Water Research 139 (2018) 108–117

Contents lists available at ScienceDirect

Water Research

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

Declining ambient water phosphorus concentrations in Massachusetts' rivers from 1999 to 2013: Environmental protection works

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A R T I C L E I N F O

Article history:
Available online 26 March 2018

Keywords:
Water quality
Phosphorus concentration
Trend analysis
Massachusetts rivers
Nutrient management
Environmental protection

A B S T R A C T

Over the last century, nutrient concentrations in streams, rivers, lakes and ponds have increased substantially in the United States. Elevated phosphorus levels are a concern due to their ability to cause changes in freshwater ecosystems that are detrimental to humans and wildlife. In the present study, long-term trends in total phosphorus (TP) concentrations from 20 rivers in central Massachusetts from 1999 to 2013 were investigated. Kendall's correlation coefficients were used to demonstrate that 18 of the 20 rivers had significant reductions in TP concentrations ($P < 0.05$). A similar trend was found when flow-adjusted TP concentrations were analyzed. At the beginning of monitoring activities, the average TP concentration in 9 of the 20 rivers was greater than 0.05 mg/L and 6 of these 9 rivers contained TP concentrations greater than 0.1 mg/L; about fifteen years later, only 3 rivers contained TP greater than 0.05 mg/L and none had concentrations> 0.1 mg/L. TP decreases were greater in rivers with more anthropogenic inputs. Principal component analysis (PCA) revealed that the decline of TP in these Massachusetts streams is likely the result of advancements in wastewater treatment and implementation of effective non-point source management practices.

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1. Introduction

Nutrients are essential for plant and animal life, but at elevated concentrations, they are one of the most critical pollutants in fresh water systems and coastal waters (Howarth and Marino, 2006; Paerl et al., 2016; Schindler, 2006). On a global scale, anthropogenic nutrient levels have exceeded the proposed planetary boundary above which the risk of destabilization of the earth ecosystem is likely to be high, with serious implications for human societal development (Steffen et al., 2015). Cultural eutrophication caused by these excessive nutrients occurs when the growth of primary producers outpaces their consumption by grazers (Carpenter et al., 1995; Rabalais and Nixon, 2002; Smith et al., 2006; Wong et al., 2016). The addition of nutrients to aquatic systems by anthropogenic enrichment can lead to biological responses that cause impairment of water uses; examples include algal blooms, noxious weed growth, extreme diel variations in dissolved oxygen and pH, taste and odor problems, turbidity, decreases in biodiversity and the elimination of important species and populations. This reduction in water quality can lead to economic losses associated with decreased property values and reduced recreational opportunities (Smith, 2006).

Excessive phosphorus may originate from both point and non-point sources. Point sources include wastewater treatment plant discharges, other industry discharges, and stormwater discharges through collection systems (Lock et al., 1990; Rabalais and Nixon, 2002; Schindler, 2006; Smith et al., 2006; Metson et al., 2017). Nonpoint source pollution generally results from land runoff during

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https://doi.org/10.1016/j.watres.2018.03.053
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precipitation events and its severity is associated with the degree of urbanization, agriculture and riparian buffers within a given drainage area (Lettenmaier et al., 1991; Dorioz and Ferhi, 1994; Alexander and Smith, 2006; Schindler, 2006; Smith et al., 2006). Globally, phosphorus accumulates faster than nitrogen in freshwater ecosystems impacted by anthropogenic inputs (Yan et al., 2016). Human-dominated river basins may undergo a prolonged but finite accumulation phase when phosphorus input exceeds agricultural demand and the accumulated phosphorus may continue to mobilize long after inputs decline (Powers et al., 2016).

In the United States, eutrophication remains one of the foremost problems in aquatic ecosystems (Schindler, 2006; Smith et al., 2006; Salerno et al., 2014; Powers et al., 2016; Copetti et al., 2017), despite significant advances made in the past four decades since the 1972 amendments to the Federal Water Pollution Control Act (the Clean Water Act). In trends analysis for streams and rivers in the continental United States from 1978 to 1987, Lettenmaier et al. (1991) found that among 389 stations, 69 stations had significant negative trends for total phosphorus (TP), i.e., TP levels decreased and 12 stations with significant positive trends. The downward trends occurred primarily in the Great Plains and in the Eastern United States. Alexander and Smith (2006) modeled nutrient trends and associated changes in trophic state in 250 large U.S. rivers between 1975 and 1994. They found that the trophic state had improved at 25% of the monitoring sites and had worsened at fewer than 5% of the sites; about 70% of the sites were unchanged (Alexander and Smith, 2006). Sprague and Lorenz (2009) found more sites with general increases than decreases in flow-adjusted TP concentrations in the eastern United States (Sprague and Lorenz, 2009). Based on periodic probability surveys of thousands of water bodies (streams and lakes) in the conterminous U.S., Stoddard et al. (2016) reported that TP concentrations increased over the 5-year periods between surveys from 2000 to 2014 with most notable increases in sites in relatively undisturbed catchments where TP concentration was initially low (e.g., <0.01 mg/L) (Stoddard et al., 2016). In studying 2913 Midwest and Northeast lakes in the United States, it was found that total nitrogen concentration declined from 1990 to 2013 while no change in TP occurred during the same period (Oliver et al., 2017).

