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Quantifying seasonal variation in total phosphorus and nitrogen from prairie streams in the Red River Basin, Manitoba Canada

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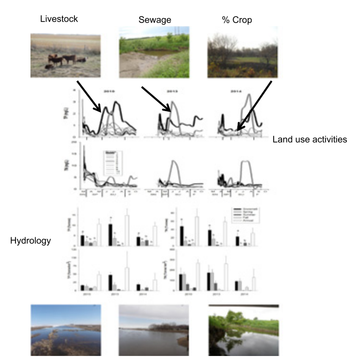
HIGHLIGHTS

- Hydrological, chemical, and land use activity data were examined.
- Discharge, TP and TN concentrations and loads were high during snowmelt.
- PLS regression indicated land use activities influenced TP and TN concentrations
- In contrast, hydrological factors influenced TP and TN loads.
- Results will aid in planning effective practices to control nutrient pollution.

GRAPHICAL ABSTRACT



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ABSTRACT

A three-year study (2010, 2013 and 2014) was conducted to identify temporal and spatial patterns in phosphorus (P) and nitrogen (N) concentrations and loads in 11 sub-watersheds of the Red River Valley, Manitoba, Canada in relation to human activity on the landscape. Discharge exhibited a strong seasonal pattern in all sub-watersheds with high discharge during snowmelt, generally lower discharge with rainfall-induced peaks during spring, summer and fall, and low or no discharge during winter. Consistent with the hydrologic pattern, nutrient concentrations were highest during snowmelt such that 62% of the annual TP load and 67% of the annual TN load were delivered during the 12–18 day snowmelt period. Partial least squares regression analysis indicated that land use activities such as fertilizer application, livestock density and sewage were critical factors influencing TP and TN concentrations. In contrast, physical aspects such as water temperature and discharge were the primary determinants of TP and TN loads. The finding that stream water nutrients concentrations are associated with human activity on the landscape whereas nutrient loads are largely influenced by hydrologic events suggests that different types of beneficial management practices are needed for protection of instream ecological processes negatively affected by high nutrient levels versus reduction of nutrient export to downstream receiving bodies such as Lake Winnipeg.

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1. Introduction

Small streams are the fundamental link between the terrestrial and aquatic elements of a watershed and the filter for nutrient and carbon transfers from the landscape to downstream waters (Dodds et al., 2004). In the Canadian prairie region of southern Manitoba, much of the post-glacial terrain has been channelized, creating streams that serve to improve drainage for agricultural production and human settlement. These changes in both land cover and hydrological connectivity have contributed to an increased risk of water pollution, particularly from nutrients derived from fertilizer or manure application but also from sewage discharge and septic seepage (Corriveau et al., 2013, Yates et al., 2014). This transfer of nutrients from land to water has resulted in environmental impairment associated with eutrophication of downstream aquatic systems (notably Lake Winnipeg) and economic loss to users of the aquatic resource (e.g., recreation activities and tourist industry; Environment Canada, 2014) as well as to farmers when N and P from commercial fertilizers are lost from cropped land (Cade-Menun 2013).

In cold climate regions, snowmelt runoff is a major driver of nutrient export from agricultural land (Corriveau et al., 2011, Uusi-Kamppa et al., 2012, Cade-Menun et al., 2013). Compared to southern temperate regions where summer storms are the major source of nutrient runoff (Fang et al., 2010), snowmelt in the Canadian prairies may contribute 80% of annual total phosphorus (TP) and total nitrogen (TN) loads to adjacent water courses (Glozier et al., 2006, Corriveau et al., 2011). During snowmelt, stream channels are hydrologically connected along their entire length whereas for the remainder of the year, these prairie streams have disconnected reaches as a result of low or no discharge caused by limited precipitation, warm temperatures, and increased evaporation (Fang et al., 2010, Corriveau et al., 2011).

Nutrient export during snowmelt runoff differs significantly from runoff produced by rain events. High surface runoff derived from snowmelt occurs as a result of rapid release of water from melting snow. During this time period, soils are often frozen and the migration of water through the snowpack is dominated by unsaturated flow to the frozen soil surface where infiltration is limited (Gray et al., 1985, Cade-Menun et al., 2013). The volume of snowmelt runoff and nutrient delivery is also affected by weather and vegetation: rapid warming during snowmelt favors runoff generation (and little infiltration) while freezing and thawing of vegetation (either crop residue left after harvest or riparian plants) lyses cells and increases nutrient concentrations in snowmelt runoff (Cade-Menun et al., 2013, Liu et al., 2013). In contrast with snowmelt, rain events generally require a greater rate of incident water to generate runoff because infiltration is greater. Further, the warmer temperatures of summer and fall favor biological activity that promotes nutrient uptake and cycling. Hence, nutrient concentrations are typically greater in snowmelt than in rain runoff, and the nutrients transported during snowmelt runoff are conveyed further and more likely to reach surface waterbodies (Cade-Menun et al., 2013). However, increased temperatures during spring in the Canadian prairies and associated increases in the rainfall fraction of total precipitation, particularly during March (Dumanski et al., 2015), may lead in future to changes in the seasonality of nutrient export.

