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A REVIEW OF WATER QUALITY RESPONSES TO AIR TEMPERATURE AND PRECIPITATION CHANGES 2: NUTRIENTS, ALGAL BLOOMS, SEDIMENT, PATHOGENS

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Abstract

In this paper we review the published, scientific literature addressing the response of nutrients, sediment, pathogens and cyanobacterial blooms to historical and potential future changes in air temperature and precipitation. The goal is to document how different attributes of water quality are sensitive to these drivers, to characterize future risk, to inform management responses and to identify research needs to fill gaps in our understanding. Results suggest that anticipated future changes present a risk of water quality and ecosystem degradation in many U.S. locations. Understanding responses is, however, complicated by inherent high spatial and temporal variability, interactions with land use and water management, and dependence on uncertain changes in hydrology in response to future climate. Effects on pollutant loading in different watershed settings generally correlate with projected changes in precipitation and runoff. In all regions, increased heavy precipitation events are likely to drive more episodic pollutant loading to water bodies. The risk of algal blooms could increase due to an expanded seasonal window of warm water temperatures and the potential for episodic increases in nutrient loading. Increased air and water temperatures are also likely to affect the survival of waterborne pathogens. Responding to these challenges requires understanding of vulnerabilities, and management strategies to reduce risk.

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SUPPORTING INFORMATION
Additional supporting information may be found online under the Supporting Information tab for this article: Tables describing the models and range of projected water quality changes for specific watersheds.

Keywords

climate variability; future climate; water quality; nonpoint source pollutants; point source pollutants; watersheds

INTRODUCTION

Nutrients (nitrogen and phosphorus), sediment, and microbial pathogens are some of the most common pollutants impacting U.S. water bodies (Bricker *et al.,* 2008; Sprague *et al.,* 2009; USEPA, 2009, 2014, 2016). Nutrient pollution has direct effects on aquatic life and contributes to cyanobacterial blooms (potentially producing toxins), hypoxia (low levels of oxygen), and other adverse ecosystem impacts. Changes in sediment loads can alter the physical habitat necessary to support fish and other aquatic life (USEPA, 2006). Sediment is also a vector for contaminants transported to water bodies (e.g., pathogens, nutrients, and metals). Waterborne pathogens (including bacteria, viruses, and protozoa sourced to fecal waste) are a direct threat to human health (an estimated 90 million illnesses occur annually), with health-care costs attributed to some of the leading causes of waterborne diseases estimated at $2.2 to $3.7 billion annually in the U.S. (DeFlorio-Barker *et al.,* 2018; Collier *et al.,* 2012). The transport of these pollutants to water bodies is driven by watershed hydrologic and biogeochemical processes interacting with land use, and is strongly mediated by air temperature and precipitation (Langland *et al.,* 2003; Belmont, 2010; Jordan *et al.*, 2014; Kaushal *et al.,* 2014; Howarth *et al.,* 2006; Howarth, 2008; Dubrovsky *et al.,* 2010).

Anticipated future increases in air temperature, changing precipitation patterns and altered watershed hydrological processes associated with climate change will affect pollutant transport in specific watershed settings (e.g., physiographic and hydro climatic setting, water management and other human activities) (Georgakakos *et al.,* 2014; USGCRP, 2017; Wear and Greis, 2012). In colder/mountainous areas influenced by snow (e.g., the northern and western U.S.), warmer air temperatures affect the timing and seasonality of snow and snowmelt, including increased winter precipitation in the form of rain as opposed to snow, and snowmelt earlier in the winter and spring.

These changes are likely to alter the magnitude and timing of seasonal peak flows, including runoff peaks earlier in the spring, and decrease summer low flows (Paul *et al.*, 2019; Birsan *et al.,* 2005; Jefferson *et al.,* 2008; Ficklin *et al.,* 2013c, USEPA, 2016). Increases in air temperature also alter nutrient biogeochemical cycling, primary productivity, solubility, reaction rates, microorganism survival, evapotranspiration, soil moisture and other factors related to water quality (e.g. stratification) (Kundzewicz *et al.,* 2008; USGCRP, 2017; Coffey *et al.,* 2014; Havens and Paerl, 2015; Wear and Greis, 2012; Chang *et al.,* 2010).

Regionally variable changes in the amount and seasonal timing of precipitation and runoff are also anticipated (Melillo *et al.,* 2014). In the U.S., historically wetter regions (e.g., northern and eastern regions) are likely to receive increased annual precipitation with corresponding increases in runoff; whereas historically drier regions (the arid southwest, southern Great Plains, and parts of the southeast) will likely receive less precipitation resulting in decreased runoff (Arnell, 2003; Milly *et al.,* 2005; USEPA, 2013). In addition,

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an increasing frequency of heavy precipitation events - even in areas that receive less annual precipitation - and longer dry periods between precipitation events are projected (Prein *et al.,* 2016). These changes will alter the mobilization and transport of pollutants from upland sources to water bodies (Jackson *et al.,* 2005; Salant *et al.,* 2008; Hancock, 2012; Ffolliott *et al.,* 2013; di Silvio and Basson, 2008; Gellis *et al.,* 2003; Ford *et al.,* 2011; Giorgi *et al.,* 2011; IPCC, 2012; Vose *et al.,* 2011; West, 2002). Rates of sediment, pathogen (from fecal sources) and nutrient transport typically correlate to precipitation and runoff (Jackson *et al.,* 2005; Salant *et al.,* 2008).

Reducing the risk of climate change impacts on water quality requires an understanding of vulnerabilities in different regional and watershed settings, which can provide a starting point for effective, sustainable adaptation strategies. The goals of this review are to document potential future water quality responses to climate change, to characterize future risk, to inform management responses and to identify research needs to fill gaps in our understanding. In this paper, we focus on potential future responses of nutrients, sediment, pathogens and cyanobacterial blooms. A companion paper (Paul *et al.,* in review) discusses streamflow, water temperature and salt water intrusion. We note that water quality changes are complex and affected by multiple, interacting climatic, watershed and human factors. In line with study objectives, we focus only on water quality sensitivity to air temperature and precipitation. Discussion of changes in land use, water management and other factors affecting water quality is beyond the scope of this effort.

APPROACH

Relevant literature was identified through a search of recently published peer-reviewed and gray literature (post 2000) examining water quality responses to historic or future changes in air temperature and precipitation. Literature searches were conducted in common scientific databases (e.g., PubMed) using appropriate search terms. Our search identified studies that evaluated either the observed sensitivity of nutrients, cyanobacterial blooms, sediment and waterborne pathogens to climate drivers, or simulations of potential future changes using water quality models driven by air temperature and precipitation scenarios. Studies of water quality responses to observed weather and natural, internal climatic variability document how different attributes of water quality are sensitive to air temperature and precipitation. Modeling studies suggest potential changes in response to alternative future conditions; however, study comparisons can be complicated due to differences in the methods and models used. To the extent possible, we synthesize information from each type of study to make inferences about the risk presented by future changes. Where possible, regional differences are identified. Note that modeling studies typically provide an “ensemble” range of outcomes in response to different future scenarios and time periods etc. In such cases, we make the simplifying assumption that the ensemble mean or median suggests a “more likely” direction of change for the purposes of risk management.

RESULTS

Nutrients

Observed Sensitivity.—Changes in air temperature and precipitation are key drivers of nutrient mobilization and transport into and within water bodies. Warmer temperatures generally increase nutrient availability, solubility, and cycling in aquatic and terrestrial ecosystems (Murdoch *et al.,* 2000; Kundzewicz *et al.,* 2008; Duan and Kaushal, 2013). Rates of nitrification (Murdoch *et al.,* 2000; Kundzewicz *et al.,* 2008; Pourmokhtarian *et al.,* 2012), mineralization (Brooks and Williams, 1999; Andersen *et al.,* 2006; Hartman *et al.,* 2014), and denitrification (N loss to the atmosphere) (Murdoch *et al.,* 2000; Andersen *et al.,* 2006; Battarbee *et al.,* 2012; Boyacioglu *et al.,* 2012; Alam and Dutta, 2013) have been shown to increase with temperature. Decomposition and mineralization rates of organic nutrients in soils increase at higher temperatures (Shrestha *et al.,* 2012). The net effects of these changes determine nutrient availability, affecting transport and fate of constituents (Ryberg *et al.,* 2017; Andersen *et al.,* 2006; Boyacioglu *et al.,* 2012; Shrestha *et al.,* 2012; Alam and Dutta, 2013; Hartman *et al.,* 2014; Worrall *et al.,* 2003).

Precipitation and runoff mobilize and transport nutrients (dissolved and sediment-adsorbed) from upland sources to water bodies (Figure 1) (Murdoch *et al.,* 2000; Howarth *et al.,* 2006; Kaushal *et al.,* 2008; Kundzewicz *et al.,* 2008; Ficklin *et al.,* 2010; Wilson and Weng, 2011; Joyner and Rohli, 2013; Jiang *et al.,* 2014). When runoff encounters nutrient-rich sources (e.g., recently fertilized fields, shallow enriched groundwater, organic waste), nutrient mobilization and transport generally increases (Creed and Band, 1998; USEPA, 2013; Murdoch *et al.,* 2000; Whitehead *et al.,* 2009b). Numerous studies show increases in nutrient loading that correlate with precipitation and runoff volume (Najjar *et al.,* 2000; Noges *et al.,* 2011; Michalak *et al.,* 2013; Jiang *et al.,* 2014; Orem *et al.,* 2015; Morse and Wollheim, 2014). For example, in the Mississippi river, precipitation patterns have been suggested to be the controlling factor in nitrogen loading from land and transport through the river system as land use and cover has remained relatively constant in recent times (Donner and Scavia, 2007). During drier periods, elevated nutrient concentrations can occur downstream of point source discharges (e.g., groundwater contributions, wastewater treatment plant discharges, industrial effluent etc.) due to reduced flow volume and decreased instream dilution (Murphy *et al.,* 2014).

Several national scale studies have examined historical nutrient trends in U.S. waterbodies (Sprague *et al.,* 2009, Howarth *et al.,* 2006; Dubrovsky *et al.,* 2010; Prasad *et al.,* 2010; Hale *et al.,* 2013; Zhang *et al.,* 2013; Howarth, 2008; Sinha and Michalak, 2016; Sprague *et al.,* 2011). Stets *et al.,* (2015) report that flow-weighted nitrate concentrations (a metric which reflects loads) increased at 22 monitoring stations throughout the U.S. (8 in the East, 5 in the Midwest, 5 in the Great Plains and mainstem Mississippi River and 4 in the West) from 1945 to 1980, but stopped increasing between 1981 and 2008. However, attribution of trends to specific drivers like air temperature and precipitation is often not possible and many studies link observations to changes in land use, fertilizer application, atmospheric deposition, point source discharges and other factors. One recent study suggests that spatial variability in loading is typically dominated by nutrient inputs but that interannual variability and the occurrence of extreme loading are driven by precipitation across much of the U.S. (Sinha and Michalak, 2016). Loecke *et al.,* (2017) showed that that changing precipitation patterns (drought-to-flood transitions), interact with agricultural land use to deteriorate water quality in the Midwestern U.S. In the Chesapeake Bay, N and P loads have been linked to changes in temperature and precipitation patterns associated with the El Niño Southern Oscillation (ENSO) and Atlantic Multi Decadal Oscillation (AMO); however, such correlations are not universally found in studies (Prasad *et al.,* 2010).

Potential Future Changes.—Nutrient load responses to future climate scenarios have been assessed in several watershed scale modeling studies, although geographic coverage is limited (see Figure 2 for nitrogen and Figure 3 for phosphorus). Understanding future changes is particularly challenging due to the uncertainty surrounding precipitation projections at the local scale, and interaction with future changes in watershed management and human activities influencing nutrients. Future increases in air temperature are more certain and are expected to affect nutrient mobility by extending the growing season, changing nutrient uptake by plants, influencing ET and altering biogeochemical cycling in soils. Some studies suggest that increasing denitrification, associated with warmer temperatures, will often outweigh the effects of increased precipitation and lead to lower nitrogen yields in some U.S. locations (Alam *et al.,* 2017; Panagopoulos *et al.,* 2014).

Modeling studies applying similar methods to watersheds across the nation generally project increases in total nutrient loads (median) for much of the eastern and northern U.S. (Fant *et al*., 2017; Sinha *et al.,* 2017; Johnson *et al.,* 2015). Other watershed scale modeling studies in northern and eastern regions also suggest increased annual riverine nutrient loads (Figure 1 and 2) in response to projected increases in rainfall and runoff (Howarth *et al.,* 2006; Tu, 2009; Pourmokhtarian *et al.,* 2012; Tong *et al.,* 2012; Chang *et al.,* 2010; Wang and Kalin, 2018). However, simulations include scenarios that differ in the direction of change (negative to positive) for many watersheds, correlating with variability in precipitation projections.

Other seasonal and episodic changes in nutrient loading are also expected due to changing precipitation patterns. Increases are more likely in winter-spring when a larger proportion of annual rainfall is projected to occur. The frequency and magnitude of heavy precipitation and runoff events is expected to increase in all parts of the U.S. (Prein *et al.,* 2016). and could increase the risk of episodic high nutrient loading from nonpoint sources (e.g., manured land etc.) (Fant *et al.,* 2017; Lee *et al.,* 2016). Heavy precipitation and runoff are often associated with the flushing of nutrients that have accumulated on the land surface, especially nutrients adsorbed to sediment particles (Loecke *et al.,* 2017).

Drier and warmer conditions in parts of the Southwest, particularly in summer-fall, are expected to contribute to decreases in annual runoff and nutrient loading to water bodies (Johnson *et al.,* 2015, Ye and Grimm, 2013; Chang *et al.,* 2010). However, it is anticipated that water bodies in other regions of the U.S. could also see a reduction in flow volume during occasional summer-fall dry periods. This is likely to reduce dilution and could cause higher nutrient concentrations downstream of point source discharges. In addition, lower summer flows are expected to result in longer water residence times and could increase the risk of eutrophication.

Anthropogenic activities, such as urbanization, deforestation, forest fragmentation and intensification of agricultural production, will interact with climate change and could increase the risk of excess nutrient loading (Tong *et al.,* 2012; Alam *et al.,* 2017; Wear, 2013). However, few studies have modeled future changes in land use and climate simultaneously to assess potential effects on nutrient loads.

Ecosystem Level Impacts.: Temperature and changes in precipitation associated with climate change could increase the risk of eutrophication (associated with excess nutrient loading) in parts of the U.S. and cause a cascade of adverse ecosystem impacts in water bodies. Eutrophication is associated with increased phototroph growth rates which are reflected in dense algal blooms/plant growth and linked to hypoxia and anoxia (Neilan *et al.,* 2013; Paerl and Huisman, 2008; Paerl *et al.,* 2011). For example, the consequences of eutrophication are particularly evident where the Mississippi River enters the Gulf of Mexico – the hypoxic, or “dead zone” here is the largest in the United States and was measured to be 13,080 km^2 in 2014 (Porter *et al.,* 2015). Increased nuisance algae and plant growth can also impact aquatic life by altering food quantity/quality, reducing physical habitat quality (e.g., disrupted visual predation and impeded movement) and ultimately influencing species composition (Feminella and Hawkins, 1995; Slavik *et al.,* 2004 Paerl *et al.,* 2006; Paerl *et al.,* 2011; Fu *et al.,* 2012; Paerl and Paul, 2012; Wang *et al.,* 2007; Evans-White *et al.,* 2009). A comprehensive description of algal blooms and associated impacts is discussed in the next section.

Nutrient enrichment of rivers and streams can also contribute to acidification in estuaries and coastal systems. Excessive coastal eutrophication causes greater respiration of fixed carbon. This increases CO_2, especially in bottom waters, and causes acidification (Borges and Gypens, 2010; Cai *et al.,* 2011; Duarte *et al.,* 2013; Wallace *et al.,* 2014). Nutrient enrichment together with increasing atmospheric carbon dioxide are considered the primary contributors to increasing acidity (higher partial pressure of CO_2/lower pH) in aquatic systems (Fu *et al.,* 2012; Duarte *et al.,* 2013; Wallace *et al.,* 2014). These changes influence a wide range of biochemical reactions, including many critical to the maintenance of water quality and fisheries. For example, coastal acidification is expected to influence algal species composition and primary production, causing disruptions to the food webs relying on algae and algal productivity, as well as harmful algal blooms (Fu *et al.,* 2012).

Cyanobacterial Blooms

Observed Sensitivity.—The number of toxic cyanobacterial blooms, water bodies affected, and toxic species reported have all increased during the past few decades in the U.S. (Loftin *et al.,* 2016; Anderson *et al.,* 2012). In August 2016, at least 19 States had public health advisories related to cyanobacterial blooms (see Figure 4). Bloom occurrences are typically not predictable because interactions among multiple natural and anthropogenic factors determine the likelihood and severity in specific water bodies (Brooks *et al.*, 2016). Eutrophication, from human activities such as agriculture and urbanization, has been suggested as a leading cause for the expansion and persistence of cyanobacteria (Taranu *et al.,* 2015; Heisler *et al.,* 2008). However, cyanobacterial blooms can also be affected by precipitation driven nutrient enrichment, solar radiation, water temperature, conditions characteristic of lentic systems (calm and still water), and other drivers (e.g., carbon dioxide, sea level rise) (Figure 5) (NSTEPS, 2015; USEPA, 2013).

Precipitation driven nutrient loading (soluble and adsorbed to sediment) has been associated with cyanobacterial blooms in large freshwater ecosystems (e.g., Lake Taihu and other large lakes in China, the U.S. Great Lakes, Lake Victoria and Lake George, Africa) (Qin *et al.,* 2010; Paerl *et al.,* 2011) as well as in estuaries like the Neuse Estuary in North Carolina, and the Potomac Estuary in Maryland (Sellner *et al.,* 1988; Robson and Hamilton, 2003; Paerl, 2008). The amount and timing of precipitation and runoff also affects key factors controlling cyanobacterial growth and dominance, including water residence time, vertical stratification, salinity in estuarine systems, and phytoplankton growth rates. Additionally, bed sediment often acts as a reservoir for nutrients and cyanobacteria for extended periods (Reichwaldt and Ghadouani, 2012; Potts, 1994). High flows following heavy precipitation can stimulate blooms by disturbing and resuspending cyanobacteria and nutrients stored in bed sediment.

Higher water temperatures and associated changes in chemical and biological processes promote cyanobacterial bloom formation and dominance in a range of aquatic ecosystems (Paerl and Paul, 2012; USEPA, 2013; Funari *et al.,* 2012; Havens and Paerl, 2015). As a group, cyanobacteria have a competitive advantage at higher temperatures - often above 25 degrees Celsius (°C) - than other algae (USEPA, 2013; Paerl and Huisman, 2009; Paerl *et al.,* 2011). Warmer surface waters strengthen vertical water column stratification which promotes the formations of cyanobacterial blooms. Without vertical mixing of the water column, cyanobacterial species can regulate intracellular gas vesicles to control their buoyancy (e.g., *Microcystis, Anabaena*), floating upward to optimize photosynthetic production (light absorption and use of atmospheric CO_2) and sinking downward to optimize nutrient acquisition. This provides a competitive advantage over heavier, algae with faster sinking rates such as diatoms (Reynolds, 1987). Increases in atmospheric CO_2 can change water chemistry, lowering pH and favoring cyanobacteria that can grow faster in such conditions (USEPA, 2013; Paerl and Huisman, 2009).

Toxin-producing cyanobacteria strains are generally poor competitors for light compared to nontoxic strains (Kardinaal *et al.,* 2007), but can thrive in stable, calm waters common during dry periods. Long water residence times and reduced flow volumes which commonly occur in the late summer-fall generally favor the occurrence of cyanobacterial blooms (Elliott, 2012; Li *et al.* 2015; Paerl and Scott, 2010; Michalak *et al.,* 2013). Under these conditions, cyanobacteria enhance their competitive advantage by forming dense surface blooms, optimizing light absorption (Kahru *et al.,* 1993; Ibelings *et al.,* 2003) while shading deeper nonbuoyant algae (Huisman *et al.,* 2004). Cyanobacteria can also cope with the cell-damaging effects of ultraviolet radiation more effectively than nontoxic strains (Paerl and Otten, 2013).

