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Phosphorus in the river corridor

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ABSTRACT

River corridor protection has been adopted by government agencies and non-governmental organizations to try to control nonpoint nutrient loading to rivers. Yet, river corridor protection and modeling strategies developed on a national basis may not fully account for dynamics that have proven to be important controls on phosphorus in river corridors. These sources of uncertainty may have economic and environmental costs, yet we know of no previous works that have proposed a broad conceptual model of phosphorus dynamics in river corridors. In this review, we develop a conceptual model of phosphorus in the river corridor under natural conditions based on existing research by: (i) evaluating how processes and controls vary among distinct landscape characteristics and among distinct segments within river networks (e.g., in confined channels versus wide valleys); and (ii) determining whether some processes and controls are generally more dominant for some landscape types and river reaches. Finally, we provide an example application of the conceptual model, and identify key areas for future research. The review suggests that phosphorus dynamics in the river corridor, and their controls, may vary substantially across different landscape types and river reaches. However, the conceptual model outlined here illustrates how certain characteristics of landscape type, and abundance, transport, and transformation of phosphorus and reactive compounds, may help to predict important river corridor phosphorus dynamics. Use of this conceptual model can better inform numerical modeling of phosphorus dynamics and management of river corridors.

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1. Introduction

Phosphorus loading to the oceans is approaching levels that have caused massive marine extinction in the past (Rockstrom, 2009). Modern loading rates are nearly eight times the natural background rate of ocean influxes (Lerman et al., 2000; Bennett et al., 2001) Efforts to control widespread marine "dead zones" below estuaries like the Mississippi River are commonly focused on reducing inputs of nitrogen from upstream farms; however, control of phosphorus may also be important in reducing eutrophication of these zones (Mitsch et al., 2001; Carpenter, 2008). High phosphorus loads also impact the rivers and lakes in which these loads are transported or stored. Phosphorus is the limiting nutrient in freshwaters and can cause eutrophication at 0.02 mg/L or higher (Correll, 1998): levels far below river concentrations in many managed watersheds. The costs of eutrophication in water treatment investments, public health, ecological integrity, traditional food sources, and recreational opportunities are well documented (Carpenter et al., 1998; Boyd et al., 2002).

In the United States, water quality impacts from point sources (such as industrial effluent or wastewater treatment) have generally improved (Carpenter et al., 1998). "Nonpoint" inputs are the majority of nutrient inputs to rivers (Carpenter et al., 2009; Son et al., 2013), but have proved extremely difficult to control through regulatory means (e.g., Jones, 2014). Restoration, rehabilitation, or conservation of the river corridor (which we subsequently call "river corridor protection") is one approach government agencies and non-governmental organizations have used to try to control nonpoint nutrient loading to rivers (Wohl et al., 2015).

We use the term "river corridor" to include areas outside of the active channel that are directly affected by river processes such as flooding (i.e., the floodplain and riparian zone), and "landscape" to refer to the hillslope and river corridor across larger spatial scales than a particular hillslope or river reach (Harvey and Gooseff, 2015). Although we do not discuss other in-channel dynamics, we briefly touch on hyporheic processes because they are an important means of exchange between the river and river corridor in some watersheds. Where wetland research is described, it is because these findings are assumed to have similarities with reaches of the river corridor (e.g., saturation and related effects, such as accumulation of organic matter and occurrence of redox processes).

Earlier work focused on surface transport of particulate phosphorus to receiving waters (King et al., 2015), yet more recent studies show that phosphorus dynamics in the hillslope and river corridor can be quite complex. For example, groundwater can also transport significant phosphorus loads to rivers and lakes (Peterjohn and Correll, 1984; Vanek, 1993; Sims et al., 1998; Djodjic et al., 2004; Holman et al., 2008); the river corridor may be a large sink of phosphorus from the hillslope (Peterjohn and Correll, 1984) or the river (Noe and Hupp, 2009), but can also release soluble phosphorus under some conditions (Dillaha et al., 1989); and the net role of the river corridor as a source or sink of phosphorus may sometimes be driven by exchanges with the river rather than with the hillslope (e.g., by the balance of sediment deposition with floods and bank erosion at the river channel-river corridor interface) (Noe and Hupp, 2009).

