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Influence of glacial landform hydrology on phosphorus budgets of shallow lakes on the Boreal Plain, Canada

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SUMMARY

A comparative study of three shallow lake catchments in contrasting glacial landscapes (coarse-textured outwash, fine-textured-till hummocky moraines and glacio-lacustrine clay-till plains) demonstrated a distinct landform control on the proportion and type of surface and groundwater sources influencing total phosphorus ([P]) and total dissolved phosphorus ([DP]) concentrations, and P budgets of lakes on the Boreal Plain of the Western Boreal Forest, Alberta, Canada. Lakes located on fine-textured landforms had high [P] and [DP] (median 148 and 148 $\mu g\,L^{-1}$ glacio-lacustrine plains; 99 and 63 $\mu g\,L^{-1}$ moraine, respectively) linked to shallow groundwater loadings from near-surface peat with high [P] from adjacent wetlands. In contrast, the lowest lake [P] and [DP] (median 50 and 11 $\mu g\,L^{-1}$, respectively) occurred on the coarse-textured landform, reflecting greater inputs of deep mineral-groundwater with low [P] from quartz-rich substrates. Annual lake P budgets reflected lake connectivity to the surrounding landform and relative contributions of P by surface versus groundwater. They also reflected distinct scales of groundwater (larger-scale versus short, shallow-flow paths) with differing [P] between landform types and occurrence of internal biogeochemical P cycling within landforms. A regional lake survey reflected trends from the catchment-scale, linking landform type to potential P sources as well as topographic position to potential trophic status across the Boreal Plain. Together, the results provide a conceptual framework for the scale of interactions between lakes and surrounding source waters influencing P loadings in differing hydrogeological landscapes, important to management strategies and predicting impacts of land-use disturbances on productivity of Boreal Plain lakes.

1. Introduction

Shallow lakes and open water wetlands are ubiquitous throughout the Boreal Plain ecozone and are a critical wildlife habitat and water resource in western Canada (Ducks Unlimited Canada, 2000). The Boreal Plain is undergoing widespread land use changes due to oil and gas development, forestry operations and associated disturbances (e.g. road construction, cut lines, well pads), each with differing degrees of impact on the biological and functional diversity of lake ecosystems. Best management strategies to sustain lake water quantity, quality and ecosystem structure, requires understanding the natural variability in hydrology and water chemistry, including water sources and nutrient exchange between lakes and the surrounding landscape. There are several regional scale frameworks that focus on spatial heterogeneity in climate, geology and soils (e.g. Wiley et al., 2003; Devito et al., 2005; Wagner et al., 2011) or characterization of hydrogeological setting (Winter, 2001; Dahl et al., 2007) to determine the relative importance of hydrologic and geologic mechanisms controlling water and nutrient exchange, the variability in hydrology and biogeochemistry. These in turn provide a scientific basis to assess the cumulative impact of disturbance on lakes. Regional delineations of landscapes with similar climate, geology and soil can provide context when extrapolating results from a given area, and guide management strategies and creation of management frameworks to protect lakes across regions.

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Previous regional scale studies examining water quality of Boreal Plain lakes show that although generally nutrient rich (e.g. Sass et al., 2008), phosphorus (P) is the limiting nutrient for phytoplankton productivity (Prepas et al., 2001). Total phosphorus concentrations ([P]) characterize lake trophic status (Environment Canada, 2013) thus, identifying potential hydrologic controls on lake [P], and in turn, lake total dissolved phosphorus concentrations ([DP]) (i.e. bioavailable form of P (Environment Canada, 2013)), will be important toward predicting lake productivity across the Boreal Plain ecozone. Although surface water P exchanges with lakes are widely investigated (e.g. streams and rivers), the importance of groundwater-lake infiltration/exfiltration influencing lake [P] is frequently disregarded in lake nutrient studies (Lewandowski et al., 2015; Rosenberry et al., 2015). In contrast to the Boreal Shield, the Boreal Plain is characterized by (generally) thicker and more heterogeneous surficial glacial deposits, i.e. coarse-textured deposits, fine-textured till disintegration moraines and glacio-lacustrine clay and till plains (Fenton et al., 2013), which result in complex and spatially varying exchange of groundwater with lakes (Ferone and Devito, 2004; Smerdon et al., 2005). The proportion of groundwater versus surface water sources to Boreal Plain lakes depends on the glacial landform type (Ferone and Devito, 2004; Smerdon et al., 2005); however, the relative importance of hydrologic exchanges for lake [P] remains unknown.

