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Key Points:
- Small ponds located in headwater catchments dominate nutrient and sediment retention compared to streams, rivers, lakes, and reservoirs
- Small ponds located directly adjacent to streams or away in upland positions have distinct effects on nitrogen, phosphorus, and sediment
- Finer-scale small streams are minor net sources of phosphorus and major net sources of sediment where soil erodibility is high

Supporting Information:
- Supporting Information S1

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Small Ponds in Headwater Catchments Are a Dominant Influence on Regional Nutrient and Sediment Budgets

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Abstract Small ponds—farm ponds, detention ponds, or impoundments below 0.01 km^2—serve important human needs throughout most large river basins. Yet the role of small ponds in regional nutrient and sediment budgets is essentially unknown, currently making it impossible to evaluate their management potential to achieve water quality objectives. Here we used new hydrography data sets and found that small ponds, depending on their spatial position within both their local catchments and the larger river network, can dominate the retention of nitrogen, phosphorus, and sediment compared to rivers, lakes, and reservoirs. Over 300,000 small ponds are collectively responsible for 34%, 69%, and 12% of the mean annual retention of nitrogen, phosphorus, and sediment in the Northeastern United States, respectively, with a dominant influence in headwater catchments (54%, 85%, and 50%, respectively). Small ponds play a critical role among the many aquatic features in long-term nutrient and sediment loading to downstream waters.

Plain Language Summary Reservoirs created by river damming have extensive impacts on downstream water quality but are not necessarily the most important elements of a diverse aquatic landscape. Many more small ponds have been constructed to serve important human needs ranging from farm irrigation in agricultural areas to flood control and trapping of nutrients and fine sediment in urban areas. The number of human-influenced small ponds is projected to rise worldwide, yet their role in the delivery of nutrients and sediment from headwaters to oceans is currently unresolved. Here we used new data sets and found that small ponds are collectively responsible for trapping a substantial amount of the nutrients and sediment that are exported annually from headwaters. These findings support the need to jointly consider features such as urban detention ponds, farm ponds, and beaver ponds in managing headwaters to decrease long-term nutrient and sediment loading to downstream waters and sensitive coastal areas.

1. Introduction

Nutrient and sediment loading from headwaters to coasts is regulated by river corridors comprised of both flowing (i.e., lotic) and ponded (i.e., lentic) waters that each distinctly influence downstream water quality (Baker et al., 2016; Harvey & Gooseff, 2015; Seitzinger et al., 2006). Ponded waters range in size from the largest lakes and reservoirs to smaller features such as naturally occurring prairie potholes, human-influenced farm ponds, and urban detention ponds. The importance of ponded waters to the global cycle of nutrients and fine sediment is growing in response to increased soil erosion from land use activity, river damming, and eutrophication (Mendonça et al., 2017). For example, large reservoirs have been estimated to retain behind their dams nearly 40% of all riverine organic carbon (Mendonça et al., 2017), up to 30% of all riverine fine sediment (Vörösmarty et al., 2003), over 12% of all riverine phosphorus (Maavara et al., 2015), and roughly 3% of all riverine nitrogen (Harrison et al., 2009).

Large reservoirs have apparent impacts on downstream water quality but are not necessarily the most important features in terms of their water quality functions. While approximately 4% of the Earth's nonglaciated land surface is covered by ponded waters, nearly a third of that coverage is likely accounted for by small ponds with surface areas less than 0.01 km^2 (Verpoorter et al., 2014), a commonly used size

