Measuring and modeling watershed phosphorus loss and transport for improved management of agricultural landscapes

Final Report for MDA Project # 92036

Jacques Finlay, Brent Dalzell, Christy Dolph, Anna Baker, Michelle Rorer

Revised
April 19, 2019

DEPARTMENT OF AGRICULTURE

CLEAN WATER LAND & LEGACY AMENDMENT

Executive Summary

Phosphorus (P) is a primary cause of eutrophication in aquatic ecosystems. Excess P, and associated impacts of eutrophication, are the most pervasive and widespread causes of degradation of freshwaters, resulting in loss of biodiversity, impairment of water quality, and reduction of services provided by streams, rivers and lakes. Nonpoint sources of P and, in particular, transport of P from agricultural fields to streams and lakes, is the most widespread pathway for P movement in many watersheds of Minnesota. Control of erosion on farms has led to a reduction in losses of particulate (sediment bound) P from agricultural fields. However excess P continues to plague Minnesota's freshwaters, posing a serious management challenge because processes that control its transport and transformation at the watershed scale are not thoroughly known, and climate trends are likely to accelerate eutrophication. This project integrated complementary approaches, combining analyses of large water quality monitoring datasets, new field measurements, sediment and P budget analyses and modeling to understand the sources, magnitude and controls over river P transport in Minnesota's agricultural landscapes.

Analyses of recent river monitoring data showed that concentration of all forms of P increased with river discharge for most sites. The presence of bluffs increased P concentration and transport, while the presence of lakes dampened it. Dissolved P was present at high concentrations across much of the year, showing minimum concentrations during cold baseflow conditions and at low flow during periods of high algal uptake that converted dissolved P to particulate form. The responsiveness of both dissolved and particulate forms of P to increasing discharge shows that rising rainfall and streamflow will mobilize greater amounts of P in the future, and that processes generating P in runoff are closely linked to riparian zones, stream banks and buffer strips. Development of P budgets for 62 watersheds (mostly HUC8) across the state revealed the primary importance of fertilizer inputs in P losses to streams and rivers. Fertilizer inputs, bluff erosion and runoff were important factors contributing to annual P losses by streams and rivers. Dissolved P yields dominated P export from agricultural sites except for watersheds with high rates of bank and bluff erosion where TSS export was high.

Detailed studies of the Le Sueur River Watershed showed that, while bank and bluff erosion contribute to total-P loading and to the formation of particulate-P via sorption, sediment is not the primary source of total-P to this basin. To determine the contribution of erosion from all sediment sources to total-P loading, we constructed a mass balance for sediment-derived P. Building upon an existing sediment budget, we collected sediment from the basin's primary erosional sources (upland agricultural fields and ditches, bluffs, streambanks, and ravines) to estimate sediment derived-P loads. Surprisingly, when we compared estimated sediment derived-P loads to measured total-P loads from the network of gages along the Le Sueur River, we found that only 24% of the total-P exiting the watershed outlet was attributable to erosion. This was unexpected because, on an average annual basis, 63% of observed total P river export occurred in particulate form. To explore this discrepancy, we incorporated two measures of P binding potential to the budget. This analysis indicated that between 2% (based on average sorbed concentration) and 24% (based on sorptive capacity) of the total-P budget may be particulate-P that is forming in the channel as a result of sorption to sediment. These results have important implications for management because, even if erosion was completely eliminated, only a 24% reduction of the total-P would result. The binding of P by sediment in the channel corridor

effectively dampens the signal of dissolved P inputs to the channel; in other words, there is more P entering the channel in dissolved form than what we measure as dissolved-P at the basin outlet. These results agreed with those of the cross-site analyses based on water chemistry data at gages, which indicated dominance of dissolved P in annual loads for most sites, except for highly erosive watersheds such as the Le Sueur. These findings suggest that, while sediment remains an important target due to its multiple impacts on water quality, we may need to manage sediment and P differently, with much more attention focused on investigating dissolved P source and fate in this basin and beyond.

Synthesis of available data, including tile drainage and sediment dynamics, was used to inform modeling using SWAT to evaluate the influence of climate, topography and farming practices on losses of dissolved and sediment associated P in the Le Sueur River, an area of high P losses with extensive supporting databases for soils, sediment, and hydrologic parameters. SWAT model assessment of components of phosphorus export for the current landscape showed that tile drainage can be an important pathway for export of soluble P from agricultural areas during years when drainage volumes are high. More specifically, tile drainage export can account for roughly 5 to 44% of annual P export. As the river increases in size, it becomes more erosive as it downcuts toward its confluence with the Greater Blue Earth River. Here eroding ravines, failing streambanks and river bluffs that are more common. This portion of the watershed (referred to as "knick zones", where rivers are rapidly incising into glacial soils, generates substantial near channel sources of sediment and phosphorus. In the knick zones of rivers in the Minnesota River Basin, sediment and associated phosphorus from near channel sources is delivered to the river channel during periods of increased water yield. This is important because it means that managing the landscape for water quantity can have benefits on water quality by reducing erosion of sediment and the associated phosphorus from near channel sources.

We used the model to evaluate potential water quality changes that may be associated with different alternative management practices in the Le Sueur River Basin. Reducing rates of P fertilizer application by 17% resulted in a predicted reduction in average annual P export of 4.6%. Implementation of cover crops into the current corn-soybean production system reduced predicted P export by 26.6%. The relatively large influence of cover crops was linked to direct effects of reductions in overland flow and tile drainage, and indirectly, through reductions of flow downstream, which decreased contributions from near channel sources of sediment and associated P.

Outreach from the project included integration with NSF and EPA funded work to extend project reach, presentations at the University of Minnesota, Minnesota Water Resource Conference, and Annual Meeting of the American Geophysical Union. Project findings are being disseminated via journal publications, newsletters, and a website (http://reach.safl.umn.edu/) showcasing cumulative research findings from related NSF and EPA research and this project.

Information generated in this project improves understanding of the factors that influence P movement in river channels within Minnesota's agricultural landscapes that can be used to guide management under variable and changing climate. For example, our work revealed the importance of landscape features in modifying relationships between river flow and P transport. These findings indicate that watershed management plans must consider the role of the entire river corridor, and the processes that affect P mobilization and storage in controlling P movement in Minnesota's watersheds. To do this, the hydrologic effects of BMPs on downstream flows must be assessed, and more research is needed to develop effective management strategies for near channel (buffer strip and riparian zone) P sources. Finally, this project adds to other recent work in showing that impacts of climate change, including increasing flows, increasing flow variability and warmer temperatures, may offset progress in controlling P losses unless management specifically targets source areas and processes that may not be considered by traditional field management strategies alone. Integration of new knowledge and watershed-based approaches are vital to control both dissolved and particulate sources of P loss from fertilizer-intensive row crops to rivers and lakes, where excess P is a major driver of water quality degradation.

Table of Contents

1.0 Introduction

High levels of phosphorus (P) and nitrogen (N), in streams, lakes and rivers impair water quality throughout Minnesota and much of the Midwest. High concentrations of P degrade local and downstream water quality with impacts including toxic algal blooms, depleted dissolved oxygen (hypoxia), and eutrophication. Large Minnesota rivers, including the Red River of the North and the Minnesota River, export significant and harmful loads of phosphorus and nitrogen to Lake Winnipeg and the Gulf of Mexico, respectively (Rabalais et al. 2002, McCullough et al. 2012). N and P loading from Midwestern row crop agriculture have been identified as leading contributors to hypoxia in the Gulf of Mexico (Rabalais et al. 2002) and, more specifically, springtime exports of nutrients from the upper Midwest are strongly correlated to the size of the zone of hypoxia (i.e., the Dead Zone) that develops annually in the Northern Gulf of Mexico. Excess concentrations of P that persist in late summer are responsible for degraded water quality in Lake Pepin and other Minnesota lakes and rivers.

Ongoing collaborative efforts are aimed at continued development of an effective strategy to reduce nutrient loads within and exported from state surface waters (MPCA 2014). The Minnesota Draft Nutrient Reduction Strategy calls for a 50% reduction in P loading from the Minnesota River Basin (MRB) in order to protect water quality in Lake Pepin and the northern Gulf of Mexico (MPCA 2014). A pressing question remains: how can P exported by Minnesota's agricultural streams and rivers be most effectively addressed by management? The answer to this question requires new information and analyses, and a continued feedback from research in multiple disciplines to guide an evolving statewide P reduction strategy.

Agricultural management practices affect nutrient export directly through fertilizer losses but also indirectly influence nutrient export through hydrologic changes (McCullough et al. 2012). The frequency and magnitude of stream flows have dramatically increased due to agricultural tile drainage, increased precipitation and crop conversions (Schottler et al. 2013, Foufoula-Georgiou et al. 2015). The average median flow in the MRB in 1986 - 2005 was approximately 300% greater than the average median flow in 1946 – 1965 and high (5% exceedance) flows have increased dramatically for the same period (Kelly et al. 2017). Despite contributing only 25% of the flow to Lake Pepin, the MRB is responsible for more than 74% of sediment and greater than half the phosphorus load, leading to water quality degradation (Engstrom et al. 2009). Of the sub basins within the MRB, the Le Sueur accounts for a disproportionally large share of the MRB phosphorus load relative to only about 7.5% of the watershed area (Belmont et al. 2011). While agricultural soil erosion in the upland fields has largely been controlled, soluble P concentrations are among the highest in the state, and downstream erosion of stream banks, bluffs, and ravines in the lower portions of the river has increased sediment export (Belmont et al., 2011). Changes in flow conditions due to climate and drainage may mobilize P from fields, inundated wetlands and near channel sediments during high flows, compounding impacts from fertilizer inputs in increasing P loss to aquatic ecosystems, and subsequent water quality degradation.

A successful strategy for phosphorus management must be informed by thorough understanding of P sources and environmental controls throughout watersheds. This information can be used to develop the most effective combination of BMPs and management to reduce P fluxes to streams and rivers at the lowest cost. Management strategies for P may need to address not only direct edge of field P losses via surface runoff but also dissolved P in tile drainage, and mobilization of local and downstream P stored in the landscape especially during high flows (Sharpley et al. 2008). Due to long storage time and exchange processes, legacy P stored in soils, aquatic sediment and pore waters can be remobilized rapidly in a storm or leached out over decades (Sharpley et al. 2013, Haygarth et al. 2014, Goyette et al. 2018). If the dominant sources and transport pathways of P are not well known, BMP practices targeting direct reductions in P export may not reduce stream P concentration or load (Dodd et al. 2015). For example, a decrease in fertilizer application rates should decrease edge-of-field P losses; however large residual stores of soil P, other management actions (e.g. reduced tillage and cover crops) and climate also influence P losses (e.g. Elliott 2013). Thus soil P can continue to bleed out in unforeseen ways and contribute large amounts of P to rivers. An individual BMP's contribution to reductions in P must be assessed at the scale where water quality degradation occurs and total maximum daily loads (TMDL) are applied, i.e. the basin scale.

Until recently, it was assumed that particulate P accounted for most P transported from the landscape to the riverine network and that surface erosional runoff was the most significant source (reviewed in Withers and Jarvie 2008). Conservation practices integrated into agriculture over the past four decades have led to dramatic improvements in soil conservation, substantially decreasing erosion from farm fields. Corresponding decreases in sediment associated phosphorus losses from fields have resulted in substantial water quality improvements in the Midwest. However, mounting evidence show that dissolved P, from overland flow during snowmelt and spring rains, subsurface seepage, and tile drainage can also represent a significant proportion of the flux of P from agricultural fields (Gentry et al. 2007, Cade-Menun et al. 2013, King et al. 2018), and stream channel erosion is increasing (Belmont et al, 2011, Schottler et al. 2013). While much work has gone into understanding particulate P sources and transport from fields, and edge of field responses of particulate P fluxes to various BMPs are fairly well defined (Ginting et al. 1998), the sources and controls over dissolved P and P from streambank erosion remain poorly known, impeding implementation of management to reduce excess P.

The rise in the importance of dissolved P to water quality degradation could be linked to management actions and changing climate. Conservation practices such as reduced tillage and cover crops are effective at decreasing particulate P from erosion and nitrogen leaching. However, such practices leave a large pool of organic P at the soil surface. When saturated overland flow occurs, during spring snowmelt and rain, this residual P is solubilized and transported overland to ditches and streams (e.g. Cade-Menun et al. 2013) leading to large losses of dissolved P. In addition, there is recent evidence that climate changes, leading to increased frequency of freeze thaw processes, and increased rainfall, and increased frequency of large events will lead to enhanced production and transport of soluble P from agricultural fields. Dissolved P from farmland has been implicated in recent reversals of water quality improvement in Lake Winnipeg and Erie (McCullough et al. 2012, Michalak et al. 2013), driving major water quality problems including cyanobacteria blooms, drinking water contamination and economic losses.

Sources of dissolved P mobilized from non point sources remain poorly identified, and thus limit management aimed at improving water quality via implementation of the most effective conservation practices to target sources. These sources are likely to vary with watershed features such as soil texture and P status, climate, and topography. Without an understanding and consideration of such controls on dissolved P losses, conservation actions may be mismatched with the actual source of P that needs to be addressed to improve water quality.

2.0 Objectives

Our central objective for this project was the evaluation of sources and environmental controls of P mobilization for Minnesota landscapes, with emphasis on agriculturally-dominated watersheds, and using this information to develop models to inform strategies for basin-wide P reduction. The project makes use of the extensive availability of monitoring data for Minnesota's rivers, as well as field data from new intensive sampling efforts to identify spatial and temporal variability throughout the basin and understand the role of environmental and human drivers of river phosphorus transport.

Our three specific objectives were:

1. **Determine the relative contribution and environmental controls over phosphorus losses from MN agricultural watersheds including a new assessment of the potential importance of dissolved P.** Synthesis and analyses of existing data were used to document the phosphorus losses to establish a spatial picture of dissolved P losses and identify the climate and watershed features that control them. Current monitoring programs run by MPCA (the Watershed Pollutant Load Monitoring Network), and Metropolitan Council have generated comprehensive databases for annual losses of P fractions from an 8 year period (longer records exist for some sites) for HUC8 and slightly smaller watersheds. These data were used to identify the spatial patterns and environmental controls over dissolved and particulate P losses from a large number of predominately agricultural watersheds in southern and western MN.

2. **Measure sources and reactivity of dissolved phosphorus within channel networks of the Le Sueur River watersheds.** Sediment budget data, and extensive hydrological and water quality monitoring were leveraged with new measurements quantifying the role of key landscape features in P inputs during snowmelt and spring. Mass balance measurements were used to assess how aquatic transformation of P occurring during transport through the watershed. This information allowed us to better define sources of soluble P loss from the landscape, and better understand its fate in stream channels. These analyses were used to identify natural landscapes features and environmental factors that control losses, as well as inform modeling goals.

3. **Integrate best available data to link alternative management actions, climate and landscape features in models of P losses at the watershed scale.** Central to overall goals of this project is the need to translate information gained from other studies, monitoring, and field scale research into a framework focused on informing best management practices to maintain and improve water quality in agricultural landscapes. While there are many field-based observations of phosphorus in agricultural runoff as well as monitoring data from Minnesota's streams and rivers, the mechanistic link between sources and transport remain poorly understood. Non-point sources of

phosphorus are abundant in the Minnesota River Basin including disproportionately high loads from tributaries such as the Le Sueur River where the predominant land use is row crop agriculture and industrial sources are absent. Disentangling the relative importance of different sources of phosphorus requires a more thorough understanding of sources and transport of phosphorus through stream channels as enabled by models that link conditions on land to water quality.

3.0 Methods and Materials

The descriptions below are summaries of the general approach used for each objective. Detailed methods descriptions for section 3.1 and 3.2 research components are provided in the appendices. Methods for the SWAT model analyses are provided below.

3.1 Controls over watershed phosphorus transport

Toward objective 1 goals for identifying controls over watershed phosphorus transport we used synthesis of data for water quality, hydrology, land cover and landscape phosphorus inputs. Data synthesis was aimed at making the best use of available information to increase understanding of the patterns and controls of river P transport in Minnesota's landscapes to identify knowledge gaps, inform management, and parameterize models. Data synthesis of existing monitoring data for agricultural watersheds was specifically used to *1) determine how much loss of P occurs in dissolved form across agricultural landscapes, 2) identify the watershed, climate and hydrological controls over watershed losses of soluble (and particulate) phosphorus*, and 3) *inform models of watershed scale BMP performance for both dissolved and particulate P* described in Objective 3, below.

3.1.1 Watershed scale phosphorus budgets

We used a comprehensive analysis of phosphorus inputs, retention and river export in 62 watersheds across Minnesota. These watersheds span major land cover and land uses in the region, ranging from largely pristine areas to intensively managed watersheds. The selected watersheds thus included gradients of landscape, hydrology and climate (e.g. lake and wetland cover, soil types, and annual rainfall). We explored nutrient retention by developing anthropogenic P input estimates for watersheds with annual load data. Methods are described briefly here, and more detail can be found in Boardman (2016) and Boardman et al. (In review and Appendix 1).

Our analyses used a database for 62 stream and river sites in watersheds with annual measurements from at least 2007 – present. Sites range from 50-87% cropland, 0-16% wetland, and 0-9% open water. Average annual precipitation and runoff from 2007- 2011 ranged from 62 and 87cm and 13 to 34cm, respectively. This information is primarily managed by MPCA (2015) but also includes data from Metropolitan Council and USGS, and consists of high quality continuous records of flow with nutrient concentration data collected from 15-35 times per year and analyzed with consistent methods. These data have been used to calculate annual loads but have not been extensively employed to analyze how climate and specific landscape characteristics influence transport at these sites. To analyze these datasets, we integrated new information on wetlands and soils moisture (MN DNR National Wetlands Inventory Update; NRCS Soil Survey Geographic Database), information for land cover (National Land Cover Database; UMN Remote Sensing Laboratory and Homer et al. 2015), and climate and runoff (MN Climatology Working Group). We also integrated data for waste water treatment plant release of P with data acquired from MPCA. A primary focus was determining the factors that control losses of both soluble and particular P. We used watershed phosphorus budgets to assess the relationships between inputs, retention, and riverine transport of dissolved and total P.

Watershed delineations provided by the MPCA and METC were used for watershed analyses. The 2011 National Land Cover Data (NLCD) was used to determine the proportion of each watershed in land cover categories such as crops, pasture or hay, urban, open water, or wetland (Homer et al. 2015). One kilometer gridded precipitation data for 2007 – 2011 complied by the PRISM Climate Group (http://prism.oregonstate.edu/) were used to determine mean annual precipitation for each watershed. We estimated the area of bluffs along river channels for each watershed using LiDAR elevation data from the Minnesota Geospatial Information Office (http://www.mngeo.state.mn.us/chouse/elevation/lidar.html). Within a moving 12 m by 12 m window, areas with elevation differences greater than 4 m were designated as bluff and then clipped with a buffer that extended 50 m from the channel centerline.

To estimate total losses of total dissolved phosphorus (TDP) we examined relationships between more commonly reported soluble reactive phosphorus (SRP) concentration and TDP, which is less often measured. Both are always measured on filtered samples. Analyses for SRP includes dissolved orthophosphate (OP) which also includes some reactive organic forms. Some dissolved organic P forms are not reactive, and this is indicated by the difference between TDP and SRP. Hereafter we refer to SRP simply as OP to represent the most common measurement of dissolved P. Our analyses of our data suggest that OP in rivers is approximately 80% of TDP (unpublished data 2013- 2014). This result is consistent with MPCA's analyses, and indicates that soluble P losses measured as OP are underestimates of dissolved P and overestimates of particulate P. Because yields of P were computed with FLUX32 without thorough knowledge of OP-TDP relationships, no correction was made. Thus estimated soluble P transport should be considered to be conservative, with additional effort made to established conversions from OP to TDP in the future.

