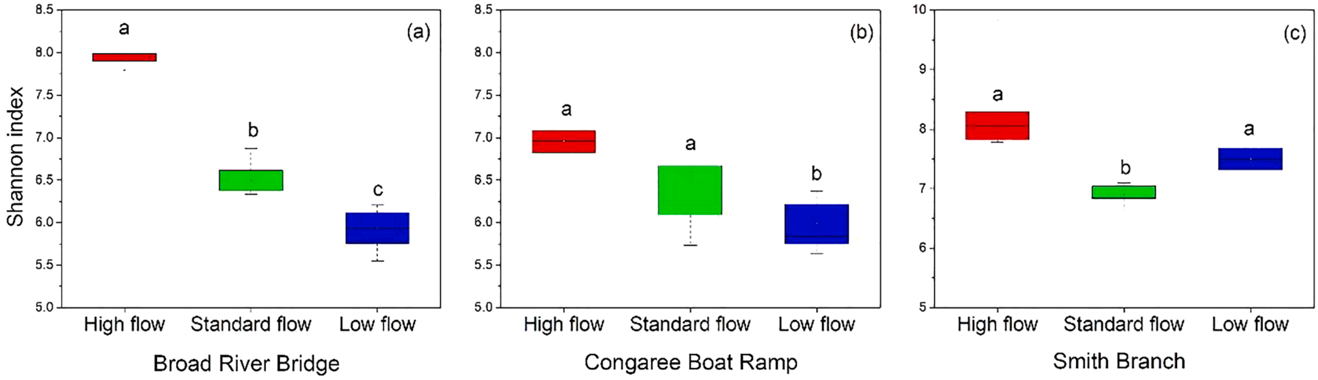

Fig. 6. Differences in alpha diversity of microbial communities between sites and flow regimes. Shannon indices were calculated on rarefied data (9900 sequences/sample) in Qiime2 and plotted. All values are presented as means ± SE with those with different lowercase letters above bars indicating significant differences. Statistical differences between flow regimes within site were calculated with ANOVA.

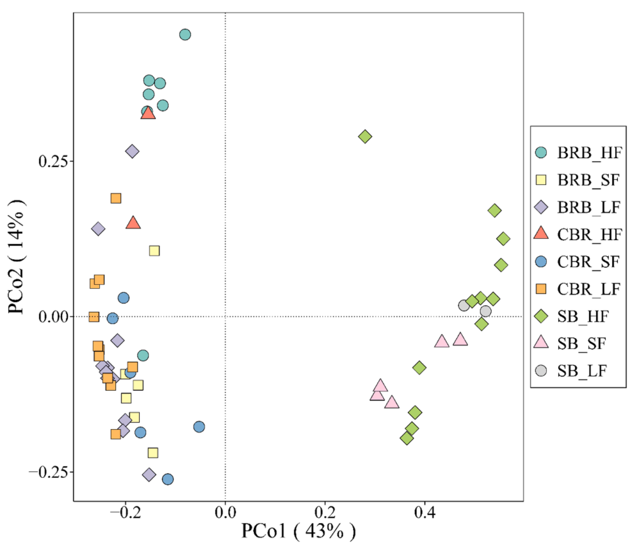

Fig. 7. Principal coordinate analysis (PCoA) plot indicating differences in the composition of microbial communities between the three sites and three flow regimes. Relative abundances of ASVs were determined in Qiime2, analyzed with Bray—Curtis similarities. BRB = Broad River Bridge; CBR = Congaree Boat Ramp; SB = Smith Branch; HF = high flow; SF = standard flow; LF = low flow.

(19.7%), and Cyanobacteria (19.6%), with lesser average abundances of Verrucomicrobia (6.1%), Planctomycetes (0.8%), and Firmicutes (0.5%) (Fig. 8). In contrast, the Smith Branch samples were dominated by Proteobacteria (54,6%), followed by Bacteroidetes (17.9%) with much less of the other phyla associated with the larger river sites (Actinobacteria, 5.4%, Cyanobacteria, 2.6%), but with increased abundances of Epsilonbacteraeota (4.2%) and Firmicutes (3.5%) compared to the two river sites.

We next examined the abundance of different families associated with fecal contamination, specifically the *Enterobacteraceae*, Clostridia and *Bacteroidaceae,* which include many bacteria associated with human and animal microbiomes. Average abundances of these groups were generally much lower from both the Broad River Bridge and Congaree Boat Ramp sites than the Smith Branch site (Fig. 9). However, at least one bacterial group, the Clostridia, from four Broad River Bridge samples was greater than 10 times more abundant than all other samples from that site. All four samples were taken during April, during high flow regimes. These bacterial groups were also at least twice as abundant from the Smith Branch samples characterized with high flow rates compared to low flow rates.