Previous observations indicate that the ideal scenario for blooms is heavy rainfall that enhances runoff and nutrient delivery, followed by a protracted drought during the summer-fall period, when water temperatures and stratification are maximal (Paerl and Scott, 2010; Reichwaldt and Ghadouani, 2012). This pattern has been seen in multiple systems (Paerl and Huisman, 2009). For example, heavy precipitation preceded the formation of a large cyanobacterial bloom outbreak in Lake Erie in 2015 that affected up to 300 square miles of the western basin (NOAA, 2015). Heavy rainfall in June (7 inches at Toledo, Ohio) resulted in high runoff and delivery of large amounts of bioavailable and reactive phosphorus into the western portion of the lake (NOAA, 2015). Subsequent calm conditions and warm waters caused an extended period of weak lake circulation, which resulted in abnormally long residence times. Those conditions provided perfect incubation, seeding, and growth conditions for bloom development. Similar drivers have been indicated for bloom events in the Ohio River, the Neuse River Estuary in North Carolina, the Potomac River and other Chesapeake Bay tributaries (Youngstrom and Emery, 2015; Sellner *et al.,* 1988; Robson and Hamilton, 2003; Paerl, 2008).

Projected Future Changes.—Few modeling studies assessing the response of cyanobacterial blooms to future conditions were identified in the current scientific literature. One recent national-scale modeling assessment reported that the extent of cyanobacterial blooms is likely to increase primarily due to higher water temperatures and increased nutrient levels associated with changing land use and precipitation patterns (see Figure 6) (USEPA, 2017; Chapra *et al.,* 2017). Simulations indicated that the mean number of days of bloom occurrence would change from about 7 days per year per water body under current conditions, to 16–23 days in 2050 and 18–39 days in 2090 (USEPA, 2017). The largest increases in occurrence were suggested for the northeast U.S., while the greatest impacts to recreation, in terms of costs, were projected in the Southeast (USEPA, 2017; Chapra *et al.,* 2017).

Other studies also point to an increased risk of cyanobacterial blooms across the U.S. in response to future climate change (Trtanj *et al.,* 2016; Najjar *et al.,* 2010). Increased air and water temperatures are expected to expand the seasonal window of occurrence, particularly at higher latitudes (Trtanj *et al.,* 2016; Wells *et al.,* 2015; Moore *et al.,* 2008). Warmer temperatures are known to promote vertical density stratification and provide conditions more favorable to cyanobacteria (Paerl and Scott, 2010; Havens and Paerl, 2015; Mantzouki *et al.,* 2018). More frequent heavy precipitation events and associated excessive nutrient loading will increase the risk of eutrophic water conditions which enhance cyanobacterial growth (Prein *et al.,* 2016 Li *et al.,* 2015). Longer dry periods are expected between precipitation events in many parts of the U.S. during the summer-fall seasonal window of bloom occurrence (USGCRP, 2017). These conditions increase water residence times, cause weak water circulation and contribute to warmer water temperatures - all of which favor bloom development. In the marine environment, increases in salinity, associated with sea level rise, could also promote stratification and increase the risk of cyanobacterial blooms (Paerl and Paul, 2012; Fu *et al.,* 2012). Any of these future conditions, alone or in combination, could trigger the development of cyanobacterial blooms and the release of harmful toxins.

Ecosystem Level Impacts.: An increase in the occurrence of cyanobacterial bloom events would have negative ecosystem and economic consequences including impacts on human health, recreation and aquatic life (Lopez *et al.,* 2008; Anderson *et al.,* 2012; Hudnell, 2010; Lopez *et al.,* 2008; USEPA, 2015a; NSTEPS, 2015). Toxins, associated with bloom events, represent a risk to human health through drinking water and recreational contact. Recent bloom events, such as in 2015 on the Ohio River, demonstrated the challenge that treatment facilities face in providing safe drinking water when encountering extreme blooms (IWG-HABHRCA, 2016). Standard drinking water treatment methods can remove cyanobacterial cells and low levels of cyanotoxins, but additional treatment technologies can be needed, especially when source waters are in the midst of a bloom or confronted with high levels of cyanotoxins (USEPA, 2015b). The effects on recreation, tourism (e.g., closed water bodies, habitat value) and aquaculture (e.g. fishing, shellfish beds) can also be significant but have not been well quantified and documented in the U.S.

Bloom events often kill aquatic organisms directly through the production of algal toxins or indirectly if dissolved oxygen supplies become depleted (NSTEPS, 2015). Hypoxia and cyanobacterial blooms are typically closely associated (Elliott, 2012; Lopez *et al.,* 2008; USEPA, 2015a). Following a bloom, bacterial decomposition of cyanobacterial detritus consumes dissolved oxygen, which may quickly decrease to levels insufficient to sustain most aquatic life, producing hypoxic or anoxic conditions (CENR, 2010). Cyanobacterial blooms also reduce water clarity and prevent sunlight from reaching submerged aquatic vegetation and benthic microalgae, reducing the release of oxygen from photosynthetic plants (IWG-HABHRCA, 2016). In lakes and reservoirs, vertical stratification reduces the rate at which oxygen can replenish deeper waters. As a result, settling and decomposition of organic matter in bottom waters and sediments can rapidly deplete available oxygen in stratified bodies of water (IWG-HABHRCA, 2016). Changes in chlorophyll-a (a measure of cyanobacterial biomass), water clarity, and dissolved oxygen are primary reasons for aquatic life use impairments in U.S. water bodies (USEPA, 2014b).

Sediment

Observed Sensitivity.—Sediment in rivers and streams is derived from upland sources transported by runoff, and from erosion of instream bed and banks. The balance between instream (channel) bed and bank erosion and sediment storage is highly dynamic. If transport (erosion and bank incision) exceeds delivery, degradation occurs. Conversely, where sediment delivery exceeds instream transport capacity, channels can aggrade and store excess sediment (Brakebill *et al.,* 2010; Zhang *et al.,* 2013; James, 2013). Few studies were identified assessing long-term precipitation related trends in sediment loads, but sediment responses to weather events have been widely reported (Jackson *et al.,* 2005; Salant *et al.,* 2008; Jordan *et al.,* 2014; Nichols *et al.,* 2013). Precipitation, together with land use, management and vegetative cover, are considered key drivers of sediment delivery to streams (Belmont, 2010; Jordan *et al.,* 2014; Swank *et al.,* 2014).

In addition to precipitation, changes in air temperature and humidity indirectly affect sediment transport through changes in evapotranspiration, soil moisture and ground cover (vegetation) that influence runoff. Vegetative cover is a key resistive force to erosion from upland areas (Sherrif *et al.,* 2018; SWCS, 2003; O' Neal *et al.,* 2005). In the Southwest, high rates of erosion due to lack of vegetation and steep topography are evident in some locations (Nichols *et al.,* 2013). Lower soil moisture reduces the production of plant biomass, leaving soils more susceptible to erosion (Baruti, 2004; Flanagan and Johnson, 2005). In contrast, high soil moisture can reduce the stability of steep hillslopes, bluffs, and stream banks, increasing sediment input from mass movement. Changes in temperature can also influence erosion rates through effects on soil microbial activity (Frey *et al.,* 2013), rates of organic matter decay (Pietikainen *et al.,* 2005) and the formation of surface crusts on soils (Pruski and Nearing, 2002).

Sediment erosion and delivery to water bodies, and instream bed and bank erosion are driven by precipitation and runoff (Lawler *et al.,* 1997). Many studies have reported that suspended sediment loads strongly correlate with rainfall and runoff (Jackson *et al.,* 2005; Salant *et al.,* 2008; Jordan *et al.,* 2014). Jiang *et al.,* (2014) found that turbidity in different U.S. regions was positively correlated to latitude and generally followed a geographic pattern of greater to lesser turbidity similar to that of average annual precipitation.

The intensity and annual timing (seasonal distribution) of precipitation are also important (Hancock, 2012). Sediment transport is highly episodic, occurring mainly during larger events which mobilize upland sediments (Ffolliott *et al.,* 2013; di Silvio and Basson, 2008; Gellis *et al.,* 2003). Heavy rainfall at times when soils have reduced vegetative cover (e.g., in spring before vegetation ground cover is established) often contribute a big proportion of the annual sediment loads (Poff, 1992; Goode *et al.,* 2012). The timing of rainfall relative to agricultural tillage can therefore be particularly important. In the Chesapeake Bay watershed, sediment loads were found to be highly sensitive to transport during heavy rainfall and high runoff, the dynamics of which are influenced by long-term weather trends as well as decadal-scale oscillations (Langland *et al.,* 2012). Intense rainfall can drive upland sheet erosion, erosion in rills and gullies, mass movements (e.g. landslides), and debris flows (di Silvio and Basson, 2008). During such events, streamflow driven bank incisions and failures (erosion and mass wasting of sediments) can be a major mechanism of erosion in some systems (Lawler *et al.,* 1997; Fraley *et al.,* 2009).

Wildfires in the western U.S. have strongly influenced short term sediment yields in some watersheds (e.g., Snake River basin, Idaho) (Goode *et al.,* 2012; Lancaster *et al.,* 2001). Wildfires typically reduce vegetative cover, expose soils, alter soil physical properties and make large areas of land more susceptible to erosion (Goode *et al.,* 2012). Drought, pests and disease outbreaks also reduce vegetative cover (Sturrock *et al.,* 2011; Wolfe *et al.,* 2008).

Projected Future Changes.—Understanding sediment load responses to potential future changes in air temperature and rainfall is challenging given the importance of episodic, heavy precipitation on erosion and transport. The long-term response of vegetation to increases in air temperature and CO_2, and changes in soil moisture is also central as vegetative cover typically reduces erosion (SWCS, 2003). Annual loads can therefore be dominated by a few heavy precipitation and high runoff events, particularly at times of the year when vegetative cover is minimal. Interactions with the local landscape and watershed conditions, including human activities such as land use change, will thus be important in a changing future. The effects of changing precipitation and runoff patterns on dynamics in different watershed settings will initially depend on whether sediment loads are source limited (i.e. loading varies little with changes in rainfall) *versus* transport limited (i.e. loading increases with increased rainfall) and subsequently whether future conditions cause a watershed to switch states (Goode *et al.,* 2012).

Figure 7 displays the locations of watershed scale studies that assess potential future sediment load responses. Many studies in the northern and eastern U.S. suggest a risk of increased annual loads. These changes broadly correlate with projected increases in annual precipitation and runoff. In parts of the interior West and Southwest, decreases in summer-fall runoff could contribute to lower annual sediment loads. Increased heavy precipitation and runoff events throughout the country (Prein *et al.,* 2016) are expected to increase the risk of episodic high sediment loading to water bodies. Studies broadly concluded that higher soil erosion rates are likely, particularly if increases in heavy precipitation (frequency and intensity) are realized (Pruski and Nearing, 2002; Sun, 2013; Marion *et al.,* 2014; Chang *et al.,* 2010; Wang and Kalin, 2018).

Stored legacy sediments (in floodplains, channel bars, streambeds, and reservoir) have the potential for remobilization as a source of secondary pollution (Langland *et al.,* 2003; Fraley *et al.,* 2009; Carter *et al.,* 2003; James, 2013; Buchty-Lemke *et al.,* 2016; Niemitz *et al.,* 2013). In areas of the mid-Atlantic and Southeast, stored legacy sediment from past agricultural practices and other human activities are currently a major source of in-stream sediment loads (James, 2013). Increased frequency and magnitude of heavy precipitation and runoff could amplify the significance of stored sediments as sources contributing to stream loads in the future.

In drier and warmer areas prone to wildfire, like California, more frequent fire-related impacts on stream sediment loads could occur (Goode *et al.,* 2012). However, studies about future effects on sediment have yet to consider changes due to this type of disturbance.

Ecosystem Level Impacts.: Sediment transport is a natural function of rivers and streams, but is also one of the most common pollutants affecting U.S. water bodies. Natural sediment storage increases the net residence time in a watershed and can provide an ecosystem service (Herman *et al.,* 2003). However, large changes in sediment deposition and transport can alter channel morphology (e.g., slope, channel cross-section) and have substantial effects on the physical habitat necessary to support fish and other aquatic life (USEPA, 2006; Poff, 1992; Brakebill *et al.,* 2010). For aquatic life, excess sediment in the water column can decrease interstitial habitat space (e.g., changes in channel form, infiltration and infilling of gravel and cobble beds), cause loss of suitable habitat, reduce light penetration and impact spawning and hatching (e.g., limiting oxygen amounts in the spawning beds, and trap newly hatched fish) (Waters, 1995; Wood and Armitage, 1997; USEPA, 2006). In addition, changes in the streambed sediment volume can affect flow depth, conduction, and hyporheic exchange, which influence water temperature and pollutant processing (Caissie, 2006). Suspended sediment and turbidity concentrations also influence water temperature through effects on the absorption or reflection of solar radiation - high turbidity focuses solar energy on the upper part of the water column. It should be noted, however, that it can be difficult to separate the direct effects of sediments from other changes that are interrelated (e.g., streamflow) and affect biota (Bond and Downes, 2003).

Excessive sediment loading often introduces high levels of sediment-adsorbed pollutants (e.g., pathogens, nutrients, metals, and toxic substances) to water bodies that can present a risk to human and ecosystem health (Stout *et al.,* 2014; Ahmadi et al 2014; Ffolliott *et al.,* 2013; Ficklin *et al.,* 2010; Ahmadi *et al.,* 2014). Concentrations of particle adsorbed pathogenic microorganisms are often higher than those dissolved in the water column (Kim *et al.,* 2010; deBrauwere *et al.*, 2014), and several studies have shown elevated turbidity to be correlated with increased outbreaks of waterborne illness (Morris *et al.,* 1996; Schwartz *et al.,* 1997). Elevated levels of sediment particles in source waters can therefore be an issue for drinking water treatment by causing physical disruption to filtration processes and other treatments challenges related to adsorbed pollutants (e.g., disinfection of pathogens and disinfection by-product formation).

Pathogens

Observed Sensitivity.—The occurrence of microbial pathogens in water bodies is influenced by temperature which affects survival, and precipitation that drives the transport of fecal waste (which may contain pathogenic organisms) from upland sources (Figure 8). Sunlight, moisture conditions, salinity, and other factors also influence survival in the natural environment (USEPA, 2001). Most waterborne pathogens sourced to fecal waste (e.g., pathogenic *E. coli*) can survive for long periods in different environmental matrices (e.g., soil, manure, and water) when temperatures are low, when they are protected from external factors such as ultraviolet radiation, and when appropriate moisture and nutrients are available (Tyrrel and Quinton, 2003; USEPA, 2013; Rogers and Haines, 2005; Pommepuy *et al.,* 1992).

Pathogenic *E. coli* can survive longer in water bodies at lower temperatures and up to two or three times longer in river and lake sediments (bedded sediment can provide sufficient moisture, availability of nutrients and protection from sunlight) (USEPA, 2009a; Davies *et al.,* 1995; Decamp and Warren, 2000; Jamieson *et al.,* 2004; Koirala *et al.,* 2008; Kim *et al.,* 2010; Characklis *et al.,* 2005; Sherer *et al.,* 1992). Protozoans, such as *Giardia* and *Cryptosporidium*, can survive from months to more than 1 year in cool water (approximately 5 °C or less) (Ziemer *et al.,* 2010).

At temperatures exceeding 30 degrees (°C), survival rates for pathogens sourced to fecal waste have been shown to decrease (Rogers and Haines, 2005; USEPA, 2001; Hofstra, 2011; Vermeulen and Hofstra, 2014; Herrador *et al.,* 2015).

However, warm summer temperatures can also contribute to human exposure by extending the period of warm-weather recreational uses. In addition, higher water temperatures provide more favorable conditions for some naturally occurring organisms, like *Naegleria fowleri*, and *Vibrio* spp. in coastal systems. Two documented cases of *Naegleria fowleri* infection in Arkansas were associated with exceptionally warm water temperatures during periods in which air temperatures were above 37 °C degrees. Health officials reported elevated water temperatures (and other factors) as being conducive to *Naegleria fowleri* at the time of exposure (Matthews *et al.,* 2014). Jiang *et al.,* (2015) reported increases in waterborne and food-borne salmonellosis risk in Maryland during extreme temperatures based on a 30-year baseline (i.e., 1960 – 2012).

Fecal bacteria levels in water bodies usually correlate positively with precipitation and runoff (Curriero *et al.,* 2001; Kistemann *et al.,* 2002; Schijven and Husman 2005; Nichols *et al.,* 2009; Kratt *et al.,* 2010; Hofstra 2011; Funari *et al.,* 2012; Cann *et al.,* 2013; Herrador *et al.,* 2015; Tryland *et al.,* 2011; Vermeulen and Hofstra, 2014). Precipitation driven sediment transport can also be important in governing the mobility and loading of sediment-adsorbed microorganisms (Kim *et al.,* 2010; de Brauwere et al 2014; Soupir and Pandey, 2016). Many waterborne disease outbreaks have been shown to be associated with heavy rainfall (Figure 8) (WHO, 2003; Rizak and Hrudey, 2008; Curriero *et al.,* 2001; Kistemann *et al.,* 2002; Cann *et al.,* 2013) and elevated turbidity (Abia *et al.,* 2016; Morris *et al.,* 1996; Schwartz *et al.,* 1997). For example, Curriero *et al.,* (2001) analyzed 548 waterborne disease outbreaks that occurred in the U.S. between 1948 and 1994 and found that over half of them were preceded by heavy rainfall. Severe winter storms and snowmelt were linked in part with the largest reported cryptosporidiosis outbreak in the U.S., which occurred in Milwaukee in 1993 (MacKenzie *et al.,* 1994). In Maryland's portion of the Chesapeake Bay, annual and seasonal precipitation totals from 1979 to 2013 had a strong positive relationship with average fecal bacteria levels in shellfish harvest waters (Leight *et al.,* 2016).

Frequent high fecal bacteria levels at times of no precipitation are typically connected to land management factors such as point sources discharges or failing septic/sewer systems (Cahoon *et al.,* 2016). In several locations, periods of dry weather followed by heavy rainfall have also preceded outbreaks of waterborne disease (TDOH, 1999; Patz *et al.,* 2000; Funari *et al.,* 2012). Extended dry periods can allow fecal waste to accumulate on land (e.g., beaches, pastures, forestry) and then be flushed by precipitation and runoff into water bodies (Stewart *et al.,* 2013; Funari *et al.,* 2012).

Many studies indicate that heavy precipitation and other weather events have been contributing factors to outbreaks of waterborne disease in the U.S. (see Figure 9). However, it is worth noting, that the interactions of human activities and management (e.g., water treatment failures) with extreme weather events are responsible in many outbreak instances.

Projected Future Changes.—Projected increases in temperature together with changes in precipitation and runoff are expected to alter pathogen survival and transport to water bodies (Trtanj *et al.,* 2016; Hofstra, 2011; Coffey *et al.,* 2014). Relatively few studies, however, use numerical modeling to assess potential future changes in pathogen fate and transport in U.S. water bodies (see Figure 9). Modeling work in Virginia, Mississippi, and Illinois suggests increased fecal indicator bacteria loads (FIB - indicate the potential presence of pathogenic organisms) in a changing future (Coffey *et al.,* 2015a, b; Liu *et al.,* 2010; Jayakody *et al.,* 2015; Patz *et al.,* 2008). Other theoretical studies suggest an increased risk of human exposure and waterborne illnesses (Lo Iacono *et al.,* 2017; Trtanj *et al.,* 2016; Levy *et al.,* 2016; Vavrus and Behnke, 2014; Uejio *et al.,* 2014; Coffey *et al.,* 2014; Jiang *et al.,* 2015).