3.1.2 Interpreting responses in P concentration and load to discharge

We used a dataset derived from extensive sampling of 281 watersheds draining intensively managed agricultural areas in Minnesota, USA to characterize P export from agricultural watersheds and investigate the potential watershed-scale controls on P transport dynamics at multiple temporal scales (Figure 1). We used *C-Q* relationships, annual load information and a suite of transport metrics to understand and characterize the contribution of both particulate and dissolved P to total P transport for 104 gaged river sites under various seasonal and flow conditions. We complemented this analysis with a field dataset collected from an additional set of 176 agricultural stream and river sites within three study watersheds (Dolph et al., 2017ab), sampled repeatedly for a suite of water chemistry over a range of flow conditions. Using these two large datasets, we examined the importance of climate (i.e., discharge), land cover (i.e., % agriculture), landscape features (i.e., bluff extent, lake interception) and biogeochemical processes in mediating transport behavior of particulate and dissolved P from agricultural watersheds.

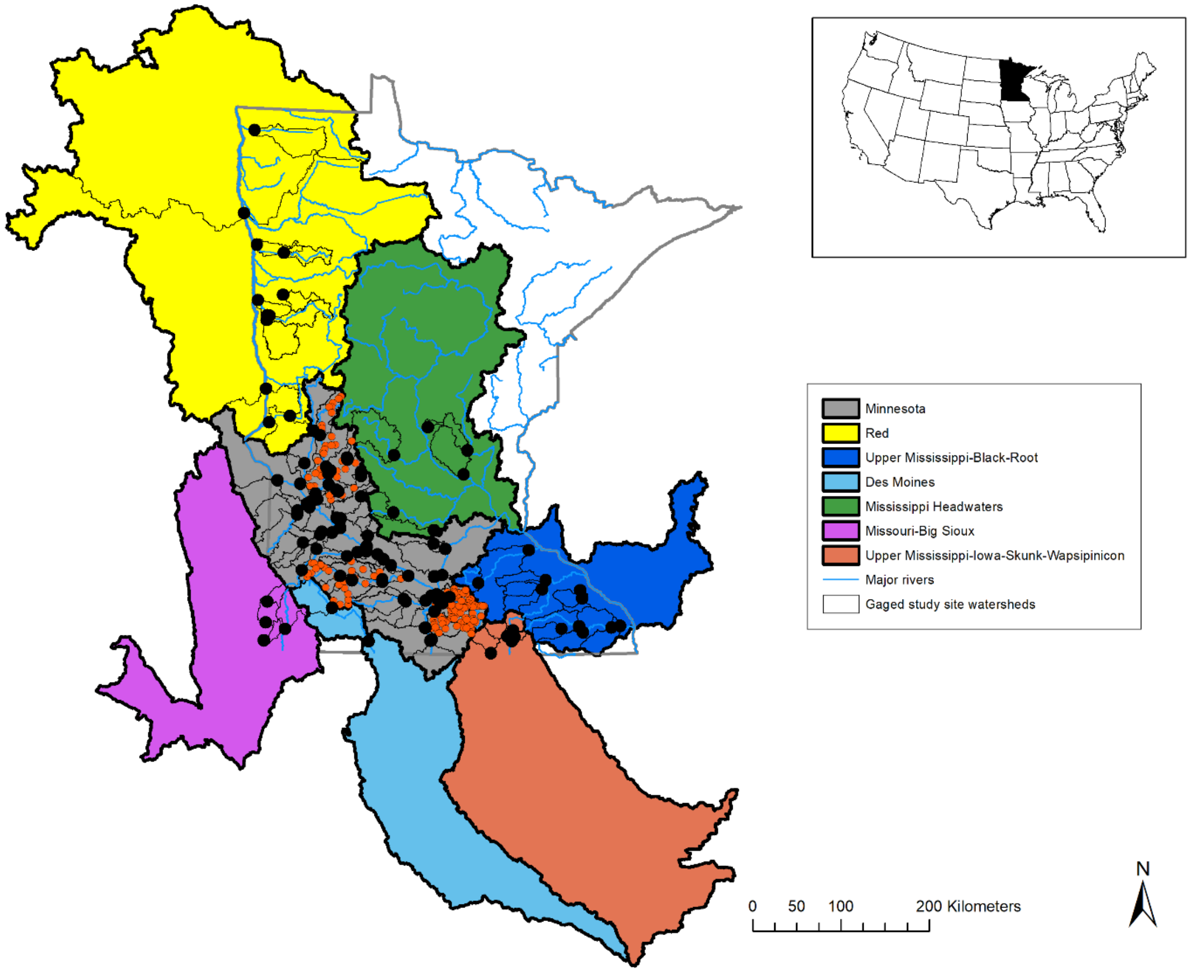

Figure 1. Locations (black circles) of 104 gages sites in agriculturally dominated watersheds included in analyses of relationships between phosphorus and river flow from monitoring data. Orange circles indicate field sites (n=176) sampled repeatedly for water chemistry under a more limited set of flow conditions during the project. Basin colors indicate major river basins (HUC4) for sampling sites.

3.1.3 Phosphorus concentration in tile drainage

Complementing our synthesis of river P export data, we also synthesized data for phosphorus forms and transport from tile drains. Data sources included Minnesota Department of Agriculture (MDA) Discovery Farms, the Minnesota River Basin Data Center (MRBDC) tile monitoring project, past studies at UMN extension research sites (e.g. Waseca, Lamberton), our own data collections and other published data sources between 1980's to 2016. Synthesis of tile drainage data was used to characterize the variability in P concentrations and losses from tiles towards integration with modeling analyses of tile drainage contributions to P transport in the Le Sueur basin (Objectives 2 & 3).

3.2 Sources and reactivity of phosphorus in the Le Sueur Watershed

3.2.1 Stream and river network sampling

To better understand how phosphorus transport was influenced by biogeochemical processes and landscape effects, we supplemented our analysis of *C-Q* relationships at gage sites with an extensive field data set collected at ditch, stream and river sites in the same study region (Figure 1). This dataset is publicly available and described in detail by Dolph et al., (2017b). Briefly, soluble reactive phosphorus (OP), particulate phosphorus (PP), and suspended chlorophyll *a* (Chla) concentrations were determined for water samples collected from 176 sites located in three major (HUC8 scale; USGS, 2017) watersheds, during 14 independent sampling events that targeted differing flow conditions and times during the growing season. Only a subset of sites was sampled during each sampling event. Two of the sampling events occurred in the Chippewa River Basin, two in the Cottonwood River Basin, and 10 in the Le Sueur River Basin. Flow conditions at the time of sampling were characterized by the 25-year exceedance probability (% EP) of flow at the gaged outlet of each major watershed (i.e., Chippewa, Cottonwood, and Le Sueur), based on daily discharge data available from MNDR (2018). Although flow at the outlet is not precisely representative of flow conditions further upstream in the basin, we have shown previously that discharge conditions across study sites scaled reasonably well with drainage area across a range of flow conditions (Dolph et al., 2017a).

We evaluated OP and PP concentration data in relation to suspended Chla, across all sampling events, to determine how suspended algal biomass affects phosphorus concentrations across a range of flow conditions. Using previously published estimates for stoichiometric relationships between algal carbon and chlorophyll (Dolph et al., 2017a), and stoichiometric ratio between algal carbon and phosphorus using the Redfield Ratio, we estimated the contribution of algal-P to PP and TP concentrations during each of our sampling events.

3.2.2 Linking a sediment budget to phosphorus sources

Soil and sediment eroded from agricultural landscapes can represent a major source of phosphorus inputs to freshwater ecosystems. Interactions between sediment and phosphorus are also known to be important in governing phosphorus bioavailability, especially in river systems with high suspended loads. Controlling erosional losses has been a major focus of management and conservation efforts, and soil losses from fields have been substantially reduced. However, changes in agricultural practices and climate have the potential to offset progress in phosphorus management achieved through the control of field erosion, by contributing to phosphorus mobilization via other pathways

To better understand the contribution of multiple phosphorus sources to total downstream phosphorus load, we integrated results of a previously developed sediment budget with the phosphorus cycle via the development of a mass balance for sediment-derived phosphorus. This research focused on the Le Sueur River watershed to leverage other data collected in this project and to help inform SWAT model analyses described in section 3.3. The Le Sueur is of particular interest because of its high erosion and P loss rates, with 63% of P loads measured at the watershed outlet transported as particulate P.

Detailed methodology for this work is described in detail in Appendix 3 and Baker (2018). Briefly, we incorporated newly collected sediment geochemical data including total and water-extractable dissolved phosphorus and sorptive capacity for sediments from the primary sources of sediment to the river with a previous developed sediment budget (Gran et al., 2011, Belmont et al., 2011, Bevis, 2015) to develop a 'sediment-phosphorus budget' that provides coupled estimates of sediment and phosphorus inputs to the watershed. Sediment sources included bluffs, stream banks, ravines, and agricultural topsoil and ditch sediment. Estimates of sediment-derived phosphorus from these distinct sources were then compared to measured loads of total and dissolved phosphorus at a network of gages maintained by the Minnesota Pollution Control Agency (MPCA 2015) and other state agencies. We also compared our estimates of sediment associated phosphorus inputs, to previous estimates of sediment associated P inputs to agricultural watersheds in southern MN (Sekely et al. 2002, Kessler, et al., 2012, Grundtner et al. 2014). Finally, we incorporated the results of sorption tests into the sediment-phosphorus budget in order to understand how equilibrium with sediment may affect partitioning of basin-scale P loads between bound and dissolved, bioavailable form.

3.3 Linking management, climate and landscape features in models of P transport

We used the SWAT model to evaluate influences of alternative management scenarios and climate on watershed phosphorus concentrations and yields in the Le Sueur Basin. The Soil and Water Assessment Tool (i.e. SWAT) is a watershed-scale model that operates on a daily time-step to predict landscape responses to precipitation and runoff. It relies on a combination of empirical and process-based approaches to determine how landscape features and management practices can interact to impact the quantity and quality of runoff with subsequent impacts on downstream water quality. The basic functional unit of the SWAT model is the Hydrologic Response Unit (HRU); comprised of unique combinations of soil, slope, and land use. For the Le Sueur River Basin SWAT model, soils data are based on the SSURGO (county-level) soil survey. Topography is based on the 30-m digital elevation model from the national elevation dataset and land cover is based on the national land cover dataset for 2006.

For land classified as cultivated cropland in the NLCD, we assume a 2-year corn-soybean rotation, the dominant practice for the region. We developed a set of typical management practices based on farmer surveys (FANMAP, administered by the MDA) as well as feedback from various stakeholder groups and expert knowledge. It is important to note that these typical management practices are used for the baseline model scenario, but we acknowledge that management of individual farms can vary considerably from the typical management schedule used in the model. The watershed scale model is useful for evaluating the relative benefits of different suites of management scenarios across the watershed, but it should not be applied to determine environmental impacts of specific farms without farm-specific management information.

Precipitation data for the model is based on the NEXRAD data that has been formatted into a synthetic network of gauges spaced on a 4km-net following spatial and temporal gap-filling by applying an approach developed by Le (2015). Daily values of temperature, relative humidity, solar radiation, and wind speed are based on the Climate Forecast System Reanalysis (CFSR; Fuka et al., 2013) dataset and formatted for the SWAT model from the Global Weather Data for

SWAT website: https://globalweather.tamu.edu/. The model simulation was run for the 12-year period from 1 Jan 2002 to 31 Dec 2013. The first two years of the simulation is treated as a warmup period and results are discarded. The remaining 10 years were divided into a calibration period (1 Jan 2004 to 31 Dec 2008) and a model validation period (1 Jan 2009 to 31 Dec 2013) for model hydrology (calibration and validation periods vary slightly for sediment and nutrients due to availability of observed data). Model performance is based on comparison of simulated and observed data based on comparison of overall mean values as well as Nash-Sutcliffe Efficiency, percent bias and coefficient of determination. The SWAT model runs described here are based on SWAT2012-rev637. In the standard release version of the SWAT model, particulate and dissolved phosphorus may only be exported from HRUs via surface runoff, and phosphorus export via subsurface tile drainage is not simulated. It has been demonstrated, however, that phosphorus is present in tile drainage and it can represent a moderate contribution to overall loading from agricultural landscapes. For example, in a study in the Maumee (Ohio) basin, Smith et al. (2015) showed that tile drainage can account for 49% of the soluble P export from agricultural fields. Other studies in the Midwest have demonstrated variable contributions of tile drainage to P export.

Lu et al. (2016) implemented changes to the SWAT model in order to simulate soluble P export via tile drainage. While these changes to the model source code have not yet been included in the release version of the model, we contacted the lead author, Dr. Shenglan Lu, and obtained a copy of her source code modifications for application to this research. This modification to the SWAT model simulates leaching of dissolved reactive phosphorus based on the Langmuir isotherm followed by transport of water to tile drains. The modified SWAT model routines to predict soluble P in tile drainage are dependent on user input of two parameter values:

K_L = Langmuir adsorption constant (L mg^{-1})
β_m = Calibration parameter related to the adsorption maximum (mg kg^{-1})

In order to ensure that the modified SWAT model was parameterized appropriately for simulating soluble P in tile drainage in Minnesota, we relied on established studies (Fang et al., 2002, Fang et al., 2005, Vadas and White, 2010) to provide guidance for locally-relevant values of these parameters, summarized below:

K_L range: 0.50 to 8.00
β_m range: 0.06 to 0.23

The Fortran Source Code was modified in order to allow the expanded range of values (especially for K_L) and an iterative approach was used to determine which combination of parameter values produces tile drainage concentrations of soluble P that most closely agree with observed data from monitoring sites in Minnesota.

The period of observed data varied slightly for calibration and validation of sediment and nutrients. For each water quality constituent, the total period of data was divided roughly in half, with the more recent period used for calibration and the earlier time period was used for validation. Actual dates for calibration and validation of different water quality constituents are summarized in Table 1. Observed data are based on periodic grab samples combined with continuous flow data. These data were used to generate estimates of monthly loads. Load analysis was conducted using the loadflex package in *R* (Appling et al., 2015). Loadflex provides functions for estimating loads via interpolation, linear regression, LOADEST regression models (USGS, 2004), as well as a "composite" approach that '*combines predictions from a regression model with an empirical 'residuals correction' to bring predictions closer to observations during the period of interest. This two-step process can reduce short-term biases and thereby lead to more accurate estimates of total fluxes or mean concentrations*' (quote from Appling et al 2015). After examining multiple models for each water chemistry parameter at each gage, we ultimately selected the best available model based on diagnostic performance criteria suggested by Appling et al. (2015). The observed sediment and nutrient loads generated by loadflex include a measure of the uncertainty inherent in generating monthly loads from monitoring data. This measure of uncertainty is factored into measures of model performance as described by Harmel et al. (2007).

Our method of load determination (loadflex) used a different regression approach than that used to estimate nutrient and sediment loads for the Minnesota Watershed Pollutant Load Monitoring Network (WPLMN). WPLMN uses FLUX32 approach to estimate loads (MPCA 2015). The fundament approaches are similar between the two methods and we found close agreement between annual loads generated using our approach vs those generated by the WMLMN (C.L. Dolph, unpublished data) indicating that our results are directly comparable to those generated by MCPA.

4.0 Results and Discussion

4.1 Identifying controls over watershed phosphorus transport with data synthesis

Data from multiple state and federal agencies were integrated to gain further understanding of phosphorus sources and sinks in watersheds, and to better understand how climate, management and landscape features affected hydrologic responses of P transport.

4.1.1 Phosphorus mass balances for large watersheds

Fertilizer inputs from row crop cultivation was the dominant source of P to agricultural watersheds, as expected. A large majority of P inputs to watersheds were retained in soils or removed in agricultural products. However, fertilizer inputs were the most important factor associated with river transport of total, dissolved, and particulate phosphorus (PP) (Boardman et al. In review), and explained significantly more variability compared to estimated net phosphorus inputs (i.e. the difference between all human inputs and removal in crops and products). Annual runoff increased total and dissolved P losses and decreased P retention (Boardman et al. In review). Dissolved P (i.e. as dissolved orthophosphate, ~ OP) made up a significant portion of annual loads at sites with high rates of P inputs and river TP export, with the ratio of dissolved to particulate P export increasing with crop cover, and fertilizer inputs, except in watersheds with extensive areas of eroding bluffs that generate high TSS and PP (Figures 2, 3). The low apparent retention of P in northern MN is discussed in Boardman et al. (In review, Appendix I). PP export was increased by the presence of eroding bluffs near channels that contribute high sediment loads due to human and climate-driven changes to river hydrology (Figure 4).

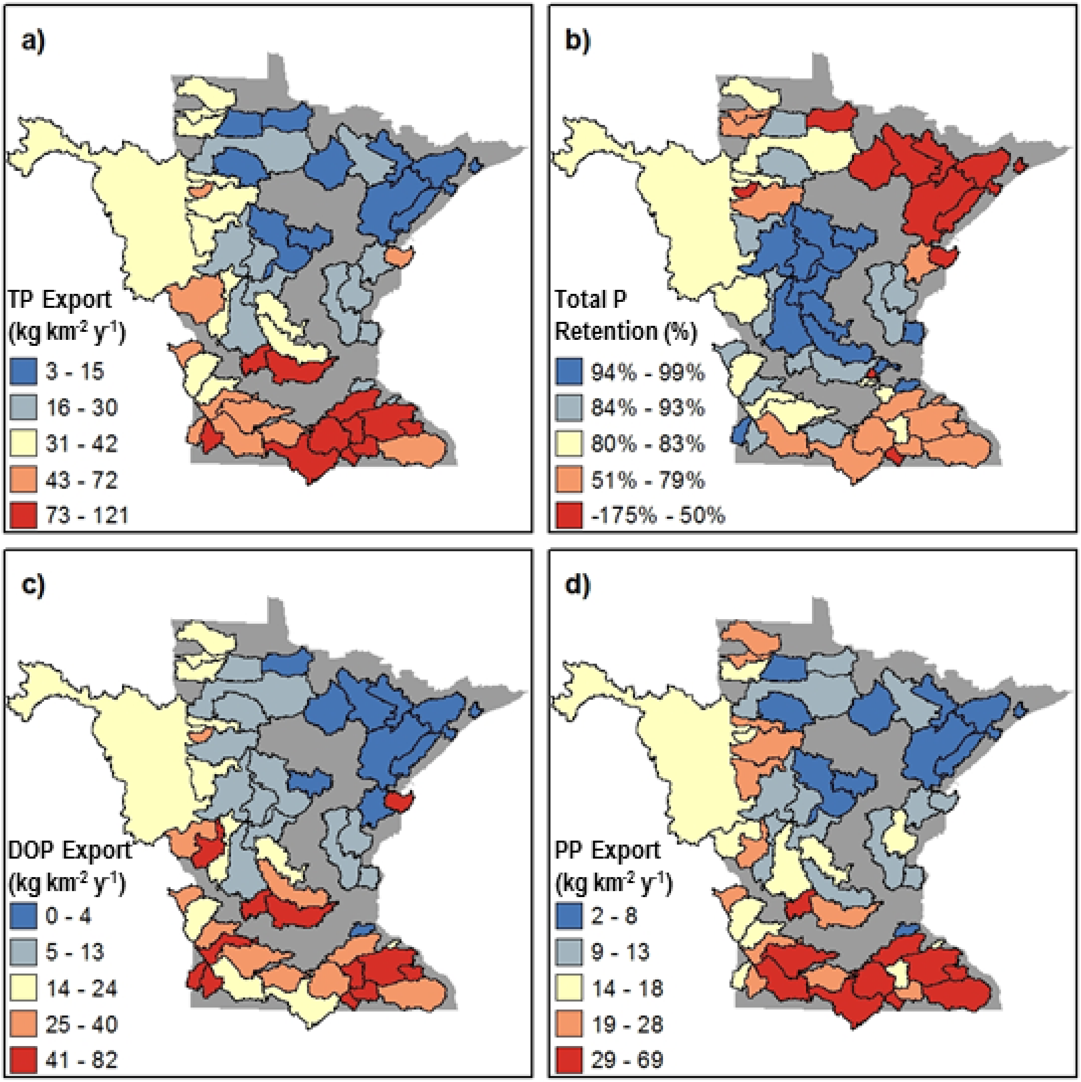

Figure 2. Total phosphorus export (a), total phosphorus retention (b), DOP (i.e. OP) export (c), and estimated particulate phosphorus export (d) for study watersheds. Export reported in kilograms per square kilometer (kg km^{-2} y^{-1}).

