CUMULATIVE EFFECTS MONITORING

IN THE TOBACCO CREEK WATERSHED

JOSEPH CULP, UNIVERSITY OF NEW BRUNSWICK; CANADIAN RIVERS INSTITUTE AND
HOWARD WHEATER, UNIVERSITY OF SASKATCHEWAN; GLOBAL INSTITUTE FOR WATER SECURITY

Canadian Water Network

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Lakes and rivers around the world are deteriorating as a result of increased algal blooms, fish kills and impaired water quality. Lake Winnipeg and its associated river network is no exception. Covering an area of approximately 1000 km^2, the Tobacco Creek Model Watershed contains Tobacco Creek and its tributaries, which flow through thousands of acres of highly productive agricultural lands and ultimately into Lake Winnipeg. Agricultural activities can be a significant source of nutrients to adjacent streams and ultimately to downstream lakes.

In 1984, local landowners and farmers in the watershed formed the Deerwood Soil and Water Management Association. Since then, they have installed numerous beneficial management practices (BMPs) in partnership with government and monitored their effectiveness. Subsequently, the South Tobacco Creek Project was established in the headwaters of the Tobacco Creek Model Watershed on the Manitoba Escarpment. Since then, research led by Agriculture and Agri-food Canada and Environment Canada has come to represent one of the most significant research efforts on agricultural BMPs globally.

In recognition of the need to understand the effects of BMPs at the broader landscape scale and in the Lake Manitoba Plain in particular, the Tobacco Creek Model Watershed (TCMW) was formed. The TCMW is a partnership of farmers, community members, scientists, government agencies and the agriculture industry with a shared goal of generating agronomically practical ways to enhance water quality.

Intensive water quality and stream flow monitoring over the past three decades has provided knowledge about the drivers of water quality degradation in Lake Winnipeg. Expanding this research beyond South Tobacco Creek is needed, including monitoring to establish baseline conditions of streamflow and water quality in the lower sections of Tobacco Creek.

Additionally, monitoring of biotic indicators throughout the watershed has been lacking. These indicators are widely used to ascertain change in the health of rivers because they integrate impacts of nutrients over large temporal and spatial scales, providing a comprehensive understanding of the status of the ecosystem. Biotic conditions in streams can serve as an early detection system for biotic changes (such as algal blooms in downstream lakes) which can take decades to show the effects of excessive nutrient additions.

As a result, two concurrent research projects were undertaken to:

- Develop biotic indicators that reflect ecosystem health
- Collect baseline data on biotic indicators, water chemistry, sediment nutrient processing and hydrology
- Develop predictive models and support understanding of BMP efficacy

Predictive models not only support understanding of current conditions, but allow numerical experimentation, or the ability to ask what-if questions about how enhanced storage might affect flood risk, how altered tillage affects hydrology, and how BMPs might be arranged in the landscape to obtain maximum benefit.

The results of this research are being used (and will continue to be used) to assess the effects of existing and future BMPs implemented within the watershed, inform design of monitoring programs for hydrology, aquatic chemistry, and biotic integrity, and to support management decisions aimed at remediating and protecting Lake Winnipeg and other prairie water bodies.

PROJECT A:

DEVELOPMENT OF AQUATIC INDICATORS TO DIAGNOSE CUMULATIVE EFFECTS FROM LAND USE

GLENN BENOY, ROBERT BRUA, PATRICIA CHAMBERS, JOSEPH CULP, AND ADAM YATES

Research conducted 2012-2014

WHY DID WE DO THIS RESEARCH?

Environmental health in the Tobacco Creek Model Watershed has been monitored over the past 20 years. The region contains several long-term chemical and flow monitoring sites, including a network of sites within the headwaters of South Tobacco Creek. Although this monitoring activity has provided excellent baseline information on water chemistry and flow, biological indicators of ecosystem health have not been assessed to date. This research project developed and applied biological indicators of ecological condition to the watershed, and at a larger spatial scale to the Red River Valley.

This baseline biological data can be used to assess the current environmental impacts of agriculture on these ecosystems. Additionally, these indices will allow monitoring and assessment of cumulative effects associated with both natural processes and agricultural management practices across multiple spatial and temporal scales. Evaluation and validation of bioindicators as diagnostic tools will help identify potential environmental drivers of ecological condition.

HOW WAS THE RESEARCH CONDUCTED?