Three of the orders/families (Pseudomondales, Enterobacteraceae, Bacteroidaceae) typically associated with fecal contamination were significantly more abundant in Smith Branch high flow samples vs. standard or low flow samples (Fig. 10). In addition, the proteobacterial classes Alphaproteobacteria and Gammaproteobacteria were also found to be significantly more abundant in high flow river samples compared to standard or low flow.

5.7. Discussion of the effect of drought and flood on microbial communities

The microbial communities in the Congaree River near Columbia, South Carolina were somewhat diverse and compositionally similar to other large river and lake systems (Newton et al., 2011). Bacterial groups mainly associated with carbon and nutrient cycling, from primary producers (Cyanobacteria) to degraders (Bacteroidetes, Actinobacteria) were found in relatively high abundance in the Congaree River (Newton et al., 2011). The community structure of the Smith Branch was much more diverse and different than that of the Congaree River sites and was dominated by Proteobacteria. The structure of the microbial communities from the three sites were separated first by site (Broad River Bridge and Congaree Boat ramp were clearly separate from the Smith Branch sample) and then by month, but less so by other factors, such as size fraction. However, while flow regime did not explain the structure of the microbial communities, flow rate was correlated to the diversity of microbes in a sample and certain samples characterized as having high flow rates from the Smith Branch and Broad River Bridge did have significantly higher abundances of bacteria associated with fecal contamination.

The types and percentages of microbes found in aquatic environments can tell us much about water quality (Ahmed et al., 2016). Certain normal river and lake phyla, including the Actinobacteria and Cyanobacteria were generally more abundant in the Congaree River sites than in the Smith Branch. The overall composition of bacterial OTUs in the Congaree River was similar to that observed in lakes (Newton et al., 2011), indicating that the Congaree River may be an important sink for CO_2, since up to 48% of the bacteria were classified as Cyanobacteria, which are primary producers. Actinobacteria, which comprised between 9 and 37% of the microbes in the Congaree River sample, are normally found in well oxygenated lake and river waters, and their abundance may decrease in oxygen-poor environments (Newton et al., 2011). The microbial communities in the Smith Branch were dominated by Proteobacteria, followed by the Bacteroidetes phylum. Interestingly, bacteria within the Firmicutes and Parcubacteria phyla were also increased in the Smith Branch. These phyla are notably found in anoxic environments and many are found in association with fecal waste, including the *Lactobacillales* and *Clostridiales* families within the Firmicutes (Harris et al., 2004; Backhed et al., 2005). In addition, members of the

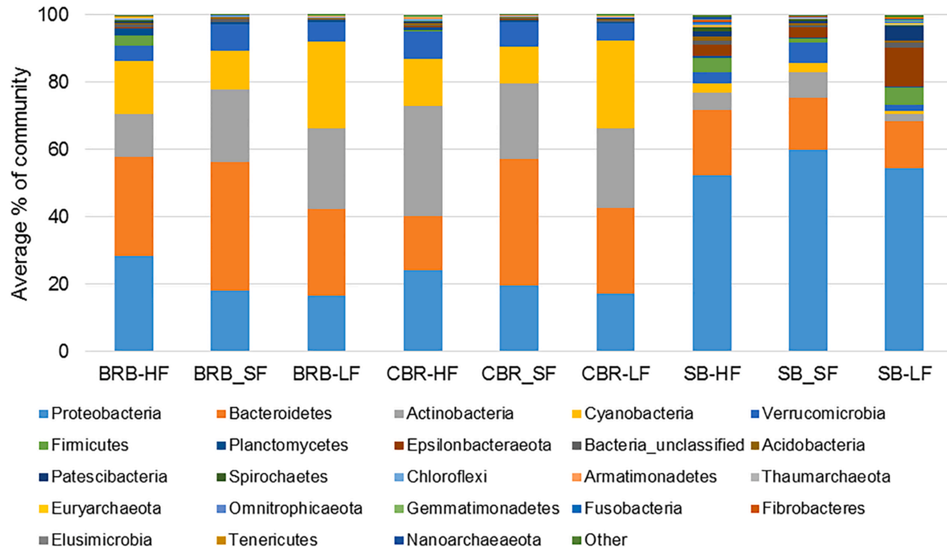

Fig. 8. Average abundances of the indicated phyla as assessed in different sites and flow regimes. BRB = Broad River Bridge; CBR = Congaree Boat Ramp; SB = Smith Branch; HF = high flow; SF = standard flow; LF = low flow. N = 7, 2, 12, 6, 6, 5, 11, 11, 2, for BRB-HF, BRB-SF, BRB-LF, CBR-HF, CBR-SF, CBR-LF, SB-HF, SB-SF, SB-LF, respectively.