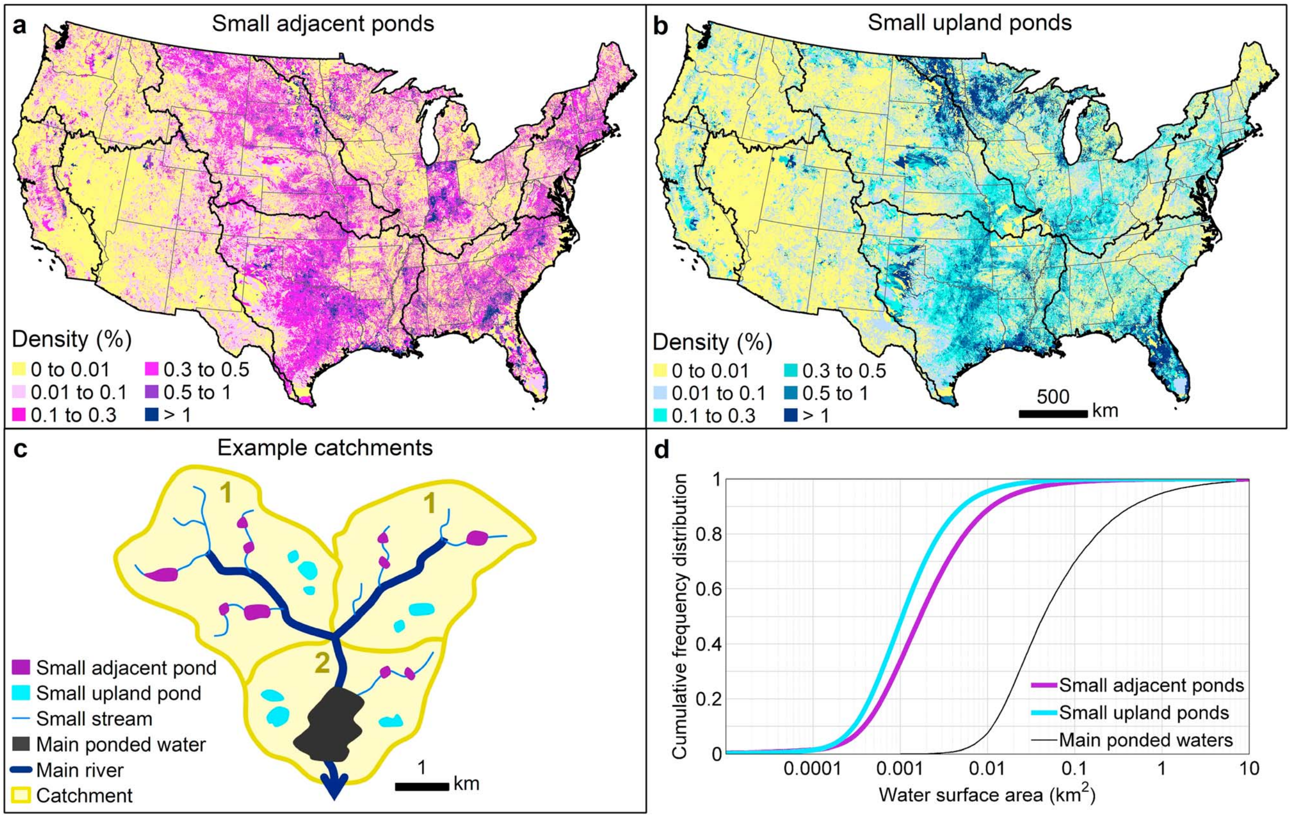

Figure 1. Density of small ponds across the contiguous United States. Areal density of (a) small adjacent ponds and (b) small upland ponds is expressed as the percent wetted area to drainage area. (c) Example catchments containing small ponds and small streams where the numbers designate stream order (i.e., headwater catchments are associated with first-order rivers). (d) Size distributions of small ponds compared to main ponded waters in the Northeastern United States. Black boundaries are major river basins.

classification for small ponds (Downing et al., 2006; Holgerson & Raymond, 2016). A preliminary analysis by Downing et al. (2006) further suggests that a vast majority of the Earth's ponded waters are small ponds. Despite their abundance, small ponds have received far less attention than large lakes and reservoirs, as well as streams and rivers, in regional water quality studies due to, in part, their lack of consistent geospatial coverages (Seekell et al., 2013; Smith et al., 2002; Verpoorter et al., 2014). Consequently, the contribution of small ponds to regional nutrient and sediment budgets is unresolved (Downing, 2010), except for some specific cases (Berg et al., 2016; Renwick et al., 2005).

New understanding of the regional role of small ponds will be important for water resources planning because small ponds can be more easily managed compared with larger reservoirs. For example, urban detention ponds and farm ponds are often, but not always, efficient management strategies to retain nutrients and fine sediment (Berg et al., 2016; Villarreal et al., 2004). Promoting naturally occurring riparian ponds, such as beaver ponds, can be more effective than land-based mitigation strategies like cover crops and land retirement in reducing nitrogen export (Hansen et al., 2018) and may be a useful strategy to reduce river channel erosion (Goldfarb, 2018).