The research team established a series of sampling sites positioned from the headwaters to the mouth of Tobacco Creek, along with sites located within other major sub-catchments of the southern Manitoba portion of the Red River Valley (Figure 1). Past research has demonstrated that several biotic indicators are appropriate for assessing cumulative impacts, including the diversity of benthic macroinvertebrate communities and the ecosystem metabolism process, gross primary production (i.e., a measure of plant growth). A suite of biotic indicators were measured at these sites over three seasons (spring, summer, autumn) to detect and diagnose the cumulative effects of land use practices on these prairie streams. We also assessed the use of two new indicators: aquatic plant size and shape, and crayfish metabolomics. This report focuses on results related to benthic macroinvertebrate and ecosystem metabolism bioindicators.

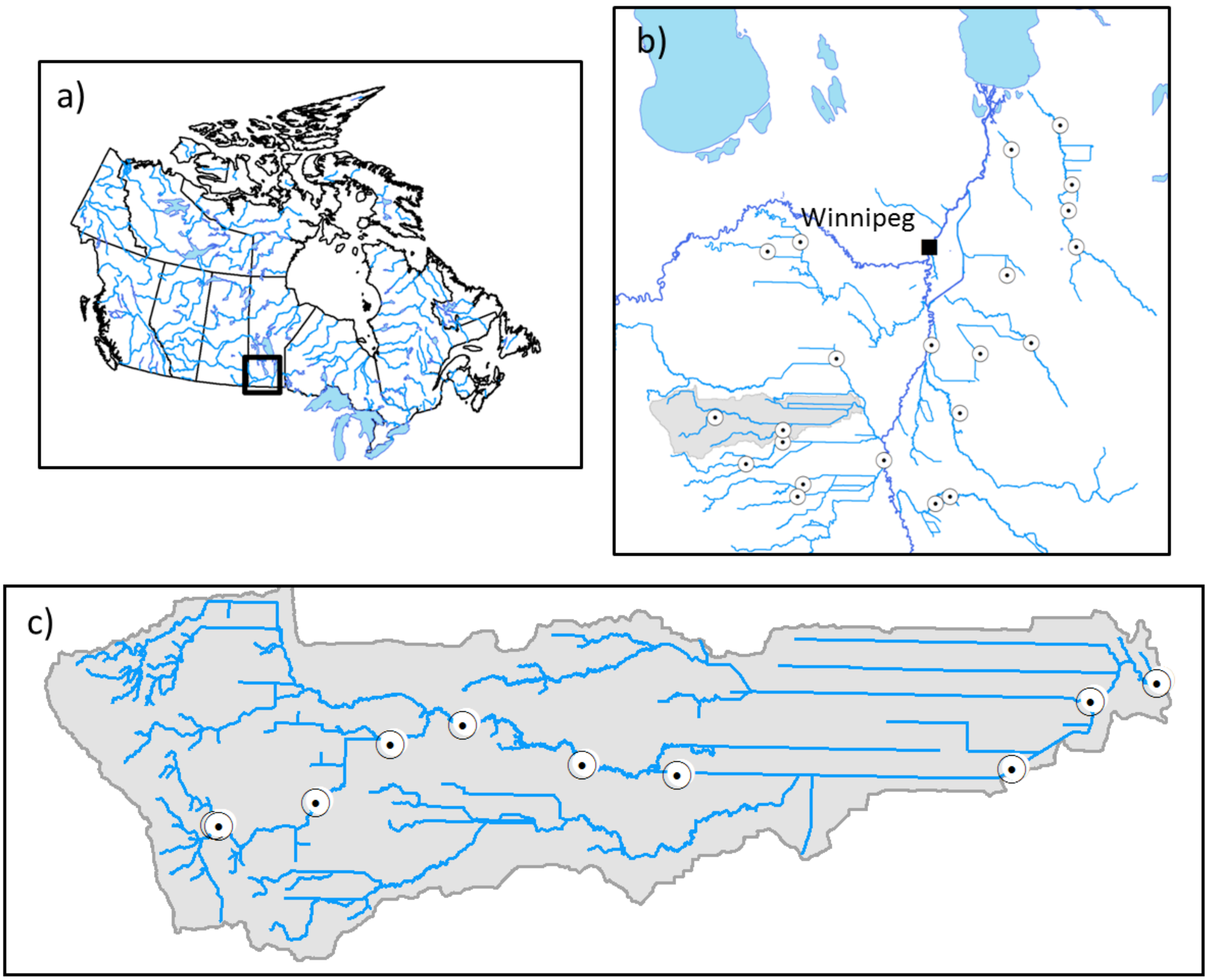

Figure 1. Location of the studied area in Southern Manitoba (a) and associated sampling sites in the Red River Valley (b) in relation to location of the Tobacco Creek Watershed (grey area) and the sampling network used to assess baseline conditions in Tobacco Creek (c).