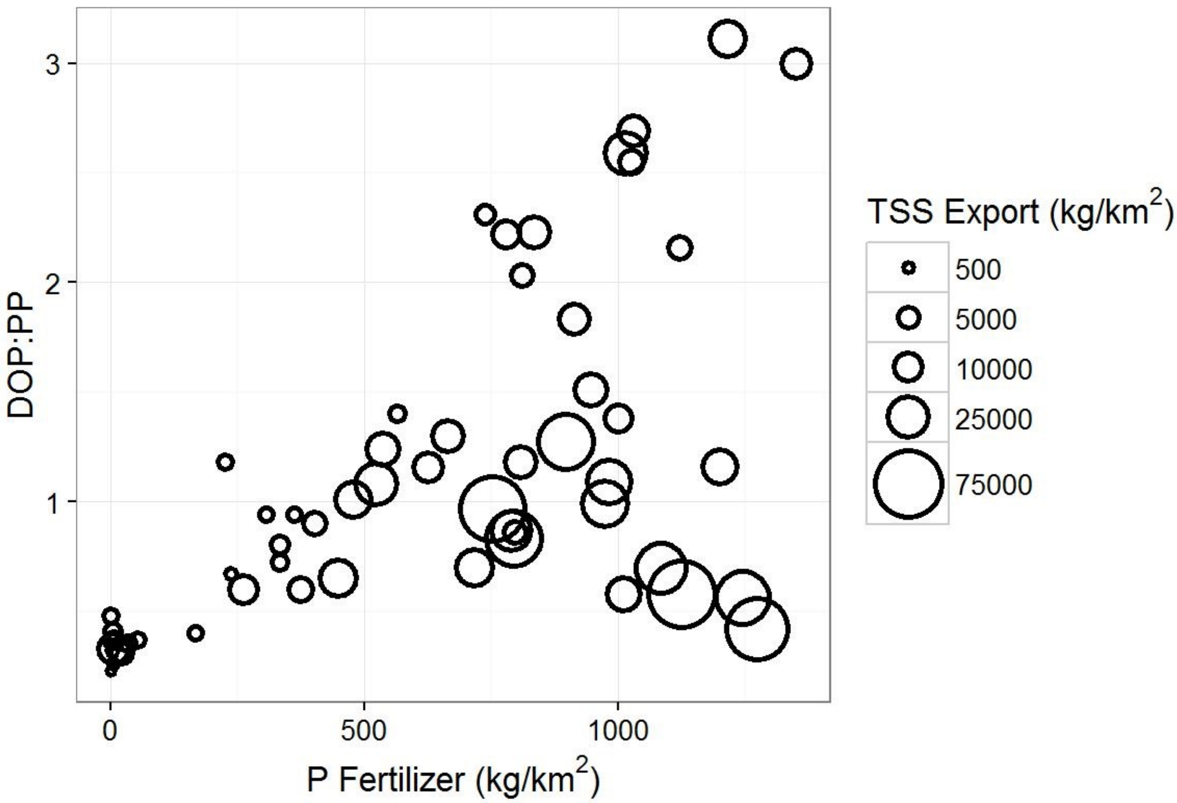

Figure 3. Relationship between fertilizer input and the ratio between annual dissolved orthophosphate (DOP and particulate annual phosphorus yields (mass/mass). The size of each circle is proportional to the annual TSS yield at each site, a parameter strongly influenced by bluff extent (Boardman et al. In review, Vaughan et al. 2017)

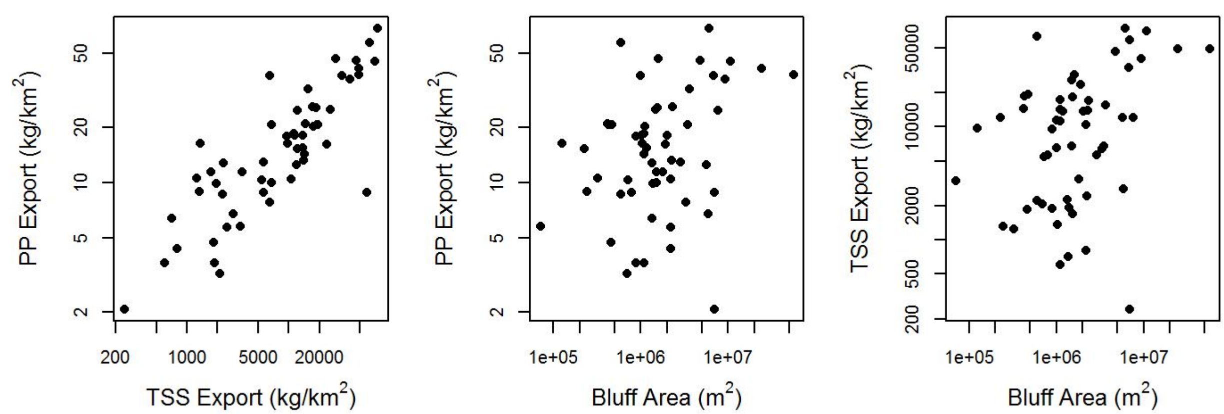

Figure 4. Particulate phosphorus export vs. TSS export (a) and watershed bluff area (b), and TSS vs bluff area (c).

Our work reveals thresholds of transitions in the form and amount of P losses to river systems with increasing human watershed perturbation due to agriculture. Our analyses show that human activities alter the dominant form of phosphorus leaving rivers, shifting annual export from largely particulate form towards increasing contributions of dissolved P under high rates of input. Furthermore, fertilizer P input was the best predictor of riverine P losses due to years of retention and accumulation of P in soils (Boardman et al. In review; see also Kusmer et al. 2019). Landscape heterogeneity (bluff and lake cover) and runoff had significant influences in annual P export. The influences of these features on event scale responses is explored further in sections 4.1.2 and 4.2. Our results also suggest that rising discharge and flow variability due to climate change and agricultural intensification coupled with sustained high rates of P inputs will maintain elevated fluvial P export from non-point source inputs into the future. Without appropriate management efforts aimed at reducing both soluble P losses and stream bank erosion, reversal of water quality degradation toward meeting realistic goals will be difficult to achieve.

4.1.2 Land use, landscape features, and climate controls on phosphorus mobilization

The majority of gaged sites exhibited mobilizing behavior (i.e. rising P concentration with higher discharge) for all forms of P at event (i.e., daily) time scales, and chemostatic or chemodynamic behavior at annual time scales. However, one third of sites showed weak to strong mobilizing behavior for dissolved P even at annual scales, suggesting spatial heterogeneity in dissolved P sources in many agricultural landscapes. These findings are documented in Dolph et al. (In revision at *Water Resources Research;* see Appendix II).

Both landscape features and biogeochemical processes modified river phosphorus transport at event scales in intensively managed watersheds. Our analyses demonstrate that P concentration-discharge relationships are mediated by diverse factors including near-channel sediment sources, glacial history (driftless vs glaciated), lake interception, and anoxic release of dissolved P under low flow conditions, and assimilation by algal P. Overall, we observed the following relationships between P transport, and landscape and/or biogeochemical controls:

- Increasing bluff area was associated with increased mobilization of total P and particulate P transport by river flows (Figure 5).
- Large inputs of bluff sediment during large storm events may ‘suppress’ concentrations of dissolved P, when relatively P-depauperate bluff sediments adsorb P from the water column (Figure 6).
- Lake interception (i.e., proportion of a watershed draining through lakes) was associated with decreased particulate P transport in watersheds with large bluff extent. Thus, in watersheds characterized by larger inputs and concentrations of sediment-bound P (i.e., watersheds with sizeable sources of near channel sediment), lake interception may have a net negative effect on particulate P concentrations, via sediment storage.
- Conversely, lake interception was associated with increased particulate P transport in upland areas with low bluff extent. At upstream sites where field erosion is largely controlled via tillage management and near channel sources are comparatively small, sediment-bound P may be relatively limited compared to other P sources. In this setting, the impact of lakes on particulate P via sediment storage may be overshadowed by the production of particulate P associated with algae and macrophytes in lakes.

- Anoxic release of dissolved P during low flows in some watersheds potentially decouples C-Q relationships, further modifying C-Q relationships towards chemodynamic behavior (Figure 7; top panels).
- Glacial history likely affects the nature of concentration-discharge relationships for soluble reactive and particulate P (Figure 7; top vs bottom panels).

Our findings detailing the hydrological and landscape response of river P are consistent with analyses of annual mass balance measurements in showing that dissolved and particulate P often contribute equally to annual P loads. On average across all agriculturally-dominated gaged sites for which load information was available (n=22), dissolved and particulate P accounted for 51% and 49% of the total P load, respectively, over the period of record between 2009-2015. At some gages, the total P load was dominated by contributions from OP, as high as 74% of total P load for the gage at Cedar River near Austin, MN. Conversely, other gages were dominated by particulate P export, with the contribution of particulate P to total P load as high as 71%, for the gage at the Le Sueur River near Rapidan (CR8 gage). These results agree with analyses of a broader set of sites (4.1.1) that found fertilizer inputs were the dominant driver of river losses, with the partitioning of dissolved vs participate P depending on sediment inputs.

Together, these findings underscore the importance of strategies to reduce both forms of P. In addition, our work strengthened arguments for implementation of management practices to control P losses with guidance from understanding of local landscape and climate conditions, as might be achieved via the Minnesota's One Watershed, One Plan framework, if appropriate geospatial analyses are incorporated.

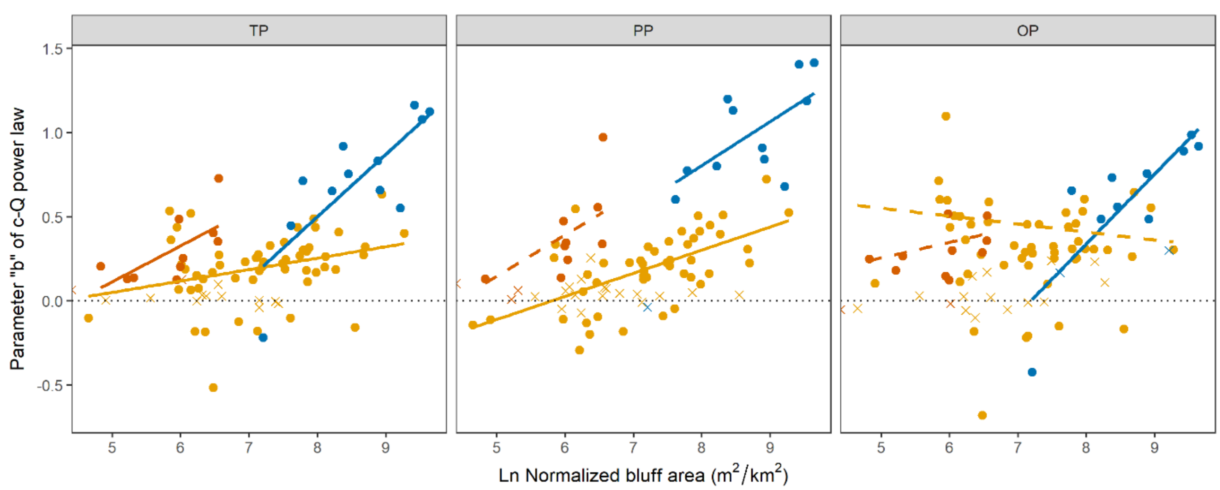

Figure 5. Relationship between bluff extent and P transport. This plot shows parameter "*b*" (i.e. slope) of the c-Q power law relationship for total P (TP), particulate P (PP) and dissolved P (orthophosphate-P; OP, in relation to normalized bluff area (log transformed), across the Red River (dark orange; n=12), Minnesota River (light orange; n=64) and Upper Mississippi-Black Root River (blue; n=12) basins. Symbols indicate whether the power law relationship for c-Q was significant ($p < 0.05$, solid circles) or not ($p > 0.05$, cross hatches) for each P constituent. Solid lines show significant statistical relationships between *b* and bluff extent for each P constituent (across sites with statistically significant power law relationships). Dashed lines

indicate non-significant statistical relationships between *b* and bluff extent. These findings indicate that both TP and PP transport, in terms of *C-Q* relationships, are strongly influenced by the availability of vulnerable near channel sediment sources (i.e., bluffs) in the Minnesota, Red and Upper Mississippi-Black Root basins. In addition, OP transport is also influenced by bluff extent in the Upper Mississippi-Black Root basin.

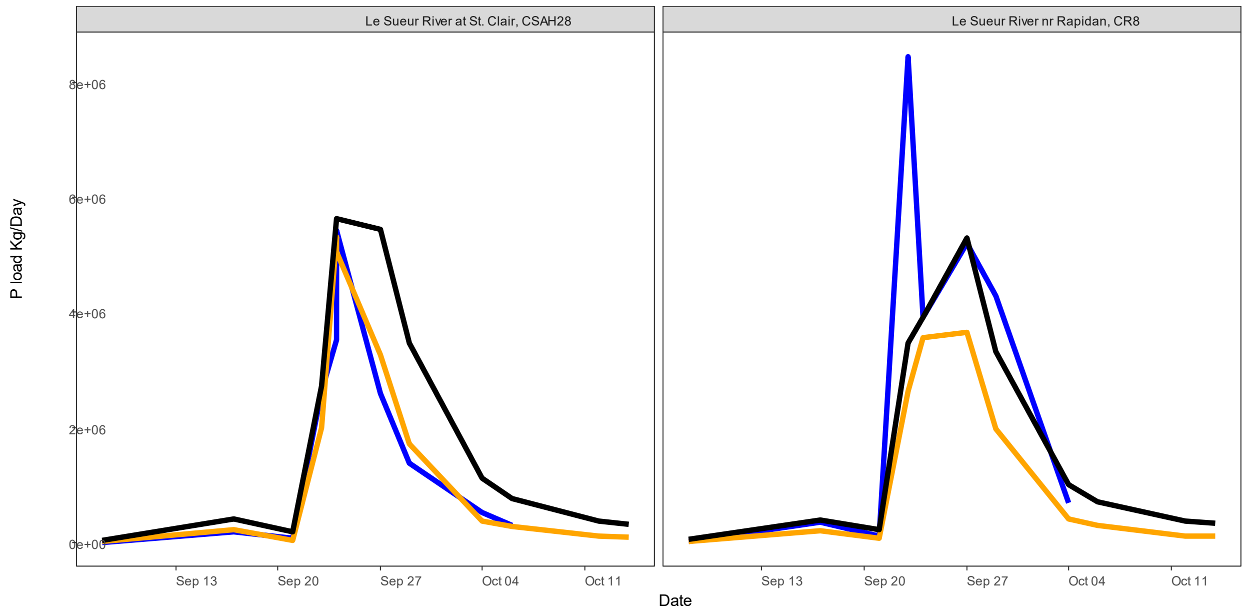

Figure 6. Gage data to examine possible effects of bluff sediment inputs on mode of P transport, for the Le Sueur River mainstem following a very large storm event in 2010. This storm was well sampled by personnel from the Water Resources Center at Minnesota State University at Mankato. We compared the load of orthophosphate (OP; orange line) and particulate phosphorus (PP; blue line) to trends in discharge (black line), at a set of gages located upstream and downstream of the incised zone (i.e., upstream and downstream of major bluff inputs) on the mainstem Le Sueur River. At the upper gage (left panel), PP and OP load peak with peak discharge, and OP and PP loads are roughly equal. At the lower gage (right panel), there is only one discharge peak, but there are two peaks in PP load. The first occurs on the rising limb of discharge and could be consistent with flushing of accumulated colluvium at the toe of stream banks and bluffs. The second peak in PP load occurs at peak discharge, and could be consistent with additional bluff collapse at high flow and associated inputs of new sediment and sediment associated-PP. At the lower gage, the OP load is 'flattened' at peak discharge and is lower than the load at the upper gage, potentially indicating suppression of OP through sorption to new inputs of sediment associated with bluff collapse. Note: discharge was scaled so as to be visible on the same scale as P load.

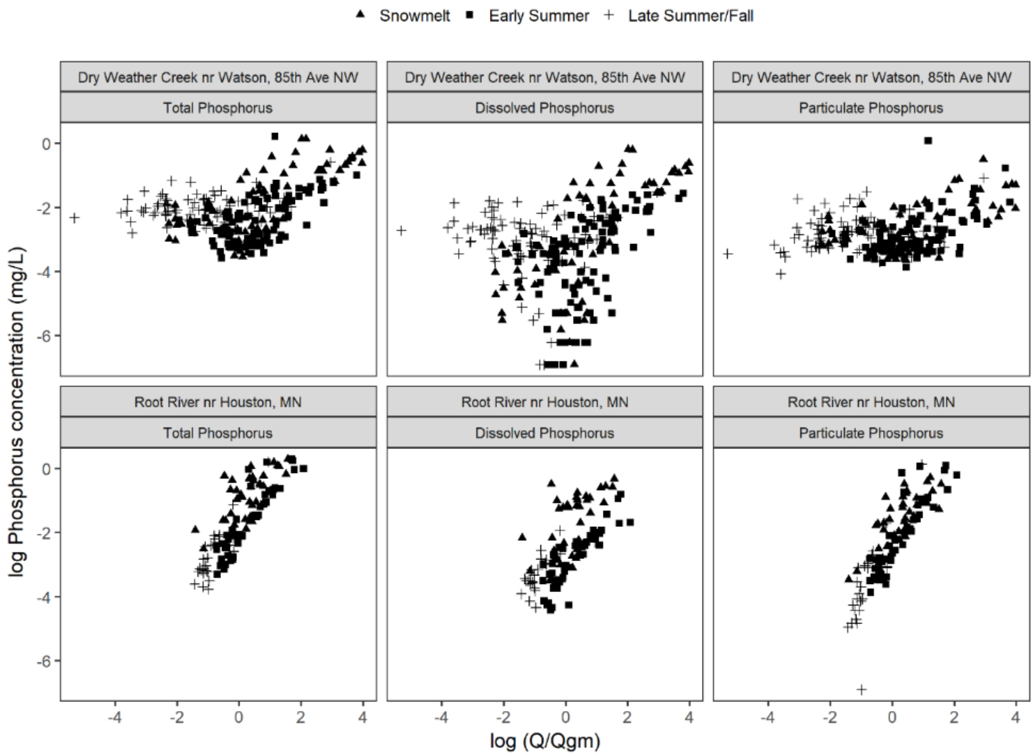

Figure 7. Concentration-discharge relationships for total, dissolved and particulate phosphorus from one representative site characterized by high bluff extent in contrasting regions (glaciated vs driftless). Complex, nonlinear relationships with flow shown for Dry Weather Creek (top) were typical of many sites in the Minnesota River Basin and while more linear relationships observed in the Root River (Bottom) were typical of the Upper Mississippi Black Root River Basin. Symbols indicate the season in which samples were collected.