Given their ubiquitous coverage (Figure 1), small ponds may have major impacts on regional nutrient and sediment budgets. To test that hypothesis, we used a spatially referenced water quality modeling approach to quantify the role of over 300,000 small ponds in the mean annual nitrogen, phosphorus, and sediment budgets of the Northeastern United States. Our approach was made possible by the availability of a new high-resolution data set of small ponds. We distinguish the effects of small ponds from other aquatic features including the high-resolution stream network (hereafter "small streams"), the medium-resolution perennial streams and larger rivers (hereafter "main rivers"), and the larger system of lakes and reservoirs (hereafter "main ponded waters"). For context, only 18,000 of the main ponded waters in this region were considered in a recent nitrogen budget study (Schmadel et al., 2018).

We distinguished small ponds from main ponded waters according to both their surface area (< 0.01 km^2) and physical proximity to streams and rivers. Small ponds located directly adjacent to small streams were classified as "small adjacent ponds" and small ponds that were not directly adjacent to streams and rivers were classified as "small upland ponds" (Figure 1c). Both small adjacent and upland ponds are prevalent across the contiguous United States (Figures 1a and 1b), and distinguishing them in water quality models recognizes that position and physical adjacency to streams may affect their interactions with flowing surface and subsurface waters that hydrologically connect small ponds with downstream waters (Cohen et al., 2015; Marton et al., 2015). The nationally consistent data sets used here will in the future allow expanded studies at the continental scale (Figure 1).

2. Methods

2.1. Overview

We used water quality, land use, and new small pond and stream data sets to build Spatially Referenced Regression On Watershed attributes (SPARROW; Schwarz et al., 2006) models. Our models estimated long-term mean annual total nitrogen, phosphorus, and suspended sediment sources, sinks, and loading throughout the Chesapeake Bay (CB) and New England (NE) basins of the Northeastern United States. We built the models on the medium-resolution National Hydrography Dataset (NHD) Plus Version 2.1 that we extended to include newly available small pond and stream information contained in the high-resolution NHD Plus (Figure 1c; see supporting information Tables S1 and S2).

Briefly, we ran medium-resolution models with added small pond and stream information from the high-resolution data set to analyze how small ponds and streams affect regional nutrient and sediment budgets while maintaining the convenience of modeling with the medium-resolution framework. Therefore, a headwater catchment is defined as the catchment associated with a first-order medium-resolution NHD reach. Incorporation of high-resolution NHD features in medium-resolution NHD catchments allowed for the accounting of ponds as small as 0.0001 km^2 (see Text S1 for details).

2.2. Summary of Model Specifications, Calibration, and Outputs

SPARROW models statistically estimate mass source and sink terms that modify a spatially referenced transport equation that represents the coupled hydro-terrestrial system and effects of specific aquatic features. The nitrogen, phosphorus, and sediment models were each calibrated to long-term mean annual observations through multi-nonlinear regression to estimate coefficients of the source and sink terms and to evaluate statistical significance of those coefficients (i.e., whether they were significantly different than 0). Model results represent a net mass balance that expresses the individual and cumulative effects of long-term constituent sinks and sources in 200,000 catchments (see Text S2 and Tables S3–S5 for calibration results).

The high-resolution small ponds and streams may be quantified as either sinks or sources depending on the constituent and local characteristics. To quantify the overall effect of small ponds on the net mass balance, we removed all small ponds in the calibrated models and ran these alternative models in simulation mode (see Text S2 for details). We also applied a generalized boosted regression model to determine where and why higher densities of small ponds occur (see Text S3 for details).

3. Results

3.1. Regional Patterns of Small Ponds

Small ponds were found to be the dominant nitrogen, phosphorus, and sediment sinks in many locations, frequently retaining over 50% of the constituent masses otherwise delivered annually from the terrestrial landscape to the river network (Figure 2). Regionally, small ponds account for 34% (±6%) of the nitrogen, 69% (±5%) of the phosphorus, and 12% (±6%) of the sediment masses retained collectively by all aquatic components (Figure 3; see Table S6 for mass equivalents). Small ponds dominate in headwater catchments—where they account for over 54% (±6%) of the nitrogen, 85% (±3%) of the phosphorus, and 50% (±19%) of the sediment masses retained collectively by the headwater aquatic system (Figure 3)—because agricultural and urban sources are greatest in headwater catchments, in close proximity to where the density of small ponds is highest (Figure S1). Therefore, management of small ponds may be an effective strategy to reduce long-term mean annual source runoff from the terrestrial landscape to the larger river network and thus decrease downstream loading and concentrations.