Higher air and water temperatures, projected throughout the U.S. (Melillo *et al.,* 2014; Hill *et al.,* 2014), are expected to reduce survival rates for some common organisms sourced to fecal waste, such as pathogenic strains of *E. coli* (Schijven and Husman, 2005). Other species like naturally occurring *Vibrio* spp. and *Legionella* grow faster in warmer water and may become more prevalent geographically and seasonally (Lipp *et al.,* 2002; Jacobs *et al.,* 2015; Trtanj *et al.,* 2016; Najjar *et al.,* 2010). Warmer temperatures could also lead to the spatial expansion of new microorganisms (e.g., such as amoeboid pathogens *Naegleria* and *Acanthamoeba*), vectors, and intermediary hosts (Harrus and Baneth, 2005; Hoskisson and Trevors, 2010).

Future changes in precipitation and runoff are likely to present an increased risk of non-point source fecal waste loading (e.g., NPSs as well as urban sanitary sewer overflows and combined sewer overflows) to water bodies. The delivery of fecal waste (which can contain pathogenic organisms) to water bodies is largely episodic, driven by rainfall. While uncertainty remains regarding regional changes in rainfall (USGRCP, 2017), future increases in the proportion occurring in large-magnitude events increase the likelihood of loading (dissolved and adsorbed to sediment) from upland fecal sources (Hofstra, 2011; Coffey *et al.,* 2014; Cann *et al.,* 2013; Trtanj *et al.,* 2016; Strauch *et al.,* 2014). Associated high streamflow volumes could also re-suspend and mobilize microorganisms stored in river and lake bed sediments (Soupir and Pandey, 2016; Wu *et al.,* 2009; Garzio-Hadzick *et al.,* 2010). In addition, potential increases in dissolved organic matter and browning of water bodies during heavy precipitation events has the potential to reduce solar UV inactivation of pathogens (Williamson *et al.,* 2017).

Dry periods are expected to become common in many regions, particularly in the mountain west and interior southwest (Melillo *et al.,* 2014). Lower flow volumes and reduced dilution during these periods could result in episodic increases in fecal waste levels downstream of point-source discharges (e.g., wastewater treatment plants) (Senhorst and Zwolsman, 2005; Johnson *et al.,* 2009; Hofstra, 2011; Funari *et al.,* 2012; Cann *et al.,* 2013; Coffey *et al.,* 2014; Strauch *et al.,* 2014).

In coastal and estuarine waters, future changes in salinity due to sea level rise could affect pathogen survival (Burge *et al.,* 2014). Most waterborne pathogens have significantly lower survival rates in high-salinity environments than in less saline environments (Canteras *et al.,* 1995; Bordalo *et al.,* 2002). However, *Vibrio vulnificus* favors more moderate salinities, while *Vibrio parahaeomolyticus* and *Vibrio alginolyticus* favor higher salinities (Trtanj *et al.,* 2016; Urquhart *et al.,* 2014).

Ecosystem Level Impacts.: An increased risk of human exposure to pathogens through drinking water and recreational contact is anticipated across the U.S. due to warming air temperatures and changing precipitation patterns (pathways are illustrated in Figure 8) (Coffey *et al.,* 2014; Sterk *et al.,* 2013). Communities relying on untreated drinking water sources (e.g., private groundwater wells and other sources not served by a treated supply) are likely to be at greater risk of exposure and waterborne illness (Pons *et al.,* 2015). Many previous waterborne disease outbreaks have been linked to drinking water supplies sourced from groundwater - shallow groundwater wells influenced by surface runoff are more vulnerable to precipitation driven fecal contamination (Levin *et al.,* 2002). In source waters used for treated drinking supply (where disinfection and filtration are effective at removing pathogens), utilities may face challenges from increased microbial contamination. For example, a higher level of disinfection (e.g., chlorination and ozone) could be required to inactivate pathogens, which would increase the potential for generation of disinfection by-products, many of which have negative human health consequences (USEPA, 2009c).

Maintaining water bodies within existing recreational water quality standards could also be an issue if projected increases in microbial loads are realized. Many waterborne illnesses occur from recreational water use during warmer weather (DeFlorio-Barker *et al.,* 2018; Hlavsa *et al.,* 2014; Curriero *et al.,* 2001; Freeman *et al.,* 2009; McBride *et al.,* 2014). Higher seasonal air temperatures are expected to expand the window of recreational water use and increase the risk of human exposure to waterborne pathogens (Casman *et al.,* 2001; Schijven and Husman, 2005). Additionally, more frequent violations of U.S. recreational water quality standards have been projected in some studies (Coffey *et al.,* 2015a, b; Liu *et al.,* 2010; Jayakody *et al.,* 2015).

FUTURE RESEARCH

This review suggests that anticipated future increases in air temperature and changes in precipitation present an increased risk of water quality and ecosystem degradation in many U.S. locations. Responding to this challenge requires a more detailed understanding of key vulnerabilities in different regional and watershed settings, and the development of effective adaptation strategies to reduce risks. Research needs emerging from this review to improve understanding and better inform management responses include the following:

i. Knowledge of potential future water quality responses is limited by the small number of studies that currently exist. Water quality is highly variable spatially among U.S. regions and in specific watershed settings, and temporally during the year in response to runoff. These spatial gaps can pose challenges for decision makers, who need to make specific decisions in the best interest of their programs (Watts *et al.,* 2015). More watershed scale assessments applying consistent approaches are needed to extend our geographic understanding, allow spatial comparisons and identify areas at most risk. This is essential to broaden our understanding of potential future responses and inform the development of local-scale response strategies for managing future water quality risks.

ii. Observed trends in water quality typically reflect the interaction between climatic variability, changes in land use, changes in management and other factors. This makes attribution of changes to specific drivers difficult. Efforts to link specific water quality changes over time to climate and weather events would add to our knowledge about responses in different watershed settings. Many current studies of observed responses to climate effects are limited to a relatively short temporal window of data availability (e.g., 1990s to 2010s) or sparse spatial distribution. Relationships between trends and climatic drivers are also often obscured by changes in other factors such as land use. Expansion and continuation of existing, long-term water quality monitoring networks could thus reveal new insights into the drivers of trends. For example, many Long Term Ecological Research sites (see https://lternet.edu/site/) (and others) continuously monitor changes in water quality, providing unique opportunities to examine connections between water quality trends and climate (Morse and Wollheim, 2014; Ford *et al.,* 2011; Worrall *et al.,* 2003; Sun *et al.,* 2008). New technologies should also be explored and/or expanded such as use of continuous in-situ monitoring, regular remotely sensed monitoring, or other approaches that can provide efficient, accurate, and reliable detection and tracking of observed water quality responses (Schaeffer *et al.,* 2015; Urquhart *et al.,* 2017; Paerl and Huisman, 2009; Brooks *et al.,* 2016).

iii. Improving the way uncertainties are characterized and communicated, particularly those associated with long-term changes in precipitation, is needed to best inform management decision making (Helgeson, 2018; Watts *et al.,* 2015; Johnson *et al.,* 2015). Precipitation and runoff are well known drivers of pollutant loading and most responses correlate with changes in precipitation. Also, effects of warming air temperatures on water quality are understood with a relatively high level of confidence. Effectively communicating relative confidence of potential impacts in a way that's meaningful to decision makers would better inform risk management.

iv. Advancing models and methods used to simulate water quality responses to future scenarios can provide additional confidence in projections. Simulations of pollutant fate and transport can be subject to error (Novotny and Stefan, 2007), and inadequacies have been reported in many studies (Tu, 2009; Crossman *et al.,* 2013; Jha *et al.,* 2015; Johnson *et al.,* 2015). Areas of concern include sediment resuspension processes (Jamieson *et al.,* 2004; Droppo *et al.,* 2009; Coffey *et al.,* 2010a, 2010b), subsurface transport, and capabilities to simulate pollutant responses during extreme flow events (Benham *et al.,* 2006; Beckers *et al.,* 2009). In addition, modeling cyanobacterial blooms is currently difficult due to the many causal factors that can initiate events (Brooks *et al.,* 2016; Lopez *et al.,* 2008; Ho and Michalak, 2015).

v. Given the risk of potentially large water quality changes, perhaps most importantly, information is needed about the type, extent and performance of Best Management Practices (BMPs) necessary to meet management objectives under changing future conditions (Alam *et al.,* 2017; Sun *et al.,* 2008). Increases in air temperature and altered precipitation, are expected to affect the performance of BMPs designed to remove pollutants (Wagena and Easton, 2018). For example, more intense precipitation increases erosion and transport from agricultural fields, increases leaching through sub-surface pathways, and reduces contact time in practices that rely on filtration. BMP performance can also be affected by changes in plant growth (e.g., for filter strips or cover crops), by increased rates of decay of surface residue, and more rapid cycling of nutrients under warmer conditions. Impacts on water quality will ultimately depend on the effectiveness of management responses (e.g., BMPs) which may not have been designed to cope with anticipated pressures (Wear and Greis, 2012). Successful adaptation strategies should therefore emphasize flexibility and robustness, and will need to select BMPs that reduce vulnerabilities across a wide range of possible future conditions (Heisler *et al.,* 2008).

SUMMARY AND CONCLUSIONS

In this paper we review the historical and potential future effects of changes in air temperature and precipitation on nutrients, cyanobacterial blooms, sediment and waterborne pathogens. Water quality changes are complex and affected by multiple, interacting climatic, watershed and human factors. This review focuses only on water quality responses to changes in climatic drivers.

Future changes in nutrients, sediment, waterborne pathogens and cyanobacterial blooms will increase the risk of water quality and ecosystem degradation in many U.S. locations. There is, however, a high degree of spatial and temporal variability among watersheds. Increasing variability of precipitation is anticipated throughout the U.S., including a greater proportion of annual precipitation occurring in heavy events, and longer dry periods between events. Projected water quality responses in different locations reflect these changes, with many studies suggesting future changes in nutrient, sediment and fecally sourced pathogen loads that correlate with projected precipitation.

Increased air and water temperatures could have wide ranging impacts on water quality, aquatic life and human use. An expanded seasonal window of warm water temperatures and the potential for more frequent episodic nutrient loading (associated with increased heavy precipitation) will increase the risk of cyanobacterial blooms in large rivers, lakes and estuaries. Warmer air and water temperatures are expected to reduce survival for some waterborne pathogens sourced to fecal waste (e.g., pathogenic *E. coli*) but increase survival and northward expansion of others (e.g., naturally occurring *Naegleria fowleri*, and *Vibrio* species in coastal systems).

Managing the risk of harmful impacts will require adaptation strategies that reduce vulnerabilities in different watershed settings, across a range of plausible future conditions. An improved understanding of the ability to manage anticipated impacts can provide a more complete assessment of where and how watersheds are vulnerable.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Research Impact Statement: Climate change will have direct and cascading effects on water quality that vary in different regional and watershed settings, and could present a risk to human health and the environment.

LITERATURE CITED

Abia AL, Ubomba-Jaswa E, Genthe B, and Momba MN. 2016. "Quantitative Microbial Risk Assessment (Qmra) Shows Increased Public Health Risk Associated with Exposure to River Water under Conditions of Riverbed Sediment Resuspension." Science of The Total Environment 566–567:1143–1151. 10.1016/j.scitotenv.2016.05.155.

Ahmadi M, Records R, and Arabi M. 2014. "Impact of Climate Change on Diffuse Pollutant Fluxes at the Watershed Scale." Hydrological Processes 28 (4):1962–1972. 10.1002/hyp.9723.

Alam MJ, and Dutta D. 2013. "Predicting Climate Change Impact on Nutrient Pollution in Waterways: A Case Study in the Upper Catchment of the Latrobe River, Australia." Ecohydrology 6 (1):73–82. 10.1002/eco.282.

Alam MJ, Goodall JL, Bowes BD and Girvetz EH, 2017. The Impact of Projected Climate Change Scenarios on Nitrogen Yield at a Regional Scale for the Contiguous United States. JAWRA Journal of the American Water Resources Association, 53(4), pp.854–870. 10.1111/1752-1688.12537

Andersen HE, Kronvang B, Larsen SE, Hoffmann CC, Jensen TS, and Rasmussen EK. 2006. "Climate-Change Impacts on Hydrology and Nutrients in a Danish Lowland River Basin." Science of The Total Environment 365 (1–3):223–237. 10.1016/j.scitotenv.2006.02.036.

Anderson DM, Cembella AD, and Hallegraeff GM. 2012. "Progress in Understanding Harmful Algal Blooms: Paradigm Shifts and New Technologies for Research, Monitoring, and Management." Annual Review of Marine Science 4:143–176. 10.1146/annurev-marine-120308-081121.

Arnell NW 2003. "Effects of Ipccsres Emissions Scenarios on River Runoff: A Global Perspective." Hydrology and Earth System Sciences 7 (5):619–641. 10.5194/hess-7-619-2003

Baruti JHM 2004. "Study of Soil Moisture in Relation to Soil Erosion in the Proposed Tancítaro Geopark, Central Mexico: A Case of the Zacandaro Sub-Watershed." International Institute for Geo-Information Science and Earth Observation.

Battarbee RW, Anderson NJ, Bennion H, and Simpson GL. 2012. "Combining Limnological and Palaeolimnological Data to Disentangle the Effects of Nutrient Pollution and Climate Change on Lake Ecosystems: Problems and Potential." Freshwater Biology 57 (10):2091–2106. 10.1111/j.1365-2427.2012.02860.x.

Beckers J, Smerdon B, and Wilson M. 2009. Review of Hydrologic Models for Forest Management and Climate Change Applications in British Columbia and Alberta. Kamloops, British Columbia, Canada, www.forrex.org/publications/forrexseries/fs25.pdf.

Belmont P. 2010. "Sediment Budget for Source Analysis: Le Sueur Watershed, Minnesota." 2nd Joint Federal Interagency Conference, Las Vegas, NV, June 27 - July 1, 2010.

Benham BL, Baffaut C, Zeckoski RW, Mankin KR, Pachepsky YA, Sadeghi AA, Brannan KM, Soupir ML, and Habersack MJ. 2006. "Modeling Bacteria Fate and Transport in Watersheds to Support TMDLs." Transactions of the Asabe 49 (4):987–1002. 10.13031/2013.21739

Belval DL and Sprague LA. 1999. Monitoring Nutrients in the Major Rivers Draining to Chesapeake Bay. U.S. Department of the Interior, U.S. Geological Survey Water-Resources Investigations Report 99–4238. https://va.water.usgs.gov/online_pubs/WRIR/99-4238/wrir_99_4238_text.pdf

Birsan MV, Molnar P, Burlando P, and Pfaundler M. 2005. "Streamflow Trends in Switzerland." Journal of Hydrology 314 (1–4):312–329. 10.1016/j.jhydrol.2005.06.008.

Bond NR, and Downes BJ. 2003. "The Independent and Interactive Effects of Fine Sediment and Flow on Benthic Invertebrate Communities Characteristic of Small Upland Streams." Freshwater Biology 48:455–465. 10.1046/j.1365-2427.2003.01016.x

Bordalo AA, Onrassami R, and Dechsakulwatana C. 2002. "Survival of Faecal Indicator Bacteria in Tropical Estuarine Waters (Bangpakong River, Thailand)." Journal of Applied Microbiology 93 (5):864–871. 10.1046/j.1365-2672.2002.01760.x. [PubMed: 12392534]

Borges AV, and Gypens N. 2010. "Carbonate Chemistry in the Coastal Zone Responds More Strongly to Eutrophication Than to Ocean Acidification." Limnology and Oceanography 55 (1):346–353. 10.4319/lo.2010.55.1.0346.

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Boyacioglu H, Vetter T, Krysanova V, and Rode M. 2012. "Modeling the Impacts of Climate Change on Nitrogen Retention in a 4th Order Stream." Climatic Change 113 (3–4):981–999. 10.1007/s10584-011-0369-1.

Brakebill JW, Ator SW, and Schwarz GE. 2010. "Sources of Suspended-Sediment Flux in Streams of the Chesapeake Bay Watershed: A Regional Application of the Sparrow Model." Journal of the American Water Resources Association 46 (4):757–776. 10.1111/j.1752-1688.2010.00450.x

Bricker SB, Longstaf B, Dennison W, Jones A, Boicourt K, Wicks C, and Woerner J. 2008. "Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change." Harmful Algae 8 (1):21–32. 10.1016/j.hal.2008.08.028.

Brooks BW, Lazorchak JM, Howard MD, Johnson MV, Morton SL, Perkins DA, Reavie ED, Scott GI, Smith SA, and Steevens JA. 2016. "Are Harmful Algal Blooms Becoming the Greatest Inland Water Quality Threat to Public Health and Aquatic Ecosystems?" Environmental Toxicology Chemistry 35 (1):6–13. 10.1002/etc.3220. [PubMed: 26771345]

Brooks PD, and Williams MW. 1999. "Snowpack Controls on Nitrogen Cycling and Export in Seasonally Snow-Covered Catchments." Hydrological Processes 13 (14–15):2177–2190. 10.1002/(sici)1099-1085(199910)13:14/15<2177:aid-hyp850>3.0.co;2-v.

Buchty-Lemke M, Frings R, Hagemann L, Lehmkuhl F, Maaß AL, and Schwarzbauer J. 2016. "Changes of Floodplain Morphology by Water Mills: Legacy Sediments Stored Behind Mill Dams as Archive and Source for Pollution - Examples from the Wurm River, Lower Rhine Embayment, Germany." Geophysical Research Abstracts 18 (EGU2016–5949).

Burge CA, Eakin CM, Friedman CS, Froelich B, Hershberger PK, Hofmann EE, Petes LE, Prager KC, Weil E, Willis BL, Ford SE, and Harvell CD. 2014. "Climate Change Influences on Marine Infectious Diseases: Implications for Management and Society." Annual Review of Marine Science 6:249–277. 10.1146/annurev-marine-010213-135029

Cahoon LB, Hales JC, Carey ES, Loucaides S, Rowland KR, and Toothman BR. 2016. "Multiple Modes of Water Quality Impairment by Fecal Contamination in a Rapidly Developing Coastal Area: Southwest Brunswick County, North Carolina." Environmental Monitoring and Assessment 188 (2):89. 10.1007/s10661-015-5081-6. [PubMed: 26769702]

Cai WJ, Hu XP, Huang WJ, Murrell MC, Lehrter JC, Lohrenz SE, Chou WC, Zhai WD, Hollibaugh JT, Wang YC, Zhao PS, Guo XH, Gundersen K, Dai MH, and Gong GC. 2011. "Acidification of Subsurface Coastal Waters Enhanced by Eutrophication." Nature Geoscience 4 (11):766–770. 10.1038/ngeo1297.

Caissie D. 2006. "The Thermal Regime of Rivers: A Review." Freshwater Biology 51 (8):1389–1406. 10.1111/j.1365-2427.2006.01597.x.

Cann KF, Thomas DR, Salmon RL, Wyn-Jones AP, and Kay D. 2013. "Extreme Water-Related Weather Events and Waterborne Disease." Epidemiology and Infection 141 (4):671–686. 10.1017/s0950268812001653. [PubMed: 22877498]

Canteras JC, Juanes JA, Perez L, and Koev KN. 1995. "Modeling the Coliforms Inactivation Rates in the Cantabrian Sea (Bay of Biscay) from in-Situ and Laboratory Determinations of T-90." Water Science and Technology 32 (2):37–44. 10.1016/0273-1223(95)00567-7.

Carter J, Owens PN, Walling DE, and Leeks GJL. 2003. "Fingerprinting Suspended Sediment Sources in a Large Urban River System." Science of the Total Environment 314–316:513–534. 10.1016/S0048-9697(03)00071-8.

Casman E, Fischhoff B, Small M, Dowlatabadi H, Rose J, and Morgan MG. 2001. "Climate Change and Cryptosporidiosis: A Qualitative Analysis." Climatic Change 50 (1–2):219–249. 10.1023/a:1010623831501.

CENR (Committee on Environment and Natural Resources). 2010. Scientific Assessment of Hypoxia in U.S. Coastal Waters. Washington, DC. 164.

