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Review

Review on groundwater as a source of nutrients to the Great Lakes and their tributaries

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ABSTRACT

The role of groundwater in delivering nutrients (nitrogen and phosphorus) to the Great Lakes and their tributaries is not well understood. Consequently, this potentially important non-point source is poorly managed and often neglected. Evaluating nutrient inputs from groundwater requires knowledge of the (i) sources of groundwater nutrient contamination, (ii) physical groundwater discharge flow paths, and (iii) geochemical processes occurring along these flow paths that control the ultimate loading of nutrients to surface waters. Although groundwater quality in the Great Lakes Basin (GLB) is generally good, nutrient concentrations in aquifers can become elevated by a range of agricultural and non-agricultural activities. Nutrients can be delivered from groundwater to the Great Lakes by indirect discharge into tributaries or direct discharge into the lakes. The factors affecting these discharge pathways and their contributions to nutrient loading are distinct. The discharge of nutrients from groundwater to surface water is strongly regulated by zones of high reactivity that exist close to the sediment-water interface (i.e., riparian zone, hyporheic zone). Understanding the functioning of these zones for the landscape and hydrogeological conditions in the GLB is essential for evaluating nutrient loading to the Great Lakes and their tributaries as well as maximizing the benefits these zones can provide for water quality management. The paper concludes with a discussion of key knowledge gaps, challenges, and future research priorities that need to be addressed to evaluate and better manage this complex nutrient input to the Great Lakes and their tributaries.

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Introduction

Elevated levels of nutrients (nitrogen [N] and phosphorus [P]) significantly degrade water quality in the Great Lakes and their tributaries. Nutrient enrichment causes eutrophic conditions, stimulates excessive plant growth, and can trigger harmful and nuisance algae blooms. These effects threaten the health of aquatic ecosystems in the Great Lakes Basin (GLB) and in some cases have led to the deterioration of fish and wildlife habitats, fish kills, and loss of species diversity (National Wildlife Federation, 2011; Phosphorous Reduction Task Force, 2012). These effects also adversely impact public health and human uses such as recreational activities, tourism, fisheries, and drinking water supply (e.g., International Joint Commission, 2011). As P typically limits primary production in freshwater ecosystems, excessive P loading is implicated as the main contributing factor to eutrophication and excessive algae growth in the Great Lakes and their tributaries (Phosphorous Reduction Task Force, 2012). Excessive N loading, however, may also promote algae growth including blooms of toxic blue green algae. This has been shown to occur when N-P ratios are shifted by, for example, dreissenid mussels (Heath et al., 1995; Moon and Carrick, 2007; National Wildlife Federation, 2011). Although other nutrients including silica and iron may also stimulate algae growth (Moon and Carrick, 2007; North et al., 2007), this review paper focuses on N and P.

Since the 1970s, considerable effort has been devoted to decreasing nutrient loading to the Great Lakes and their tributaries with early efforts focused mainly on reducing point sources such as wastewater treatment plants. Although it is now well recognized that non-point sources also contribute to nutrient loading, the complexity of non-point sources makes their management and mitigation extremely difficult (International Joint Commission, 2011; National Wildlife Federation, 2011). Groundwater is often identified as a non-point source of nutrients to the Great Lakes and their tributaries (e.g., Barton et al., 2013), but there is considerable uncertainty regarding its contribution. This is in part due to the difficulty in quantifying groundwater nutrient loading to surface waters as it is mostly diffuse and exhibits high spatial and temporal variability (Kornelsen and Coulibaly, 2014).

The interactions between groundwater and surface water are complex and predicting nutrient loading from groundwater to the Great Lakes and their tributaries presents numerous challenges. The factors affecting nutrient loading from groundwater discharging directly to the Great Lakes compared with groundwater discharging to their tributaries are distinct (Fig. 1) (Grannemann et al., 2000; Kornelsen and Coulibaly, 2014). While groundwater also interacts with other surface water bodies in the GLB (e.g., reservoirs and ponds), this paper focuses on nutrient inputs to the Great Lakes and their tributaries. Herein use of the term "surface waters in the GLB" refers to these water entities. Evaluating groundwater as a source of nutrients to surface waters in the GLB requires knowledge of the (i) sources of groundwater nutrient contamination, (ii) physical flows linking aquifers to the surface waters and the associated nutrient transport pathways, and (iii) geochemical processes occurring along these transport pathways that control the absolute nutrient fluxes to surface waters as well as the ratios and chemical forms of the nutrients delivered.