Small ponds are more prevalent than main ponded waters in many areas but not everywhere, revealing striking regional differences in nutrient and sediment retention (Figures 2 and S2). In central Maine, for example, main ponded waters play a larger role in nutrient and sediment budgets than small ponds in part because many of the main ponded waters are natural features of a glacier-influenced landscape or were accentuated by damming wide and slowly flowing stream-wetland systems. Conversely, small ponds are much more extensive than main ponded waters in CB where natural ponded waters are scarce (although reservoirs are common) and thus small ponds play a larger role than main ponded waters in CB.

Small streams and main rivers are also important controls on CB and NE nutrient and sediment budgets. Small ponds or main ponded waters are the dominant nutrient and sediment sinks in many areas, but main rivers also play a significant role in regional nitrogen retention because their influence is more widespread (Figure S2). In contrast, only the larger main rivers, or those located on coastal plains, are significant sediment sinks. Our results further suggest that small streams are minor, but important, sources of phosphorus and major sources of sediment, with the largest sources occurring in locations of high soil erodibility (Figure S3).

Whether a small pond is located directly adjacent to a stream or away from a stream in an upland position is important. Small adjacent ponds are significant nitrogen sinks, while small upland ponds are significant phosphorus sinks (Figures 2a and 2b). There are distinct portions of the region where small adjacent ponds dominate nitrogen retention (e.g., eastern Virginia; Figure 2a) and small upland ponds dominate phosphorus retention (e.g., from northern Maryland to southeast New York; Figure 2b). Small upland ponds located in lower-slope (<14%) catchments retain sediment (Figure 2c); however, those located in steep catchments enhance the delivery of sediment to the larger river network (Figure S3b).

3.2. The Where and Why of Small Pond Functions

Determining why small ponds are present on the landscape and where they are sources or sinks for constituents will further help reveal their role in water quality. In the Northeastern United States, small ponds were mainly found to occur in low-slope headwater catchments of agricultural or urban areas, indicating that most are human-made or managed natural features such as small impoundments for farm irrigation in agricultural areas or stormwater detention in urban areas (Figure S4). For example, a scenario-based manipulation of pond areal density in a calibrated model suggests that a change in the areal density of small adjacent ponds from 0 to 1%—an extreme example, yet 1% is a common density in many agricultural areas (Figure S1)—could decrease nitrogen export from a watershed by nearly 50% (Figure 2). Alternatively, a change from 0 to 1% areal density of small upland ponds could reduce phosphorus export by an astonishing 80%. Clearly, these scenarios will need more development to be directly useful in management planning; however, they demonstrate the large impact of small ponds and suggest the potential to accomplish water quality targets through collective small pond management.

3.3. Roles of Small Ponds and Streams Relative to Larger Rivers and Ponded Waters

The relative role of each aquatic component varies throughout the river network depending on landscape features and interactions with sources. We quantified the relative role of each aquatic component (small adjacent and upland ponds, small streams, main rivers, and main ponded waters) to determine where the dominant aquatic sinks and sources occur and why. A breakdown by stream order reveals that the location of a small pond and small stream within the larger river network is important—the relative influence of both small ponds and small streams decreases in progressively larger river basins (Figure 3).

The aquatic components collectively retained 29% of all nitrogen sources, leaving a net 71% exported to the ocean (Figure 3a; see Table S6 for mass estimates). Of the nitrogen mass retained by the aquatic components, main rivers (53%) make up the largest proportion, closely followed by small adjacent ponds (34%), with main ponded waters (13%) consisting of the smallest yet still important proportion.

Small adjacent ponds are the dominant nitrogen sinks in headwater catchments because they have greatest effect where agricultural, urban, and atmospheric deposition sources are highest (Figure 3d). Nitrogen sources delivered from the landscape decrease with increasing stream order, leading to main ponded