In cumulative effects monitoring, a good indicator varies predictably across a gradient of environmental stressors in such a way that it accurately and sensitively reflects changes in ecological health. These indicators should be tested across the spatial and seasonal range of potential exposure to human activities of interest to determine the range of indicator values. The seasonal sampling conducted by the research team coincided with time periods when different management activities occur (e.g., cultivation, fertilization and wastewater treatment lagoon discharge). Specific details and guidance for the sample methods are documented in a stream biomonitoring users guide developed for the project. The wide range of human activities (Figure 2) used in this study provided information on the capacity of the indicators to diagnose the cause of effects as well as information on the ecological condition of sites in the watershed relative to other sites throughout the Red River Valley.

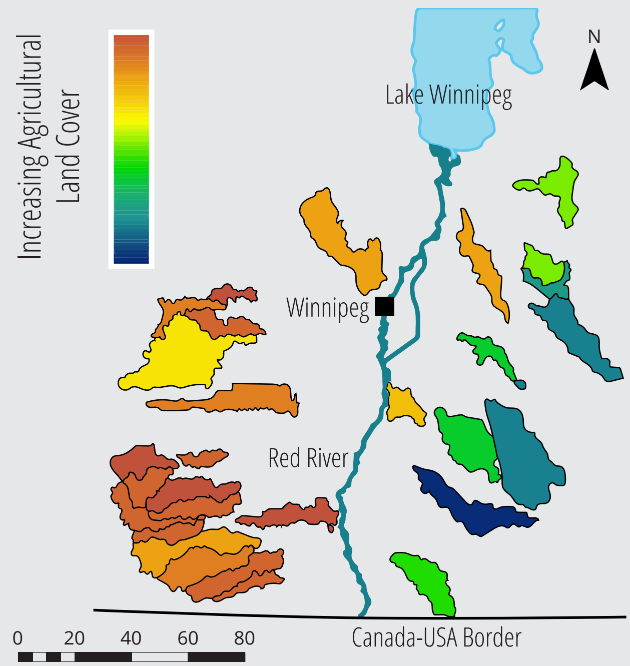

Figure 2. Map showing the relative amount of agricultural activity in study streams of the Red River Valley region.

WHAT WERE THE RESULTS?

There was substantial variation in the current ecological health conditions of Tobacco Creek, depending on the location of sampling and the season. Drier summer and autumn seasons showed strong differences (described below) from the wetter, spring season. Two of the indicators — aquatic invertebrate community composition (measured as the percent of the community made up of mayflies, stoneflies and caddisflies) and stream metabolism (measured as gross primary production) were particularly sensitive to these seasonal changes in stream condition (Figure 3). Both indicators clearly identified differences between sampling locations within 40 km of the headwaters of Tobacco Creek, compared to those more than 60 km away. For example, gross primary production was on average four times greater in some downstream locations and the amount of insects intolerant to pollution was greatest at the most upstream sites.

The ecological conditions in Tobacco Creek were in similar condition to other similarly-sized rivers throughout the Red River Valley region exposed to significant amounts of agricultural activity (Figure 4). However, ecological conditions in Tobacco Creek appear to deteriorate as one travels downstream from the creek's origins in the Manitoba escarpment. In sites across the Red River Valley, regional differences in ecological conditions were associated with the percentage of the stream catchment used for agriculture. Conditions decline if more than 50% of the catchment is used for agriculture.

Deterioration of the same indicators were also associated with the increased size of sewage lagoons discharging municipal wastewater to streams, suggesting that these activities, along with agriculture land use, cumulatively impact the ecological conditions in streams within the Red River Valley.