In its implementation of the U.S. Federal Clean Water Act, the Massachusetts Department of Environmental Protection (MassDEP) has a more than 40-year history of investigation and management of water quality issues attributed to anthropogenic enrichment. Although phosphorus and/or nitrogen can be the limiting nutrient for both freshwater and marine environments, eutrophication-related water quality policy in the United States and Europe is directed primarily toward phosphorus control for freshwater ecosystems (Smith et al., 2006 and reference therein). In the nutrient-poor glaciated areas of north-central and northeastern United States, phosphorus is the nutrient most often limiting and easiest to control in fresh waters and, in Massachusetts, phosphorus is the nutrient most often targeted in controlling eutrophication (Mattson and Godfrey, 1994; Mattson, 2015). Even in cases where nitrogen is found to be limiting in freshwater, eutrophic conditions are usually caused by excessive anthropogenic phosphorus inputs, and the remedy is not to regulate nitrogen, but rather to reduce anthropogenic phosphorus sources until the latter is again the limiting nutrient (Cooke et al., 1993). In some instances nitrogen may need to be controlled in conjunction with phosphorus in order to maintain natural N/P ratios (e.g., the Refield atomic ratio 16/1) and natural species composition. Details on policies and recommendations for lake management in Massachusetts are presented in MassDEP's final Generic Environmental Impact Report (GEIR) (Mattson et al., 2004). In Massachusetts, TP has long been identified as the primary cause of cultural eutrophication in the state's freshwaters, with nutrient impairments directly or indirectly linked to approximately 48% of water quality impairments (Department of Environmental Protection, 2011).

In the present study, our goal was to examine the trend of total phosphorus concentrations in 20 rivers in central Massachusetts from 1999 to 2013 and identify management activities within these river basins to assess their potential effectiveness on phosphorus mitigation.

2. Methods

2.1. Study area

This study focuses on 20 rivers (Table 1) in central Massachusetts (Fig. 1). Each of the river basins has several types of land use within its boundaries that vary from urban to natural (undisturbed) lands (Table 1). Historic water quality data collected from the 1970's to 1990's by MassDEP (and under its previous name, the Department of Environmental Quality Engineering, or DEQE) was used in the original station selection process to tentatively label each stream as “least” or “highly” impacted. For the purposes of this analysis, “least impacted” refers to streams with minimal anthropogenic disturbance (e.g., urbanization, industrial/commercial development, major transportation corridors), and “highly impacted” refers to those affected by several significant sources of pollution (Massachusetts Department of Environmental Protection, 2008). Seven of the rivers in the study were categorized “least impacted” based on the higher percentage of natural (i.e., undisturbed) land; the remaining 13 rivers were categorized as “highly impacted”, with an overall higher percentage of impervious cover (6.5% or greater), developed or agricultural land (Table 1).

2.2. Water sample collection and analysis

From 1999 to 2013, typically bi-monthly water samples were collected from each of the 31 monitoring stations in the 20 rivers by MassDEP's Strategic Monitoring and Assessment for River basin Teams (SMART) program staff. Generally there was one monitoring station for each river; however, for larger rivers such as the Nashua and Ware Rivers, one or more stations were added to address anticipated changes in water quality associated with major sources of pollutants. To minimize spatial correlation within a river with multiple sampling stations, only data from the downstream-most station were analyzed (Legendre and Fortin, 1989; Chang, 2008; Sprague and Lorenz, 2009). Grab samples were collected for laboratory analysis including total phosphorus (TP) and others either by wading into the stream (the preferred method) or by extending a sampling pole from shore. Standard operating procedures (SOPs) on sampling program design, field operations, laboratory analysis, and data quality objectives and quality control (QA/QC) were followed according to the Quality Assurance Project Plan (QAPP) for the SMART monitoring program which specifies these and other program-specific details (Massachusetts Department of Environmental Protection, 2008). The Chain-of-Custody (COC) procedures insure the integrity of the collected samples by documenting sample possession from the time of collection to disposal. All field and laboratory protocols and QA/QC methods were presented in formal written documents describing the detailed quality control procedures used to achieve data quality requirements. Using the standard collection methods (I-4650-03) developed by the U.S. Geological Survey (USGS) (Patton and Kryskalla, 2003), TP samples were collected in plastic bottles, preserved with acid, and stored in a cooler with ice before being transported to MassDEP's environmental laboratory, the William X. Wall Experimental Station (WES) for analysis. TP concentration was

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