These plots also show that c-Q relationships can be modified by seasonality in environmental conditions related to changing flowpaths and biogeochemical processes. For example, at many sites (e.g., Dry Weather Creek (top), elevated concentrations of dissolved phosphorus at low flow conditions in late summer obscured and/or weakened c-Q relationships that otherwise would have conformed more strongly to power law relationships. High concentrations of dissolved phosphorus at this time of year are consistent with anoxic conditions that can result in phosphorus release from aquatic sediments (Hupfer and Lewandowski 2008, Dupas et al. 2015, Gu et al. 2017) and effects of seasonal drying and rewetting (Kinsman-Costello et al. 2016). Soluble P release due to anoxic conditions during warm, low flow conditions can co-occur with periods of high primary productivity, leading to uptake and conversion of dissolved P to particulate forms. These biogeochemical processes can conditionally modify and sometimes obscure flow-driven changes in phosphorus concentrations due to flushing from terrestrial source areas.

4.2 Sources and reactivity of phosphorus in the Le Sueur Watershed

4.2.1 Algal assimilation and P transport

Analysis of our field dataset indicated that particulate (Figure 8) and dissolved P concentrations were often influenced by water column chlorophyll *a* concentrations. These findings suggest that high rates of assimilation and algal production in some agricultural river networks may be associated with draw down of dissolved phosphorus and conversion to particulate phosphorus in the water column, and thus modifying c-Q relationships towards chemodynamic behavior. Our findings also indicate that role of algal biomass in modifying phosphorus concentrations is much stronger at moderate to low flow conditions; at high flows dilution of algal biomass and mobilization of sediment sources likely renders the contribution of algal P relatively small compared to inorganic PP sources, especially for sites with considerable extent of near channel sediment sources.

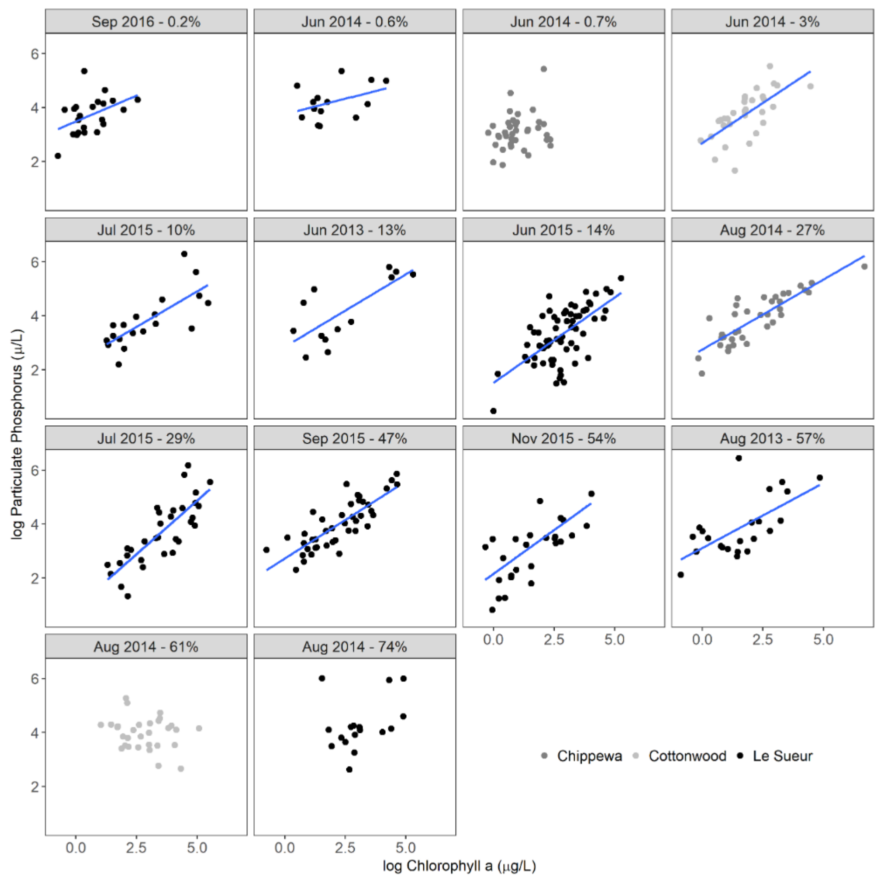

Figure 8. Particulate phosphorus concentrations in relation to chlorophyll a concentrations measured at a total of 176 ditch, stream and river sites sampled over 12 different sampling events and three major (HUC8 scale) watersheds. Point color indicates major watershed where sites were located. Lines indicate statistically significant linear regression relationships. The % values in the facet titles indicate the exceedance probability of flow at the outlet of each major watershed during sampling.

Legacy phosphorus, that is inputs previously introduced by human activities and stored in soils or sediments, and slowly mobilized to freshwaters, is increasingly recognized as a major driver of excess P in agricultural watersheds (e.g. Powers et al. 2016, Goyette et al. 2018, Kusmer et al. 2019).

Data for tile drainage from our samples combined with other data shows that under most conditions, concentrations are low and cannot explain the generally much higher levels observed in ditches, streams and rivers (Figures 9, 13). Ditch P concentrations were often considerably higher, with variability introduced by seasonal changes and algal uptake (see Figure 9). While wetlands may be sources of dissolved P to streams, under most conditions concentrations were not different from that of sites without wetlands (Figure 9), suggesting other important sources in the landscape. These wetlands have existed for many years, suggesting that increased wetland cover, implemented to reduce nitrate (Hansen et al. 2018) and flood peaks, may have positive or at worst, neutral impacts on P removal.

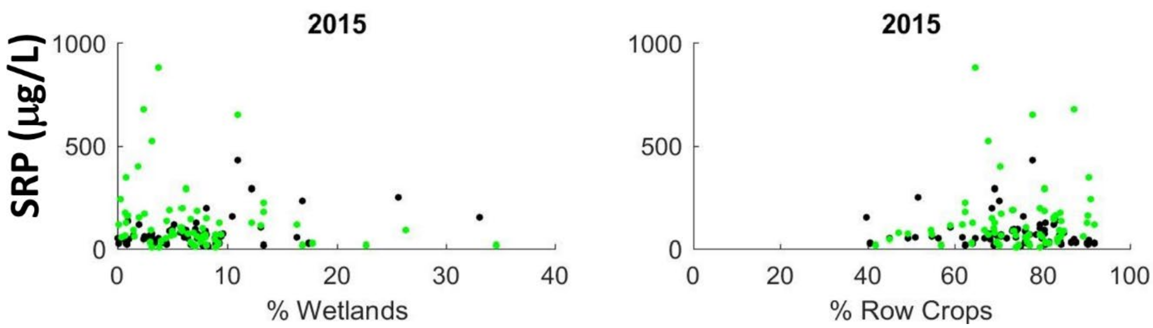

Figure 9.   Concentration of dissolved P (as OP) across gradients of wetland and crop cover. **Black** symbols indicate samples collected in June at relatively high flow conditions, and **green** indicate August at low flow.

Given that tile drainage, and wetlands cannot account for the observed dissolved P in channels, we considered other potential sources. These sources could include field runoff, riparian zone wetlands and near stream sources. Field runoff occurs during large rain events and at snowmelt (Stuntebeck et al. 2008), which is revealed also in MN Discovery farms data (https://discoveryfarmsmn.org). Contributions from field runoff could explain some of the increases in dissolved P with discharge observed in our analyses. However, because field runoff only occurs during intense rainfall during unfrozen conditions, and only for brief periods of time, this pathway cannot entirely account for the high levels of dissolved P. In particular, the sustained high concentrations of dissolved P observed throughout agricultural watersheds during summer and fall, including dry periods prior to or immediately following rain events cannot simply be linked to direct influences of field runoff.

Our analyses suggest the most likely source of much of the dissolved P in streams and rivers is riparian zones and near channel areas. Such areas generally have soils rich in P and organic matter, with redox (i.e. low oxygen leading to release of iron bound P) and hydrologic conditions (frequent changes in water level, movement of shallow groundwater into channels) conductive to sustained mobilization to streams. Our data show that water extractable OP, an indicator of the potential of soils and sediment to produce dissolved P that can be hydrologically transported, are most closely associated with two factors: soil TP and organic matter content. Together these two factors explain over 72% of variability in water extractable OP for fine sediments and soils across representative range all major soil and sediment types (Figure 10). Both of these factors were highest levels in ditch banks, and surface soils, as well as some stream sediments, which were not included in the analyses. The small dataset for in-stream and river sediments showed similarly high levels of TP and potential mobilization of dissolved P (data not shown). Overall, our findings are consistent with and supported by other recent studies that point to the role of near stream areas and P enriched surface soils as large dissolved P sources (Roberts et al. 2012; Dodd and Sharpley, 2015; Dupas et al. 2015; Dodd et al. 2018; Satchithanantham et al. 2018).

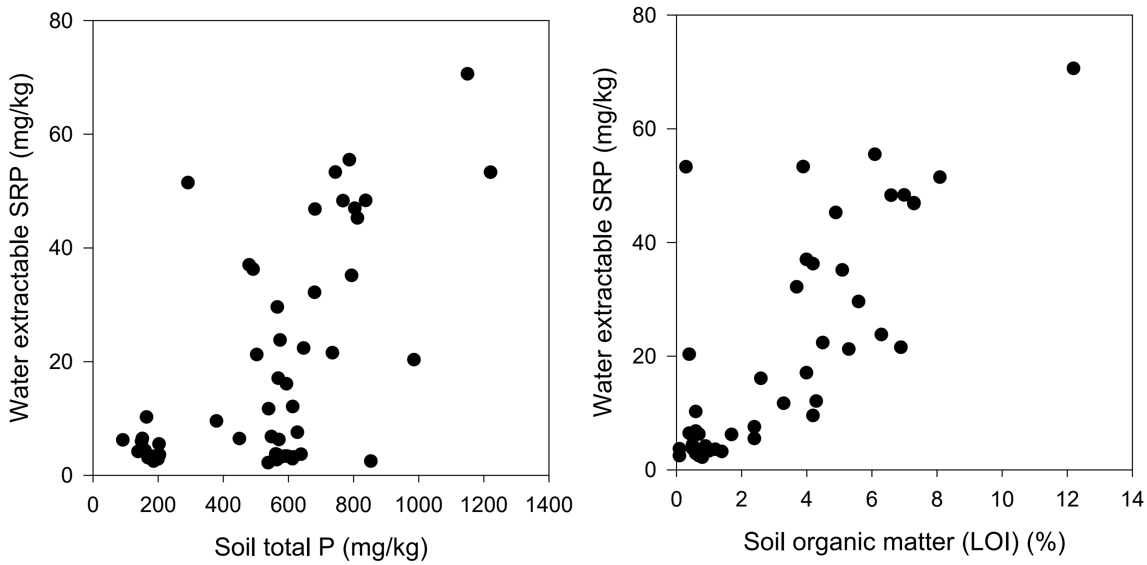

Figure 10. Relationship between water extractable OP and soil total P and organic content, the two dominant factors determining availability of soluble P availability for hydrologic transport in the Le Sueur watershed.

4.2.2 The role of erosion and sediment-phosphorus interactions in regulating watershed-scale phosphorus dynamics

A major finding of this work is that despite high rates of soil erosion, primarily from bluffs in the lower basin, sediment input in the Le Sueur watershed accounted for only a quarter of phosphorus inputs to the Le Sueur river channel. Integration of sediment and phosphorus budgets showed that 24% of total phosphorus exiting the basin was derived from erosional sediment inputs on an average annual basis, with 23% of this in particulate form and 1% in dissolved form (Figure 12). Dissolved orthophosphate comprised 37% of the measured average annual total phosphorus load at the Le Sueur watershed outlet. This estimate contrasts with the observed load of particulate (i.e. suspended sediment associated) phosphorus of around 63% of total P export.

The difference between the estimated input of P from erosion into the channel and the amount of particulate P observed exiting via river flow at the basin outlet is potentially related to a number of factors including 1) binding of dissolved phosphorus by eroded reactive soil, 2) algal and bacterial uptake (forming particulate P from dissolved P) in stream channels or lakes. While effects of measurement error must also be considered, our results for erosional inputs approximately agree with past estimates of erosion associated P in the area (Grundnter et al. 2014). Sekely et al. (2002) estimated that 7-10% of total-P may be derived from streambank slumping in the neighboring Blue Earth River, while our results show that approximately 16% of total-P may be derived from erosion of bluffs in the Le Sueur (unpublished estimate using our budget).

Incorporation of data describing the sorptive properties of sediment into this budget suggests that the true dissolved phosphorus load is masked by sorption of dissolved phosphorus to sediment, potentially reducing the fraction of total phosphorus that we observe as dissolved load by as much as 39%. This finding is consistent with cross site analyses (Figure 2) that show an increasing ratio of dissolved (as OP) to particulate annual loads with higher fertilizer inputs, except for rivers with high levels of erosional losses from bluffs, and high annual TSS loads (Boardman et al. In review). While adding some P to rivers, the larger impact of bluff erosion appears to be in converting dissolved P to particulate P.

These results were further supported by sorption tests to assess the capacity of sediments in channels to bind or release OP. These tests were conducted to mimic natural stream conditions using natural stream water from the Le Sueur River (collected during winter when values were lowest), and used a range of dissolved phosphorus spikes that mimics observed concentrations from the monitoring network on the Le Sueur with a ratio of sediment to solution that was representative of high TSS in the basin. Details of these methods are provided in Baker (2018). Results of these tests showed that, under average stream conditions during storm events which export high sediment loads, agricultural top soil and ditch sediment desorb phosphorus while glacial till bluff sediment and alluvial streambank sediment serve to bind phosphorus from the water column (Figure 11).

These findings have important implications for management. These results suggest that despite high sediment loading rates, even controls of 100% of erosion would only reduce total phosphorus loads by at most 24%. Furthermore, as the signal of dissolved phosphorus loss is muted by sorption to sediment from bluffs, then reducing erosion serves largely to alter the form of phosphorus in transport, resulting in higher dissolved, bioavailable phosphorus loads. Therefore, management strategies which reduce dissolved phosphorus sources are as (or potentially more) important to decreasing phosphorus export in rivers as erosion control.

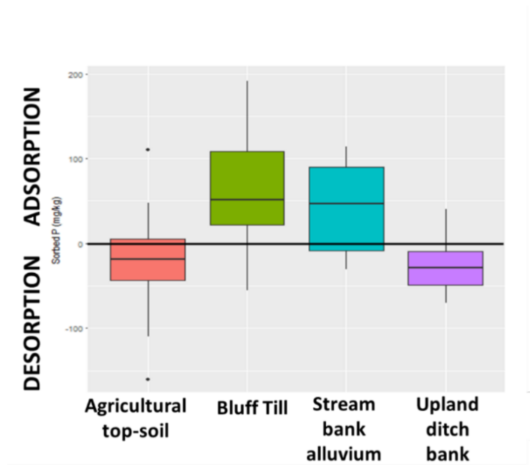

Figure 11. Boxplots showing distribution of sorbed phosphorus corresponding to stream orthophosphate conditions that occur when a majority of sediment export occurs.

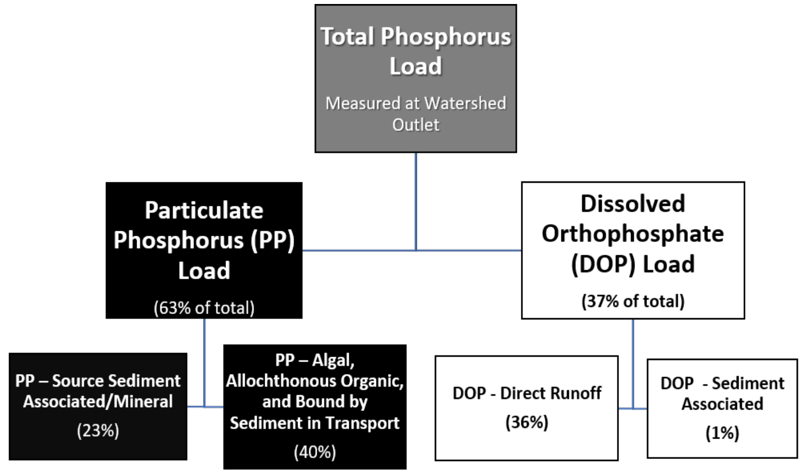

Figure 12. Flow chart showing apportionment of total phosphorus load into distinct pools, approximated using load monitoring data from the network of gages on the Le Sueur and its tributaries and results of mass balance for sediment associated phosphorus. This mass balance reveals that only 24% of total phosphorus measured at the watershed outlet can be attributed directly to source-sediment.

4.3 Linking management, climate and landscape features in models of P transport

4.3.1 Simulating soluble P export from tile drainage.

As a result of comparing tile drainage soluble P concentrations from Discovery Farms monitoring data against SWAT-simulated soluble P concentrations, we established the following parameter values to the SWAT model of the Le Sueur River Basin:

$K_L = 0.50$
$\beta_m = 0.06$

When aggregating results at an annual time step, the median observed and simulated values for soluble P in tile drainage were 0.050 and 0.055, respectively. The average observed and simulated values were 0.086 and 0.057 mg/L, respectively. Soluble P concentrations in tile drainage simulated by the SWAT model exhibited a narrower range of values than those reported from MN Discover Farms plots (Figure 13), which included diverse sites within agricultural areas of the state. This suggest that there are additional sources of variability that can influence soluble P concentrations in tile drainage that are not represented by the model. This likely includes local to regional differences in soil conditions and management history that are difficult to quantify and represent in a watershed scale modeling context. Nevertheless, the addition of soluble P to model outputs represents an advancement in our ability to quantify the relative importance of different mechanisms of P export from Minnesota's agricultural landscapes.

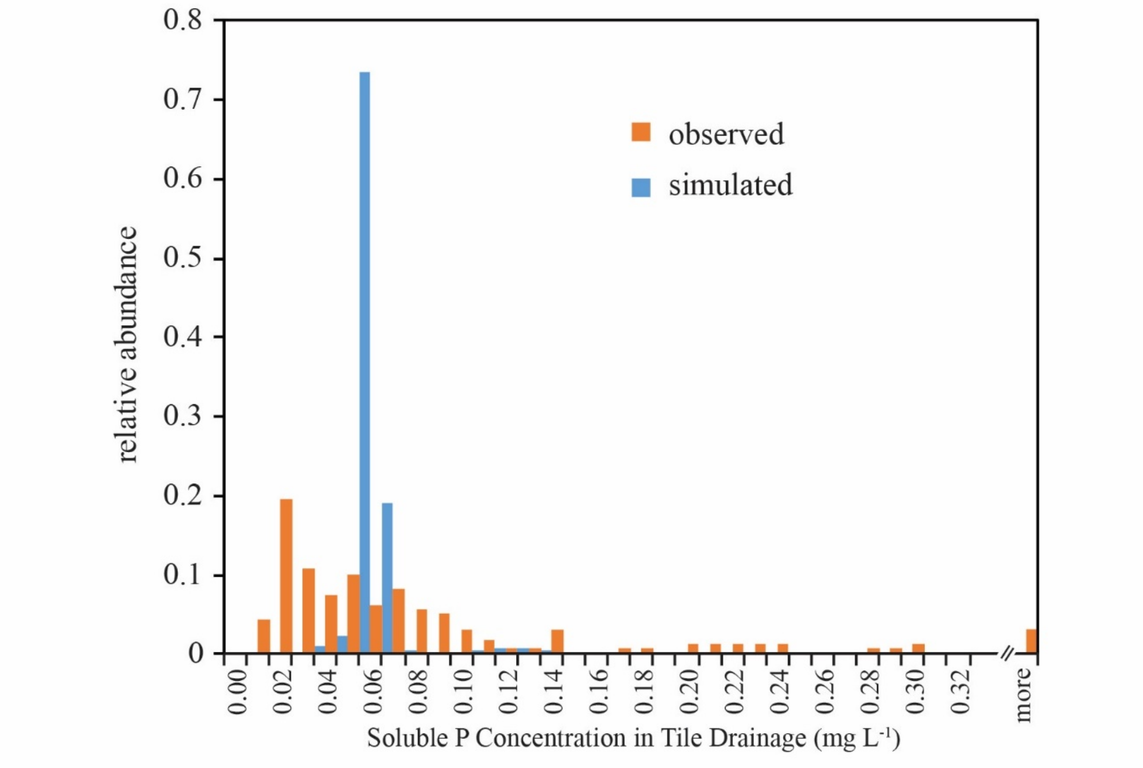

Figure 13. Comparison of predicted and observed concentrations of soluble P in tile drainage. The SWAT model was calibrated and validated for flow, sediment, and nutrients.