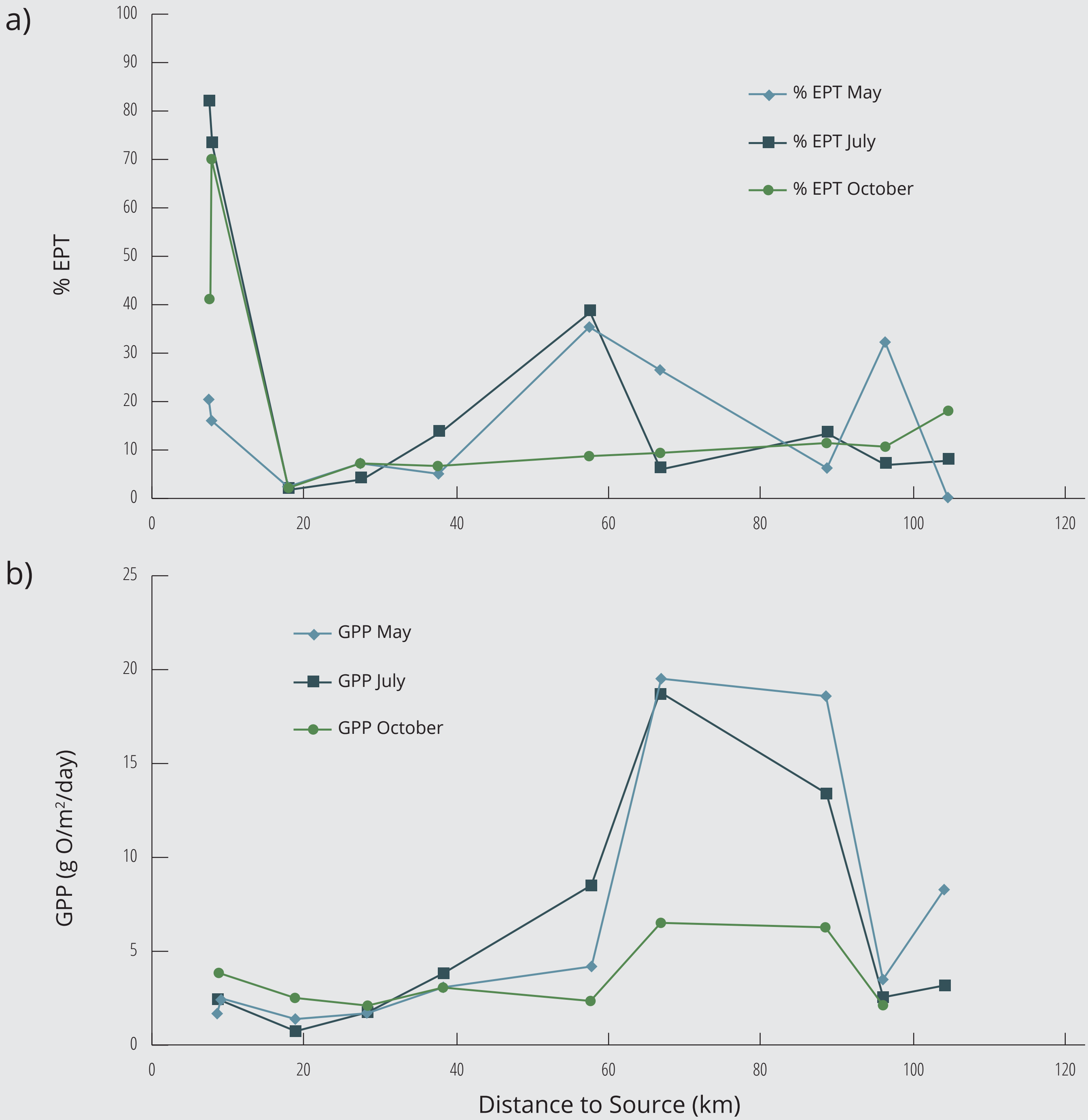

Figure 3. Ecological conditions along Tobacco Creek as indicated by the percentage of aquatic invertebrates consisting of mayflies, stoneflies and caddisflies (%EPT) and the amount of gross primary production (GPP) for samples collected in May, July and October.