Chang H, Jones J, Gannett M, Tullos D, Moradkhani H, Vache K Parandvash H, Shandas V, Nolin A, fountain A, Johnson S, Jung IW, House-Peters L, Steele M, and Copeland B, 2010. "Climate Change and Fresh Water Resources in Oregon." In Oregon Climate Change Research Institute, Oregon Climate Assessment Report, Dello KD and Mote PW(Eds.) College of Oceanic and Atmospheric Sciences, Oregon State University, Corvalis, OR. http://archives.pdx.edu/ds/psu/8421

Chapra SC, Boehlert B, Fant C, Bierman VJ, Henderson J, Mills D, Mas DML, Rennels L, Jantarasami L, Martinich J, Strzepek KM, and Paerl HW. 2017. “Climate Change Impacts on Harmful Algal Blooms in U.S. Freshwaters: A Screening-Level Assessment.” Environmental Science & Technology 51 (16):8933–8943. 10.1021/acs.est.7b01498. [PubMed: 28650153]

Characklis GW, Dilts MJ, Simmons OD, Likirdopulos CA, Krometis LAH, and Sobsey MD. 2005. “Microbial Partitioning to Settleable Particles in Stormwater.” Water Research 39 (9):1773–1782. 10.1016/j.watres.2005.03.004. [PubMed: 15899275]

Coffey R, Benham B, Kline K, Wolfe ML, and Cummins E. 2015a. “Modeling the Impacts of Climate Change and Future Land Use Variation on Microbial Transport.” Journal of Water and Climate Change 6 (3):449–471. 10.2166/wcc.2015.049

Coffey R, Benham B, Kline K, Wolfe ML, and Cummins E. 2015b. “Potential Microbial Load Reductions Required to Meet Existing Freshwater Recreational Water Quality Standards for a Selection of Mid-Century Environmental Change Scenarios.” Environmental Processes 2 (4):609–629. 10.1007/s40710-015-0114-2.

Coffey R, Benham B, Krometis L-A, Wolfe ML, and Cummins E. 2014. “Assessing the Effects of Climate Change on Waterborne Microorganisms: Implications for EU and U.S. Water Policy.” Human and Ecological Risk Assessment: An International Journal 20 (3):724–742. 10.1080/10807039.2013.802583.

Coffey R, Cummins E, O’Flaherty V, and Cormican M. 2010a. “Analysis of the Soil and Water Assessment Tool (Swat) to Model Cryptosporidium in Surface Water Sources.” Biosystems Engineering 106 (3):303–314. 10.1016/j.biosystemseng.2010.04.003.

Coffey R, Cummins E, Bhreathnach N, Flaherty VO, and Cormican M. 2010b. “Development of a Pathogen Transport Model for Irish Catchments Using Swat.” Agricultural Water Management 97 (1):101–111. 10.1016/j.agwat.2009.08.017.

Collier SA, Stockman LJ, Hicks LA, Garrison LE, Zhou FJ, and Beach MJ. 2012. “Direct Healthcare Costs of Selected Diseases Primarily or Partially Transmitted by Water.” Epidemiology and Infection 140 (11):2003–2013. 10.1017/s0950268811002858. [PubMed: 22233584]

Creed IF, and Band LE. 1998. “Export of Nitrogen from Catchments within a Temperate Forest: Evidence for a Unifying Mechanism Regulated by Variable Source Area Dynamics.” Water Resources Research 34 (11):3105–3120. 10.1029/98WR01924

Crossman J, Futter MN, Oni SK, Whitehead PG, Jin L, Butterfield D, Baulch HM, and Dillon PJ. 2013. “Impacts of Climate Change on Hydrology and Water Quality: Future Proofing Management Strategies in the Lake Simcoe Watershed, Canada.” Journal of Great Lakes Research 39 (1):19–32. 10.1016/j.jglr.2012.11.003.

Curriero FC, Patz JA, Rose JB, and Lele S. 2001. “The Association between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994.” American Journal of Public Health 91 (8):1194–1199. 10.2105/ajph.91.8.1194. [PubMed: 11499103]

Davies CM, Long JAH, Donald M, and Ashbolt NJ. 1995. “Survival of Fecal Microorganisms in Marine and Fresh-Water Sediments.” Applied and Environmental Microbiology 61 (5):1888–1896. 10.1029/98WR01924 [PubMed: 7646026]

de Brauwere A, Ouattara NK, and Servais P. 2014. “Modeling Fecal Indicator Bacteria Concentrations in Natural Surface Waters: A Review.” Critical Reviews in Environmental Science and Technology 44 (21):2380–2453. 10.1080/10643389.2013.829978.

Decamp O, and Warren A. 2000. “Investigation of Escherichia Coli Removal in Various Designs of Subsurface Flow Wetlands Used for Wastewater Treatment.” Ecological Engineering 14 (3):293–299. 10.1016/s0925-8574(99)00007-5.

DeFlorio-Barker S, Wing C, Jones RM and Dorevitch S. 2018. Estimate of incidence and cost of recreational waterborne illness on United States surface waters. Environmental Health, 17(1), p.3. 10.1186/s12940-017-0347-9 [PubMed: 29316937]

di Silvio G, and Basson G. 2008. Erosion and Sediment Dynamics from Catchment to Coast. International Hydrological Program (IHP) Technical Documents in Hydrology No. 82., UNESCO, Paris. 48. https://www.protos.ngo/sites/default/files/library_assets/312_DIS_E13_erosion_sediment.pdf

Donner SD and Scavia D. 2007. How climate controls the flux of nitrogen by the Mississippi River and the development of hypoxia in the Gulf of Mexico. Limnology and oceanography, 52(2), pp.856–861. 10.4319/lo.2007.52.2.0856

Droppo IG, Liss SN, Williams D, Nelson T, Jaskot C, and Trapp B. 2009. “Dynamic Existence of Waterborne Pathogens within River Sediment Compartments. Implications for Water Quality Regulatory Affairs.” Environmental Science & Technology 43 (6):1737–1743. 10.1021/es802321w. [PubMed: 19368165]

Duan SW, and Kaushal SS. 2013. “Warming Increases Carbon and Nutrient Fluxes from Sediments in Streams across Land Use.” Biogeosciences 10 (2):1193–1207. 10.5194/bg-10-1193-2013.

Duarte CM, Hendriks IE, Moore TS, Olsen YS, Steckbauer A, Ramajo L, Carstensen J, Trotter JA, and McCulloch M. 2013. “Is Ocean Acidification an Open-Ocean Syndrome? Understanding Anthropogenic Impacts on Seawater Ph.” Estuaries and Coasts 36 (2):221–236. 10.1007/s12237-013-9594-3.

Dubrovsky NM, Burow KR, Clark GM, Gronberg JM, Hamilton PA, Hitt KJ, Mueller DK, Munn MD, Nolan BT, Puckett LJ, Rupert MG, Short TM, Spahr NE, Sprague LA, and Wilber WG. 2010. The Quality of Our Nation’s Water—Nutrients in the Nation’s Streams and Groundwater, 1992–2004. Circular 1350. Reston, VA. 184.

Elliott JA 2012. “Is the Future Blue-Green? A Review of the Current Model Predictions of How Climate Change Could Affect Pelagic Freshwater Cyanobacteria.” Water Research 46 (5):1364–1371. doi.10.1016/j.watres.2011.12.018. [PubMed: 22244968]

Evans-White MA, Dodds WK, Huggins DG, and Baker DS. 2009. “Thresholds in Macroinvertebrate Biodiversity and Stoichiometry across Water-Quality Gradients in Central Plains (USA) Streams.” Journal of the North American Benthological Society 28 (4):855–868. 10.1899/08-113.1.

Fant C, Srinivasan R, Boehlert B, Rennels L, Chapra SC, Strzepek KM, Corona J, Allen A. and Martinich J, 2017. Climate change impacts on US water quality using two models: HAWQS and US basins. Water, 9(2), p.118. 10.3390/w9020118

Feminella JW, and Hawkins CP. 1995. “Interactions between Stream Herbivores and Periphyton: A Quantitative Analysis of Past Experiments.” Journal of the North American Benthological Society 14 (4):465–509. 10.2307/1467536.

Ffolliott PF, Brooks KN, Neary DG, Tapia RP, and Garcia-Chevesich P. 2013. “Soil Erosion and Sediment Production on Watershed Landscapes: Processes and Control.” International Hydrological Programme for Latin America and the Caribbean:73.

Ficklin DL, Luo Y, Luedeling E, Gatzke S, and Zhang M. 2010. “Sensitivity of Agricultural Runoff Loads to Rising Levels of Co2 and Climate Change in the San Joaquin Valley Watershed of California.” Environmental Pollution 158 (1):223–234. 10.1016/j.envpol.2009.07.016. [PubMed: 19660846]

Ficklin DL, Stewart IT, and Maurer EP. 2013. “Climate Change Impacts on Streamflow and Subbasin-Scale Hydrology in the Upper Colorado River Basin.” PLoS ONE 8 (8):e71297. 10.1371/journal.pone.0071297.

Flanagan LB, and Johnson BG. 2005. “Interacting Effects of Temperature, Soil Moisture and Plant Biomass Production on Ecosystem Respiration in a Northern Temperate Grassland.” Agricultural and Forest Meteorology 130 (3–4):237–253. 10.1016/j.agrformet.2005.04.002.

Ford CR, Laseter SH, Swank WT, and Vose JM. 2011. Can forest management be used to sustain water-based ecosystem services in the face of a changing climate? Ecological Applications 21(6): 2049–2067. 10.1890/10-2246.1 [PubMed: 21939043]

Fraley LM, Miller AJ, and Welty C. 2009. “Contribution of in-Channel Processes to Sediment Yield of an Urbanizing Watershed.” Journal of the American Water Resources Association 45 (3):748–766. 10.1111/j.1752-1688.2009.00320.x.

Freeman JT, Anderson DJ, and Sexton DJ. 2009. “Seasonal Peaks in Escherichia Coli Infections: Possible Explanations and Implications.” Clinical Microbiology and Infection 15 (10):951–953. 10.1111/j.1469-0691.2009.02866.x. [PubMed: 19845705]

Frey SD, Lee J, Melillo JM, and Six J. 2013. “The Temperature Response of Soil Microbial Efficiency and Its Feedback to Climate.” Nature Clim. Change 3 (4):395–398. https://http://www.nature.com/nclimate/journal/v3/n4/abs/nclimate1796.html#supplementary-information.

Fu FX, Tatters AO, and Hutchins DA. 2012. “Global Change and the Future of Harmful Algal Blooms in the Ocean.” Marine Ecology Progress Series 470:207–233. 10.3354/meps10047.

Funari E, Manganelli M, and Sinisi L. 2012. “Impact of Climate Change on Waterborne Diseases.” Annali Dell Istituto Superiore Di Sanita 48 (4):473–487. 10.4415/ann_12_04_13. [PubMed: 23247142]

Garzio-Hadzick A, Shelton DR, Hill RL, Pachepsky YA, Guber AK, and Rowland R. 2010. “Survival of Manure-Borne E. Coli in Streambed Sediment: Effects of Temperature and Sediment Properties.” Water Research 44 (9):2753–2762. 10.1016/j.watres.2010.02.011. [PubMed: 20219232]

Gellis A, Smith S, and Stewart S. 2003. “Watershed Sediment Sources.” In A Summary Report of Sediment Processes in Chesapeake Bay and Watershed. Water-Resources Investigations Report 03–4123. Edited by Langland M. and Cronin T, 29–33. New Cumberland, PA: U.S. Geological Survey.

Georgakakos A, Fleming P, Dettinger M, Peters-Lidard C, Richmond Terese (T.C.), Reckhow K, White K, and Yates D, 2014: Ch. 3: Water Resources. Climate Change Impacts in the United States: The Third National Climate Assessment, Melillo JM, Richmond Terese (T.C.), and Yohe GW, Eds., U.S. Global Change Research Program, 69–112. 10.7930/J0G44N6T.

Giorgi F, Im E-S, Coppola E, Diffenbaugh NS, Gao XJ, Mariotti L, and Shi Y. 2011. Higher Hydroclimatic Intensity with Global Warming. American Meteorological Society 24 (20): 5309–5324. 10.1175/2011JCLI3979.1

Goode JR, Luce CH, and Buffington JM. 2012. “Enhanced Sediment Delivery in a Changing Climate in Semi-Arid Mountain Basins: Implications for Water Resource Management and Aquatic Habitat in the Northern Rocky Mountains.” Geomorphology 139:1–15. 10.1016/j.geomorph.2011.06.021.

Hale RL, Hoover JH, Wollheim WM, and Vorosmarty CJ. 2013. “History of Nutrient Inputs to the Northeastern United States, 1930–2000.” Global Biogeochemical Cycles 27 (2):578–591. 10.1002/gbc.20049.

Hancock GR 2012. “Modelling Stream Sediment Concentration: An Assessment of Enhanced Rainfall and Storm Frequency.” Journal of Hydrology 430–431:1–12. 10.1016/j.jhydrol.2012.01.022.

Harrus S, and Baneth G. 2005. “Drivers for the Emergence and Re-Emergence of Vector-Borne Protozoal and Bacterial Diseases.” International Journal for Parasitology 35 (11–12):1309–1318. 10.1016/j.ijpara.2005.06.005. [PubMed: 16126213]

Hartman MD, Baron JS, Ewing HA, and Weathers KC. 2014. “Combined Global Change Effects on Ecosystem Processes in Nine Us Topographically Complex Areas.” Biogeochemistry 119 (1–3):85–108. 10.1007/s10533-014-9950-9.

Havens KE, and Paerl HW. 2015. “Climate Change at a Crossroad for Control of Harmful Algal Blooms.” Environmental Science & Technology 49 (21):12605–12606. 10.1021/acs.est.5b03990. [PubMed: 26465060]

Heisler J, Glibert PM, Burkholder JM, Anderson DM, Cochlan W, Dennison WC, Dortch Q, Gobler CJ, Heil CA, Humphries E, Lewitus A, Magnien R, Marshall HG, Sellner K, Stockwell DA, Stoecker DK, and Suddleson M. 2008. “Eutrophication and Harmful Algal Blooms: A Scientific Consensus.” Harmful Algae 8 (1):3–13. doi.10.1016/j.hal.2008.08.006. [PubMed: 28781587]

Helgeson C. 2018. Structuring Decisions Under Deep Uncertainty. Topoi, pp.1–13. 10.1007/s11245-018-9584-y

Herman J, Hupp C, and Langland M. 2003. “Watershed Sediment Deposition and Storage.” In A Summary Report of Sediment Processes in Chesapeake Bay and Watershed. Water-Resources Investigations Report 03–4123. Edited by Langland M. and Cronin T, 42–48. New Cumberland, PA: U.S. Geological Survey.

Herrador BRG, de Blasio BF, MacDonald E, Nichols G, Sudre B, Vold L, Semenza JC, and Nygard K. 2015. “Analytical Studies Assessing the Association between Extreme Precipitation or Temperature and Drinking Water-Related Waterborne Infections: A Review.” Environmental Health 14:29. 10.1186/s12940-015-0014-y. [PubMed: 25885050]

Hill RA, Hawkins CP, and Jin J. 2014. “Predicting Thermal Vulnerability of Stream and River Ecosystems to Climate Change.” Climatic Change 125 (3–4):399–412. 10.1007/s10584-014-1174-4.

Hlavsa MC, Roberts VA, Kahler AM, Hilborn ED, Wade TJ, Backer LC, and Yoder JS. 2014. "Recreational Water-Associated Disease Outbreaks - United States, 2009–2010." Morbidity & Mortality Weekly Report 63 (1):6–10. https://europepmc.org/articles/pmc5779330 [PubMed: 24402466]

Ho JC, and Michalak AM. 2015. "Challenges in Tracking Harmful Algal Blooms: A Synthesis of Evidence from Lake Erie." Journal of Great Lakes Research 41 (2):317–325. doi.10.1016/j.jglr.2015.01.001.

Hofstra N. 2011. "Quantifying the Impact of Climate Change on Enteric Waterborne Pathogen Concentrations in Surface Water." Current Opinion in Environmental Sustainability 3 (6):471–479. 10.1016/j.cosust.2011.10.006.

Hoskisson PA, and Trevors JT. 2010. "Shifting Trends in Pathogen Dynamics on a Changing Planet." Antonie Van Leeuwenhoek International Journal of General and Molecular Microbiology 98 (4):423–427. 10.1007/s10482-010-9485-6.

Howarth RW 2008. "Coastal Nitrogen Pollution: A Review of Sources and Trends Globally and Regionally." Harmful Algae 8 (1):14–20. 10.1016/j.hal.2008.08.015.

Howarth RW, Swaney DP, Boyer EW, Marino R, Jaworski N, and Goodale C. 2006. "The Influence of Climate on Average Nitrogen Export from Large Watersheds in the Northeastern United States." Biogeochemistry 79 (1–2):163–186. 10.1007/s10533-006-9010-1.

Hudnell HK 2010. "The State of U.S. Freshwater Harmful Algal Blooms Assessments, Policy and Legislation." Toxicon 55 (5):1024–1034. doi.10.1016/j.toxicon.2009.07.021. [PubMed: 19646465]

Huisman J, Sharples J, Stroom JM, Visser PM, Kardinaal WEA, Verspagen JMH, and Sommeijer B. 2004. "Changes in Turbulent Mixing Shift Competition for Light between Phytoplankton Species." Ecology 85 (11):2960–2970. 10.1890/03-0763.

Ibelings BW, Vonk M, Los HFJ, van der Molen DT, and Mooij WM. 2003. "Fuzzy Modeling of Cyanobacterial Surface Waterblooms: Validation with Noaa-Avhrr Satellite Images." Ecological Applications 13 (5):1456–1472. 10.1890/01-5345.

IPCC. 2012. Managing risks of extreme events and disasters to advance climate change adaptation. In: A Special Report of the Intergovernmental Panel on Climate Change, Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, and Midgley PM (eds.). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 1–582 pp.

IWG-HABHRCA (Interagency Working Group Harmful Algal Bloom and Hypoxia Research and Control Act). 2016. Harmful Algal Blooms and Hypoxia Comprehensive Research Plan and Action Strategy: An Interagency Report. Washington, DC. 104.

Jackson CR, Martin JK, Leigh DS, and West LT. 2005. "A Southeastern Piedmont Watershed Sediment Budget: Evidence for a Multi-Millennial Agricultural Legacy." Journal of Soil and Water Conservation 60 (6):298–310.

Jacobs JH, Moore SK, Kunkel KE, and Sun L. 2015. A framework for examining climate-driven changes to the seasonality and geographical range of coastal pathogens and harmful algae. Climate Risk Management 8:16–27. 10.1016/j.crm.2015.03.002

James LA 2013. "Legacy Sediment: Definitions and Processes of Episodically Produced Anthropogenic Sediment." Anthropocene 2:16–26. 10.1016/j.ancene.2013.04.001.

Jamieson RC, Lee JH, Kostaschuk R, and Gordon RJ. 2004. "Persistence of Enteric Bacteria in Alluvial Streams." Journal of Environmental Engineering and Science 3 (3):203–212. 10.1139/s04-001.

Jayakody P, Parajuli PB, and Brooks JP. 2015. "Assessing Climate Variability Impact on Thermotolerant Coliform Bacteria in Surface Water." Human and Ecological Risk Assessment 21 (3):691–706. 10.1080/10807039.2014.909188.

Jefferson A, Nolin A, Lewis S, and Tague C. 2008. "Hydrogeologic Controls on Streamflow Sensitivity to Climate Variation." Hydrological Processes 22 (22):4371–4385. 10.1002/hyp.7041.

Jiang C, Shaw KS, Upperman CR, Blythe D, Mitchell C, Murtugudde R, Sapkota AR, and Sapkota A. 2015. "Climate Change, Extreme Events and Increased Risk of Salmonellosis in Maryland, USA: Evidence for Coastal Vulnerability." Environment International 83:58–62. 10.1016/j.envint.2015.06.006 [PubMed: 26093493]

Jiang JP, Sharma A, Sivakumar B, and Wang P. 2014. “A Global Assessment of Climate-Water Quality Relationships in Large Rivers: An Elasticity Perspective.” Science of The Total Environment 468:877–891. 10.1016/j.scitotenv.2013.09.002.