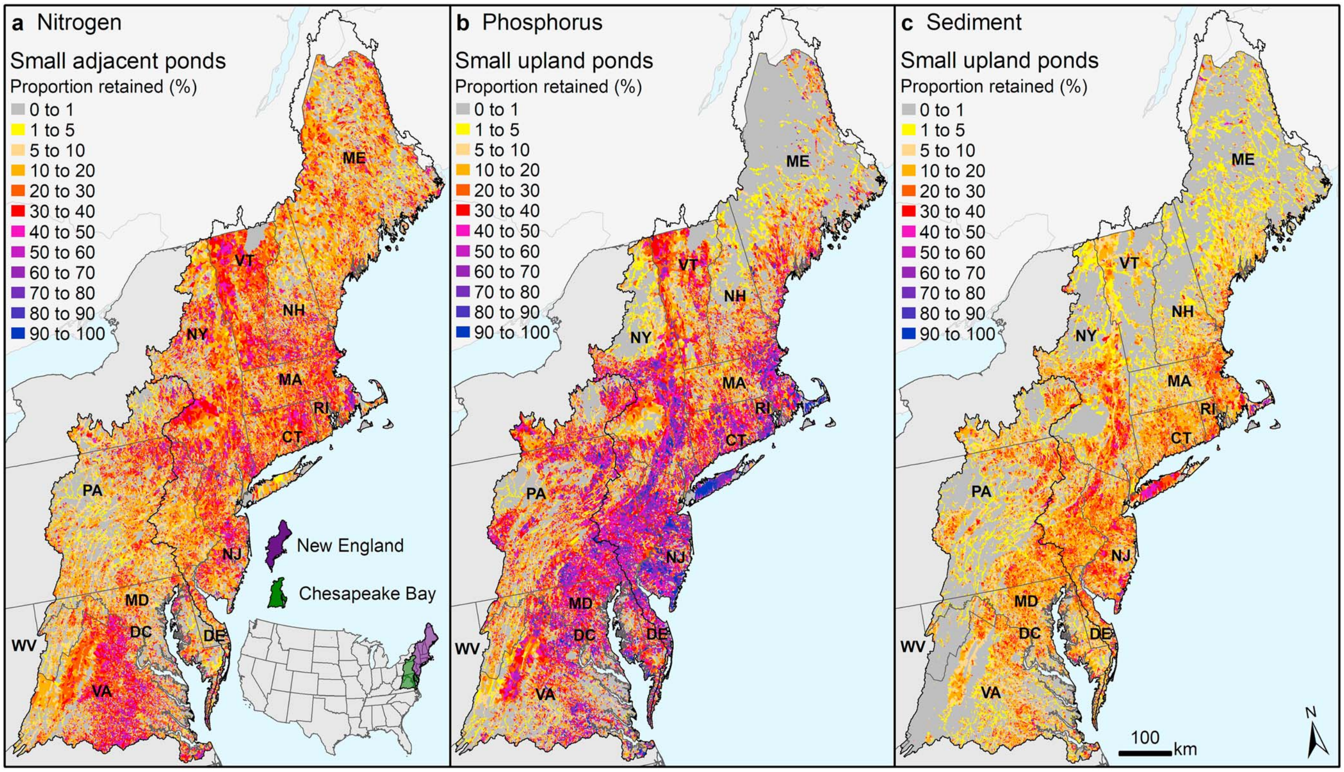

Figure 2. Proportion of nitrogen, phosphorus, and sediment source retained by small ponds in the Northeastern United States. Small adjacent ponds are significant mass sinks for (a) nitrogen while small upland ponds are significant mass sinks for (b) phosphorus and (c) sediment.

waters playing a more important role lower in the river network. Main ponded waters are not as pervasive as small ponds and, therefore, do not directly affect nitrogen sources from the landscape to the same extent. Point sources, on the other hand, are unaffected by small ponds but are influenced by main rivers and main ponded waters lower in the river network. Main rivers are a large nitrogen sink at every stream order because they make up a much larger total benthic surface area than main ponded waters. Consequently, main rivers play a larger role than main ponded waters in CB compared to NE because main rivers comprise more of the total benthic surface area in CB (Figure S5). Yet agricultural sources are overall higher in CB than in NE (Figure S6), leading to small adjacent ponds having an increased role in reducing agricultural runoff.

Small upland ponds are responsible for a surprising 69% of the phosphorus mass retained (Figure 3b). Small upland ponds retain more phosphorus than main ponded waters from first- to third-order catchments because small upland ponds are more pervasive across the landscape than main ponded waters and, therefore, have a greater effect where runoff from agricultural and urban land uses are highest (Figures 3b and 3e). The transition to main ponded waters becoming dominant sinks lower in the river network is also due to a decrease in land-based sources and an increase in point sources—which are not affected by small upland ponds—and larger sizes of main ponded waters lower in the river network (Figure 3e). For example, main ponded waters are the dominant phosphorus sinks in seventh-order catchments of CB due to larger reservoirs such as the Conowingo Dam on the Susquehanna River (Figure S5).