SWAT model performance was evaluated for monthly values of Nash Sutcliffe Efficiency (NSE) and compared against guidelines presented in Moriasri et al. (2007). Overall model performance was satisfactory for flow and ranged from satisfactory to very good for sediment, total P, and total N export. Comparison of observed and model-simulated values are shown in Figures 14 to 17 and measures of model performance are summarized in Table 1. Model simulated average values were generally less than observed values during the calibration period. This is mostly the result of under prediction of flood events that occurred in 2010 and 2011. Shaded regions in Figures 15 to 17 indicate the 95% confidence interval of the monthly load estimates produced by the loadflex model.

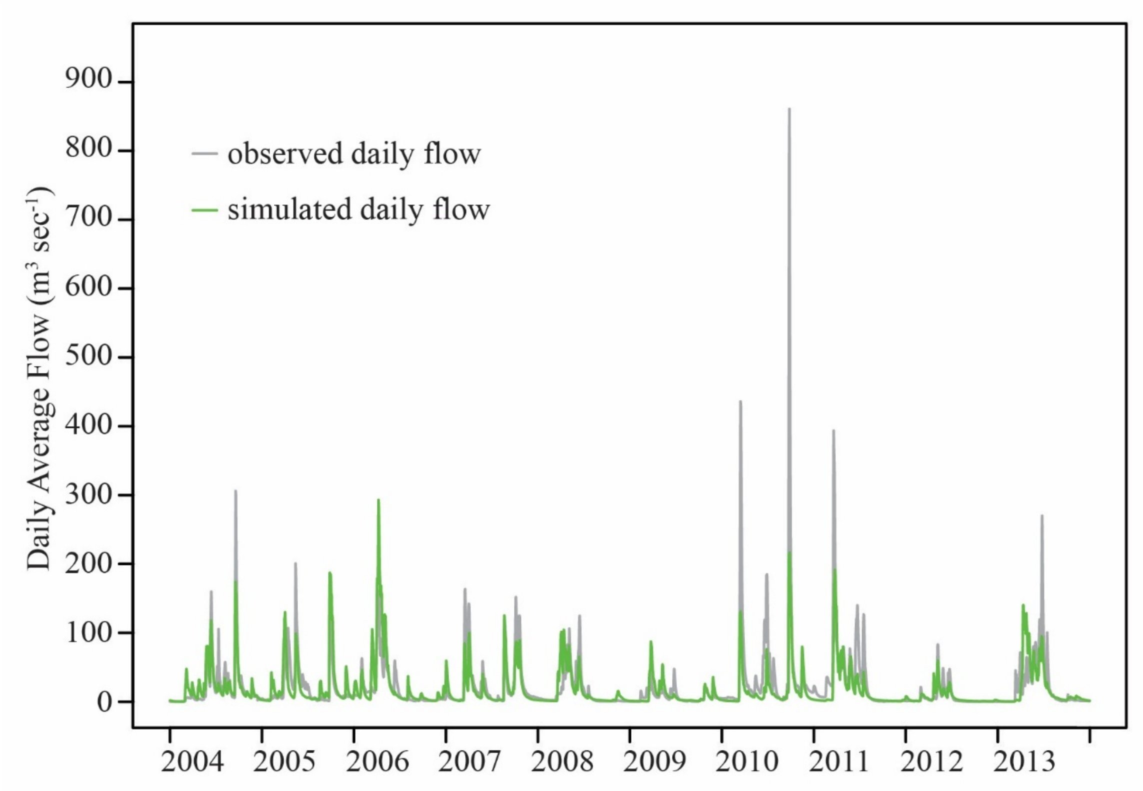

Figure 14. Comparison of observed and model-simulated daily stream flow from the Le Sueur River Basin. Summary values and model calibration and validation performance statistics are provided in Table 1.

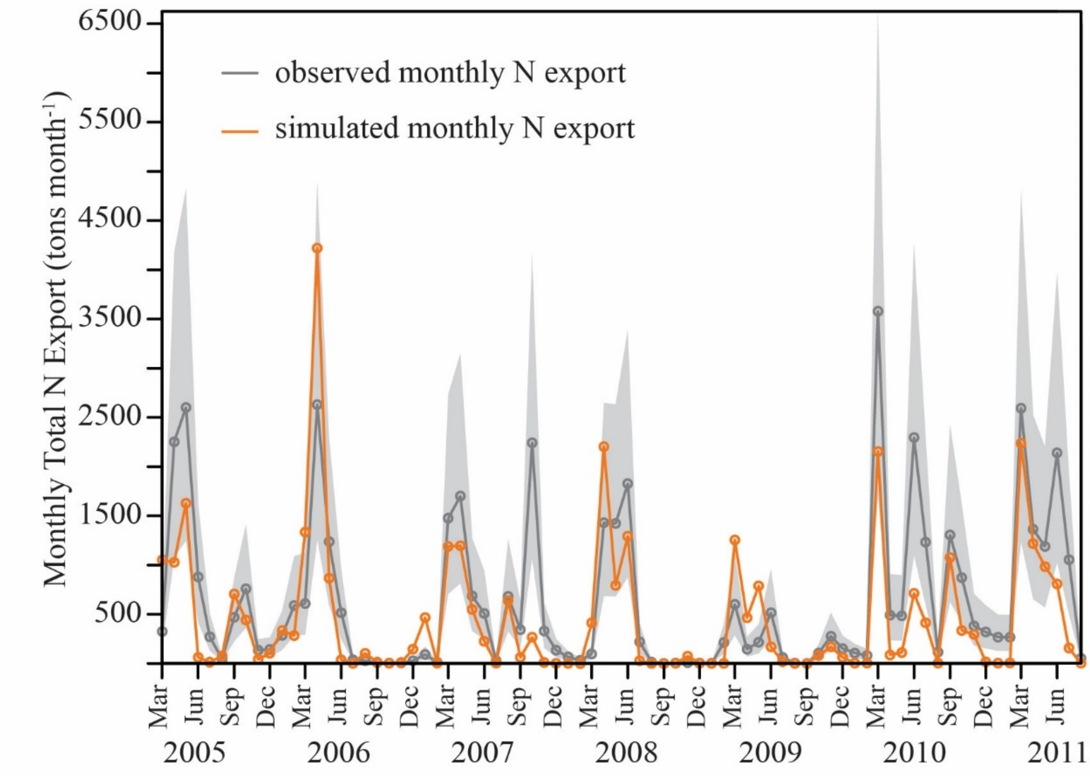

Figure 15. Comparison of observed and model-simulated monthly total N export from the Le Sueur River Basin. Summary values and model calibration and validation performance statistics are provided in Table 1.

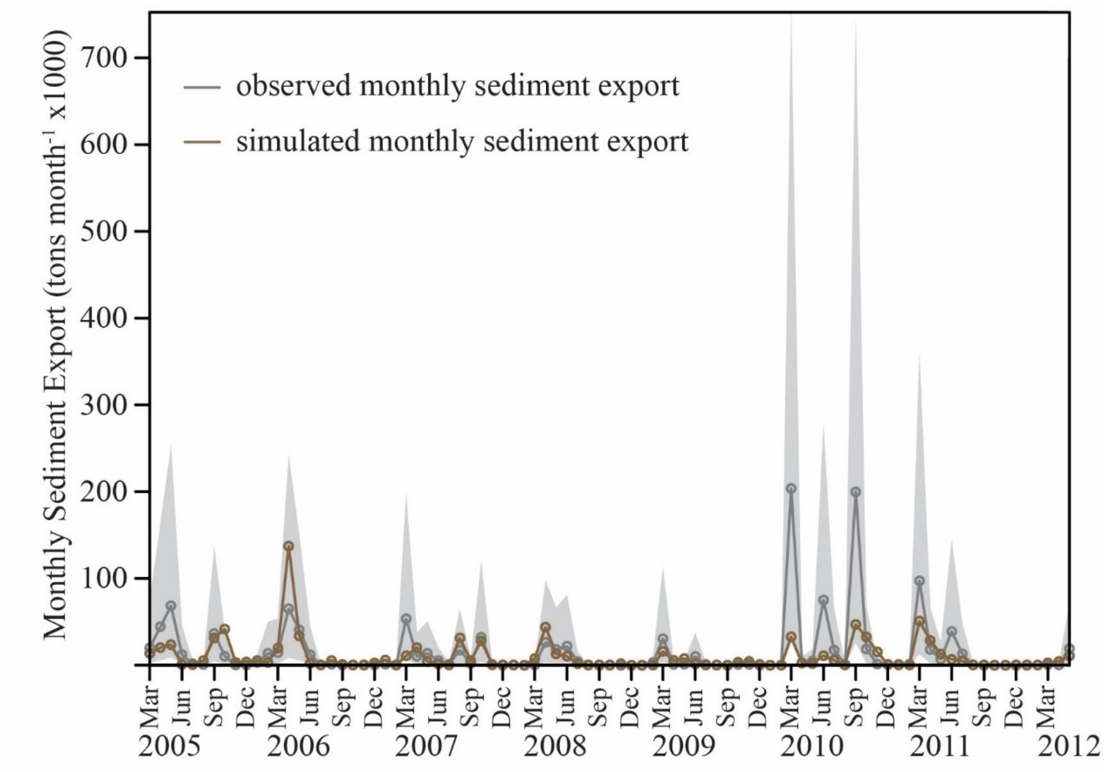

Figure 16. Comparison of observed and model-simulated monthly total suspended sediment export from the Le Sueur River Basin. Summary values and model calibration and validation performance statistics are provided in Table 1.

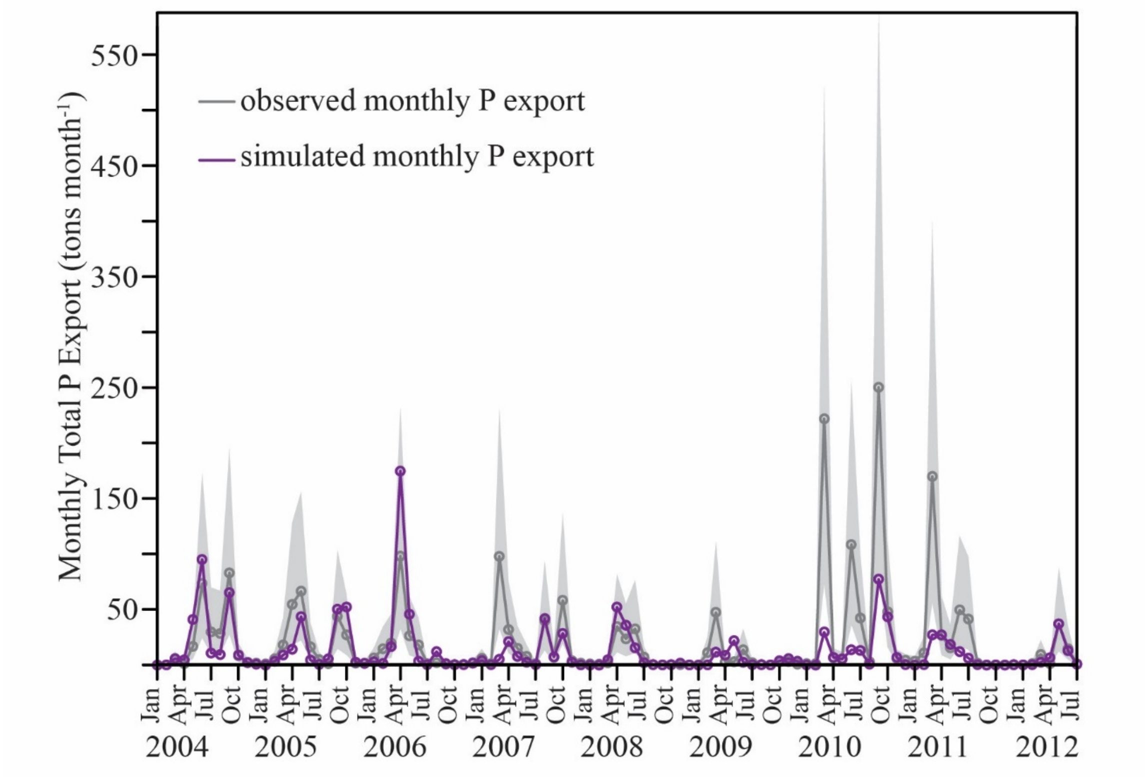

Figure 17. Comparison of observed and model-simulated monthly total P export from the Le Sueur River Basin. Summary values and model calibration and validation performance statistics are provided in Table 1.

	Calibration	Validation
Streamflow	1/1/2009 to 12/31/2013	1/1/2004 to 12/31/2008
Simulated Average (m3 sec-1)	15.45	21.94
Observed Average (m3 sec-1)	23.32	21.23
Nash Sutcliffe Efficiency (monthly)	0.52	0.61
Percent Bias	0.61	-3.3
Sediment	7/1/2008 to 5/31/2012	3/1/2005 to 6/30/2008
Simulated Average (tons month-1)	6,789	13,522
Observed Average (tons month-1)	16,517	13,777
Nash Sutcliffe Efficiency (monthly)	0.86	0.73
Percent Bias	21.6	(10.1)
Total Phosphorus	1/1/2008 to 7/31/2012	1/1/2004 to 12/31/2007
Simulated Average (kg month-1)	9,422	16,915
Observed Average (kg month-1)	23,088	19,850
Nash Sutcliffe Efficiency (monthly)	0.58	0.63
Percent Bias	44.2	8.2
Total Nitrogen	1/1/2009 to 8/31/2011	3/1/2005 to 12/31/2008
Simulated Average (tons month-1)	361.7	545.6
Observed Average (tons month-1)	598.2	674.1
Nash Sutcliffe Efficiency (monthly)	0.73	0.58
Percent Bias	30.5	12.6

Table 1. SWAT model results summary and performance statistics for flow, sediment, total phosphorus, and total nitrogen export from the Le Sueur River watershed. Nash Sutcliffe Efficiency values are computed following the approach presented in Harmel and Smith (2007).

4.3.2 Modeled export of phosphorus and sediment at the watershed scale.

The typical application of the SWAT model is to quantify the impacts of farm-level management on export of water, sediment, and nutrients. In tributaries of the Minnesota River Basin, and many other watersheds, there are important non-field sources of sediment that originate from eroding ravines and failing stream banks and river bluffs (Belmont et al., 2011). In order to account for these additional sediment sources in the SWAT model of the Le Sueur River Basin, we rely on an empirically-derived rating curve and daily water yield (Cho et al., 2017; Wilcock et al., 2016) to estimate the contribution of near channel sediments (NCS) and associated phosphorus (referred to as near channel phosphorus, NCP) into the three main tributaries of the Le Sueur River: (1) The Maple River, (2) The Big Cobb River, and (3) The Le Sueur River. These daily contributions of NCS and NCP are included in the calibrated model and permit a more comprehensive accounting of sediment and phosphorus sources in the watershed. Once the NCS and NCP have been added to the stream channel in the model, however, it is not possible to directly keep track of the relative contributions of field vs. near channel-derived sediment and phosphorus because of mixing and settling that occurs within the stream channel. However, it is possible to estimate the relative contributions of near channel sediment and phosphorus to the overall load near the watershed outlet by comparing simulated loads both upstream and downstream of the model subbasins where they are added. It is important to reiterate that these estimates do not account for the settling of sediment and phosphorus from all sources within a modeled channel reach. It is also important to note that not all sediment or phosphorus delivered to the stream channel from fields or from near channel sediments will be delivered from the watershed. Annual estimates of area–normalized sediment and phosphorus contributions are illustrated in Figures 18 and19, respectively.

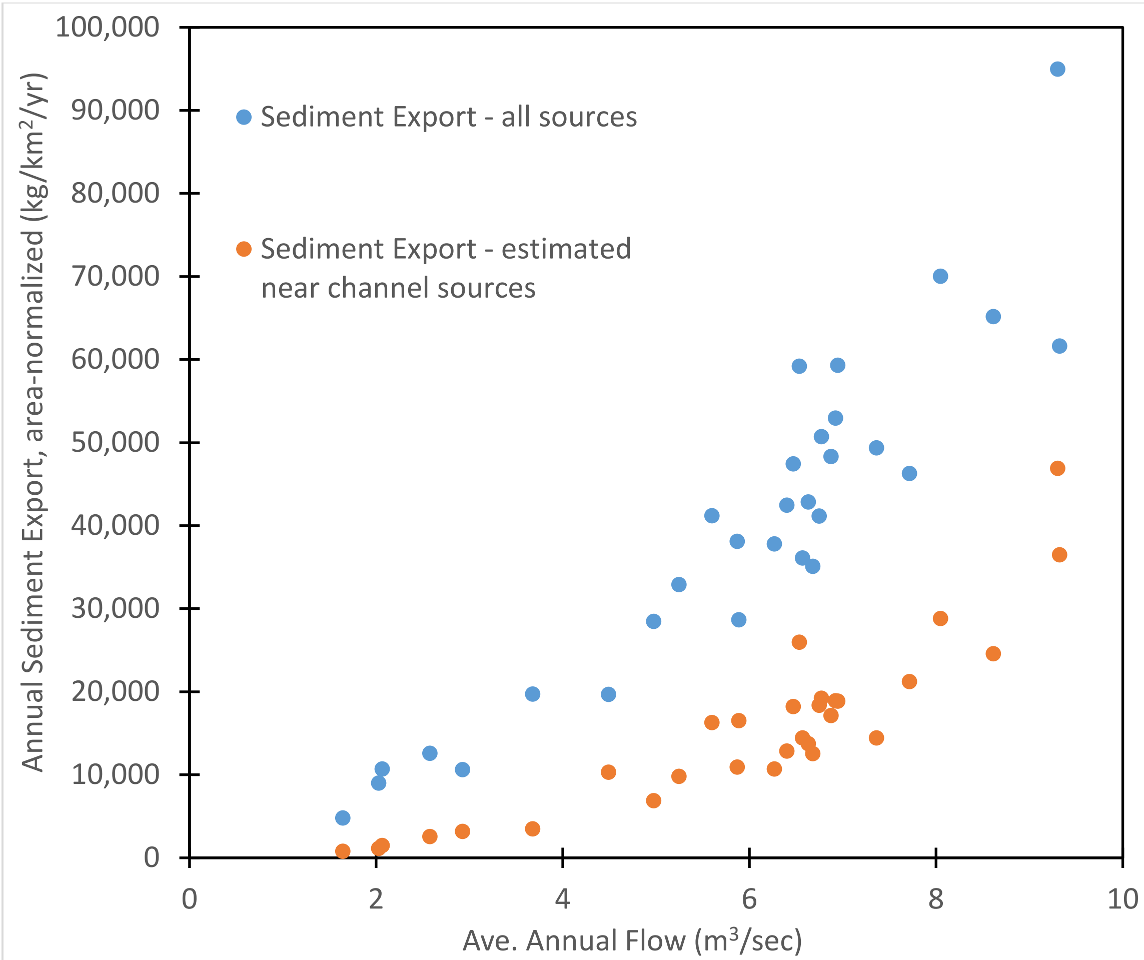

Figure 18. Modeled sediment export from the Le Sueur River Basin from 2004 through 2013. Data points reflect model outputs for the three main tributaries of the Le Sueur (The Big Cobb, Maple, and Le Sueur Rivers) at points downstream of the knick zone, where near channel sediment is contributed. Estimated contributions from near channel sources are conservative because they do not account for mixing and settling that occurs within the stream channel.