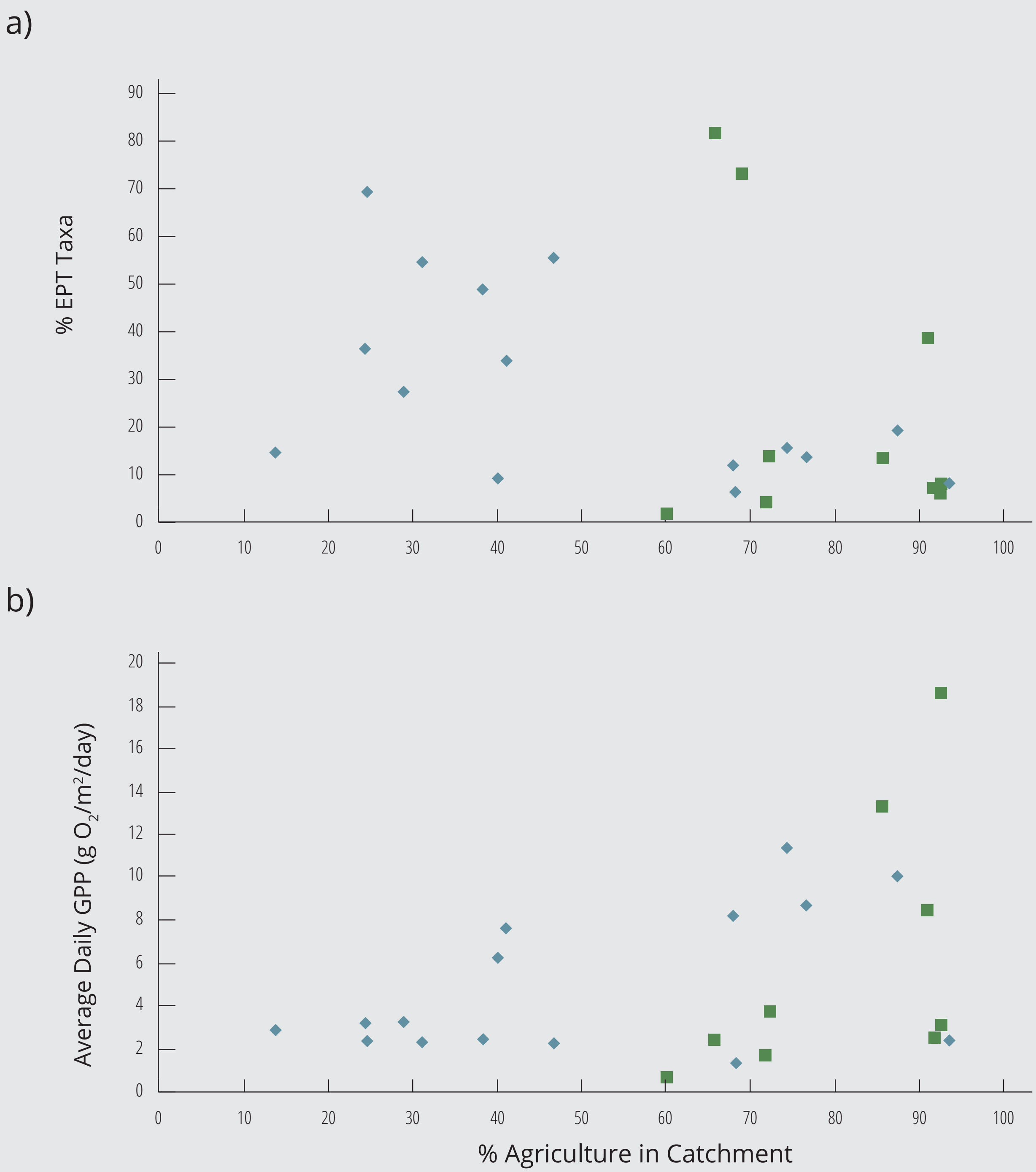

Figure 4. Comparison of ecological conditions in Tobacco Creek (green squares) to other streams in the Red River Valley (blue diamonds) as indicated by the percentage of mayflies, stoneflies and caddisflies (%EPT) and the amount of gross primary production (GPP) in relation to the percentage of land in the stream catchment used for agriculture.

WHAT DO THESE FINDINGS MEAN?

Deterioration of Lake Winnipeg water quality galvanized research activities across governments, academia, and agricultural producer and watershed stewardship organizations. This project adds to this body of knowledge, emphasizing the development and evaluation of biological indicators of cumulative effects for use by the Tobacco Creek Model Watershed Consortium and other end users of the knowledge, data and decision support tools generated through this project.

The monitoring framework uses biological indicators to assess the cumulative effects of both natural processes and human activities on aquatic biota. Baseline data from the project augments existing historical information and fills gaps where no data existed. Bioindicators that were associated with human activities were also identified, such as the %EPT that was negatively associated with percent agriculture within the watershed. Similarly, stream metabolism could detect the addition of nutrients from municipal lagoon releases. Future biological sampling would include annual sampling of benthic macroinvertebrates during autumn, as well as stream metabolism measurement in summer to detect the effectiveness of best management practices aimed at reducing nutrient loadings to streams during runoff events.

The indicators developed through this project contribute important approaches to the monitoring and assessment toolbox for streams in the Red River Valley region. This toolbox, together with the collected baseline data, will assist the TCMW Consortium, provincial and federal agencies, local conservation districts and stewardship organizations to better detect and manage changes in the health of streams in the region. Future assessments could use these indicators to determine the relative importance of the various human impacts (e.g., agriculture versus input from sewage effluent) on river health.

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CANADIAN RIVERS INSTITUTE

CANADIAN WATER NETWORK

ENVIRONMENT CANADA

PROJECT B: MONITORING AND ASSESSMENT OF BENEFICIAL MANAGEMENT PRACTICES

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Research conducted 2012-2014

WHY DID WE DO THIS RESEARCH?