Small adjacent ponds and small streams are minor (only 4% each of regional total) net sources of phosphorus over the annual timescale that generally decrease with increasing stream order (Figure 3e). Our model results suggesting that small adjacent ponds tend to be more efficient than main ponded waters for total nitrogen retention but less efficient for total phosphorus retention are generally consistent with observed processes (Figure S7 and Table S7). For example, field-based studies indicate that small adjacent ponds may more frequently reduce total nitrogen yet increase total phosphorus downstream (Fairchild & Velinsky, 2006).

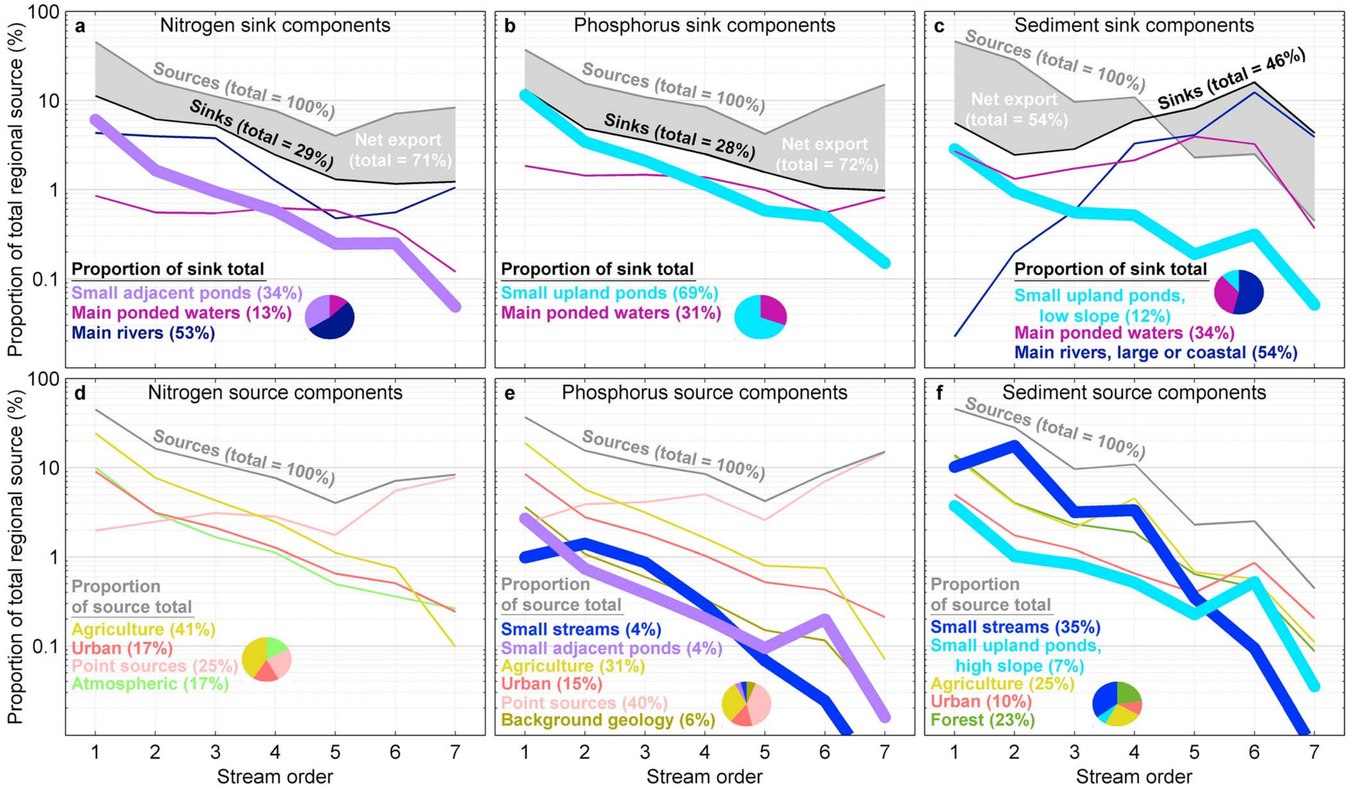

Figure 3. Proportions of aquatic mass sinks and sources throughout the river network. The proportion of mass sinks relative to the total regional source of (a) nitrogen, (b) phosphorus, and (c) sediment are associated with aquatic components, including small ponds (adjacent and upland), main ponded waters, and main rivers, revealing their relative roles per stream order. The source components relative to the total regional source (resulting in a proportion) for (d) nitrogen, (e) phosphorus, and (f) sediment. The thicker lines emphasize newly accounted for small ponds and small streams.