When quantified from stream channel of the three major tributaries of the Le Sueur River Basin at locations downstream from the knick zone, area-normalized average annual sediment export ranged from 4,806 to 94,960 kg/km^2/yr (Fig. 18). At the same sites, sediment export from estimated near channel sources ranged from 795 to 46,911 kg/km^2/yr. Overall, sediments from near channel sources are estimated to comprise from 13.7 to 59.2% of the overall sediment export from the Le Sueur river basin tributaries. Total phosphorus export was estimated to range from 7.7 to 118.1 kg/km^2/yr while phosphorus export from near channel sources was estimated to range from 0.3 to 22.5 kg/km^2/yr (Fig. 19). Phosphorus from near channel sources was estimated to contribute from 3.4 to 37% of the total phosphorus export at these sites. This is consistent with results from our sediment and phosphorus budget work above (section 4.2.2) which showed that 24% of total phosphorus exiting the basin was derived from erosional sediment inputs on an average annual basis. Unsurprisingly, export of sediment and phosphorus from the Le Sueur River basin was positively correlated with stream flow (Figs 18 and 19). Runoff and tile drainage mechanisms responsible for water, sediment and phosphorus export from upland areas (fields, and ditch networks) are tightly linked to stream flow through the lower basins, which drive the addition of near-channel sediment and phosphorus into the river. In particular, high flows drive bluff and streambanks failure and mobilization of sediments from channels. This area-normalized comparison of sediment and phosphorus from upland vs near channel sources is intended to provide a frame of comparison for how NCS and NCP compare to the overall export from the watershed. It is important to emphasize that although the drivers are similar (high flows), the specific sources and mechanisms of bluff and stream bank failure are different than those that erode sediment and phosphorus from the landscape (see Fig. 25). Finally, the NCS and NCP contributions estimated here are lower than values reported elsewhere (Belmont et al., 2011; Baker et al. In review) because they do not account for in channel mixing and settling that occurs within the modeled stream reach. NCS contributions that are closer to 75% of the total load have been estimated based on sediment fingerprinting techniques (Belmont et al., 2011) and those values based on more direct measurements should be considered to be more representative of long-term contributions from near channel vs. upland sources of sediment. The modeled values presented here help to quantify the magnitude of inter-annual differences in NCS and NCP contributions that may result from differences in stream flow.

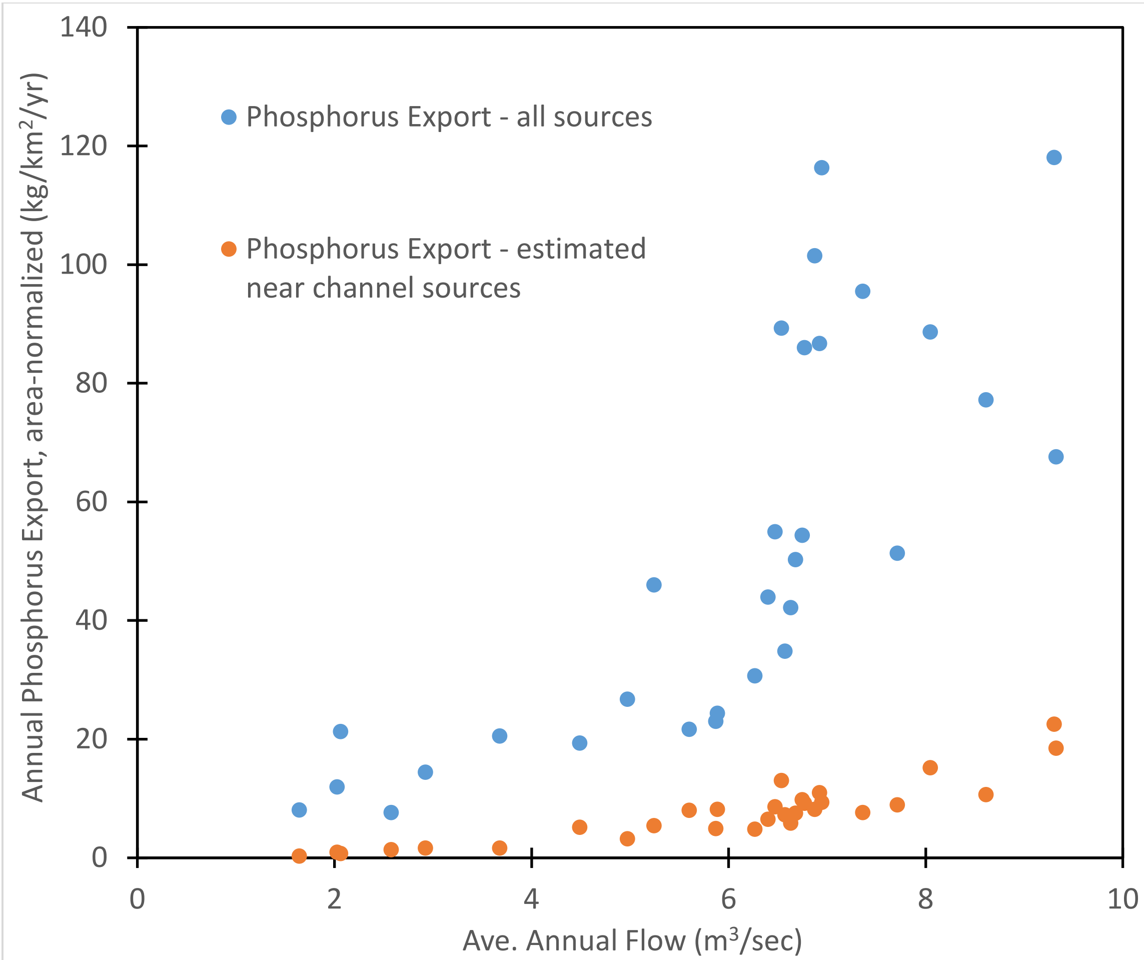

Figure 19. Modeled phosphorus export from the Le Sueur River Basin from 2004 through 2013. Data points reflect model outputs for the three main tributaries of the Le Sueur (the Big Cobb, Maple, and Le Sueur Rivers) at points downstream of the knick zone, where a large majority of near channel phosphorus is input. Estimated contributions from near channel sources are conservative because they do not account for mixing and settling that occurs within the stream channel.

4.3.3 Modeled export of phosphorus at the field scale.

SWAT model outputs are helpful for quantifying the different pathways by which phosphorus can be exported from farm fields into ditches and streams. Field-scale export values are typically greater than values observed at the watershed outlet because of in-channel settling that occurs in the model. Based on modeled results, average annual phosphorus export from agricultural HRUs in the Le Sueur River Basin ranged from 27 to 122 $kg/km^2/yr$ and tile drainage contributed from 4.9 to 43.8 % of the total average annual load (Fig 20). Box plots of data from all HRUs (Figs. 21-23) show that annual phosphorus export from all HRUs (including those without tile drainage; Fig. 21) includes some large outlier values that typically reflect areas where cropland is simulated on steeper slopes and predicted losses from overland flow are great. In HRUs with tile drainage present (Figs. 22-23), large outlier values are less common but overall P export is similar and dissolved P export via tile drainage represents an important part of the overall annual P budget.

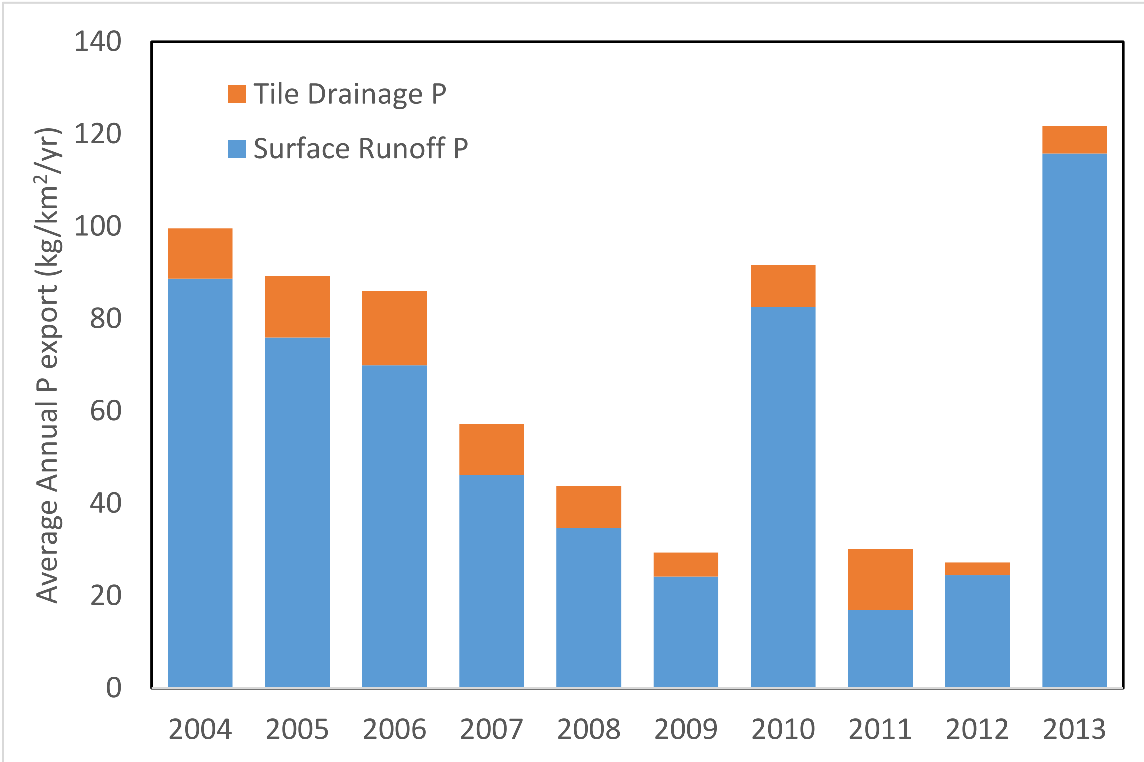

Figure 20. Average annual P export from agricultural HRUs with tile drainage in the Le Sueur River watershed simulated by the SWAT model for the baseline landscape scenario.

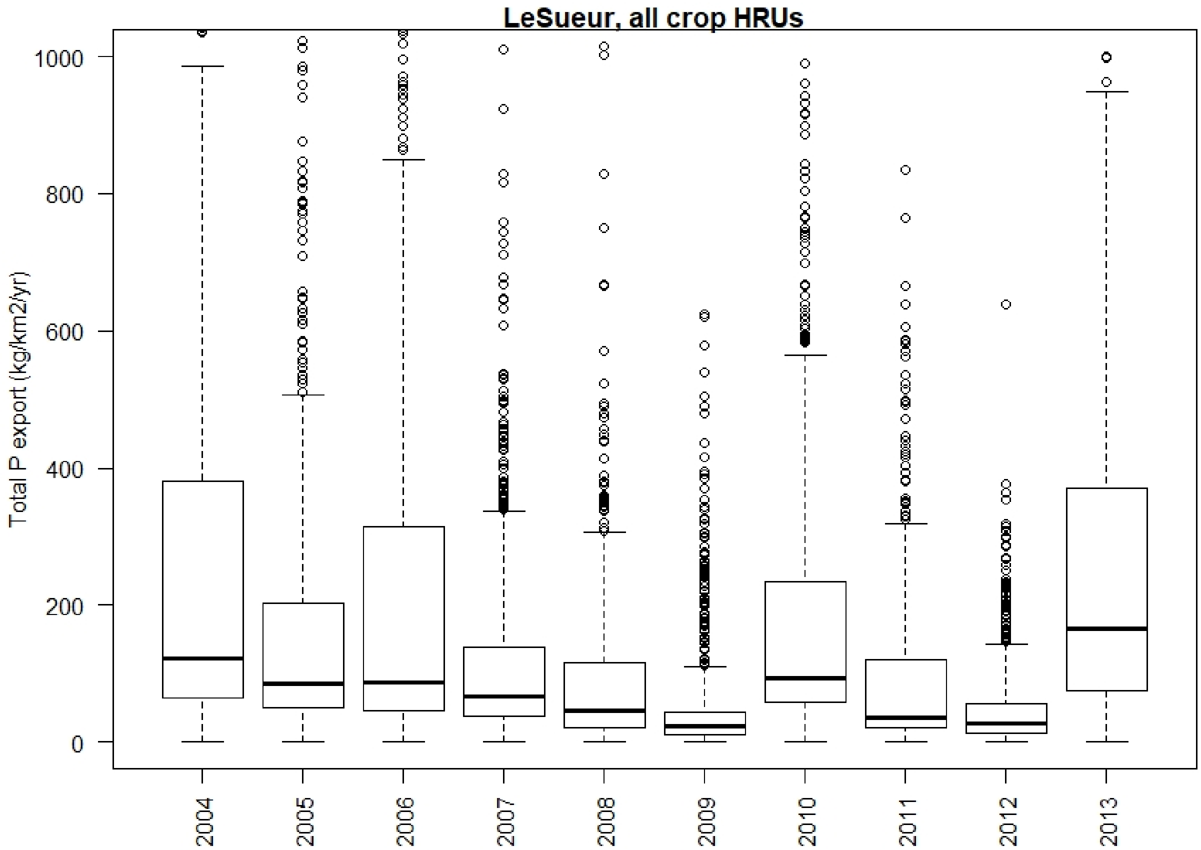

Figure 21. Box plots summarizing annual total P export from all modeled HRUs with row crop land use (corn and soybeans). The box indicates the median value and interquartile range; points that extend beyond the whiskers are more than two times the interquartile range from the box. *In most years, a small number of large values extend off the range of the y-axis. The y-axis scale is set to show the inter annual variability of the most typical values and represents over 99.1% of all data.

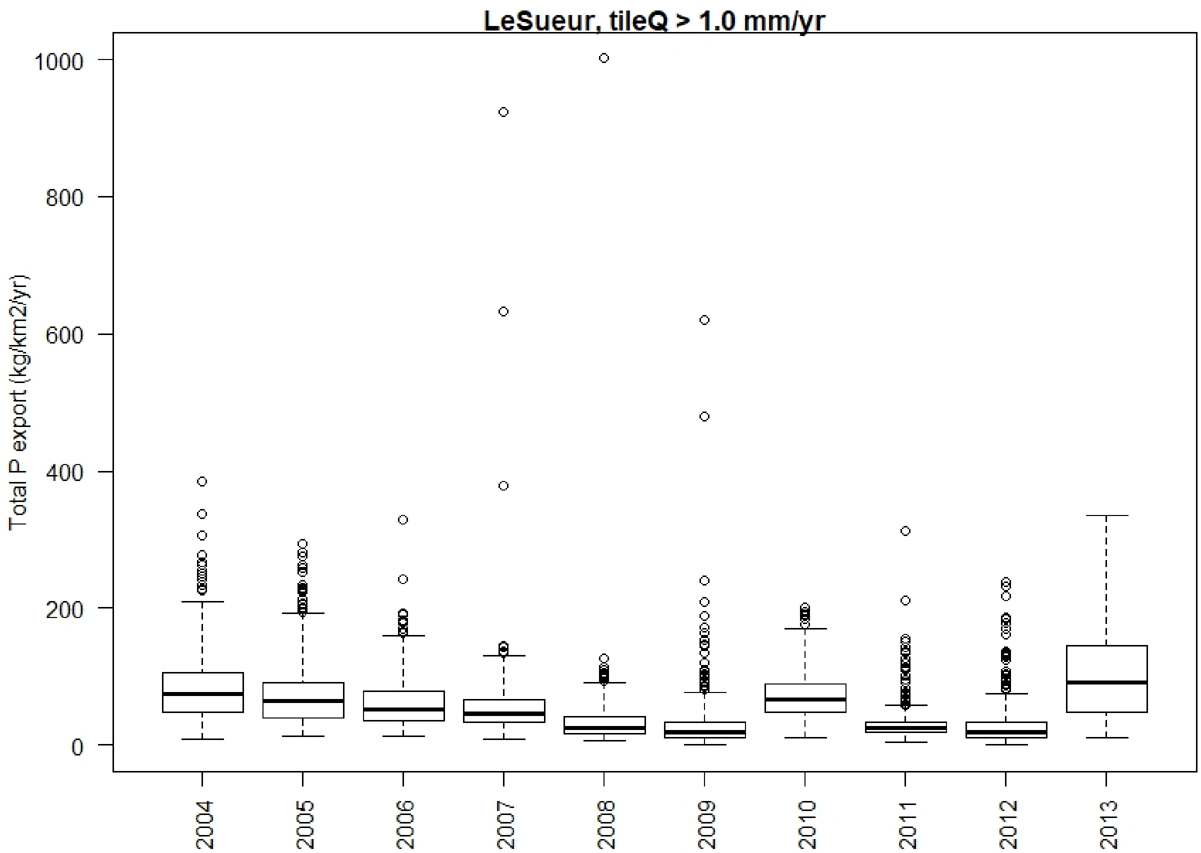

Figure 22. Box plots summarizing annual total P export from all modeled HRUs with row crop land use (corn and soybeans) and subsurface tile drainage present. The box indicates the median value and interquartile range; points that extend beyond the whiskers are more than two times the interquartile range from the box. *In most years, a small number of large values extend off the range of the y-axis. The y-axis scale is set to show the inter annual variability of the most typical values and includes over 99.6% of all data.

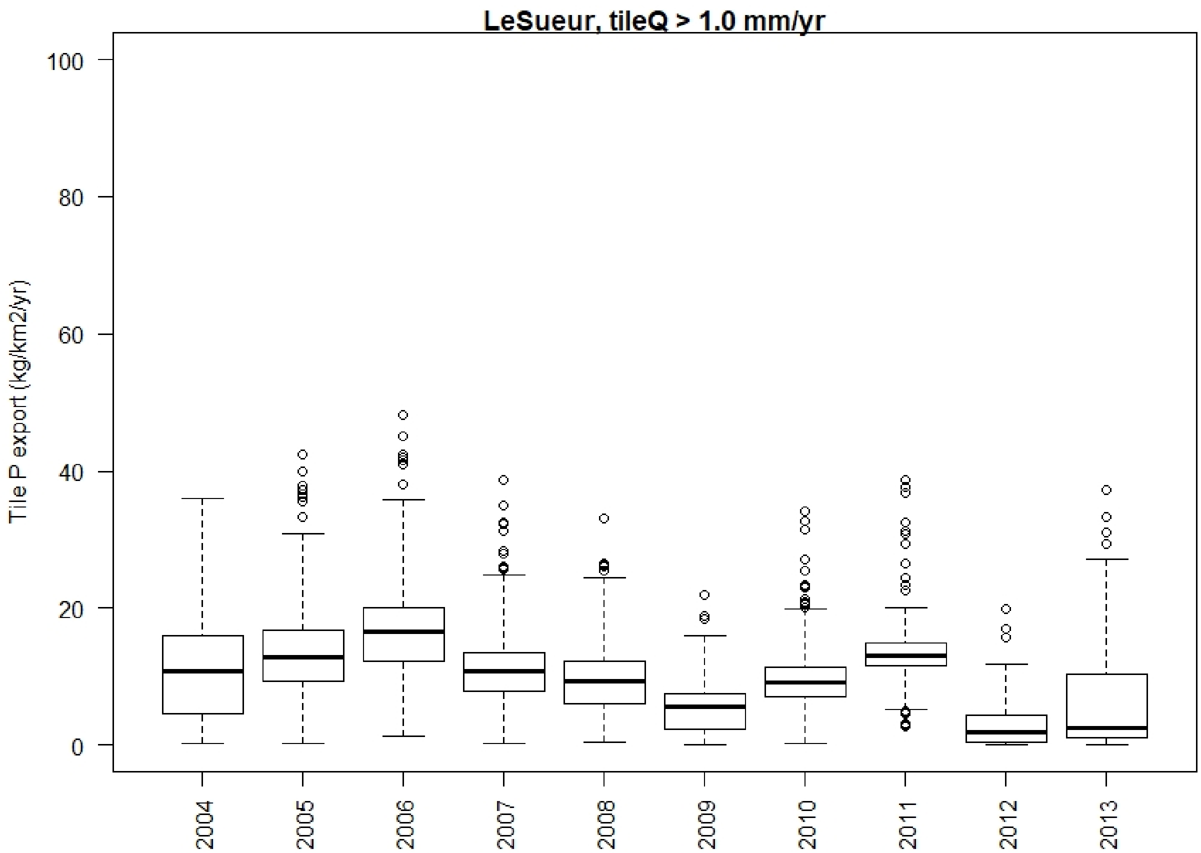

Figure 23. Box plots summarizing annual soluble P export via tile drainage from all modeled HRUs with row crop land use (corn and soybeans) and subsurface tile drainage present. The box indicates the median value and interquartile range; points that extend beyond the whiskers are more than two times the interquartile range from the box.