Jha MK, Gassman PW, and Panagopoulos Y. 2015. “Regional Changes in Nitrate Loadings in the Upper Mississippi River Basin under Predicted Mid-Century Climate.” Regional Environmental Change 15 (3):449–460. 10.1007/s10113-013-0539-y.

Johnson AC, Acreman MC, Dunbar MJ, Feist SW, Giacomello AM, Gozlan RE, Hinsley SA, Ibbotson AT, Jarvie HP, Jones JI, Longshaw M, Maberly SC, Marsh TJ, Neal C, Newman JR, Nunn MA, Pickup RW, Reynard NS, Sullivan CA, Sumpter JP, and Williams RJ. 2009. “The British River of the Future: How Climate Change and Human Activity Might Affect Two Contrasting River Ecosystems in England.” Science of The Total Environment 407 (17):4787–4798. 10.1016/j.scitotenv.2009.05.018.

Johnson T, Butcher J, Deb D, Faizullabhoy M, Hummel P, Kittle J, McGinnis S, Mearns LO, Nover D, Parker A, Sarkar S, Srinivasan R, Tuppad P, Warren M, Weaver C, and Witt J. 2015. “Modeling Streamflow and Water Quality Sensitivity to Climate Change and Urban Development in 20 U.S. Watersheds.” Journal of the American Water Resources Association 51 (5):1321–1341. 10.1111/1752-1688.12308

Jordan YC, Ghulam A, and Hartling S. 2014. “Traits of Surface Water Pollution under Climate and Land Use Changes: A Remote Sensing and Hydrological Modeling Approach.” Earth-Science Reviews 128:181–195. 10.1016/j.earscirev.2013.11.005.

Joyner TA, and Rohli RV. 2013. “Atmospheric Influences on Water Quality: A Simulation of Nutrient Loading for the Pearl River Basin, USA.” Environmental Monitoring and Assessment 185 (4):3467–3476. 10.1007/s10661-012-2803-x. [PubMed: 22972315]

Jung AV, Le Cann P, Roig B, Thomas O, Baures E, and Thomas MF. 2014. “Microbial Contamination Detection in Water Resources: Interest of Current Optical Methods, Trends and Needs in the Context of Climate Change.” International Journal of Environmental Research and Public Health 11 (4):4292–4310. 10.3390/ijerph110404292. [PubMed: 24747537]

Kahru M, Leppanen JM, and Rud O. 1993. “Cyanobacterial Blooms Cause Heating of the Sea-Surface.” Marine Ecology Progress Series 101 (1–2):1–7. 10.3354/meps101001.

Kardinaal WEA, Tonk L, Janse I, Hol S, Slot P, Huisman J, and Visser PM. 2007. “Competition for Light between Toxic and Nontoxic Strains of the Harmful Cyanobacterium Microcystis.” Applied and Environmental Microbiology 73 (9):2939–2946. 10.1128/AEM.02892-06. [PubMed: 17337540]

Kaushal SS, Groffman PM, Band LE, Shields CA, Morgan RP, Palmer MA, Belt KT, Swan CM, Findlay SEG, and Fisher GT. 2008. “Interaction between Urbanization and Climate Variability Amplifies Watershed Nitrate Export in Maryland.” Environmental Science & Technology 42 (16):5872–5878. 10.1021/es800264f. [PubMed: 18767638]

Kaushal SS, Mayer PM, Vidon PG, Smith RM, Pennino MJ, Newcomer TA, Duan S, Welty C, and Belt KT. 2014. “Land Use and Climate Variability Amplify Carbon, Nutrient, and Contaminant Pulses: A Review with Management Implications.” Journal of the American Water Resources Association 50 (3):585–614. 10.1111/jawr.12204.

Kim JW, Pachepsky YA, Shelton DR, and Coppock C. 2010. “Effect of Streambed Bacteria Release on E. Coli Concentrations: Monitoring and Modeling with the Modified Swat.” Ecological Modelling 221 (12):1592–1604. 10.1016/j.ecolmodel.2010.03.005.

Kistemann T, Classen T, Koch C, Dangendorf F, Fischeder R, Gebel J, Vacata V, and Exner M. 2002. “Microbial Load of Drinking Water Reservoir Tributaries During Extreme Rainfall and Runoff.” Applied and Environmental Microbiology 68 (5):2188–2197. 10.1128/aem.68.5.2188-2197.2002. [PubMed: 11976088]

Koirala SR, Gentry RW, Perfect E, Schwartz JS, and Sayler GS. 2008. “Temporal Variation and Persistence of Bacteria in Streams.” Journal of Environmental Quality 37 (4):1559–1566. 10.2134/jeq2007.0310. [PubMed: 18574188]

Kratt K, Maraldo D, and Cleland B. 2010. “Climate Change and Tmdls: Anticipating Potential Effects/Weighing Options.” Watershed Management Conference 2010, Madison, Wisconsin, August 23–27, 2010.

Kundzewicz ZW, Mata LJ, Arnell NW, Doll P, Jimenez B, Miller K, Oki T, Sen Z, and Shiklomanov I. 2008. “The Implications of Projected Climate Change for Freshwater Resources and Their Management.” Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 53 (1):3–10, <Go to ISI>://WOS:000253632500001.

Lancaster ST, Hayes SK, and Grant GE. 2001. “Modeling Sediment and Wood Storage and Dynamics in Small Mountainous Watersheds.” In Geomorphic Process and Riverine Habitat. Edited by Dorava JM, Montgomery DR, Palcsak BB and Fitzpatrick FA. Washington, D.C: American Geophysical Union.

Langland M, Blomquist J, Moyer D, and Hyer K. 2012. Nutrient and Suspended-Sediment Trends, Loads, and Yields and Development of an Indicator of Streamwater Quality at Nontidal Sites in the Chesapeake Bay Watershed, 1985–2010. U.S. Geological Survey Scientific Investigations Report 2012–5093. 26.

Langland M, Cronin T, and Phillips SW. 2003. “Executive Summary.” In A Summary Report of Sediment Processes in Chesapeake Bay and Watershed. Water-Resources Investigations Report 03–4123. Edited by Langland M. and Cronin T. New Cumberland, PA, 1–18, U.S. Geological Survey.

Lawler DM, Couperthwaite J, Bull LJ, and Harris NM. 1997. “Bank Erosion Events and Processes in the Upper Severn Basin.” Hydrol. Earth Syst. Sci. 1 (3):523–534. 10.5194/hess-1-523-1997.

Lee M, Shevliakova E, Malyshev S, Milly PCD, and Jaffé PR. 2016. “Climate variability and extremes, interacting with nitrogen storage, amplify eutrophication risk.” Geophysical Research Letters, 43(14), pp.7520–7528. 10.1002/2016GL069254

Leight AK, Hood R, Wood R, and Brohawn K. 2016. “Climate Relationships to Fecal Bacterial Densities in Maryland Shellfish Harvest Waters.” Water Research 89:270–281. 10.1016/j.watres.2015.11.055. [PubMed: 26689664]

Levin RB, Epstein PR, Ford TE, Harrington W, Olson E, and Reichard EG. 2002. “U.S. Drinking Water Challenges in the Twenty-First Century.” Environmental Health Perspectives 110:43–52.

Levy K, Woster AP, Goldstein RS and Carlton EJ, 2016. Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. Environmental science & technology, 50(10), pp.4905–4922. [PubMed: 27058059]

Li X, Huang T, Ma W, Sun X, and Zhang H. 2015. “Effects of Rainfall Patterns on Water Quality in a Stratified Reservoir Subject to Eutrophication: Implications for Management.” Science of The Total Environment 521–522:27–36. doi.10.1016/j.scitotenv.2015.03.062.

Lipp EK, Huq A, and Colwell RR. 2002. “Effects of Global Climate on Infectious Disease: The Cholera Model.” Clinical Microbiology Reviews 15 (4):757–770. 10.1128/cmr.15.4.757-770.2002. [PubMed: 12364378]

Liu ZJ, Hashim NB, Kingery WL, and Huddleston DH. 2010. “Fecal Coliform Modeling under Two Flow Scenarios in St. Louis Bay of Mississippi.” Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances & Environmental Engineering 45 (3):282–291. 10.1080/10934520903467949.

Loecke TD, Burgin AJ, Riveros-Iregui DA, Ward AS, Thomas SA, Davis CA, and Clair MAS. 2017. Weather whiplash in agricultural regions drives deterioration of water quality. Biogeochemistry, 133(1), pp.7–15. 10.1007/s10533-017-0315-z

Loftin KA, Clark JM, Journey CA, Kolpin DW, Van Metre PC, Carlisle D, and Bradley PM. 2016. “Spatial and Temporal Variation in Microcystin Occurrence in Wadeable Streams in the Southeastern United States.” Environmental Toxicology and Chemistry 35 (9):2281–2287. 10.1002/etc.3391. [PubMed: 26844812]

Iacono GL, Armstrong B, Fleming LE, Elson R, Kovats S, Vardoulakis S. and Nichols GL, 2017. Challenges in developing methods for quantifying the effects of weather and climate on water-associated diseases: A systematic review. PLoS neglected tropical diseases, 11(6), p.e0005659. 10.1371/journal.pntd.0005659

Lopez CB, Jewett EB, Dortch Q, Walton BT, and Hudnell HK. 2008. Scientific Assessment of Freshwater Harmful Algal Blooms. Washington, DC. 78.

MacKenzie WR, Hoxie NJ, Proctor ME, Gradus MS, Blair KA, Peterson DE, Kazmierczak JJ, Addiss DG, Fox KR, Rose JB, and Davis JP. 1994. "A Massive Outbreak in Milwaukee of Cryptosporidium Infection Transmitted through the Public Water Supply." New England Journal of Medicine 331 (3):161–167. 10.1056/NEJM199407213310304.

Mantzouki E, Lürling M, Fastner J, de Senerpont Domis L, Wilk-Woźniak E, Koreivienė J, Seelen L, Teurlincx S, Verstijnen Y, Krztoń W. and Walusiak E., 2018. Temperature effects explain continental scale distribution of cyanobacterial toxins. Toxins, 10(4), p.156. 10.3390/toxins10040156

Marion DA, Sun G, Caldwell PV, Miniat CF, Ouyang Y, Amatya DM, Clinton BD, Conrads PA, Laird SG, Dai Z. and Clingenpeel JA. 2014. Managing forest water quantity and quality under climate change. In Climate Change Adaptation and Mitigation Management Options (Vol. 249, No. 305, pp. 249–305). ROUTLEDGE in association with GSE Research.

Matthews HS, Hulitt R, Paul T, Jones T, Wheeler JG, and Haselow DT. 2014. "Environmental Investigation and Response to Second Naegleria Fowleri Case Associated with a Community Water Park in Arkansas July 2013." 2014 Council of State and Territorial Epidemiologists Annual Conference, Nashville, Tennessee, June 22–26, 2014.

McBride G, Tait A, and Slaney D. 2014. "Projected Changes in Reported Campylobacteriosis and Cryptosporidiosis Rates as a Function of Climate Change: A New Zealand Study." Stochastic Environmental Research and Risk Assessment 28 (8):2133–2147. 10.1007/s00477-014-0920-5.

Melillo JM, Richmond TC, and Yohe GW (Eds.). 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. Washington, DC. 841. 10.7930/J0Z31WJ2.

Michalak AM, Anderson EJ, Beletsky D, Boland S, Bosch NS, Bridgeman TB, Chaffin JD, Cho K, Confesor R, Daloglu I, DePinto JV, Evans MA, Fahnenstiel GL, He LL, Ho JC, Jenkins L, Johengen TH, Kuo KC, LaPorte E, Liu XJ, McWilliams MR, Moore MR, Posselt DJ, Richards RP, Scavia D, Steiner AL, Verhamme E, Wright DM, and Zagorski MA. 2013. "Record-Setting Algal Bloom in Lake Erie Caused by Agricultural and Meteorological Trends Consistent with Expected Future Conditions." Proceedings of the National Academy of Sciences of the United States of America 110 (16):6448–6452. 10.1073/pnas.1216006110. [PubMed: 23576718]

Milly PCD, Dunne KA, and Vecchia AV. 2005. "Global Pattern of Trends in Streamflow and Water Availability in a Changing Climate." Nature 438 (7066):347–350. 10.1038/nature04312. [PubMed: 16292308]

Moore SK, Trainer VL, Mantua NJ, Parker MS, Laws EA, Backer LC, and Fleming LE. 2008. "Impacts of Climate Variability and Future Climate Change on Harmful Algal Blooms and Human Health." Environmental Health 7 (2):S4. 10.1186/1476-069x-7-s2-s4.

Morris RD, Naumova EN, Levin R, and Munasinghe RL. 1996. "Temporal Variation in Drinking Water Turbidity and Diagnosed Gastroenteritis in Milwaukee." American Journal of Public Health 86 (2):237–239. 10.2105/ajph.86.2.237. [PubMed: 8633742]

Morse NB and Wollheim WM. 2014. Climate variability masks the impacts of land use change on nutrient export in a suburbanizing watershed. Biogeochemistry, 121(1), pp.45–59. 10.1007/s10533-014-9998-6

Murdoch PS, Baron JS, and Miller TL. 2000. "Potential Effects of Climate Change on Surface-Water Quality in North America." Journal of the American Water Resources Association 36 (2):347–366. 10.1111/j.1752-1688.2000.tb04273.x.

Murphy JC, Hirsch RM, and Sprague LA: Antecedent flow conditions and nitrate concentrations in the Mississippi River basin, Hydrol. Earth Syst. Sci, 18, 967–979, 10.5194/hess-18-967-2014, 2014.

Najjar RG, Walker HA, Anderson PJ, Barron EJ, Bord RJ, Gibson JR, Kennedy VS, Knight CG, Megonigal JP, O'Connor RE, Polsky CD, Psuty NP, Richards BA, Sorenson LG, Steele EM, and Swanson RS. 2000. "The Potential Impacts of Climate Change on the Mid-Atlantic Coastal Region." Climate Research 14 (3):219–233. 10.3354/cr014219.

Najjar RG, Pyke CR, Adams MB, Breitburg D, Hershner C, Kemp M, Howarth R, Mulholland MR, Paolisso M, Secor D, and Sellner K. 2010. Potential climate-change impacts on the Chesapeake Bay. Estuarine, Coastal and Shelf Science, 86(1), pp.1–20. 10.1016/j.ecss.2009.09.026

Neilan BA, Pearson LA, Muenchhoff J, Moffitt MC, and Dittmann E. 2013. "Environmental Conditions That Influence Toxin Biosynthesis in Cyanobacteria." Environmental Microbiology 15 (5):1239–1253. 10.1111/j.1462-2920.2012.02729.x. [PubMed: 22429476]

Nichols G, Lane C, Asgari N, Verlander NQ, and Charlett A. 2009. “Rainfall and Outbreaks of Drinking Water Related Disease and in England and Wales.” Journal of Water and Health 7 (1):1–8. 10.2166/wh.2009.143. [PubMed: 18957770]

Nichols MH, Nearing MA, Polyakov VO, and Stone JJ. 2013. “A Sediment Budget for a Small Semiarid Watershed in Southeastern Arizona, USA.” Geomorphology 180-181:137–145. 10.1016/j.geomorph.2012.10.002.

Niemitz J, Haynes C, and Lasher G. 2013. “Legacy Sediments and Historic Land Use: Chemostratigraphic Evidence for Excess Nutrient and Heavy Metal Sources and Remobilization.” Geology 41 (1):47–50. 10.1130/g33547.1.

NOAA (National Oceanic and Atmospheric Administration). 2015. Experimental Lake Erie Harmful Algal Bloom Bulletin. Edited by National Centers for Coastal Ocean Science and Great Lakes Environmental Research Laboratory. Silver Spring, MD: NOAA.

Noges P, Noges T, Ghiani M, Sena F, Fresner R, Friedl M, and Mildner J. 2011. “Increased Nutrient Loading and Rapid Changes in Phytoplankton Expected with Climate Change in Stratified South European Lakes: Sensitivity of Lakes with Different Trophic State and Catchment Properties.” Hydrobiologia 667 (1):255–270. 10.1007/s10750-011-0649-9.

Novotny EV, and Stefan HG. 2007. “Stream Flow in Minnesota: Indicator of Climate Change.” Journal of Hydrology 334 (3–4):319–333. 10.1016/j.jhydrol.2006.10.011.

NSTEPS (Nutrient Scientific Technical Exchange Partnership and Support). 2015. “Harmful Algal Blooms.” Accessed May 16, 2015. http://www.nsteps.org/library/HarmfulAlgalBlooms.html.

O’Neal MR, Nearing MA, Vining RC, Southworth J, and Pfeifer RA. 2005. Climate change impacts on soil erosion in Midwest United States with changes in crop management. CATENA 61(2–3):165–184. 10.1016/j.catena.2005.03.003

Orem W, Newman S, Osborne TZ, and Reddy KR. 2015. “Projecting Changes in Everglades Soil Biogeochemistry for Carbon and Other Key Elements, to Possible 2060 Climate and Hydrologic Scenarios.” Environmental Management 55 (4):776–798. 10.1007/s00267-014-0381-0. [PubMed: 25365946]

Paerl H. 2008. “Nutrient and Other Environmental Controls of Harmful Cyanobacterial Blooms Along the Freshwater-Marine Continuum.” In Cyanobacterial Harmful Algal Blooms: State of the Science and Research Needs. Edited by Hudnell HK, 217–237.

Paerl HW, Hall NS, and Calandrino ES. 2011. “Controlling Harmful Cyanobacterial Blooms in a World Experiencing Anthropogenic and Climatic-Induced Change.” Science of The Total Environment 409 (10):1739–1745. 10.1016/j.scitotenv.2011.02.001.

Paerl HW, and Huisman J. 2009. “Climate Change: A Catalyst for Global Expansion of Harmful Cyanobacterial Blooms.” Environmental Microbiology Reports 1 (1):27–37. 10.1111/j.1758-2229.2008.00004.x. [PubMed: 23765717]

Paerl HW, and Huisman J. 2008. “Climate - Blooms Like It Hot.” Science 320 (5872):57–58. 10.1126/science.1155398. [PubMed: 18388279]

Paerl HW, and Otten TG. 2013. “Blooms Bite the Hand That Feeds Them.” Science 342 (6157):433–434. 10.1126/science.1245276. [PubMed: 24159037]

Paerl HW, and Paul VJ. 2012. “Climate Change: Links to Global Expansion of Harmful Cyanobacteria.” Water Research 46 (5):1349–1363. 10.1016/j.watres.2011.08.002. [PubMed: 21893330]

Paerl HW, and Scott JT. 2010. “Throwing Fuel on the Fire: Synergistic Effects of Excessive Nitrogen Inputs and Global Warming on Harmful Algal Blooms.” Environmental Science & Technology 44 (20):7756–7758. 10.1021/es102665e. [PubMed: 20804137]

Paerl HW, Valdes LM, Piehler MF, and Stow CA. 2006. “Assessing the Effects of Nutrient Management in an Estuary Experiencing Climatic Change: The Neuse River Estuary, North Carolina.” Environmental Management 37 (3):422–436. 10.1007/s00267-004-0034-9. [PubMed: 16456630]

Panagopoulos Y, Gassman PW, Arritt RW, Herzmann DE, Campbell TD, Valcu A, Jha MK, Kling CL, Srinivasan R, White M. and Arnold JG, 2015. Impacts of climate change on hydrology, water quality and crop productivity in the Ohio-Tennessee River Basin. International Journal of Agricultural and Biological Engineering, 8(3), p.36. 10.3965/j.ijabe.20150803.1497

Patz JA, McGeehin MA, Bernard SM, Ebi KL, Epstein PR, Grambsch A, Gubler DJ, Reiter P, Romieu I, Rose JB, Samet JM, and Trtanj J. 2000. “The Potential Health Impacts of Climate Variability and Change for the United States: Executive Summary of the Report of the Health Sector of the U.S. National Assessment.” Environmental Health Perspectives 108 (4):367–376. 10.2307/3454357. [PubMed: 10753097]

Patz JA, Vavrus SJ, Uejio CK, and McLellan SL. 2008. “Climate Change and Waterborne Disease Risk in the Great Lakes Region of the Us.” American Journal of Preventive Medicine 35 (5):451–458. 10.1016/j.amepre.2008.08.026. [PubMed: 18929971]

Paul MP, Stamp J, Hamilton A, Coffey R, and Johnson T. 2019. “A Review of Potential Climate Change Effects on U.S. Water Quality - Part I: Sea Level Rise, Flow, and Temperature.” Journal of the American Water Resources Association 55(4):824–843. 10.1111/1752-1688.12710

Pietikäinen J, Pettersson M, and Bååth E. 2005. “Comparison of Temperature Effects on Soil Respiration and Bacterial and Fungal Growth Rates.” FEMS Microbiology Ecology 52 (1):49–58. 10.1016/j.femsec.2004.10.002. [PubMed: 16329892]

Poff NL 1992. “Regional Hydrologic Responses to Climate Change: An Ecological Perspective.” In Global Climate Change and Freshwater Ecosystems. Edited by Firth P. and Fisher SG, 88–115. New York: Springer-Verlag.