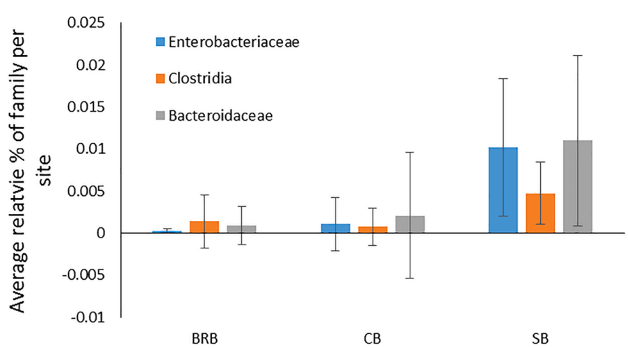

Fig. 9. Average relative abundance of the indicated bacterial groups from the three sites. N = 24 (Broad River Bridge, BRB); 19 (Congaree Boat Ramp, CB), and 19 (Smith Branch, SB). Error bars indicate standard deviations.

Enterobacteriaceae within the Proteobacteria phylum, as well as the *Bacteroideaceae* family, which includes *Bacteroides* sp., a very common species in the human gut microbiome, were also variably present, and most abundant during high flow regime samples.

6. Conclusions

Extreme weather events such as drought, wildfires, and flooding are predicted to increase throughout the world. Although the impacts of climate extremes on water quantity are widely studied, their water quality assessment effects are limited. This review highlighted the complex variety of water quality responses during extreme events in rivers/streams. In addition to climate variables and extremes, the watershed characteristics such as geology, slope, land use, and point or non-point sources of pollutions play a significant role in controlling the stream water quality indicators. The following conclusions can be drawn from this study:

- Several studies highlighted an increase in benthic algal levels in rivers and streams during the drought period. The impact of drought on nutrient concentrations (Phosphorus and Nitrogen) and Turbidity in streams can vary. It mainly depends on the land-use settings in a watershed (e.g., agriculture, urban, forest). Specifically, lower nutrient concentrations and Turbidity were observed during droughts across several rivers and streams. However, point source facilities can increase the turbidity and nutrient concentrations during drought events. Mixed responses during droughts were observed for Dissolved Oxygen, while the salinity and bacterial content showed a positive correlation in most streams/rivers with the droughts.
- The majority of studies examined the effects of wildfire on water quality suggested a significant increase in nutrient concentrations, metal concentrations, and mass loading rates of nitrite, orthophosphate, phosphate, total and dissolved Phosphorus post-wildfire. This change in water quality constituents relies mainly on the wildfire's severity and scale, the timing of storm events, and the post-wildfire vegetation in a watershed. Additionally, the biogeochemical processes can have ecological impacts on aquatic ecosystems. Flooding events can increase suspended particulate matter concentrations, dissolved organic carbon, and particulate organic carbon. On the other hand, mixed responses during floods were observed for Phosphorous, Dissolved Oxygen, and nitrates.
- There are significant and striking differences in the overall diversity and composition of the microbial communities observed between low and high urbanized areas. Only a subset of samples collected under high or very high flow rates tended to have significantly higher bacteria associated with fecal contamination indicators, suggesting that flooding events correlate with poor water quality, as hypothesized by us and others (Whitehead et al., 2009).
- The cascading of extreme events (e.g., drought-flood regime) can significantly affect water quality indicators. However, the knowledge is fragmented and limited about quantifying such impacts in real-time conditions. In the drought-flood regime, Turbidity can substantially increase (can be greater than 100%) in streams. This extreme regime can increase DO and decrease the magnitude of pH and SC, although the land use characteristics can also influence these characteristics.