Within Lake Winnipeg and many other water bodies in Canada, a summer swim can mean diving into water that looks like cool pea soup. Excessive algal growth (i.e., eutrophication) is caused by increased concentrations of nutrients in the water from urban and agricultural sources (see Figure 1). To prevent eutrophication, advanced treatment of wastewater is required, as well as on-farm solutions to decrease nutrient runoff, particularly during snowmelt, which is the dominant period of runoff and nutrient export in the prairies. Cold, flat, and dry conditions in the prairies pose unique challenges with respect to nutrient management, as well as flood and drought risk.

Beneficial management practices (BMPs) are land use practices intended to reduce environmental risk. Although all jurisdictions across Canada encourage their use and billions have been invested in their implementation, there has been surprisingly little research addressing their efficacy. New tools are needed to assess the effectiveness of BMPs and to understand where in the landscape different practices will be most advantageous. Although farm nutrient inputs and outputs in Tobacco Creek are close to balanced (Figure 2), the relatively small amount of nutrient runoff in terms of farm budgets can have a large effect on downstream ecology.

Figure 1. Algal bloom on Buffalo Pound Lake (Regina and Moose Jaw's drinking water source)

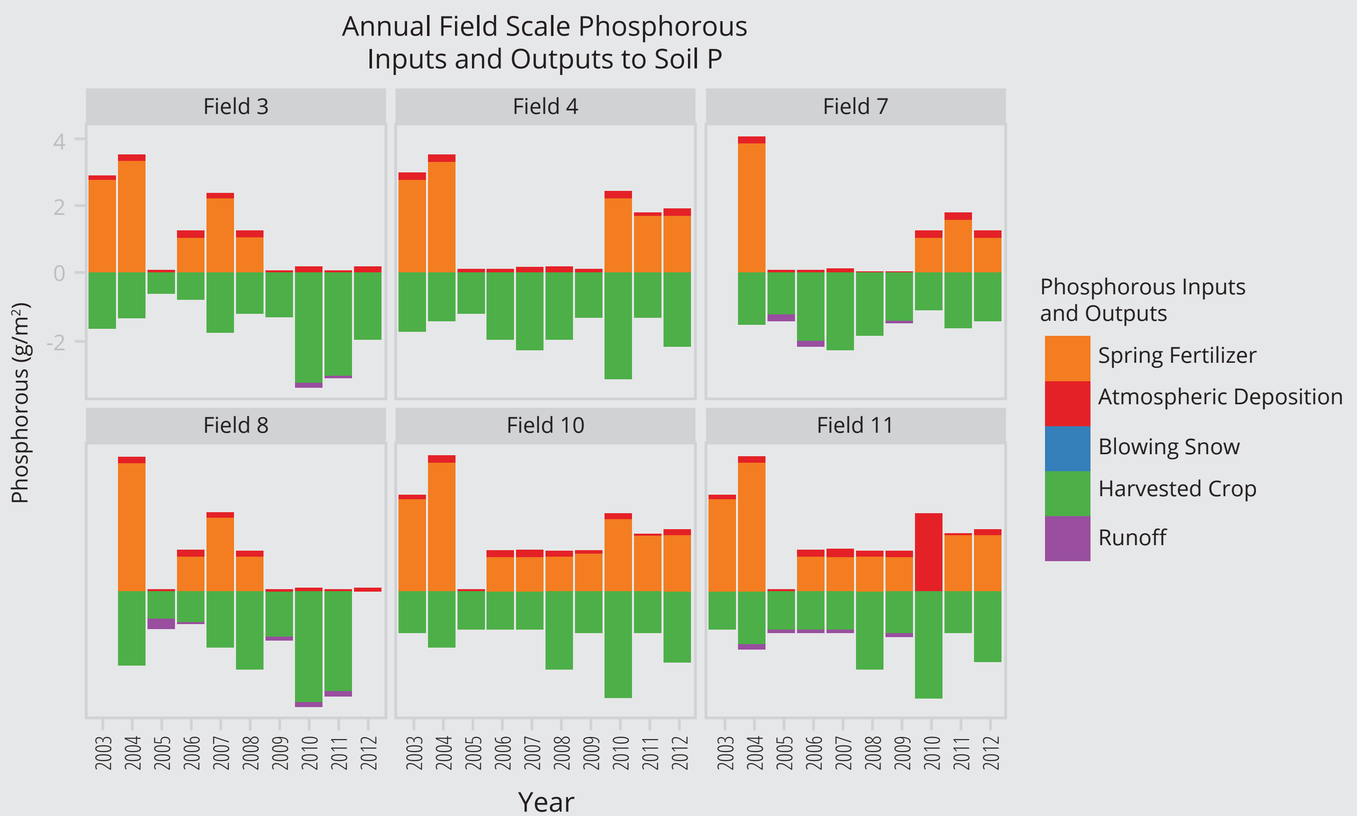


Figure 2. Field scale phosphorus inputs and outputs. Analyses by Jen Roste, data courtesy of Agriculture & Agri-Food Canada, and Environment Canada.