Pommepuy M, Guillaud JF, Dupray E, Derrien A, Leguyader F, and Cormier M. 1992. “Enteric Bacteria Survival Factors.” Water Science and Technology 25 (12):93–103. 10.2166/wst.1992.0341

Pons W, Young I, Truong J, Jones-Bitton A, McEwen S, Pintar K. and Papadopoulos A, 2015. A systematic review of waterborne disease outbreaks associated with small non-community drinking water systems in Canada and the United States. PLoS One, 10(10), p.e0141646. 10.1371/journal.pone.0141646

Potts M. 1994. “Desiccation Tolerance of Prokaryotes.” Microbiological Reviews 58 (4):755–805, <Go to ISI>://WOS:A1994PV32400007. [PubMed: 7854254]

Pourmokhtarian A, Driscoll CT, Campbell JL, and Hayhoe K. 2012. “Modeling Potential Hydrochemical Responses to Climate Change and Increasing Co2 at the Hubbard Brook Experimental Forest Using a Dynamic Biogeochemical Model (Pnet-Bgc).” Water Resources Research 48. 10.1029/2011wr011228.

Porter PA, Mitchell RB and Moore KJ. 2015. Reducing hypoxia in the Gulf of Mexico: Reimagining a more resilient agricultural landscape in the Mississippi River Watershed. Journal of Soil and Water Conservation, 70(3), pp.63A–68A. 10.2489/jswc.70.3.63A

Prasad MBK, Sapiano MRP, Anderson CR, Long W, and Murtugudde R. 2010. “Long-Term Variability of Nutrients and Chlorophyll in the Chesapeake Bay: A Retrospective Analysis, 1985–2008.” Estuaries and Coasts 33 (5):1128–1143. 10.1007/s12237-010-9325-y.

Prein AF, Rasmussen RM, Ikeda K, Liu C, Clark MP, and Holland GJ. 2016. “The Future Intensification of Hourly Precipitation Extremes.” Nature Climate Change 7:48–52. 10.1038/nclimate3168.

Pruski FF, and Nearing MA. 2002. “Climate-Induced Changes in Erosion During the 21st Century for Eight Us Locations.” Water Resources Research 38 (12). 10.1029/2001wr000493.

Qin BQ, Zhu GW, Gao G, Zhang YL, Li W, Paerl HW, and Carmichael WW. 2010. “A Drinking Water Crisis in Lake Taihu, China: Linkage to Climatic Variability and Lake Management.” Environmental Management 45 (1):105–112. 10.1007/s00267-009-9393-6. [PubMed: 19915899]

Reichwaldt ES, and Ghadouani A. 2012. “Effects of Rainfall Patterns on Toxic Cyanobacterial Blooms in a Changing Climate: Between Simplistic Scenarios and Complex Dynamics.” Water Research 46 (5):1372–1393. 10.1016/j.watres.2011.11.052. [PubMed: 22169160]

Reynolds CS 1987. “Cyanobacterial Water-Blooms.” Advances in Botanical Research Incorporating Advances in Plant Pathology 13:67–143. 10.1016/s0065-2296(08)60341-9.

Rizak S, and Hrudey SE. 2008. “Drinking-Water Safety--Challenges for Community-Managed Systems.” Journal of Water and Health 6:33–41. 10.2166/wh.2008.033. [PubMed: 18401127]

Robson BJ, and Hamilton DP. 2003. “Summer Flow Event Induces a Cyanobacterial Bloom in a Seasonal Western Australian Estuary.” Marine and Freshwater Research 54 (2):139–151. 10.1071/mf02090.

Rogers S, and Haines J. 2005. Detecting and Mitigating the Environmental Impact of Fecal Pathogens Originating from Confined Animal Feeding Operations: Review. EPA/600/R-06/021. Cincinnati, OH. 185.

Ryberg KR, Blomquist JD, Sprague LA, Sekellick AJ, and Keisman J. 2018. Modeling drivers of phosphorus loads in Chesapeake Bay tributaries and inferences about long-term change. Science of the Total Environment, 616, pp.1423–1430. 10.1016/j.scitotenv.2017.10.173

Salant NL, Hassan MA, and Alonso CV. 2008. “Suspended Sediment Dynamics at High and Low Storm Flows in Two Small Watersheds.” Hydrological Processes 22 (11):1573–1587. 10.1002/hyp.6743.

Schaeffer BA, Loftin K, Stumpf RP, and Werdell PJ (2015), Agencies collaborate, develop a cyanobacteria assessment network, Eos, 96, 10.1029/2015EO038809.

Schijven JF, and Husman AMD. 2005. “Effect of Climate Changes on Waterborne Disease in the Netherlands.” Water Science and Technology 51 (5):79–87.

Schwartz J, Levin R, and Hodge K. 1997. “Drinking Water Turbidity and Pediatric Hospital Use for Gastrointestinal Illness in Philadelphia.” Epidemiology 8 (6):615–620. 10.1097/00001648-199710000-00001. [PubMed: 9345659]

Sellner KG, Lacouture RV, and Parrish CR. 1988. “Effects of Increasing Salinity on a Cyanobacteria Bloom in the Potomac River Estuary.” Journal of Plankton Research 10 (1):49–61. 10.1093/plankt/10.1.49.

Senhorst HAJ, and Zwolsman JJG. 2005. “Climate Change and Effects on Water Quality: A First Impression.” Water Science and Technology 51 (5):53–59. 10.2166/wst.2005.0107

Sherer BM, Miner JR, Moore JA, and Buckhouse JC. 1992. “Indicator Bacterial Survival in Stream Sediments.” Journal of Environmental Quality 21 (4):591–595. 10.2134/jeq1992.00472425002100040011x

Sherriff SC, Rowan JS, Fenton O, and Jordan P. 2018. Sediment fingerprinting as a tool to identify temporal and spatial variability of sediment sources and transport pathways in agricultural catchments. Agriculture, Ecosystems & Environment, 267, pp.188–200. 10.1016/j.agee.2018.08.023

Shrestha RR, Dibike YB, and Prowse TD. 2012. “Modeling Climate Change Impacts on Hydrology and Nutrient Loading in the Upper Assiniboine Catchment.” Journal of the American Water Resources Association 48 (1):74–89. 10.1111/j.1752-1688.2011.00592.x.

Sinha E. and Michalak AM, 2016. Precipitation dominates interannual variability of riverine nitrogen loading across the continental United States. Environmental science & technology, 50(23), pp.12874–12884. 10.1021/acs.est.6b04455 [PubMed: 27771946]

Sinha E, Michalak AM and Balaji V, 2017. Eutrophication will increase during the 21st century as a result of precipitation changes. Science, 357(6349), pp.405–408. 10.1126/science.aan2409 [PubMed: 28751610]

Slavik K, Peterson BJ, Deegan LA, Bowden WB, Hershey AE, and Hobbie JE. 2004. “Long-Term Responses of the Kuparuk River Ecosystem to Phosphorus Fertilization.” Ecology 85 (4):939–954. 10.1890/02-4039.

Soil and Water Conservation Society (SWCS). 2003. Conservation Implications of Climate Change: Soil Erosion and Runoff from Cropland. Ankeny, IA: Soil and Water Conservation Society.

Soupir M, and Pandey P. 2016. “Sediment E. Coli as a Source of Stream Impairment.” Resource: Engineering & Technology for a Sustainable World 23 (2):4–5.

Sprague LA, Mueller DK, Schwarz GE, and Lorenz DL. 2009. Nutrient Trends in Streams and Rivers of the United States, 1993–2003: U.S. Geological Survey Scientific Investigations Report 2008–5202. Reston, Virginia. 196 pp.

Sprague LA, Hirsch RM and Aulenbach BT. 2011. Nitrate in the Mississippi River and its tributaries, 1980 to 2008: Are we making progress?. Environmental Science & Technology, 45(17), pp.7209–7216. 10.1021/es201221s [PubMed: 21823673]

Sterk A, Schijven J, de Nijs T, and Husman AMD. 2013. “Direct and Indirect Effects of Climate Change on the Risk of Infection by Water-Transmitted Pathogens.” Environmental Science & Technology 47 (22):12648–12660. 10.1021/es403549s. [PubMed: 24125400]

Stets EG, Kelly VJ, and Crawford CG. 2015. “Regional and Temporal Differences in Nitrate Trends Discerned from Long-Term Water Quality Monitoring Data.” Journal of the American Water Resources Association 51 (5):1394–1407. 10.1111/1752-1688.12321.

Stewart BC, Kunkel KE, Stevens LE, Sun L, and Walsh JE. 2013. Regional Climate Trends and Scenarios for the U.S. National Climate Assessment. Part 7. Climate of Alaska. NOAA Technical Report NESDIS 142–7. Washington, DC.

Stout JC, Belmont P, Schottler SP, and Willenbring JK. 2014. “Identifying Sediment Sources and Sinks in the Root River, Southeastern Minnesota.” Annals of the Association of American Geographers 104 (1):20–39. 10.1080/00045608.2013.843434.

Sturrock RN, Frankel SJ, Brown AV, Hennon PE, Kliejunas JT, Lewis KJ, Worrall JJ, and Woods AJ. 2011. Climate change and forest diseases. Plant Pathology 60:133–149. 10.1111/j.1365-3059.2010.02406.x

Strauch AM, Mackenzie RA, Bruland GL, Tingley R, and Giardina CP. 2014. Climate change and land use drivers of fecal bacteria in tropical Hawaiian rivers. Journal of environmental quality, 43(4), pp.1475–1483. 10.2134/jeq2014.01.0025 [PubMed: 25603095]

Sun G. 2013. Impacts of climate change and variability on water resources in the Southeast USA. In Climate of the Southeast United States (pp. 210–236). Island Press, Washington, DC.

Sun Ge, McNulty Steven G., Moore Myers Jennifer A., and Cohen Erika C., 2008. Impacts of Multiple Stresses on Water Demand and Supply Across the Southeastern United States. Journal of the American Water Resources Association (JAWRA) 44(6):1441–1457. DOI: 10.1111/j.1752-1688.2008.00250.x

Swank WT, Knoepp JD, Vose JM, Laseter SN, and Webster JR. 2014. Response and recovery of water yield and timing, stream sediment, abiotic parameters, and stream chemistry following logging. In: Swank WT; Webster JR eds. Long-term Response of a Forest Watershed Ecosystem. New York, NY: Oxford University Press

Taranu ZE, Gregory-Eaves I, Leavitt PR, Bunting L, Buchaca T, Catalan J, Domaizon I, Guilizzoni P, Lami A, McGowan S, Moorhouse H, Morabito G, Pick FR, Stevenson MA, Thompson PL, and Vinebrooke RD. 2015. “Acceleration of Cyanobacterial Dominance in North Temperate-Subarctic Lakes During the Anthropocene.” Ecology Letters 18 (4):375–84. 10.1111/ele.12420. [PubMed: 25728551]

TDOH (Texas Department of Health). 1999. Cryptosporidiosis at Brushy Creek. In Epidemiology in Texas: 1998 Annual Report. Austin, TX: Texas Department of Health Associateship for Disease Control and Prevention. 21–23, http://www.tdh.state.tx.us/epidemiology.

Tong STY, Sun Y, Ranatunga T, He J, and Yang YJ. 2012. “Predicting Plausible Impacts of Sets of Climate and Land Use Change Scenarios on Water Resources.” Applied Geography 32 (2):477–489. 10.1016/j.apgeog.2011.06.014.

Trtanj J, Jantarasami L, Brunkard J, Collier T, Jacobs J, Lipp E, McLellan S, Moore S, Paerl H, Ravenscroft J, Sengco M, and Thurston J. 2016. “Climate Impacts on Water-Related Illness.” In The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment, 157–188. Washington, DC: U.S. Global Change Research Program.

Tryland I, Robertson L, Blankenberg AGB, Lindholm M, Rohrlack T, and Liltved H. 2011. “Impact of Rainfall on Microbial Contamination of Surface Water.” International Journal of Climate Change Strategies and Management 3 (4):361–373. 10.1108/17568691111175650.

Tu J. 2009. “Combined Impact of Climate and Land Use Changes on Streamflow and Water Quality in Eastern Massachusetts, USA.” Journal of Hydrology 379 (3–4):268–283. 10.1016/j.jhydrol.2009.10.009.

Tyrrel SF, and Quinton JN. 2003. “Overland Flow Transport of Pathogens from Agricultural Land Receiving Faecal Wastes.” Journal of Applied Microbiology 94 (s1):87–93. 10.1046/j.1365-2672.94.s1.10.x

Uejio CK, Yale SH, Malecki K, Borchardt MA, Anderson HA, and Patz JA. 2014. “Drinking Water Systems, Hydrology, and Childhood Gastrointestinal Illness in Central and Northern Wisconsin.” American Journal of Public Health 104 (4):639–646. 10.2105/ajph.2013.301659. [PubMed: 24524509]

Urquhart EA, Zaitchik BF, Waugh DW, Guikema SD, and Del Castillo CE. 2014. Uncertainty in model predictions of Vibrio vulnificus response to climate variability and change: a Chesapeake Bay case study. PloS one, 9(5), p.e98256. 10.1371/journal.pone.0098256

Urquhart EA, Schaeffer BA, Stumpf RP, Loftin KA and Werdell PJ. 2017. A method for examining temporal changes in cyanobacterial harmful algal bloom spatial extent using satellite remote sensing. Harmful algae, 67, pp.144–152. 10.1016/j.hal.2017.06.001 [PubMed: 28755717]

USEPA (U.S. Environmental Protection Agency). 2001. Protocol for Developing Pathogen TMDLs. EPA 841-R-00–002. Washington, DC. 132.

USEPA (U.S. Environmental Protection Agency). 2006. Framework for Developing Suspended and Bedded Sediments (SABs) Water Quality Criteria. EPA-822-R-06–001., Washington, DC: U.S. Environmental Protection Agency, Office of Water, Office of Research and Development. https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=164423&CFID=65935138&CFTOKEN=46465426.

USEPA (U.S. Environmental Protection Agency). 2009a. National Lakes Assessment: A Collaborative Survey of the Nation's Lakes. EPA 841-R-09–001. Office of Water and Office of Research and Development, Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2009b. Review of Zoonotic Pathogens in Ambient Waters. EPA 822-R-09–002. Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2009c. Water Systems, disinfection byproducts, and the use of monochloramine - Why are disinfection byproducts a public health concern? 2009c. https://www.epa.gov/sites/production/files/2015-09/documents/why_are_disinfection_byproducts_a_public_health_concern.pdf

USEPA (U.S. Environmental Protection Agency). 2013a. Watershed Modeling to Assess the Sensitivity of Streamflow, Nutrient and Sediment Loads to Potential Climate Change and Urban Development in 20 U.S. Watersheds. EPA/600/R-12/058F. Washington, DC. 196, https://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=256912#Download.

USEPA (U.S. Environmental Protection Agency). 2013b. Impacts of Climate Change on the Occurrence of Harmful Algal Blooms. EPA 820-S-13–001. Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2013c. Literature Review of Contaminants in Livestock and Poultry Manure and Implications for Water Quality. EPA 820-R-13–002. Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2014a. National Rivers and Streams Assessment 2008–2009: A Collaborative Survey Draft. EPA/841/D-13/001. Office of Water and Office of Research and Development, Washington, DC.

USEPA (U.S. Environmental Protection Agency). 2014b. "National Summary of Impaired Waters and TMDL Information." US Environmental Protection Agency. https://iaspub.epa.gov/waters10/attains_nation_cy.control?p_report_type=T#main-content.

USEPA (U.S. Environmental Protection Agency). 2015a. Algal Toxin Risk Assessment and Management Strategic Plan for Drinking Water. 810R04003. Washington, DC. 81.

USEPA (U.S. Environmental Protection Agency). 2015b. Drinking Water Health Advisory for the Cyanobacterial Microcystin Toxins. EPA-820R15100. Washington, DC. 75.

USEPA (U.S. Environmental Protection Agency). 2016a. National Coastal Condition Assessment 2010. EPA/841/R-15/006, Washington, DC: U.S. Environmental Protection Agency, Office of Water and Office of Research and Development.

USEPA (U.S. Environmental Protection Agency). 2016b. "Climate Change Indicators: Great Lakes Water Levels and Temperatures." U.S. Environmental Protection Agency, Last Modified 17 December 2016. https://www.epa.gov/climate-indicators/great-lakes.

USEPA (U.S. Environmental Protection Agency) 2017. Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, EPA 430-R-17–001.

USGCRP. 2017. Climate Science Special Report: Fourth National Climate Assessment, Volume I. Edited by Wuebbles DJ, Fahey DW, Hibbard KA, Dokken DJ, Stewart BC and Maycock TK. Washington, DC, USA. 470. 10.7930/J0J964J6.

Vavrus SJ, and Behnke RJ. 2014. “A Comparison of Projected Future Precipitation in Wisconsin Using Global and Downscaled Climate Model Simulations: Implications for Public Health.” International Journal of Climatology 34 (10):3106–3124. 10.1002/joc.3897.

Vermeulen LC, and Hofstra N. 2014. “Influence of Climate Variables on the Concentration of Escherichia Coli in the Rhine, Meuse, and Drentse Aa During 1985–2010.” Regional Environmental Change 14 (1):307–319. 10.1007/s10113-013-0492-9.

Vose JM, Sun G, Bredemeier M, Ostsuki K, Wei A, Zhang Z, and Zhang L. 2011. Forest ecohydrological research in the 21st century: what are the critical needs? Ecohydrology 4: 146–158. 10.1002/eco.193

Wagena MB and Easton ZM. 2018. Agricultural conservation practices can help mitigate the impact of climate change. Science of The Total Environment, 635:132–143. 10.1016/j.scitotenv.2018.04.110

Wallace RB, Baumann H, Grear JS, Aller RC, and Gobler CJ. 2014. “Coastal Ocean Acidification: The Other Eutrophication Problem.” Estuarine Coastal and Shelf Science 148:1–13. 10.1016/j.ecss.2014.05.027

Wang L, Robertson DM, and Garrison PJ. 2007. “Linkages between Nutrients and Assemblages of Macroinvertebrates and Fish in Wadeable Streams: Implication to Nutrient Criteria Development.” Environmental Management 39 (2):194–212, http://proxytu.researchport.umd.edu/login?ins=tu&url=http://search.ebscohost.com/login.aspx?direct=true&db=cmedm&AN=17122998&site=eds-live&scope=site. [PubMed: 17122998]

Wang R. and Kalin L. 2018. Combined and synergistic effects of climate change and urbanization on water quality in the Wolf Bay watershed, southern Alabama. Journal of Environmental Sciences, 64, pp.107–121. 10.1016/j.jes.2016.11.021

Waters TF 1995. Sediment in Streams: Sources, Biological Effects, and Control, http://proxy-tu.researchport.umd.edu/login?ins=tu&url=http://search.ebscohost.com/login.aspx?direct=true&db=cat01451a&AN=towson.002271414&site=eds-live&scope=site. American Fisheries Society Monograph 7. Bethesda, MD: American Fisheries Society.

