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Research article

Proactive modeling of water quality impacts of extreme precipitation events in a drinking water reservoir

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ABSTRACT

Extreme precipitation events are of concern to managers of drinking water sources because these occurrences can affect both water supply quantity and quality. However, little is known about how these low probability events impact organic matter and nutrient loads to surface water sources and how these loads may impact raw water quality. This study describes a method for evaluating the sensitivity of a water body of interest from watershed input simulations under extreme precipitation events. An example application of the method is illustrated using the Wachusett Reservoir, an oligo-mesotrophic surface water reservoir in central Massachusetts and a major drinking water supply to metropolitan Boston. Extreme precipitation event simulations during the spring and summer resulted in total organic carbon, UV-254 (a surrogate measurement for reactive organic matter), and total algae concentrations at the drinking water intake that exceeded recorded maximums. Nutrient concentrations after storm events were less likely to exceed recorded historical maximums. For this particular reservoir, increasing inter-reservoir transfers of water with lower organic matter content after a large precipitation event has been shown in practice and in model simulations to decrease organic matter levels at the drinking water intake, therefore decreasing treatment associated oxidant demand, energy for UV disinfection, and the potential for formation of disinfection byproducts.

1. Introduction

Future climate projections based on global climate models (GCMs) indicate that average annual surface temperatures around the globe will increase while changes in precipitation will vary with geographic region and seasons. There is growing evidence that historically low-probability "extreme" weather events such as floods, droughts, and heat waves are occurring more frequently and in different locations than they have occurred in the past due to a more dynamic hydrologic cycle (IPCC, 2013; NOAA, 2013). Extreme weather events are generally defined as those that have less than 1%–5% probability of annually occurring in a specific region and are the result of any substantial change in weather type, severity, frequency, duration, or combination of events (Stanford et al., 2014). In the United States, for example, analyses of precipitation events during the 20th century demonstrated an increase in precipitation and an increase in precipitation intensity, especially during recent decades in the eastern US (Groisman et al., 2004, 2005). Increased precipitation and precipitation intensity in the eastern US have led to increased streamflows in the region, and GCM projections indicate a continuation of this trend (Groisman et al., 2004, 2005).

Climate induced changes to watershed hydrology and water quality, such as changes to tributary volumes, inflow timing, and constituent loads, affect receiving water quality. If the receiving water is a drinking water supply reservoir, decreased raw water quality increases treatment costs, impairs finished water aesthetics, and may risk public health. The ability of a waterbody to withstand the stress of altered inflows and loads depends on waterbody current trophic state under current hydrologic conditions (Murdoch et al., 2000). Additionally, the hydrology of water supply reservoirs is often anthropogenically controlled and therefore responses to climate change will be influenced by the specific features of the individual system. Gradual changes in meteorology and hydrology as well as the increased occurrences of low-probability, short-term events are equally important to understand with respect to water quality impacts. Continued climate stress may lead to exceeding

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system thresholds and can result in water quality degradation (Murdoch et al., 2000; Whitehead et al., 2009). Currently impaired water bodies will require less climate stress to exceed water quality thresholds, while less impaired water bodies will be able to tolerate higher stress and change while maintaining high water quality.

Increasing occurrences of low-probability extreme events can result in short-term water quality changes (e.g. spikes in nutrient loadings) and long-term water quality impacts (e.g. the compounding effect of greater annual nutrient loads) to drinking water sources. Water quality degradation as a result of extreme short-term changes in air temperature, precipitation in the form of rain or snow (as well as a lack of precipitation, i.e., droughts), tributary flow rates and timings, and runoff amounts all affect nutrient, organic matter, and sediment loads, in addition to receiving water organic matter composition, algae dynamics, and water age/flushing rates. The frequency and likelihood of event occurrence are also important to consider when evaluating impacts of extreme events on water quality, since combinations of several events can result in more gradual degradation in water quality over a period of months or years.

Extreme precipitation events are a major driver for the export of terrigenous organic carbon and organic-bound nutrients because erosion and sediment transport during large precipitation events are greater than during normal flow conditions. Higher streamflows can lead to greater mobility and dilution of constituents as well as greater sediment loads, altering the morphology of rivers and sediment transport to surface water bodies (Whitehead et al., 2009). Despite the knowledge of the importance of precipitation events controlling carbon and nutrient fluxes to water bodies, there have been few published studies that have analyzed fluxes from large or extreme precipitation events.