Slope is an important driver of how the relative sediment sources and sinks vary throughout a river network. The largest sediment source is small streams (35% of regional total), which is mostly delivered to the river network in higher-slope first- to fourth-order catchments, sharply decreasing thereafter (Figure 3f). Small upland ponds located in higher-slope (>14%) catchments slightly enhance the delivery of sediment, while those located in shallower catchments are sinks (Figures 3c and 3f). Small upland ponds are the dominant sediment sinks in headwater catchments where land-based sources are highest, but their relative role quickly decreases with increasing stream order (Figure 3c). Lower in the river network, larger main rivers, and those located on coastal plains have more favorable hydraulic conditions for sediment deposition, retaining more than the sources that enter the river network (Figure 3c), especially in CB (Figures S2 and S5). As a result, main rivers comprise more than half of the sediment retained by all aquatic components.

4. Discussion

4.1. Improving Long-Term Water Quality Predictions

The expanding global human footprint—river damming, deforestation, use of fertilizers, energy production, soil erosion, and changes in climate—requires management efforts that lead to more sustainable practices for improved water quality and ecosystem health and, in turn, food and water security. Maximizing the value of management investment requires accurately quantifying the spatial distribution of pollution sources and the aquatic components responsible for transporting and processing those sources in larger river basins. This study provides a fundamental step toward improved predictive and forecasting capabilities of regional water quality models by better identifying the relative roles of aquatic components and understanding how and why those roles vary between different constituents and throughout a river network.

The role of small ponds in regional nutrient and sediment budgets may be substantial due to the sheer abundance of small ponds nationally (Figure 1) and worldwide (Downing, 2010). For example, small ponds may play a more important role in global greenhouse gas emissions than previously assumed (Holgerson & Raymond, 2016), yet the amount of carbon sequestered can depend on the amount of available nitrogen and phosphorus that enter small ponds (Chen et al., 2015). Small ponds also may be larger contributors to sediment retention in other culturally influenced regions than estimated in this study (Renwick et al., 2005). Although the number of large reservoirs is decreasing in the United States due to age (Foley et al., 2017), the density of human-caused small ponds (e.g., impoundments, farm ponds, and urban detention ponds) has increased over the past few decades and is likely to increase worldwide (Downing, 2010).

Our results indicate that small ponds can have a dominant influence on regional nutrient and sediment budgets and must be considered in water quality predictions. Consistently between the nitrogen, phosphorus, and sediment models, we found that small ponds and small streams collectively explained more variance than main rivers and main ponded waters combined (Tables S3–S5). Without accounting for major aquatic components like small ponds, predictions of where and why the retention or sourcing of nutrients and sediment is occurring may be inaccurate, limiting the ability to strategize effective management efforts.

4.2. Small Pond Management Potential

Small ponds play a dominant role in nutrient and sediment budgets in many areas but not everywhere. Our results indicate that the distinct effect of a small pond depends both on its position within the local catchment and within the larger river network. For example, small ponds dominate nutrient and sediment retention in headwater catchments primarily because a majority of the land-based sources originate in headwater catchments (Alexander et al., 2007).

There is a greater tendency for small adjacent ponds to occur in areas of intensive agricultural activity in the Northeastern United States (Figure S4), suggesting that their purpose is often serving human needs such as water storage for farm irrigation and flood control. Small upland ponds tend to occur in open urban spaces, also indicating that they are human influenced but serve different needs such as stormwater detention, wastewater treatment, and preventing contaminant spills from industrial operations. These findings coincide with efforts to increase urban detention ponds as best management practices for pollution and sediment mitigation (Villarreal et al., 2004).

Increasing the number of small ponds in certain headwater catchments may be a viable management option to mitigate constituent loading downstream, meet total maximum daily load requirements, and thus improve aquatic ecosystem health. We must be careful, however, to not assume that retention is always beneficial because some well-intended environmental regulations have caused unintended water quality consequences by focusing on one problem at a time. Selectively mandating phosphorus loading reduction, for example, can inadvertently increase the delivery of nitrogen to sensitive coastal areas (Bernhardt, 2013; Finlay et al., 2013).