Watts G, Battarbee RW, Bloomfield JP, Crossman J, Daccache A, Durance I, Elliott JA, Garner G, Hannaford J, Hannah DM, Hess T, Jackson CR, Kay AL, Kernan M, Knox J, Mackay J, Monteith DT, Ormerod SJ, Rance J, Stuart ME, Wade AJ, Wade SD, Weatherhead K, Whitehead PG, and Wilby RL. 2015. “Climate Change and Water in the UK - Past Changes and Future Prospects.” Progress in Physical Geography 39 (1):6–28. 10.1177/0309133314542957.

Wells ML, Trainer VL, Smayda TJ, Karlson BS, Trick CG, Kudela RM, Ishikawa A, Bernard S, Wulff A, Anderson DM, and Cochlan WP. 2015. “Harmful Algal Blooms and Climate Change: Learning from the Past and Present to Forecast the Future.” Harmful Algae 49:68–93. 10.1016/j.hal.2015.07.009. [PubMed: 27011761]

Wear DN and Greis JG. 2012. The Southern Forest Futures Project: summary report. Gen. Tech. Rep. SRS-GTR-168. Asheville, NC: USDA-Forest Service, Southern Research Station. 54 p.

Wear DN 2013. Forecasts of Land Uses. In: Pp. 45–71; Wear DN; Greis JG, eds. The Southern Forests Futures Project. Gen. Tech. Rep. SRS-178. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station.

West B. 2002. Water quality in the South. In Southern Forest Resource Assessment, 455–477. General Tech. Report SRS-53. Wear DNand Greis J, eds. Asheville NC: USDA Forest Service, Southern Research Station.

Whitehead PG, Wilby RL, Battarbee RW, Kernan M, and Wade AJ. 2009. “A Review of the Potential Impacts of Climate Change on Surface Water Quality.” Hydrological Sciences Journal-Journal Des Sciences Hydrologiques 54 (1):101–123. 10.1623/hysj.54.1.101.

WHO (World Health Organization). 2003. Climate Change and Human Health: Risks and Responses. Edited by McMichael AJ, Campbell-Lendrum DH, Corvalan CF, Ebi KL, Githeko AK, Scheraga JD and Woodward A. Geneva, Switzerland: World Health Organization.

Williamson CE, Madronich S, Lal A, Zepp RG, Lucas RM, Overholt EP, Rose KC, Schladow SG, and Lee-Taylor J. 2017. “Climate Change-Induced Increases in Precipitation Are Reducing the Potential for Solar Ultraviolet Radiation to Inactivate Pathogens in Surface Waters.” Scientific Reports 7 (1):13033. 10.1038/s41598-017-13392-2. [PubMed: 29026153]

Wilson CO, and Weng QH. 2011. “Simulating the Impacts of Future Land Use and Climate Changes on Surface Water Quality in the Des Plaines River Watershed, Chicago Metropolitan Statistical Area, Illinois.” Science of The Total Environment 409 (20):4387–4405. 10.1016/j.scitotenv.2011.07.001.

Wolfe DW, Ziska L, Petzoldt C, Seaman A, Chase L, and Hayhoe K. 2008. Projected change in climate thresholds in the Northeastern U.S.: implications for crops, pests, livestock, and farmers. Mitigation and Adaptation Strategies for Global Change 13(5):555–575. 10.1007/s11027-007-9125-2.

Wood PJ, and Armitage PD. 1997. “Biological Effects of Fine Sediment in the Lotic Environment.” Environmental Management 21 (2):203–217. 10.1007/s002679900019. [PubMed: 9008071]

Worrall F, Swank WT, and Burt TP. 2003. Changes in stream nitrate concentrations due to land management practices, ecological succession, and climate: developing a systems approach to integrated catchment response. Water Resources Research, 39(7). 10.1029/2000WR000130

Wu JY, Rees P, Storrer S, Alderisio K, and Dorner S. 2009. “Fate and Transport Modeling of Potential Pathogens: The Contribution from Sediments.” Journal of the American Water Resources Association 45 (1):35–44. 10.1111/j.1752-1688.2008.00287.x.

Ye L, and Grimm NB. 2013. Modelling potential impacts of climate change on water and nitrate export from a mid-sized, semiarid watershed in the US Southwest. Climatic Change. 120(1–2):419–431. 10.1007/s10584-013-0827-z

Youngstrom G, and Emery E. 2015. 2015 Ohio River Hab Event. Cincinnati, OH: https://www.epa.gov/sites/production/files/2015-11/documents/ohio-river-hab-2015.pdf

Zhang Q, Brady DC, and Ball WP. 2013. “Long-Term Seasonal Trends of Nitrogen, Phosphorus, and Suspended Sediment Load from the Non-Tidal Susquehanna River Basin to Chesapeake Bay.” Science of The Total Environment 452:208–221. 10.1016/j.scitotenv.2013.02.012.

Ziemer CJ, Bonner JM, Cole D, Vinje J, Constantini V, Goyal S, Gramer M, Mackie R,Meng XJ, Myers G, and Saif LJ. 2010. “Fate and Transport of Zoonotic, Bacterial, Viral, and Parasitic Pathogens During Swine Manure Treatment, Storage, and Land Application.” Journal of Animal Science 88 (13 Suppl):E84–94. 10.2527/jas.2009-https://10.0.9.223/jas.2009-23312331. [PubMed: 20348375]

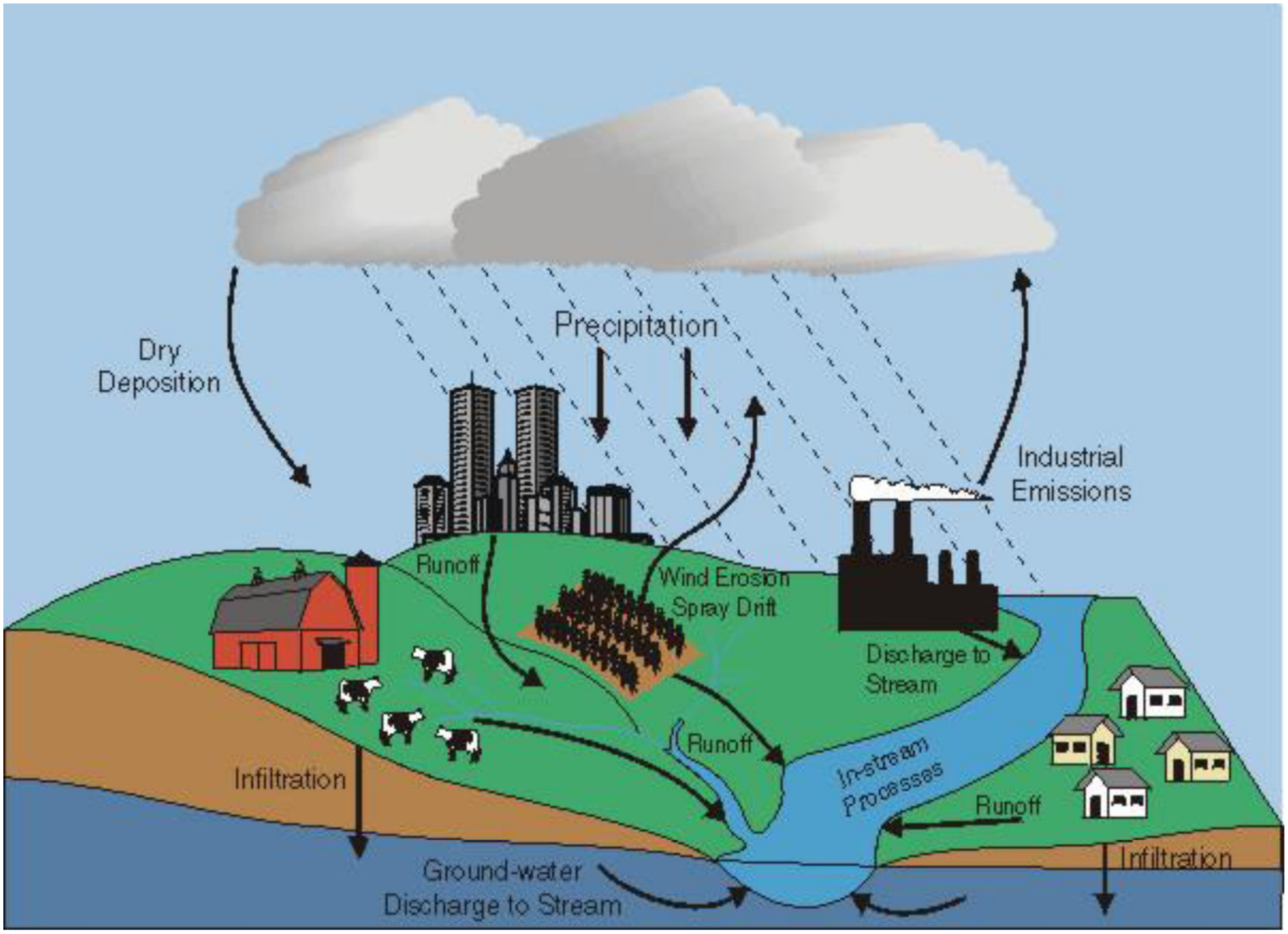

FIGURE 1.
Nutrient movement in the hydrological cycle. Source: Belval and Sprague (1999).

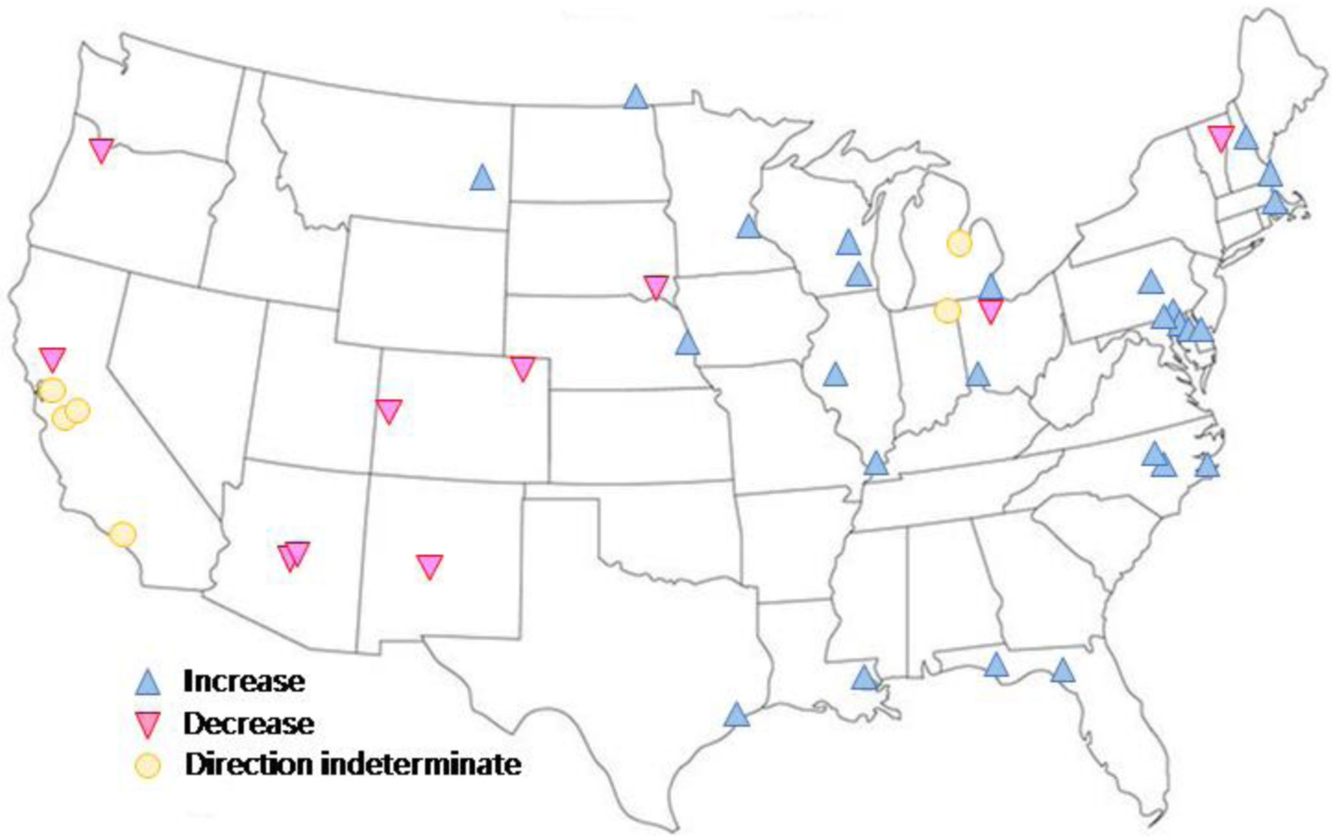

FIGURE 2.

Location of watershed modeling studies assessing nitrogen load responses to future climate change scenarios. Symbols indicate the suggested direction of change (based on ensemble median, annual loads). Studies not reporting an ensemble median (e.g., a range, or sensitivity) are shown as “Direction indeterminate.” Detailed information about each study is provided in the Supporting Information.

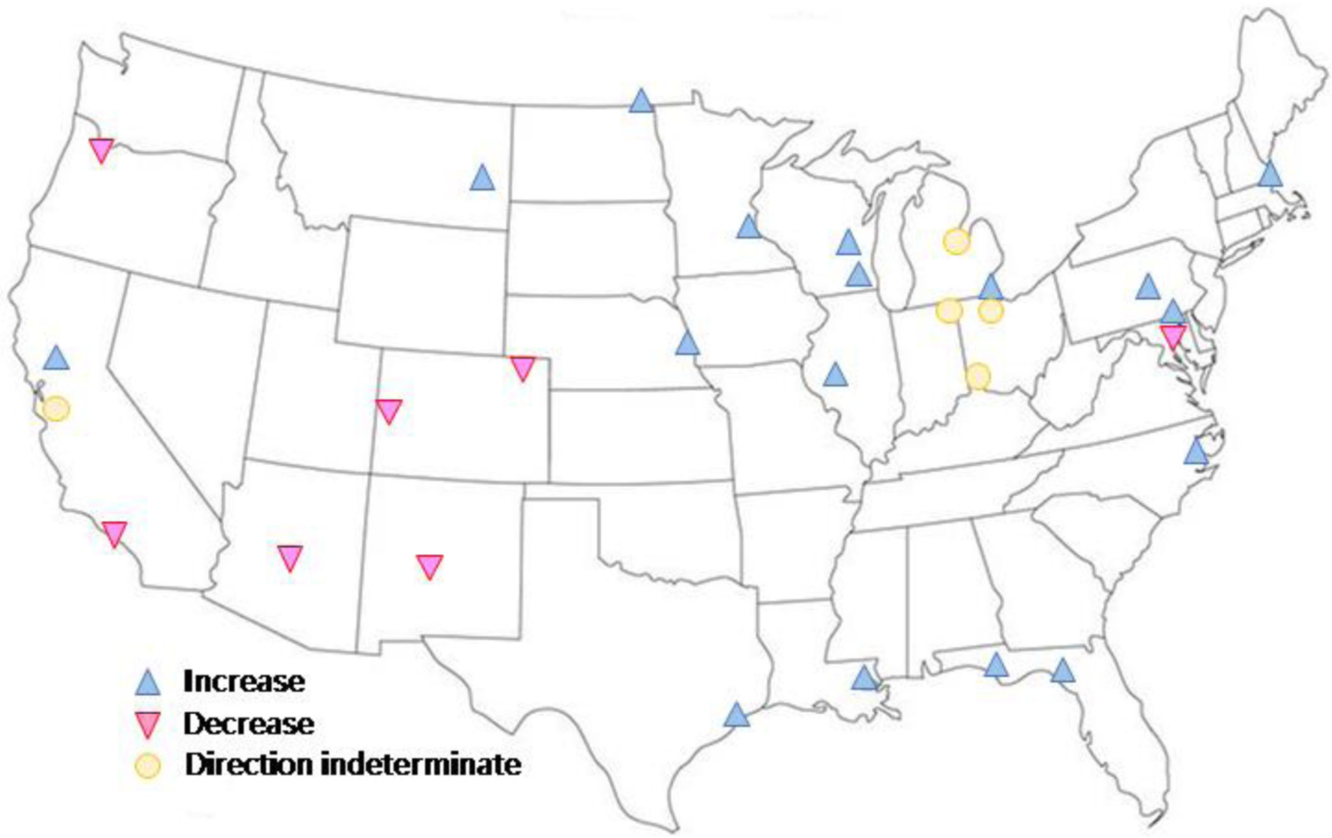

FIGURE 3.
Location of watershed modeling studies assessing phosphorus load responses to future climate change scenarios. Symbols indicate the suggested direction of change (based on ensemble median, annual loads). Studies not reporting an ensemble median (e.g., a range, or sensitivity) are shown as “Direction indeterminate.” Detailed information about each study is provided in the Supporting Information.

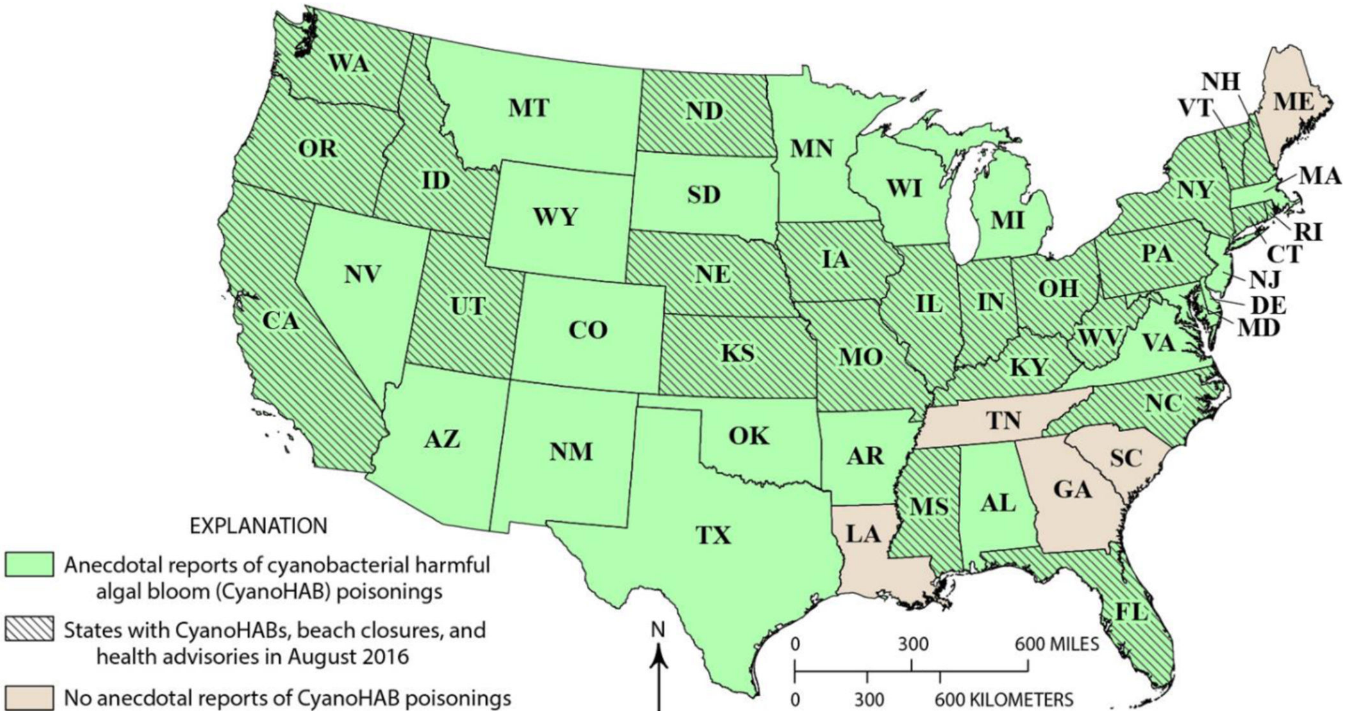

FIGURE 4.
National status for cyanobacterial blooms in August 2016. Source: USGS (2016).