Further, such processes affecting phosphorus fluxes in the hillslope and river corridor may vary significantly along the river network (Noe et al., 2012); in acid versus alkaline systems (Carignan and Vaithiyanathan, 1999); and in different soil types, climates or land use histories (Macdonald et al., 2012). Guidelines for river corridor protection strategies are commonly developed on a national basis (e.g., USDA NRCS, 2015a), and so may not yet fully account for such place-specific phosphorus dynamics.

Environmental phosphorus models may not include dynamics that have proven to be important controls of river corridor phosphorus in field studies (e.g., only some models simulate different sorption rates for calcareous and non-calcareous soils, although lab studies show there is marked difference between the two) (Darke et al., 1996; McGechan and Lewis, 2002; Havlin et al., 2005; Robson, 2014). These place-specific variations in phosphorus dynamics may influence how sensitive distinct watersheds are to future human activities (whether river corridor protection or urbanization) and climate change, and the time scales over which such responses may occur; yet place-specific variations may not be reflected explicitly either in management or decision support tools such as environmental models.

These sources of uncertainty may have economic and environmental costs. River restoration supports a multibillion dollar industry and is particularly widespread in the United States, Europe and Australia (Wohl et al., 2015). Although many restoration activities are focused on channels, riparian (Osborne and Kovacic, 1993) and floodplain (Brookes, 1996; Hughes et al., 2001; Roley et al., 2012; Koebel and Bousquin, 2014) restoration have been considered important for river water quality improvements for some time, and such projects are increasingly being evaluated for their water quality benefits (Wohl et al., 2015). River corridor protection has been implemented for water quality improvements (Hoffmann et al., 2009), at national (Palmer and Filoso, 2009), regional (Buffering the Bay - Forestry Workgroup, 2013), and local (California Department of Forestry and Fire Protection, 2013) levels in diverse countries (Muotka and Laasonen, 2002; Brooks and Lake, 2007; Campana et al., 2014). However, most floodplain and riparian restoration intended to improve water quality has not yet been effective. Possible reasons include the small areas restored relative to altered areas within the contributing watershed (Palmer et al., 2005; Wohl et al., 2015), and "legacy" phosphorus from past management that is mobilized when the river corridor is hydrologically reconnected to rivers, or when external phosphorus loads to the river decrease (Sharpley et al., 2013). Water quality trading, another increasingly popular mechanism for river water quality improvements, commonly relies on environmental models to set transaction costs (US EPA, 2008). The success of these approaches—riparian and floodplain restoration, and water quality trading—is contingent on place-specific scientific understanding of the river corridor and its relationships with the landscape.

Conceptual models are an important way to synthesize scientific knowledge into testable hypotheses about a system. Such models are an important component of river restoration and management (Wohl et al., 2005) and are essential to improving environmental model capabilities and appropriate use of environmental models (Jakeman et al., 2006; Gupta et al., 2012). A number of previous works have synthesized key phosphorus processes and human influences on phosphorus dynamics in watersheds (e.g., Walbridge and Struthers, 1993; Axt and Walbridge, 1999; Reddy et al., 1999; Hendricks and White, 2000; Reddy and DeLaune, 2008; Withers and Jarvie, 2008; Hoffmann et al., 2009; Vidon et al., 2010; Noe, 2013; Sharpley et al., 2013). Other investigators have used a phosphorus index approach to indicate the susceptibility to phosphorus loading of watersheds with certain characteristics (e.g., Andersen and Kronvang, 2006). Several works have assessed lateral and longitudinal variations in phosphorus cycling (Noe et al., 2012; Noe, 2013 and references therein). The effect of storms and short-term meteorological events on phosphorus fluxes has been well studied (e.g., Jarvie et al., 2011). However, we are unaware of any broad conceptual model of phosphorus dynamics in the river corridor, particularly in a whole-watershed context.

Humans have altered phosphorus cycling at global scales, and at the watershed level in many regions (e.g., Withers and Jarvie, 2008; Rockstrom, 2009). Human activities (e.g., fertilizer application) may be a much greater source of phosphorus in the environment than background sources (Newman, 1997), and phosphorus from such activities may accumulate in the hillslope only to be released to waterways later (Sharpley et al., 2013). This "legacy phosphorus" is a key concern in managing watersheds for long-term water quality. Although much phosphorus loading to rivers may be from anthropogenic sources (Withers and Jarvie, 2008), how and when this phosphorus is