Lake Winnipeg (Manitoba, Canada) is the world's 10th largest lake and has experienced increased frequency and intensity of algal blooms during the past 45 years due to excessive nutrient loading (McCullough et al., 2012). While three rivers (Winnipeg, Saskatchewan and Red) account for about 80% of the discharge into Lake Winnipeg, the agriculturally-dominated Red River watershed supplies 68% of the P load and 34% of the N load to the lake despite delivering only 16% of the discharge (1994–2007 data; Lake Winnipeg Watershed Stewardship Board, 2006). Human activities occurring with the Red River Valley are likely key sources of nutrients supplied to the Lake. Bourne et al. (2002) estimated 27.1 and 41.4% of the Red River TP and TN loads, respectively, are derived from point sources (such as wastewater releases) with the remaining input largely attributed to agricultural losses but also runoff from impervious land (urban development). Southern Manitoba has experienced an intensification and diversification of agricultural practices in the 20th century that have been associated with the decline in ecological condition of Lake Winnipeg. From paleolimnological analyses of nutrient concentrations and algal biomass in Lake Winnipeg sediments, Bunting et al. (2011) identified a switch from mesotrophic conditions in the 1800s to eutrophic conditions in the 1900s that was associated with increased livestock and crop production. Subsequently (1990–2010), the southern basin of the Lake experienced an ecosystem state change associated with an increase (and intensification) of hog production and cereal, oilseed and alfalfa production (Bunting et al., 2011 and Liu et al., 2014). As livestock density increases, land for manure application that is within an economical transport distance becomes inadequate and over application of manure nutrients is more likely to occur (Flaten et al., 2003). Manure is applied to crops based on crop N requirements; however, the N:P ratio of manure is usually ~3:1 whereas the N:P ratio of crops is 2:1 (Flaten et al., 2003, Manitoba Phosphorus Expert Committee, 2006). Indeed, P budgets calculated for Manitoba agricultural regions in 2000 and 2001 identified watersheds in the Red River Basin as having received P fertilizer in excess of crop requirements (Flaten et al., 2003). The result is that when manure is applied to meet a crop's N requirements, the long term consequence is a surplus of P in the soil.

The aim of this study was to quantify nutrient export from agriculturally dominated watersheds located Red River Valley, Manitoba, Canada in relation to the types of human activity on the land base. Because the rate and timing of nutrient delivery may vary in relation to both human activity (crop cultivation, livestock production, and wastewater discharge) and climate, we measured nutrient concentrations and determined nutrient loads for 11 streams over three hydrologic years (2010, 2013, and 2014). The multi-year data collected in this study allowed us to test whether human activity influences the magnitude, seasonality, and interannual trends of nitrogen and phosphorus export from cold-climate prairie watersheds. Such information can assist in devising land use specific management plans aimed at improving the health of the Red River Basin and Lake Winnipeg.

2. Methods

2.1. Study area

Our study was conducted in the Red River Valley (RRV) of southern Manitoba (Fig. 1). The RRV has low topographic relief (elevation change of 72 m from river source in the U.S.A. to mouth) with soils dominated by fine silt and clay (Yates et al., 2012). The region experiences a continental climate with the warmest month being July (20 °C) and the coldest January (−14.6 °C) (1980–2010 records for Morden, MB (Climate ID: 5021848; http://climate.weather.gc.ca/). Annual precipitation averages 427 mm, with 27.1% occurring as snow (1980–2010 records for Morden, MB; www.climate.weatheroffice.gc.ca). Most snowfall occurs from October to May, with 19–59 mm of precipitation in each of those months. Historically, the RRV was dominated by tall grass prairie and wetlands; however, in the 1920′s, most of the natural cover was removed and the wetlands drained for agricultural fields. Currently, the land is used primarily for crop (grain, corn, oilseed) and livestock production (poultry, cattle, pigs, horses) with a human population of 750,000 living predominately in the City of Winnipeg (population 730,000) but also in rural towns and villages. These small towns and villages use sewage lagoons (also known as effluent ponds) to provide wastewater treatment equivalent to secondary treatment. The lagoons are drained to adjacent water courses on one or two occasions between June 15th and October 31st each year.

Eleven sub-watersheds were chosen to represent a gradient of nutrient-emitting human activities, namely livestock and crop production as well as discharge of wastewater from sewage lagoons (Table 1). The 11