This paper first provides an overview on the behavior of N and P in groundwater, including transformation pathways and current knowledge of N and P concentrations in aquifers in the GLB. Current knowledge of the various sources that contribute to groundwater nutrient contamination in the GLB is then detailed. Following this, factors affecting the delivery of nutrients from groundwater to the tributaries as well as directly to the Great Lakes are described. The paper concludes with discussion of knowledge gaps and challenges and provides recommendations for future research priorities. The material presented in this paper is summarized from an unpublished review report produced for Environment Canada on the contribution of groundwater as a source of nutrients to surface waters in the GLB (Robinson, 2014). While this review focuses on the GLB, where appropriate, it also provides a summary of the state of the science globally.

Overview of nitrogen and phosphorus in groundwater

Groundwater quality, including various forms of N and P, is routinely monitored at wells throughout the GLB especially at the municipal level where groundwater is a source of drinking water. While groundwater quality is generally good, N and P concentrations vary widely due to land use practices, landscape characteristics, and hydrogeological and geochemical conditions (International Joint Commission Great Lakes Science Advisory Board, 2010). The various chemical forms of N and P behave differently in groundwater. Knowledge of these behaviors is needed to understand the fate and transport of N and P in groundwater and subsequent inputs to surface waters.

The forms of N present in groundwater include nitrate (NO_3^-), ammonium (NH_4^+), nitrite (NO_2^-), soluble organic N, and N associated with sediment as exchangeable NH_4^+ or organic N. N cycling is dynamic with complex processes, mostly microbially mediated, controlling the form of N (Burgin and Hamilton, 2007; Rivett et al., 2008). Organic N can be transformed to NH_4^+ through a mineralization process called ammonification; NH_4^+ can be oxidized to NO_2^- and NO_3^- by nitrification; and NO_3^- can be taken up during plant growth and be transformed back to organic N. In addition, N can be removed from groundwater by denitrification, where NO_3^- is reduced to N_2O (nitrous oxide gas) and N_2 (nitrogen gas), or alternatively by anammox, where NH_4^+ combines with NO_2^- to produce N_2 (see Rivett et al. (2008) for further details). NO_3^- is generally the most common form of N in groundwater. As it is mobile, very soluble, and does not adsorb to sediment, it can migrate large distances through aquifers, and groundwater can be a dominant pathway for delivering NO_3^- to surface waters (e.g., Dubrovsky et al., 2010; Pärn et al., 2012; Ranalli and Macalady, 2010). NO_3^- is particularly mobile in highly permeable coarse-grained aquifers with low availability of electron donors such as organic matter, ferrous iron, and sulfide (Balderacchi et al., 2013; Ranalli and Macalady, 2010; Rivett

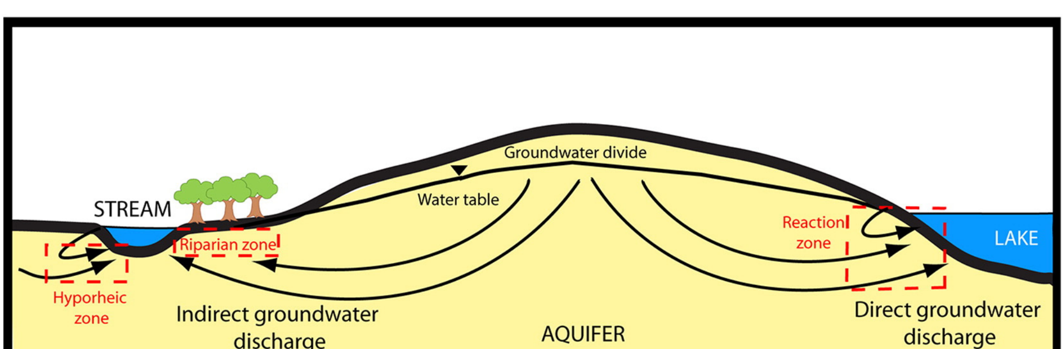

Fig. 1. Indirect and direct groundwater discharge into the Great Lakes.

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