Organic carbon has an important role in ecosystems since it is involved in the complexation and transport of toxic metals and organic contaminants. The costs to remove organic matter during drinking water treatment scale with source water organic matter content. Greater organic matter concentrations can increase coagulant and oxidant demands (so higher doses needed) and increase the formation of regulated and unregulated disinfection byproducts (DBPs) during the disinfection process. It is widely accepted that dissolved organic carbon (DOC) and particulate organic carbon (POC) fluxes increase during precipitation events, however it is less clear how the ratio of DOC:POC changes with different precipitation volumes and intensities or watershed characteristics such as land-use, vegetation, and geology (Dhillon and Inamdar, 2013; Inamdar et al., 2006; Yoon and Raymond, 2012). Measurements from a forested watershed during extreme events indicate POC:DOC ratios greater than one in contrast to an agricultural watershed where the POC:DOC ratio were observed to be 1:2 (Dhillon and Inamdar, 2013; Caverly et al., 2013). Water quality measurements in a New York watershed after Hurricane Irene (a 200-year event for the region) indicated that roughly 40 and 31% of the annual mass inputs of DOC and DON, respectively, were from this event (Yoon and Raymond, 2012). Measurements of DOC and POC from a forested watershed draining the Maryland Piedmont during Hurricane Irene (a 25-year event for the region) were 20% and over 50% of the annual 2011 DOC and POC fluxes, respectively (Dhillon and Inamdar, 2013). Events occurring in lower portions of a large watershed may have a greater and faster impact on raw drinking water quality at an intake, since there is less attenuation time for particles and organic matter in the system, as observed in a Phoenix, Arizona watershed (Barry et al., 2016).

Nutrient concentrations and exports during heavy precipitation events in forested watersheds are even less well understood, since these vary widely with watersheds, seasonal conditions, land cover types, hydrology, geology, and other landscape characteristics. Concentrations of nitrogen species in the northeastern United States have been observed to be higher during spring events, which can be attributed to snowmelt and the flushing of nitrate (NO_3^-) accumulated in the soil during the dormant winter season (Correll et al., 1999; Inamdar et al., 2006). For a glaciated forested watershed in western New York, NO_3^- concentrations increased from pre-event conditions by 60% during spring snowmelt events from May 2003 through April 2004 but decreased as much as 92% during large precipitation events in the summer and fall (Inamdar et al., 2006). Total phosphorous (TP) concentrations observed across four adjacent watersheds of differing land uses on the Atlantic Coastal Plain in Maryland were higher during summer storms than in the winter and spring (Correll et al., 1999). Nutrient concentrations in the forested watershed were the least impacted by increasing tributary discharges due to precipitation events compared to croplands and mixed-land use watersheds (Correll et al., 1999). Phosphorus exports from forested catchments have been shown to be primarily associated with episodes of high discharge and sediment loads (Meyer and Likens, 1979).

One typical approach to simulating climate change impacts on water quantity and quality employs the use of downscaled GCMs to drive watershed, systems, and hydrodynamic and water quality models. However, this was deemed inappropriate for this particular study for several reasons: 1) the poor sub-daily meteorological temporal resolution of downscaled projections, 2) the great uncertainty associated with regional precipitation projections, especially short term precipitation events (Baker and Peter, 2008; Willems et al., 2012). There are also limitations to methods commonly used to estimate or simulate watershed nutrient loads during average watershed conditions when they are applied to large precipitation events such as 1) the current inability to accurately model the relevant processes governing constituent concentrations during large events, 2) the lack of or limited temporal and spatial sampling of a variety of constituents during extreme rain events in most watersheds, 3) the inability to generalize measurements and observations from different studies across different watersheds, 4) and the inability in some cases to generalize measurements across one watershed.

Hydrodynamic and water quality models are commonly used to simulate receiving water quality in response to changes in watershed inputs and/or climate change. The 2-D model CE-QUAL-W2 is an example of a model that has been applied to over 200 water bodies around the world and has been used to evaluate climate change impacts on water quality for many water bodies across the globe (Cole and Wells, 2015; Fang et al., 2007; Jeznach and Tobiason, 2015; Lee et al., 2012; Samal et al., 2013). Lake and reservoir models coupled with watershed models have simulated changes in nutrient and organic matter watershed loads (Debele et al., 2008; Narasimhan et al., 2010). Model simulations of future long-term increases in precipitation over a watershed indicate increased nutrient loads to a receiving water body (Chang et al., 2001).

This study and the (Hagemann, 2016)) companion study, presents a method to quantify the potential impacts of extreme precipitation events on watershed tributaries and receiving water quality. The method was applied in both studies to the Wachusett Reservoir, a major drinking water supply reservoir to metropolitan Boston MA, as an example to ultimately quantify source drinking water quality sensitivity to potential extreme precipitation event nutrient loads from the surrounding watershed. To the authors' knowledge, this is the first published study that links hypothetical extreme short-term precipitation event watershed nutrient loads with simulated receiving water body quality and proactively models the impacts of such an event. The method and example application presented are beneficial to water managers since this