HOW WAS THE RESEARCH CONDUCTED?

A group of landowners and scientists have been working for more than a decade in the South Tobacco Creek Model Watershed (TCMW) to better understand BMP effectiveness. This program built upon past work assessing BMP effectiveness by installing and monitoring BMPs at a broader spatial scale, and in low-relief areas characteristic of much of the prairies. The objectives of the program were to:

- Better characterize prairie hydrology — the primary determinant of nutrient fluxes
- Improve capacity for modelling hydrology and nutrient fluxes
- Examine the use of headwater dams as a BMP to help guide its further application

Mathematical modelling was used as a tool to better understand watershed conditions, how BMPs might affect them, and how effects could be detected by a monitoring program. The group wanted to better understand climatic variability as a determinant of runoff and nutrient export, as recent wet conditions have been implicated as one driver of high nutrient loads and degraded ecosystem health in Lake Winnipeg.[1]

WHAT WERE THE RESULTS?

PRAIRIE HYDROLOGY, MODELLING AND NUTRIENT FLUXES

Interannual climatic variability is a critical determinant of runoff and nutrient export. Snowmelt tends to dominate runoff and nutrient export. However, during wet summers in 2002, 2005, 2011 and 2013, rainfall runoff exceeded snowmelt runoff, and in some cases, rainfall was also responsible for a larger fraction of nutrient transport. Important thresholding behavior is shown in rainfall runoff, with three distinct results ranging from no runoff to extreme runoff based on the fractional contribution of heavy rainfall days (Figure 3).

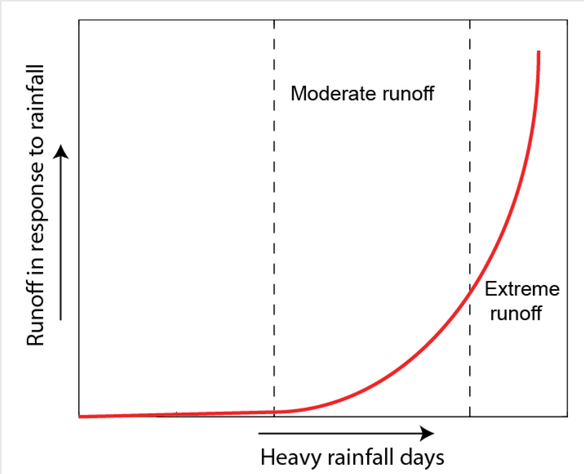


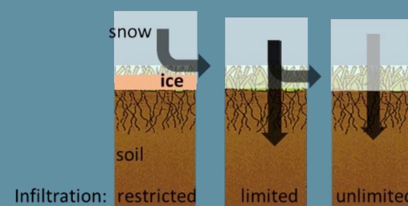
Figure 3. Annual rainfall runoff in the South Tobacco Creek Watershed as a function of the fractional contribution of heavy rainfall days (>25mm) to summer rainfall[4]

Minimum tillage and forages are BMPs that leave vegetation in the field throughout the year; these practices are aimed at reducing soil erosion and maintaining soil organic carbon. This vegetation is associated with significant leaching of nitrogen and phosphorus to meltwater runoff (Figure 4). These processes are not adequately represented using typical modelling approaches, but require further research to develop a satisfactory algorithm.

Given the importance of snowmelt to nutrient export, the highest priority in modelling prairie hydrochemistry should be placed upon improving representation of snowmelt nutrient transport. Key factors that need to be considered include the effects of restricted infiltration on soil-water interaction and nutrient uptake, the effects of frozen soils on erodability, the importance of microscale topography in dictating flowpaths, time and soil-water interactions.

KEY POINTS FOR HYDROCHEMICAL MODELLING:

- Runoff from frozen soils is controlled by the infiltrability of the soil. There appears to also be an effect on nutrient chemistry, with runoff from years with restricted infiltration more closely reflecting snowpack chemistry than years with unlimited infiltration.