Our results provide a basis for considering how nitrogen, phosphorus, and sediment may interact throughout river networks. Differential effects of small adjacent and upland ponds on nutrient and sediment retention may complicate management strategies but could provide an advantage by allowing for selective targeting to adjust the nitrogen to phosphorus ratio in receiving waters. Considering how to manage nitrogen, phosphorus, and sediment together may promote healthier aquatic ecosystems and prevent negative outcomes such as harmful algal blooms (Conley et al., 2009; Schindler et al., 2008).

Our results further suggest that small ponds function differently than main ponded waters because small adjacent ponds in headwater catchments dominate nitrogen retention yet enhance phosphorus export (Figure 3). Different functions may relate to important distinguishing characteristics of small ponds. For example, small ponds tend to be much shallower for a given volume of water (i.e., larger surface area to volume ratio) than main ponded waters (Table S8), which potentially provides more opportunity for contact with biogeochemically active sediment surfaces if vertical mixing is enhanced. Small ponds are, therefore, more likely to undergo resuspension of sediment but remain oxygenated at the bottom sediment interface, both of which could affect phosphorus retention differently (Carpenter, 2005). Fairchild and Velinsky (2006) showed that soluble reactive phosphorus is more typically retained by well-oxygenated small ponds, while particulate forms are exported, indicating that nutrient speciation also may be important to evaluate for certain management strategies. When data availability permits, our models could be improved to track individual nutrient species, but attempting that before enough data are available to constrain regional models would be counterproductive.

The timescale over which water quality predictions are made may also serve different management strategies. Our predictions improve the scientific guidance for planning how best to achieve long-term annual reductions in nutrient and sediment loading in response to land use change and regulatory incentives in both upland and aquatic systems (Van Meter et al., 2018). Other types of modeling that target short-term (e.g., daily to seasonal) mass balances may be important because nitrogen and phosphorus stored in small ponds may be episodically released under changes in flow, dissolved oxygen, or temperature (Fairchild & Velinsky, 2006; Palmer-Felgate et al., 2011).

The capacity of small ponds to retain nutrients and fine sediment may combat soil erosion that has led to increased sources of nitrogen, phosphorus, and carbon in agricultural areas (Quinton et al., 2010; Van Oost et al., 2007). Appropriate siting for construction of small ponds could improve habitat conditions by storing water that can sustain low flows at later times. Encouragement of beaver dam construction is a fast growing stream restoration technique; however, beaver ponds could cause flooding of property or trap too much sediment (Goldfarb, 2018). Conversely, small ponds can eventually reach their capacity and shift to become sources (Villarreal et al., 2004), or in the event of a dam removal, a pulse of nutrient-rich fine sediment can clog the streambed (Stanley & Doyle, 2003), reducing the amount of denitrification and assimilation of reactive phosphorus (Hall et al., 2013). Future efforts could evaluate and compare small pond function with other river corridor components, such as hyporheic zones, floodplains, and wetlands, to more fully understand dominant water quality processes (Harvey et al., 2018; Wohl et al., 2018).

5. Conclusions

This study provides a fundamental step toward improving prediction and forecasting of regional water quality by quantifying the relative importance of specific aquatic features that control downstream water quality outcomes. We found that small ponds can dominate the retention of nitrogen, phosphorus, and sediment compared with small streams, rivers, and lakes and reservoirs, but their distinct effects depend on both their physical adjacency to streams and their position within the larger river network. Accounting for major aquatic components like small ponds and streams improves estimates of where and why the retention or sourcing of nutrients and sediment is occurring to support strategizing effective management efforts.

Small ponds located adjacent to streams and in headwater catchments dominate total nitrogen retention. Rivers and larger ponded waters dominate nitrogen retention lower in the river network; consequently, regional nitrogen retention is dominated by rivers, closely followed by small ponds, with larger ponded waters consisting of the smallest yet still important regional proportion.

Small ponds located away from streams in upland positions dominate total phosphorus retention both in headwater catchments and regionally. Lower in the river network, larger ponded waters become more important than small ponds to phosphorus retention.

Small ponds located in lower-slope headwater catchments and in positions upland from streams dominate total suspended sediment retention, but the regional sediment budget is dominated by larger lowland rivers that have favorable hydraulic conditions for sediment deposition. Similarly, larger ponded waters are more important than small ponds to sediment retention lower in the river network. The finer-scale stream network consists of the largest proportion of sediment sources that mostly enter the upper portion of the river network.

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