4.3.4 Evaluation of alternative management practices in the Le Sueur River Basin

Inclusion of factors that modify nutrient dynamics in models is critical for accurate scaling across time and space. Agricultural lands with tile drains tend to have high rates of soluble P, because they decrease the surface runoff that often transports particle-bound P while continuing to transport soluble nutrients. Lakes, where present, can reduce the amount and variability of nutrient export by processing P, but these P trapping features may be altered or disconnected in developed areas (Powers et al. 2014). Climate variation, especially how the frequency and intensity of storms in a given year influences the quantity of runoff and nutrient loads in watersheds, can confound changes over time due to land use. Our modeling of P in the Le Sueur was aimed at inclusion of these factors in a modeling framework to assess how different management scenarios may influence P export with particular emphasis on practices that change field-scale export. This study included simulation of three alternative management scenarios (in addition to the baseline landscape) in order to quantify the potential for alternative management practices to reduce phosphorus export from the watershed in order to meet Minnesota's water quality goals.

1. **Reduced Fertilizer Application:** 10% reduction of N and 17% reduction in P fertilizer. These reductions are based on guidelines from the IA Nutrient reduction strategy document. All other crop management practices remained the same.
2. **Cover Crops:** Immediately following harvest of the corn or soybean crop, winter rye was planted as a cover crop. The cover crop was terminated in the spring immediately prior to planting the cash crop. All other management practices remained the same.
3. **Perennial Grass Restoration:** This scenario represents a dramatic change that is unlikely under current conservation programs. Results from this scenario can be instructive, however, because it helps to provide define the range of potential watershed outcomes for this landscape.

Results from simulation of alternative management scenarios showed reduced average P export by 4.6, 26.6, and 47.8% under reduced fertilizer, cover crop, and prairie grass restoration scenarios, respectively. The reduced fertilizer scenario reflects the reduction of inputs to the landscape, but contributions from near channel sources are unchanged. Legacy P, from accrual of P in soils and sediments, may affect the trajectory of decrease of P from current levels in response to fertilizer reductions (e.g. Goyette et al. 2018). The cover crop scenario, by contrast acts to decrease both the field scale phosphorus contributions through reduction of overland runoff as well as reductions in water yield owing to transpiration from the cover crop. This reduced water yield acts to reduce phosphorus export in two ways: (1) directly through reduced overland flow and tile drainage, and (2) indirectly through reductions in streamflow that, in turn, reduce the contributions from near channel sources. While research on cover cropping management techniques is still ongoing, results presented here show promise for working toward water quality goals while still allowing farmers to grow corn and soybeans. The effects of cover crops on P export during snowmelt is poorly known, and further work is necessary to assess and develop management for the possible buildup of labile P at the soil surface with cover crop expansion.

Table 2. Average annual P export from the Le Sueur River Basin under baseline and three alternative management scenarios.

Scenario	**Ave. Total P export ($kg/km^2/yr$)**	**% reduction**
Baseline	56.1	0.0%
Reduced Fertilizer	53.5	4.6%
Cover Crop	41.2	26.6%
Grassland Restoration	29.3	47.8%

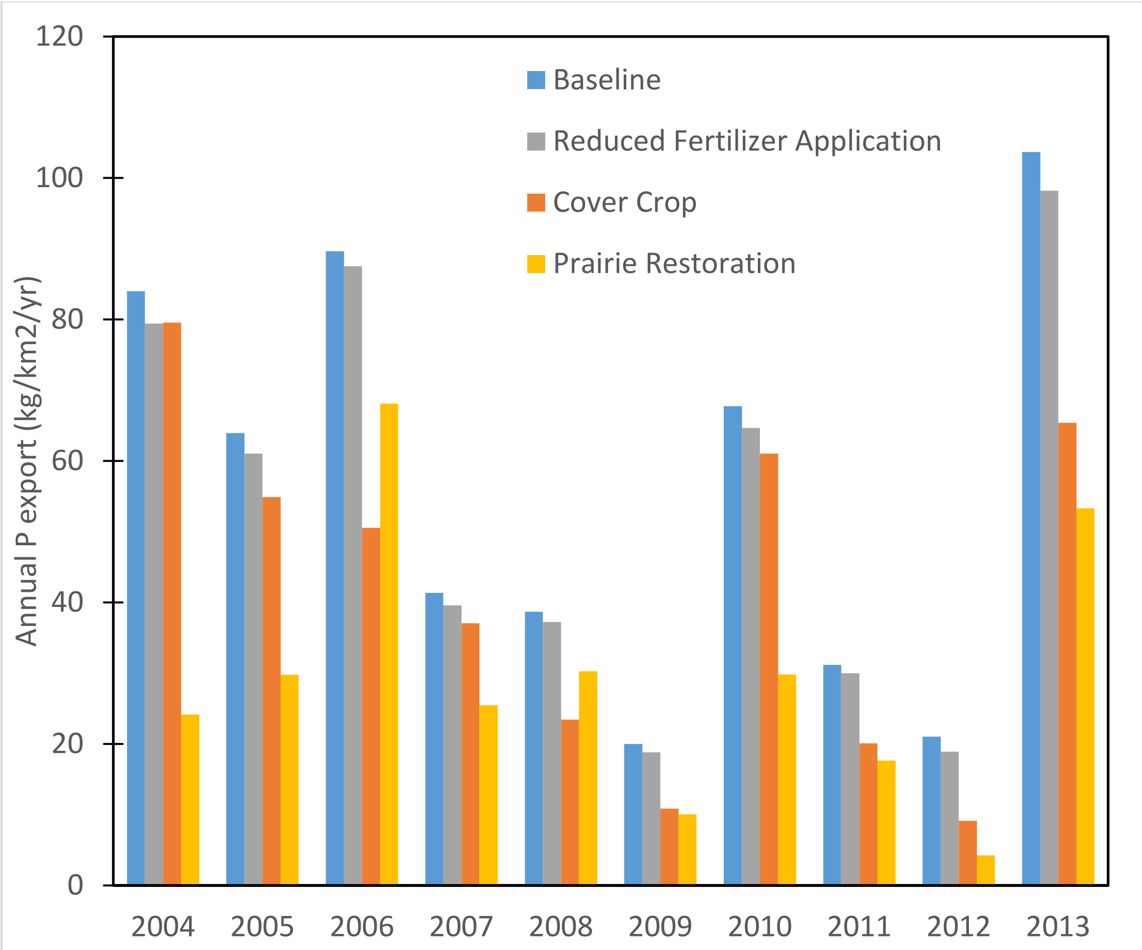

Figure 24. Comparison of average annual P export from the Le Sueur River basin under different management scenarios.

4.4 Integration and summary

Data from this project and related research were used to estimate sources of the three main water quality stressors affecting Minnesota's waters. Using information from the period 2009-2012 (the years for which sediment, sediment-phosphorus, tile, and watershed outlet loads for TSS, TP and nitrate were available), the proportion of annual loads contributed by major sources were estimated. These sources were defined as near channel erosion (stream bank and bluff sediment erosion, derived from Gran et al. 2011, Bevis 2015), field runoff TP (from SWAT modeling, section 4.3), tile drainage P and nitrate-N (from SWAT modeling, section 4.3), near channel runoff of dissolved P (as the difference between observed loads and other P sources). The period of analyses was slightly drier compared to some of the following years (2013-2016), but because nitrate, phosphorus and TSS all show strong increases in concentration and load with increasing flow, it is likely the results will be similar with consideration of higher precipitation years. Source attribution estimates provided here are preliminary, and will be refined as more information is available. However, these estimates reveal that the dominant sources of each water quality stressors in the Le Sueur watershed are spatially distinct within the basin.

This synthesis shows strong spatial contrasts in nutrient and sediment sources in the watershed. Nitrate is largely derived from tile drainage from fields, a finding consistent with other local and regional studies (e.g., Sands et al., 2008), while sediment is overwhelmingly generated at the downstream incised area of the watershed from banks and unstable bluffs (Fig. 25). Phosphorus showed greater diversity of sources with surface runoff from fields and near channel areas together contributing nearly 75% of the basin outlet P yield (Fig. 25). The diversity of sources for TSS, nitrate, and phosphorus show the challenges to management in addressing high flows, which mobilize N, P and sediment from different areas of the landscape. BMPs that retain water and reduce peak flows while allowing time for denitrification of nitrate and retention of P will be most effective at improving water quality conditions in the Le Sueur and similar watersheds within the Minnesota River Basin.

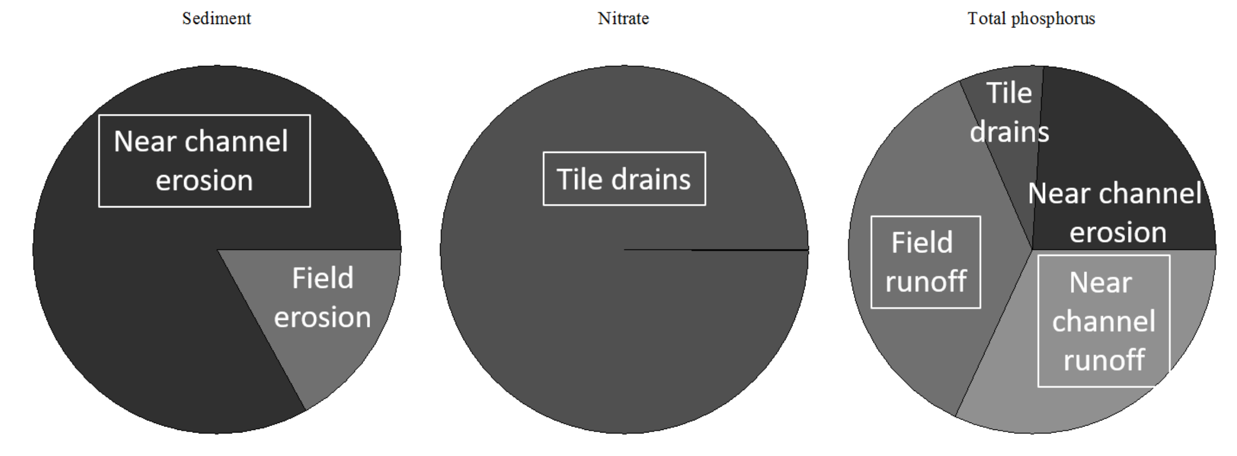

Figure 25. Sources of sediment (TSS), nitrate-N, and total phosphorus estimated for the Le Sueur River for 2009-2012. White boxes indicate dominant sources for each parameter.

While many standard BMPs intended to reduce nutrient losses are currently in widespread use, such as fertilizer management, buffer strips (Miller et al. 2014), and reduced tillage (Baker et al. 2017), there is mounting evidence that they can have unintended negative effects on dissolved P losses (see Dodd and Sharpley 2015, and Duncan et al. 2017 for reviews). Thus many common BMPs may not provide controls of near channel sources of P and sediment downstream. Management of non-point P losses requires a comprehensive plan guided by hydrologic models, assessment of current practices and soils and cropping systems, and landscape features. Information gained in this project was used to identify knowledge management actions needed to reduce excess P, and to identify gaps in our understanding that could eventually be resolved to improve the efficiency of phosphorus management.

4.5 Research needs and future directions

The mechanisms responsible for enrichment and losses of P in stream bank and identification of management to reduce it represent a key knowledge gap (see also Roberts et al. 2012, Dodd and Sharpley 2015, Fox et al. 2016). A combination of high resolution critical source tools (Thomas et al. 2016) could be used with knowledge of processes leading to soluble P generation and transport to assess the potential for near stream fields to lose P to buffer zones under winter or summer storms. Tillage management to destratify soil P (Baker et al. 2017) , fertilizer reductions, or altered cropping systems could be employed in sensitive areas near or within buffer strips and riparian zones to reduce P movement downslope, but further research is likely necessary to test and validate these methods. Further, buffer zone design and management, including biomass harvest, could be used to reduce excess P in riparian soils, or to minimize mobilization of dissolved P. Knowledge to effectively manage buffer strip and riparian zone to reduce P losses to aquatic systems is currently incomplete. These two gaps represent significant barriers to water quality improvement in Minnesota's agricultural landscapes.

5.0 Dissemination and Outreach

Two University of Minnesota masters students' thesis research projects were supported by this project (Baker 2018, Boardman 2016). Both students have moved into professional positions in water resources, and are actively collaborating on continued work to publish research findings. Eleven undergraduates were involved in research associated with the project. Three are coauthors on manuscripts, and at least five have applied or gone on to graduate school. Two post-doctoral research associates (Dr. Christy Dolph and Dr. Amy Hansen) were supported on the project. Dr. Dolph continues work on this and related NSF and EPA projects. Dr. Hansen recently started as an assistant professor at Kansas State University and continues to collaborate and develop associated research.

A total of 19 presentations have been made so far from research results from this project, including 10 at national/regional meetings, and 8 at Universities. Data from the project are included in publicly accessible formats permanently archived by the University of Minnesota. Water chemistry can be found in Dolph et al. (2017b), and soil and sediment P data in Baker et al. (2019).

6.0 Data, models and planned peer-reviewed publications from on this project

Abstracts for manuscripts undergoing peer-review associated with this project are included in this section (see below). These manuscripts are in various stages of the peer review process at the time of preparation of this report, and therefore must be considered confidential and work in progress. References to updated versions of these will be available in the future on PI Finlay's University of Minnesota website (https://cbs.umn.edu/finlay-lab/home). Complete draft versions these manuscripts are included in Appendices I-III as separate attachments. In addition, this project contributed significantly to the REACH (*Resilience under accelerated change*) observatory, described in a manuscript recently accepted at Water Resource Research (Gran et al. In press). The project website for the broader REACH project can be found at http://reach.safl.umn.edu.

Data collected in this project are available in permanent, publically available repositories. See Dolph et al. (2017b) and Baker et al. (2019) for links to data and documentation. State, federal, and University data used for analyses are available via the state of Minnesota, USDA, USGS and other sources as described in the Appendices.

At least two other manuscripts derived from this project are planned. These manuscripts have not been drafted but will include analyses based on SWAT model, and synthesis of research to identify cost effective strategies for control over phosphorus, nitrogen and sediment in the Le Sueur River.

6.1 Fertilizer, landscape features and climate regulate phosphorus retention and river export in diverse Midwestern watersheds (Boardman et al. In review, and Appendix I)

Abstract
Nonpoint source pollution of phosphorus (P) is a primary cause of eutrophication of aquatic ecosystems, posing a serious management challenge because processes that control the transport and transformation of P at the watershed scale are not thoroughly known. We examined phosphorus inputs, retention, and riverine losses in 62 watersheds of Minnesota, USA, that included a wide range of land cover and use (minimally disturbed to human dominated) and human P input. Fertilizer inputs from row crop cultivation was the dominant source of P to agricultural watersheds. A large majority of P inputs to watersheds were retained in soils or removed in agricultural products. However, fertilizer inputs were the most important factor associated with river transport of total, dissolved, and particulate phosphorus (PP). Annual runoff increased total and dissolved P losses and decreased P retention. Dissolved P made up a significant portion of annual loads at sites with high rates of P inputs and river TP export, with the ratio of dissolved to particulate P export increasing with crop cover, and fertilizer inputs. PP export was increased by the presence of eroding bluffs near channels that contribute high sediment loads due to human and climate-driven changes to river hydrology. Together, our results suggest that rising discharge and flow variability due to climate change and agricultural intensification coupled with high rates of P inputs will maintain elevated fluvial P export from non-point source inputs into the future. Without appropriate management efforts aimed at reducing both soluble P losses and stream bank erosion, reversal of water quality degradation toward meeting realistic goals will be difficult to achieve.

6.2 Landscape Features and Biogeochemical Processes Modify River Phosphorus Transport in Intensively Managed Watersheds (Dolph et al. In revision, and Appendix II)

Abstract
Phosphorus (P) transport through river networks is complex because of diverse sources and complex transformations between dominant forms (i.e., dissolved vs particulate), mediated by multiple biogeochemical and physical processes. Understanding controls of P movement through watersheds is essential for improved landscape management in intensively managed regions. Here, we analyze total, dissolved and particulate P dynamics at daily to annual scales for 104 gaged river sites to understand the role of landscape features and climate variability in determining P transport in agriculturally-dominated watersheds of Minnesota, USA. We supplemented these analyses with detailed water chemistry data collected from spatially extensive sampling of 176 stream and river sites, to better understand the effects of biological processes on instream P. Our analyses demonstrate that P concentration-discharge relationships are mediated by diverse factors including near-channel sediment sources, lake interception, anoxic release of dissolved P under low flow conditions, and assimilation by algal P. The majority of gaged sites exhibited mobilizing behavior for all forms of P at event (i.e., daily) time scales, and chemostatic or chemodynamic behavior at annual time scales. However, one third of sites showed weak to strong mobilizing behavior for dissolved P even at annual scales, suggesting spatial heterogeneity in dissolved P sources in many agricultural landscapes. Our findings indicate that P transport behavior can exhibit diverse patterns across watersheds, seasons and flow conditions. Implementation of management practices to control P losses must therefore be guided by understanding of local landscape and climate conditions.

6.3 Sediment as a modulator rather than a primary source of phosphorus transport and fate in the Le Sueur River Basin, Minnesota (Baker et al. In review, and Appendix III)

Abstract
Intensive agricultural land use in the upper Midwestern United States has led to widespread degradation of aquatic ecosystems from excess sediment and phosphorus (P). Soil erosion is often assumed to be a major source of P, with management targeting sediment reduction as a means to also decrease P loads. However, sediments vary widely in their P content and reactivity due to glacial history, landscape evolution, and land use. Associations between sediment and P are thus complex, yet important for understanding outcomes of land use, management and climate change in agricultural regions. To understand the role of sediment in influencing P dynamics, we explore these associations in the Le Sueur River basin in southern Minnesota, which has among the highest yields of sediment and P of Midwestern watersheds. We used a mass balance for sediment-derived P to explore sources and loading rates, and incorporated sediment P-sorption data to estimate the portion of total P load formed via in-stream transformations. The mass balance revealed that only 24% of the total P load exiting the basin could be attributed to source sediment. Further, the results suggest that sorption of dissolved P to sediment masked the dissolved P inputs to the river, reducing the fraction of total P observed as dissolved P at the basin outlet by as much as 31%. These findings highlight the need for better understanding of dissolved P source and transport mechanisms as well as the dynamics of P as it moves between particulate (bound) and dissolved (bioavailable) forms.