Low topographic relief and poorly integrated drainage on the Boreal Plain encourages wetland formation, whereby diverse types (e.g. swamps, fens, bogs) cover up to 50% of the land area in the region (Kuhry et al., 1993; Vitt et al., 1995) and development of large shallow lake-wetland complexes are common (National Wetlands Working Group, 1988). The riparian wetlands represent important sources of water and solutes to Boreal Plain lakes (Whitfield et al., 2010; Olefeldt et al., 2013). Groundwater [P] in Boreal Plain wetlands (Vitt et al., 1995; Thormann and Bayley, 1997; Macrae et al., 2005) are typically classified as eutrophic or hypereutrophic (Environment Canada, 2013), but can vary greatly between wetland types and differences in composition and depth of organic material (Vitt et al., 1995; Bayley et al., 2007). Similar to Boreal Shield lakes (e.g. D'Arcy and Carignan, 1997), some studies on the Boreal Plain report a positive correlation of lake [P] and wetland surface coverage of the effective catchment area (Halsey et al., 1997; Devito et al., 2000; Evans et al., 2000). In contrast, Sass et al. (2008) observed lower concentrations of remotely sensed chlorophyll-a (indicator of trophic status) in Boreal Plain lakes with a larger area of connected wetlands. It is not clear if the observed variability in Boreal Plain lake [P] and trophic status is linked to differences in flow paths of source waters through uplands with high absorptive affinity mineral soils limiting P transport (Macrae et al., 2005) or a change in wetland type (e.g. swamps, fens and bogs) within different landscapes and related differences in P retention capacity (Halsey et al., 1997; Prepas et al., 2001). These previous studies on lake variability relied heavily on the assumption that the percentage of wetland surface coverage reflects the only hydrologic connectivity between wetlands and lakes. Further, direct geologic sources of P to lakes, or groundwater seepage of P from lake sediments can also be important in these landscapes (Shaw et al., 1990; Hagerthey and Kerfoot, 1998). As such, the apparent contradictions in the literature may be attributed to differences in hydrologic P transport and landscape flow patterns emerging with changes in scale, or reflect the challenges of correlational studies and inferring processes from patterns.

Variation in landscape position and the lakes position in a groundwater flow system, along with the type and texture of the glacial landform influences the proportion of local vs. intermediate or regional groundwater flow paths (Ferone and Devito, 2004; Smerdon et al., 2005; Toth, 1999; Winter, 1999; Devito et al., 2000; Webster et al., 1996). The scale of groundwater flow paths will have a great influence on the transport of P from different source water types (organic versus mineral substrates) to lakes, as will the state and magnitude of lake–groundwater connectivity (e.g. perched, isolated, flow through, discharge) and the chemistry of the source waters (Brinson, 1993; Hill and Devito, 1997). Therefore, knowledge of potential groundwater P exchange in context of the local and regional groundwater flow patterns and lake position within the different hydrogeological landform types will improve the understanding of regional patterns in lake [P] and underpin the capacity to predict impacts of land use disturbances on lake productivity across the ecozone (Bedford, 1999; Winter, 1999; Devito et al., 2000; Winter et al., 2003).

Lake chemical budgets provide valuable insight into the dominant groundwater and surface water loadings of constituents to lakes and the relative importance of hydrology to changes in lake chemistry (Wentz et al., 1995; LaBaugh et al., 1997). As such, the objectives of this study were to apply a landscape linkage and lake chemical budget approach, utilizing previously published hydrologic studies and water balances (Ferone and Devito, 2004; Smerdon et al., 2005) to compare [P] and [DP] of three shallow lakes to that of potential surface and groundwater sources in three catchments across the major contrasting glacial landform types on the Boreal Plain (i.e. coarse-textured glacio-outwash, fine-textured till disintegration moraines and glacio-lacustrine clay and till plains). The combination of detailed catchment studies and a regional survey of groundwater and lakes across a hydrogeologic transect was used to examine how glacial landform type may influence: (1) [P] of groundwater sources in different parts of the subsurface (mineral substrate, swamps and sedge fens, poor fen and bog peatlands, and gyttja); (2) the proportion and/or source water types to influence lake [P], [DP] and annual lake P budgets; and (3) the regional scale distribution of [P] between mineral and wetland groundwater source waters and landscape position (high, intermediate and low relative elevation; i.e. proxy for position in groundwater flow system) to influence lake [P] and [DP] across the Boreal Plain ecozone.

2. Methods

2.1. Utikuma region study area

This study was carried out in the Utikuma Region Study Area (URSA) within the Central Mixedwood Natural sub-region of the Boreal Forest in Alberta (Natural Regions Committee, 2006) or Mid-Boreal Uplands Ecoregion of the Boreal Plain ecozone of northern Alberta, Canada (Ecological Stratification Working Group, 1996) (Fig. 1). The study area overlies the Smoky Group shale unit of the Upper Cretaceous period and the Quaternary glacial deposits vary from 40 to 90 m in thickness (Vogwill, 1978; Ceroici, 1979). The surficial geology at URSA is typical of the Boreal Plain, varying from rolling hummocky terrain and plains of coarse-textured glacial–fluvial (outwash) deposits in the northwest, through hummocky terrain and fine-textured clay-rich tills of disintegration moraine deposits to fine-textured near flat undifferentiated moraine (fluted, thrust) and glacio-lacustrine plain deposits in the southeast (Vogwill, 1978; Fenton et al., 2003; Paulen et al., 2004) (Fig. 1). Low relief and poorly integrated drainage encourages organic wetland formation across the study area (Fig. 1). Long-term hydrochemical and hydrogeologic studies have been conducted on thirty-three lakes in this region, see Olefeldt et al. (2013).

The climate of URSA is continental with summer (July) and winter (January) long-term mean temperatures of 15.7 °C and −14.6 °C, respectively (Environment Canada, 2003). Annual average precipitation (P_i, 483 mm) is slightly less than the potential evapotranspiration (PET) (513 mm) (Environment Canada, 2003).