Overall, the complex interaction between climate, watershed, and anthropogenic activities controls hydrologic extremes (Veettil and Mishra, 2020; Konapala and Mishra, 2020), as well as water quality indicators (Alnahit et al., 2020). Therefore, it is essential to develop robust frameworks in the context of sustainability science to quantify the interaction between different extreme events and coupled natural and human systems that influence stream water quality. There is also a need

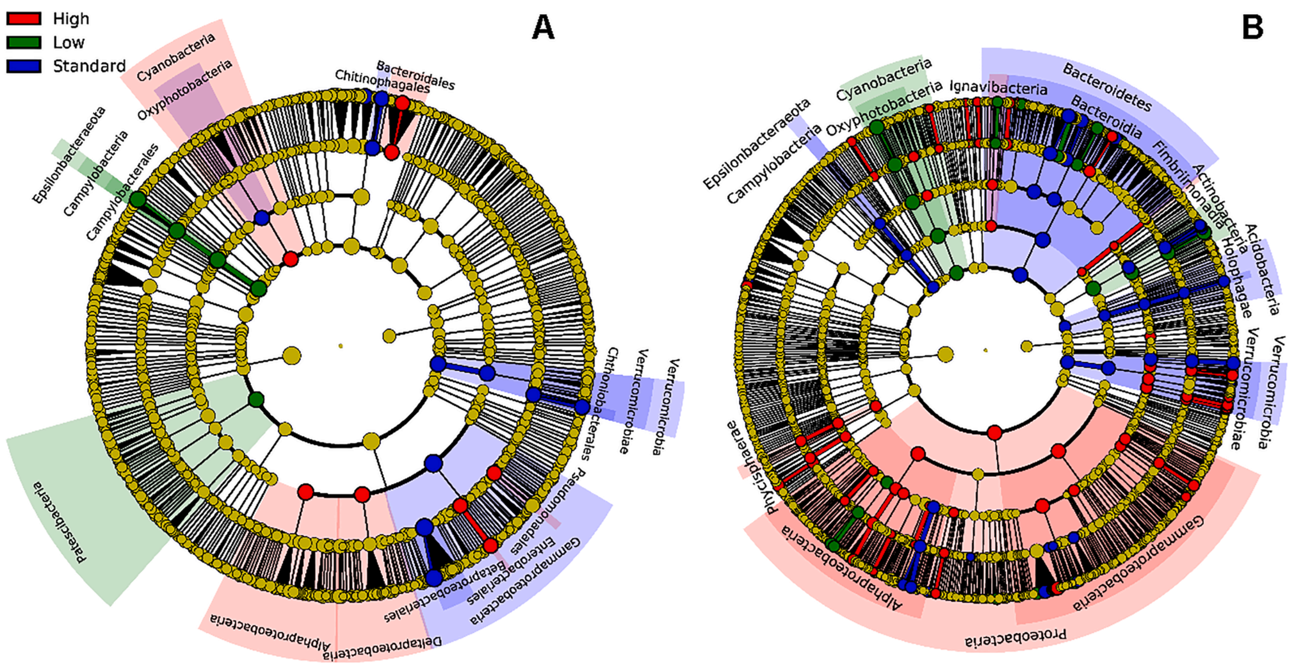

Fig. 10. Linear discriminant analysis (LDA) effect size (LEfSe) cladogram highlighting the stream (A) and river (B) taxa that statistically and biologically differentiate flow regimes. A cutoff value of ≥ 3.0 was used for the linear discriminant analysis (LDA). The six rings of the cladogram stand for the domain (innermost), phylum, class, order, family, and genus. Small nodes and shading with different colors (red, green, and blue) in the diagram represent significant increases in abundance of those taxa in the high, low, or standard flow regimes, respectively. Yellow circles represent non-significant differences in abundance between treatments for that particular taxonomic group. To simplify the diagrams, only the phylum, class, and order (stream, A) or phylum and class (river, B) or are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to develop robust machine learning and process-based models to generate water quality information in ungauged river basins. The remote sensing products can be useful, especially for data scarce regions in many parts of the world (Chawla et al., 2020). Multidisciplinary efforts are necessary to integrate different systems (e.g., watershed, hydrology, climate, microbial communities, and social systems) to generate new knowledge about their interactions in different geographical settings with varying spatial scales to maintain a healthy stream- ecosystem.

CRediT authorship contribution statement

Ashok Mishra: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Ali Alnahit:** Formal analysis, Investigation, Validation, Writing - original draft, Writing - review & editing. **Barbara Campbell:** Formal analysis, Investigation, Project administration, Software, Supervision, Writing - original draft, Writing - review & editing.

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.

Acknowledgement

This study was supported by the National Science Foundation (NSF, USA) award # 1653841 and 1602451. Authors acknowledge Somnath Mondal, Ramprasad Yaddanapudi, for their assistance in compiling the literature and Kenneth Vogel for collecting the water quality samples from the study area.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2020.125707.

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