7.0 References

Appling, A. P., M. C. Leon, and W. H. McDowell. 2015. Reducing bias and quantifying uncertainty in watershed flux estimates: the R package loadflex. Ecosphere 6(12):269. http://dx.doi.org/10.1890/ES14-00517.1

Baker, D. B., L. T. Johnson, R. B. Confesor, and J. P. Crumrine. 2017. Vertical Stratification of Soil Phosphorus as a Concern for Dissolved Phosphorus Runoff in the Lake Erie Basin. Journal of Environmental Quality 46:1287-1295.

Baker, A., J.C. Finlay, K. Gran et al. 2019. Le Sueur River Basin Sediment Characterization - chemical and physical properties of sediments collected 2015-2018. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/zbm3-9d68. Accessible at https://conservancy.umn.edu/handle/11299/201752

Baker, A. 2018. *Phosphorus – sediment interactions and their implications for watershed scale phosphorus dynamics in the Le Sueur River Basin.* University of Minnesota Masters Thesis. Retrieved from the University of Minnesota Digital Conservancy http://hdl.handle.net/11299/201757.

Baker, A. J.C. Finlay, K.B. Gran, D.R. Engstrom, D.L Karwan, C.L. Dolph, W.S.C. Atkins, M. Muramoto-Mathieu In review. Sediment as a modulator rather than a primary source of phosphorus transport and fate in the Le Sueur River Basin, Minnesota. Water Resources Res.

Belmont, P., K. B. Gran, S. P. Schottler, P. R. Wilcock, S. S. Day, C. Jennings, J. W. Lauer, E. Viparelli, J. K. Willenbring, D. R. Engstrom, and G. Parker. 2011. Large Shift in Source of Fine Sediment in the Upper Mississippi River. Environmental Science & Technology 45:8804-8810.

Bevis, M. 2015. *Sediment budgets indicate Pleistocene base level fall drives erosion in Minnesota's greater Blue Earth River basin* University of Minnesota, Duluth. Master's Thesis. Retrieved from https://conservancy.umn.edu/handle/11299/170661

Boardman, E., J.C. Finlay, M. Danesh, E. Foufoula-Georgiou. In review. Fertilizer, landscape features and climate regulate phosphorus retention and river export in diverse Midwestern watersheds. Biogeochemistry.

Boardman E. 2016. *Nutrient dynamics in Minnesota watersheds.* University of Minnesota Masters Thesis.

Cade-Menun, B. J., G. Bell, S. Baker-Ismail, Y. Fouli, K. Hodder, D. W. McMartin, C. Perez-Valdivia, and K. Wu. 2013. Nutrient loss from Saskatchewan cropland and pasture in spring snowmelt runoff. Canadian Journal of Soil Science 93:445-458.

Cho, S. J., Wilcock, P. R., Gran, K. B., Belmont, P., Hobbs, B. F. 2017. Management Option Simulation Model (MOSM) and supporting documents. University of Minnesota Digital Conservancy. Retrieved from http://hdl.handle.net/11299/191082

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: a review. Journal of Environmental Quality 27: 261-266.

Dodd, R. J. and A. N. Sharpley. 2015. Conservation practice effectiveness and adoption: unintended consequences and implications for sustainable phosphorus management. Nutrient Cycling in Agroecosystems 104:373-392.

Dodd, R. J., A. N. Sharpley, and L. G. Berry. 2018. Organic Phosphorus Can Make an Important Contribution to Phosphorus Loss from Riparian Buffers. Agricultural & Environmental Letters 3.

Dolph, C.L., Boardman, E., Danesh-Yazdi, M., Finlay, J.C., Hansen, A.T., Baker, A.C., and Dalzell, B. in revision. Landscape features and biogeochemical processes modify river phosphorus transport in intensively managed watersheds. Water Resources Research.

Dolph, C.L., Hansen, A.T., and Finlay, J.C. 2017a. Flow-related dynamics in suspended algal biomass and its contribution to suspended particulate matter in an agricultural river network of the Minnesota River Basin, USA. Hydrobiologia 785, 127. http://doi.org/10.1007/s10750-016-2911-7

Dolph, C.L. Hansen, A.T. Kemmitt, K. L. Janke, B. Rorer, M, et al. 2017b. Characterization of streams and rivers in the Minnesota River Basin Critical Observatory: water chemistry and biological field collections, 2013-2016. Retrieved from the Data Repository for the University of Minnesota, https://doi.org/10.13020/D6FH44.

Duncan, E. W., K. W. King, M. R. Williams, G. LaBarge, L. A. Pease, D. R. Smith, and N. R. Fausey. 2017. Linking Soil Phosphorus to Dissolved Phosphorus Losses in the Midwest. Agricultural & Environmental Letters 2.

Dupas, R., G. Gruau, S. Gu, G. Humbert, A. Jaffrézic, and C. Gascuel-Odoux. 2015. Groundwater control of biogeochemical processes causing phosphorus release from riparian wetlands. Water Research 84:307-314.

Elliott, J. 2013. Evaluating the potential contribution of vegetation as a nutrient source in snowmelt runoff. Canadian Journal of Soil Science 93:435-443.

Engstrom, D.R., Almendinger, J.E., and Wolin, J.A. 2009. Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. Journal of Paleolimnology 41, 563-588. doi: 10.1007/s10933-008-9292-5

Fang, F., P.L. Brezonik, D.J. Mulla, and L.K. Hatch. 2002. Estimating runoff phosphorus losses from calcareous soils in the Minnesota River Basin. J. Environ. Qual. 31: 1918-1929.

Fang, F., P.L. Brezonik, D.J. Mulla, and L.K. Hatch. 2005. Characterization of soil algal bioavailable phosphorus in the Minnesota River Basin. Soil Sci. Soc. Am. J. 69:1016-1025.

Foufoula-Georgiou, E., Z. Takbiri, J. A. Czuba, and J. Schwenk. 2015. The change of nature and the nature of change in agricultural landscapes: Hydrologic regime shifts modulate ecological transitions. Water Resources Research 51:6649-6671.

Fox, G. A., R. A. Purvis, and C. J. Penn. 2016. Streambanks: A net source of sediment and phosphorus to streams and rivers. Journal of Environmental Management 181:602-614.

Fuka, D.R., C.A. MacAllister, A.T. Degaetano, and Z.M. Easton. 2013. Using the Climate Forecast System Reanalysis dataset to improve weather input data for watershed models. *Hydrol. Proc.* DOI: 10.1002/hyp.10073.

Gentry, L. E., M. B. David, T. V. Royer, C. A. Mitchell, and K. M. Starks. 2007. Phosphorus transport pathways to streams in tile-drained agricultural watersheds. Journal of Environmental Quality 36:408-415.

Ginting, D., J. F. Moncrief, S. C. Gupta, and S. D. Evans. 1998. Interaction between Manure and Tillage System on Phosphorus Uptake and Runoff Losses. J. Environ. Qual. 27:1403-1410.

Goyette, J. O., E. M. Bennett, and R. Maranger. 2018. Low buffering capacity and slow recovery of anthropogenic phosphorus pollution in watersheds. Nature Geoscience.

Gran, K. B., P. Belmont, S. S. Day, N. Finnegan, C. Jennings, J. W. Lauer & P. R. Wilcock, 2011. Landscape evolution in south-central Minnesota and the role of geomorphic history on modern erosional processes. GSA Today 21, 7–9.

Gran, K., C. Dolph, A. Baker, M. Bevis, T. Campbell, S.J. Cho, J. Czuba, B. Dalzell, A. Hansen, S. Kelly, Z. Lang, J. Schwenck, P. Belmont, J.C. Finlay, E. Foufoula-Georgiou, P. Kumar, S. Rabotyagov, G. Roehrig, P. Wilcock. In press. The power of environmental observatories for advancing multidisciplinary research, outreach, and decision support: the case of the Minnesota River Basin. Water Resources Research.

Grundtner, A., S. Gupta, and P. Bloom. 2014. River bank materials as a source and as carriers of phosphorus to Lake Pepin. J. Environ. Qual. 43:1991-2001.

Gu, S., G. Gruau, R. Dupas, C. Rumpel, A. Crème, O. Fovet, C. Gascuel-Odoux, L. Jeanneau, G. Humbert, and P. Petitjean. 2017. Release of dissolved phosphorus from riparian wetlands: Evidence for complex interactions among hydroclimate variability, topography and soil properties. Science of The Total Environment 598:421-431.

Hansen, A.T., Dolph, C.L., Foufoula-Georgiou, E., & Finlay, J.C. 2018. Contribution of wetlands to nitrate removal at the watershed scale. Nature Geoscience 11, 127-132. https://doi.org/10.1038/s41561-017-0056-6

Harmel, R.D., and P.K. Smith. 2007. Consideration of measurement uncertainty in the evaluation of goodness-of-fit in hydrologic and water quality modeling. Journal of Hydrology 337, 326-336. doi: 10.1016/j.jhydrol.2007.01.043

Haygarth, P. M., H. P. Jarvie, S. M. Powers, A. N. Sharpley, J. J. Elser, J. Shen, H. M. Peterson, N.-I. Chan, N. J. K. Howden, T. Burt, F. Worrall, F. Zhang, and X. Liu. 2014. Sustainable Phosphorus Management and the Need for a Long-Term Perspective: The Legacy Hypothesis. Environmental Science & Technology 48:8417-8419.

Homer, C. G., J. Dewitz, L. Yang, S. Jin, P. Danielson, G. Z. Xian, J. Coulston, N. Herold, J. Wickham, and K. Megown. 2015. Completion of the 2011 National Land Cover Database for the conterminous United States – Representing a decade of land cover change information. Photogrammetric Engineering and Remote Sensing 81:345-354.

Hupfer, M. and J. Lewandowski. 2008. Oxygen Controls the Phosphorus Release from Lake Sediments - a Long-Lasting Paradigm in Limnology. International Review of Hydrobiology 93:415-432.

Kelly, S. A., Z. Takbiri, P. Belmont, and E. Foufoula-Georgiou. 2017. Human amplified changes in precipitation–runoff patterns in large river basins of the Midwestern United States. Hydrol. Earth Syst. Sci. 21:5065-5088.

Kessler, A.C., S.C. Gupta, H.A.S. Dolliver, and D.P. Thoma. 2012. Lidar quantification of bank erosion in Blue Earth County, Minnesota. Journal of Environmental Quality. 41:197-207.

King, K. W., M. R. Williams, G. A. LaBarge, D. R. Smith, J. M. Reutter, E. W. Duncan, and L. A. Pease. 2018. Addressing agricultural phosphorus loss in artificially drained landscapes with 4R nutrient management practices. Journal of Soil and Water Conservation 73:35-47.

Kinsman-Costello, L. E., S. K. Hamilton, J. M. O’Brien, and J. T. Lennon. 2016. Phosphorus release from the drying and reflooding of diverse shallow sediments. Biogeochemistry 130:159-176.

Kusmer, A. S., J.-O. Goyette, G. K. MacDonald, E. M. Bennett, R. Maranger, and P. J. A. Withers. 2019. Watershed Buffering of Legacy Phosphorus Pressure at a Regional Scale: A Comparison Across Space and Time. Ecosystems 22:91-109.

Le, L.O. 2015. Modeling stream discharge and nitrate loading in the Iowa-Cedar River basin under climate and land use change. Ph.D. Thesis. University of Iowa. Available online at: https://ir.uiowa.edu/etd/1872

Lu, S., H.E. Andersen, H. Thodsen, G.H.Rubaek, and D. Trolle. 2016. Extended SWAT model for dissolved reactive phosphorus transpoer in tile-drained fields and catchments. Agricultural Water Management 175, 78-90. doi: 10.1016/j.agwat.2015.12.008

Madison, A. M., M. D. Ruark, T. D. Stuntebeck, M. J. Komiskey, L. W. Good, N. Drummy, and E. T. Cooley. 2014. Characterizing phosphorus dynamics in tile-drained agricultural fields of eastern Wisconsin. Journal of Hydrology 519:892-901.

McCullough, G. K., S. J. Page, R. H. Hesslein, M. P. Stainton, H. J. Kling, A. G. Salki, and D. G. Barber. 2012. Hydrological forcing of a recent trophic surge in Lake Winnipeg. Journal of Great Lakes Research 38:95-105.

Michalak, A. M., E. J. Anderson, D. Beletsky, S. Boland, N. S. Bosch, T. B. Bridgeman, J. D. Chaffin, K. Cho, R. Confesor, I. Daloğlu, J. V. DePinto, M. A. Evans, G. L. Fahnenstiel, L. He, J. C. Ho, L. Jenkins, T. H. Johengen, K. C. Kuo, E. LaPorte, X. Liu, M. R. McWilliams, M. R. Moore, D. J. Posselt, R. P. Richards, D. Scavia, A. L. Steiner, E. Verhamme, D. M. Wright, and M. A. Zagorski. 2013. Record-setting algal bloom in Lake Erie caused by agricultural and meteorological trends consistent with expected future conditions. Proceedings of the National Academy of Sciences 110:6448-6452.

Miller, R. B., G. A. Fox, C. J. Penn, S. Wilson, A. Parnell, R. A. Purvis, and K. Criswell. 2014. Estimating sediment and phosphorus loads from streambanks with and without riparian protection. Agriculture, Ecosystems & Environment 189:70-81.

Mitchell, N., K. Kumarasamy, S. J. Cho, P. Belmont, B. Dalzell, and K. Gran. 2018. Reducing High Flows and Sediment Loading through Increased Water Storage in an Agricultural Watershed of the Upper Midwest, USA. Water 10:1053.

Moriasi, D.N., J.G. Arnold, M.W. VanLiew, R.L. Binger, R.D. Harmel, and T.L. Veith. 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Transactions of the ASABE. 50(3), 885-900

MPCA. 2014. Minnesota Nutrient Reduction Strategy. Minnesota Pollution Control.

MPCA. 2015. Watershed Pollutant Load Monitoring Network (WPLMN) Standard Operating Procedures and Guidance. Minnesota Pollution Control.

Musolff, A., Schmidt, C., Selle, B., & Fleckenstein, J.H. 2015. Catchment controls on solute export. Advances in Water Resources 86, 133-146.

Peterson, H. M., L. A. Baker, D. Bruening, J. L. Nieber, J. S. Ulrich, and B. N. Wilson. 2017. Agricultural Phosphorus Balance Calculator: A tool for watershed planning. Journal of Soil and Water Conservation 72:395-404.

Powers, S. M., T. W. Bruulsema, T. P. Burt, N. I. Chan, J. J. Elser, P. M. Haygarth, N. J. K. Howden, H. P. Jarvie, Y. Lyu, H. M. Peterson, A. N. Sharpley, J. Shen, F. Worrall, and F. Zhang. 2016. Long-term accumulation and transport of anthropogenic phosphorus in three river basins. Nature Geosci 9:353-356.

Powers, S. M., D. M. Robertson, and E. H. Stanley. 2014. Effects of lakes and reservoirs on annual river nitrogen, phosphorus, and sediment export in agricultural and forested landscapes. Hydrological Processes 28: 5919-5937.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman. 2002. Gulf of Mexico hypoxia, aka "The dead zone". Ann. Rev. Ecology and Systematics 33:235-263.

Roberts, W. M., M. I. Stutter, and P. M. Haygarth. 2012. Phosphorus Retention and Remobilization in Vegetated Buffer Strips: A Review. Journal of Environmental Quality 41:389-399.
Sands, G.R., I. Song, L.M. Busman, and B.J. Hansen. 2008. The effects of subsurface drainage depth and intensity on nitrate loads in the northern cornbelt. Trans. ASABE. 51(3): 937-946.
Schottler, S., P., J. Ulrich, P. Belmont, R. Moore, J. W. Lauer, D. Engstrom, R., and J. Almendinger, E. 2013. Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes 28:1951-1961.
Sekely, A. C., D. J. Mulla, and D. W. Bauer. 2002. Streambank slumping and its contribution to the phosphorus and suspended sediment loads of the blue earth river, minnesota. Journal of Soil and Water Conservation 57:243-250.
Sharpley, A., H. P. Jarvie, A. Buda, L. May, B. Spears, and P. Kleinman. 2013. Phosphorus Legacy: Overcoming the Effects of Past Management Practices to Mitigate Future Water Quality Impairment. Journal of Environmental Quality 42:1308-1326.
Sharpley, A. N., P. J. A. Kleinman, A. L. Heathwaite, W. J. Gburek, G. J. Folmar, and J. P. Schmidt. 2008. Phosphorus Loss from an Agricultural Watershed as a Function of Storm Size. J. Environ. Qual. 37:362-368.
Smith, D.R., K.W. King, L. Johnson, W. Francesconi, P. Richards, D. Baker, and A.N. Sharpley. 2015. Surface runoff and tile drainage transport of phosphorus in the Midwestern United States. Journal of Environmental Quality. 44, 495-502. doi:10.2134/jeq2014.04.0176
Søndergaard, M., Peder Jensen, J., & Jeppesen, E. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. Hydrobiologia 506-509, 135-145.
Stuntebeck, T. D., M. J. Komiskey, D. W. Owens, and D. W. Hall. 2008. Methods of data collection, sample processing, and data analysis for edge-of-field, streamgaging, subsurface-tile, and meteorological stations at Discovery Farms and Pioneer Farm in Wisconsin, 2001. 51 p.
Satchithanantham, S., B. English, and H. Wilson. 2018. Seasonality of Phosphorus and Nitrate Retention in Riparian Buffers. Journal of Environmental Quality 10.2134/jeq2018.07.0280
Thomas, I. A., P. E. Mellander, P. N. C. Murphy, O. Fenton, O. Shine, F. Djodjic, P. Dunlop, and P. Jordan. 2016. A sub-field scale critical source area index for legacy phosphorus management using high resolution data. Agriculture, Ecosystems & Environment 233:238-252.
Thompson, S.E., Basu, N.B., Jascurain, J., Aubeneau, A., & Rao, P.S.C. 2011. Relative dominance of hydrologic vs biogeochemical factors on solute export across impact gradients. Water Resources Research 47, W00J05. doi:10.1029/2010WR009605.
USGS, 2017. Watershed Boundary Dataset. United States Geological Survey, Washington, D.C. Accessed 7-25-2018. https://water.usgs.gov/GIS/huc.html
USGS. 2004. Load Estimator (LOADEST): A FORTRAN program for estimating constituent loads in streams and rivers. Techniques and Methods Book 4, Chapter A5. United States Geological Survey, Washington D.C.
Vadas, P.A., and M.J. White. 2010. Validating soil phosphorus routines in the SWAT model. Trans. ASABE. 53(5): 1469-1476.

Vaughan, A. A., P. Belmont, C. P. Hawkins, and P. Wilcock. 2017. Near-Channel Versus Watershed Controls on Sediment Rating Curves. Journal of Geophysical Research: Earth Surface 122:1901-1923.

Ward, A., A. Sharpley, K. Miller, W. Dick, J. Hoorman, J. Fulton, and G. A. LaBarge. 2018. An assessment of in-field nutrient best management practices for agricultural crop systems with subsurface drainage. Journal of Soil and Water Conservation 73:5A-10A.

Wilcock, P. R., Cho, S. J., Gran, K. B., Hobbs, B. F., Belmont, P., Bevis, M., et al. 2016. CSSR: Collaborative for Sediment Source Reduction Greater Blue Earth River Basin, Final Report. Minneapolis, MN.

Withers, P. J. A. and H. P. Jarvie. 2008. Delivery and cycling of phosphorus in rivers: A review. Science of The Total Environment 400:379-395.