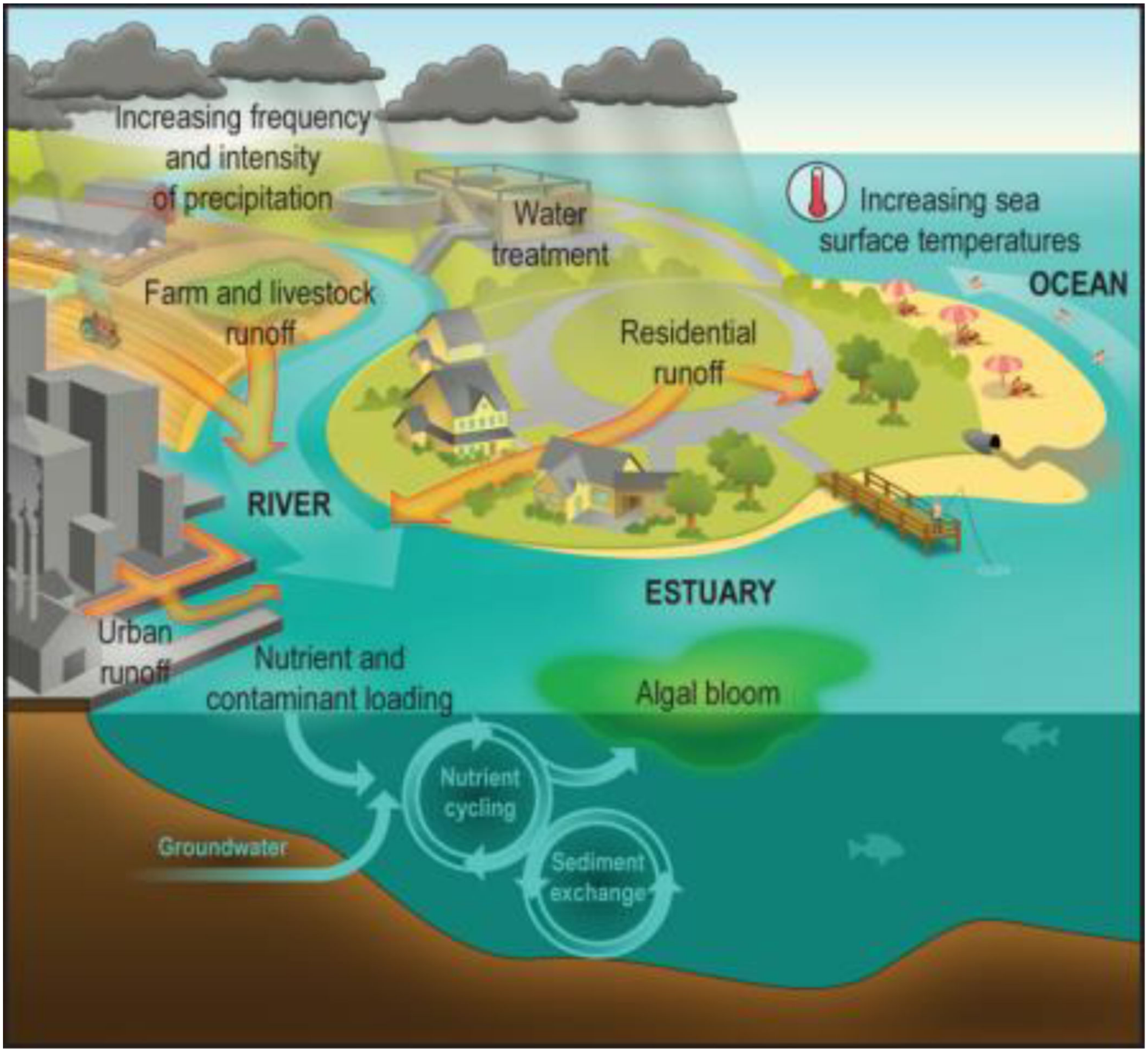

FIGURE 5.
Factors influencing the formation of cyanobacterial blooms. Source: Trtanj et al. (2016).

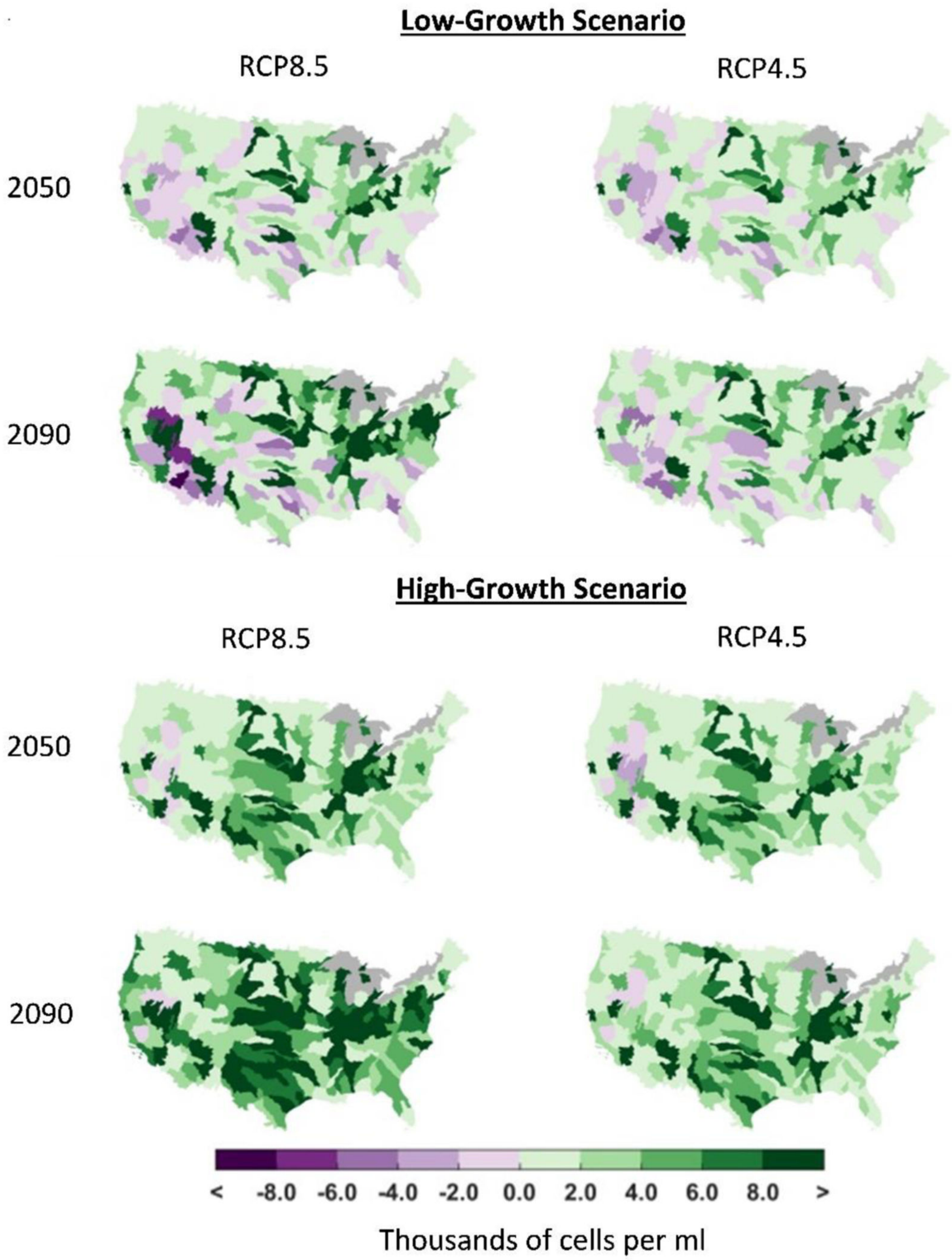

FIGURE 6.

Changes in average annual water body surface cyanobacteria (thousands of cells per mL) for a low growth (plateaus as temperatures reach 26°C) and a high growth scenario (assumes a linear growth rate with changes in temperature) in 2050 (2040–2059) and 2090 (2080–2099) relative to a control scenario. Values for each representative concentration pathway (RCP) are associated with the average results for five future scenarios and are aggregated to the four-digit hydrologic unit code level, weighted by water body surface area. See USEPA (2017) and Chapra et al. (2017) for information about the modeling approach.

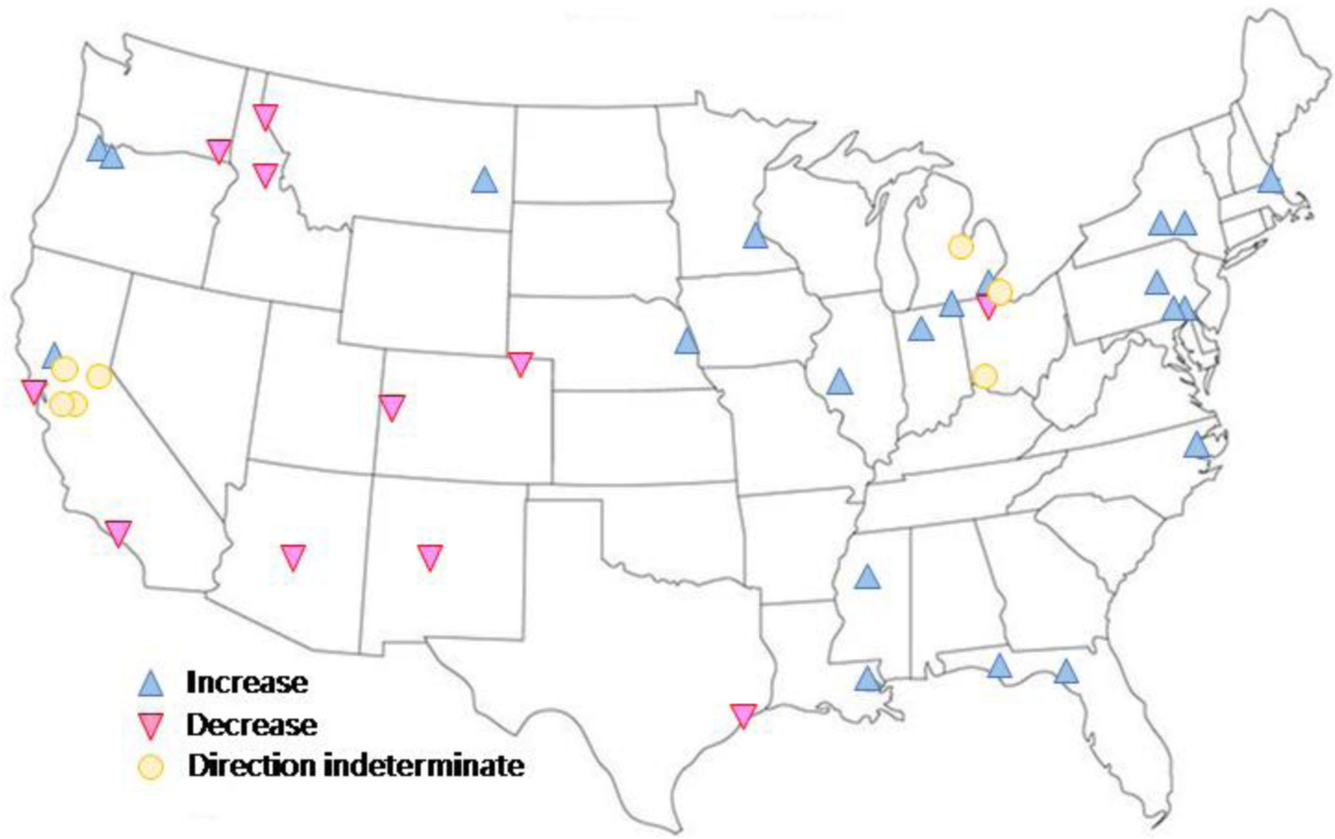

FIGURE 7.

Location of watershed modeling studies assessing sediment load responses to future climate change scenarios. Symbols indicate the suggested direction of change (based on ensemble median, annual loads). Studies not reporting an ensemble median (e.g., a range, or sensitivity) are shown as “Direction indeterminate.” Detailed information about each study is provided in the Supporting Information.

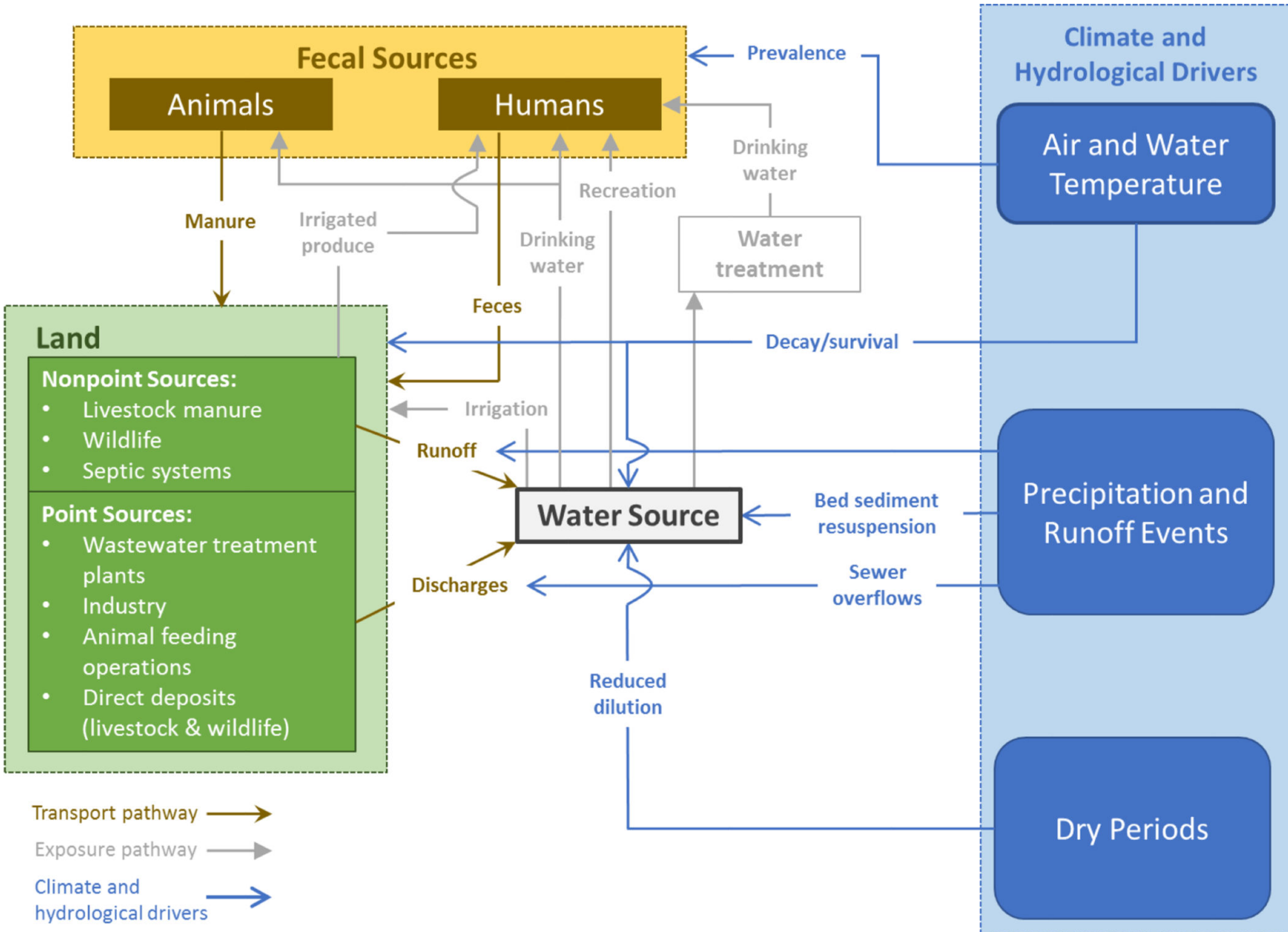

FIGURE 8.
Conceptual model of waterborne pathogens responses to climate and hydrological drivers. Adapted from Coffey et al. (2014) and Hofstra (2011).

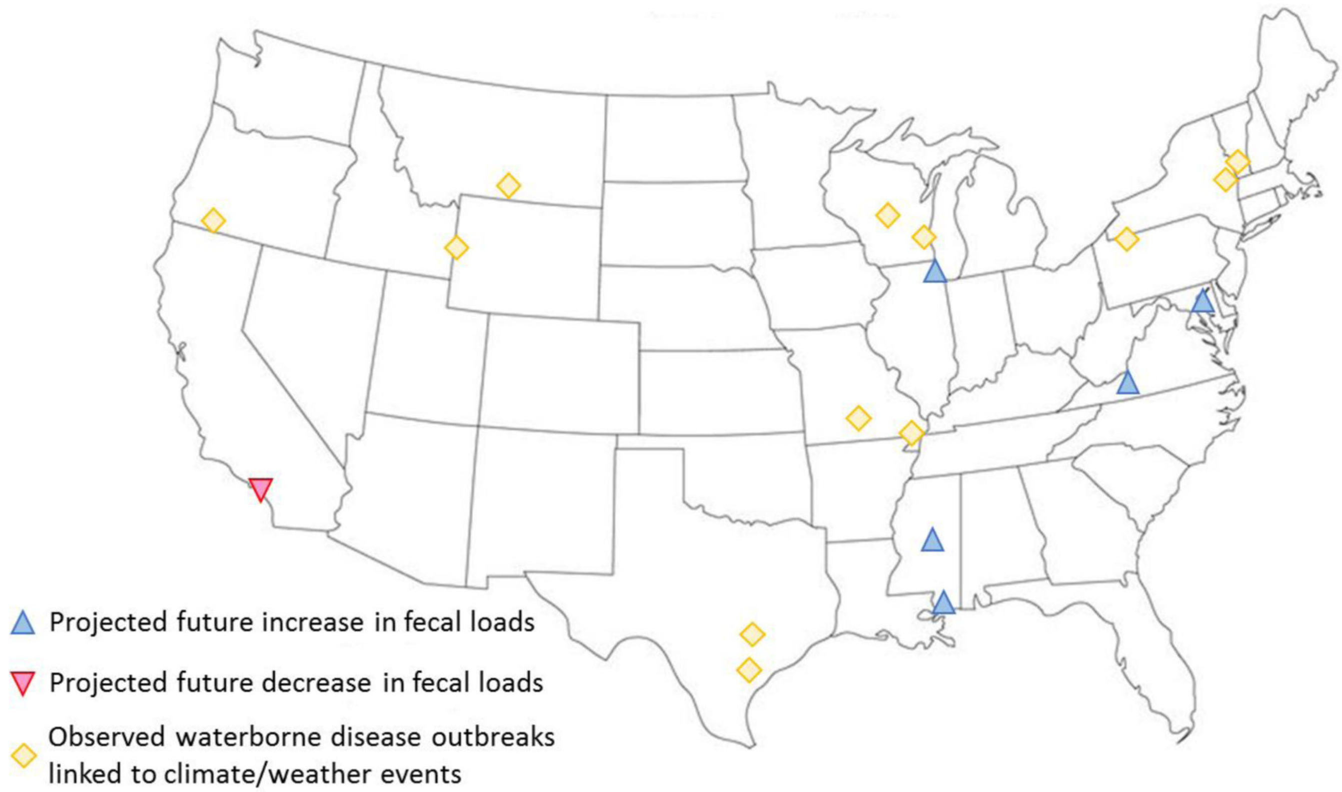

FIGURE 9.

Location of watershed modeling studies assessing fecal load responses to future climate change scenarios. Projected future symbols indicate the suggested direction of change (based on ensemble median, annual loads). The locations of some observed waterborne illness outbreaks that have been linked to weather events are also given. Detailed information about each study is provided in the Supporting Information.