- Nutrient exports are snowmelt-dominated. Phosphorus and nitrogen export is dominated by dissolved forms derived from soil, atmospheric deposition to snow and vegetation.
- Reduced tillage practices and forages leave vegetation on the fields through winter that is an important source of dissolved nutrients. More work is required to characterize controls on leaching to the snowpack and later transport.
- Hydrological modelling and nutrient transport modelling in cold regions at a field scale and hourly timestep is a challenging, data-intensive exercise. Nonetheless, given the short-duration of runoff in the prairies, hydrological monitoring and modelling with high temporal intensity is required. The timescale of nutrient monitoring can be optimized reflective of the relatively low degree of variation in chemical concentrations with respect to variation in flows.
- Runoff-nutrient concentration relationships vary between snowmelt, rain on snow, and rainfall runoff. This indicates that distinct modelling approaches are required to represent key processes.

HEADWATER DAMS: A SUCCESSFUL BMP IN A PRAIRIE LANDSCAPE

Small headwater dams have been identified as a useful BMP to reduce flood risk and decrease downstream transport of nitrogen, phosphorus and sediments.[2] Design and siting determine their efficacy in flood control and may also impact the permanence of nutrient and sediment storage. Although sediments across the watershed show a high potential to sorb phosphorus, dams show a greater capacity for denitrification than stream pools.

Higher denitrification rates were linked to near-ideal sediment conditions in dams, associated with lower dissolved oxygen concentrations and higher organic carbon in sediments. Dams did not have higher capacity to sorb phosphorus than stream sediments. Instead, site chemistry such as calcium and magnesium concentrations, as well as the proportion of fine sediments (i.e., clay and silt) dictated the amount of phosphorus bound to sediments under equilibrium conditions.

75% of measurements indicated sediments were a net sink of phosphorus from the water column

100x Factor by which denitrification rates in reservoirs exceeded denitrification rates in stream pools

49% of measurements indicated that denitrification was nitrate-saturated[3]

Higher calcium concentrations in areas off the Manitoba escarpment were associated with lower equilibrium phosphorus concentrations. Sediments off the escarpment have a higher capacity to sorb phosphorus, which emphasizes the point that local conditions will be important in dictating BMP efficacy.

Dams showed a greater ability to respond to higher nitrate concentrations. However, the results suggested that large areas of the watershed were suffering from nitrate saturation. Concentrations were sufficiently high that microbes could not further increase their rates of denitrification. This is considered an indicator of poor ecosystem health.

Headwater dams have also been installed to help mitigate flooding, a frequent occurrence during snowmelt. Although these dams have been demonstrated to reduce peak flows, our modelling results suggest that localized flood mitigation benefits have minimal impact in downstream areas of the catchment. Although local farmers may see some benefit, the storage capacity of the ~50 existing headwater dams in the South Tobacco Creek catchment is not sufficient to mitigate flooding in the lower watershed. Herein lies a key tradeoff in BMP design (Figure 5): The installation of additional dams to increase storage capacity without sacrificing large areas of productive lands necessitates that future dams be deep. However, deep dams would have lesser sediment-water interactions, which are believed to be key to nutrient retention.

Benefits of dams (in blue) may be in opposition. For example, flood control benefits may be maximal with deep dams, but sediment processes contributing to nutrient retention may be maximal within shallow dams. Potential costs of dams (in purple) also merit consideration.

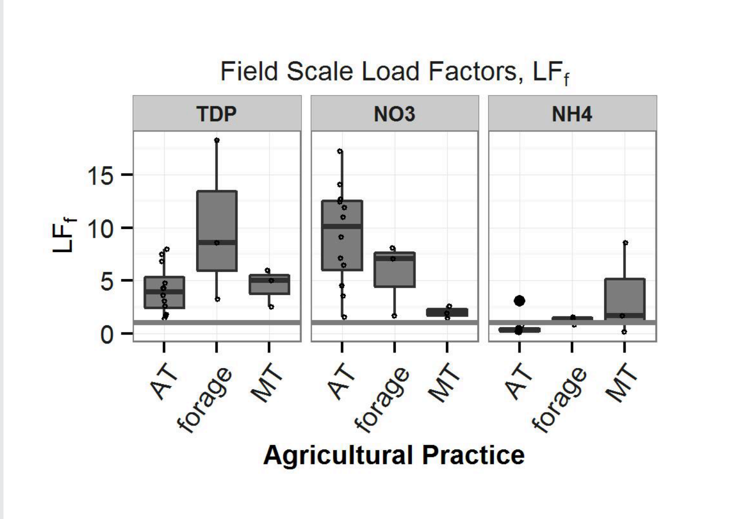


Figure 4. Load factors for different management practices. A load factor is defined as the ratio of meltwater solute to snowcover solute (by mass). AT refers to annually tilled, MT refers to no tillage disturbance. Data courtesy of Agriculture and Agri-Food Canada, and Environment Canada.

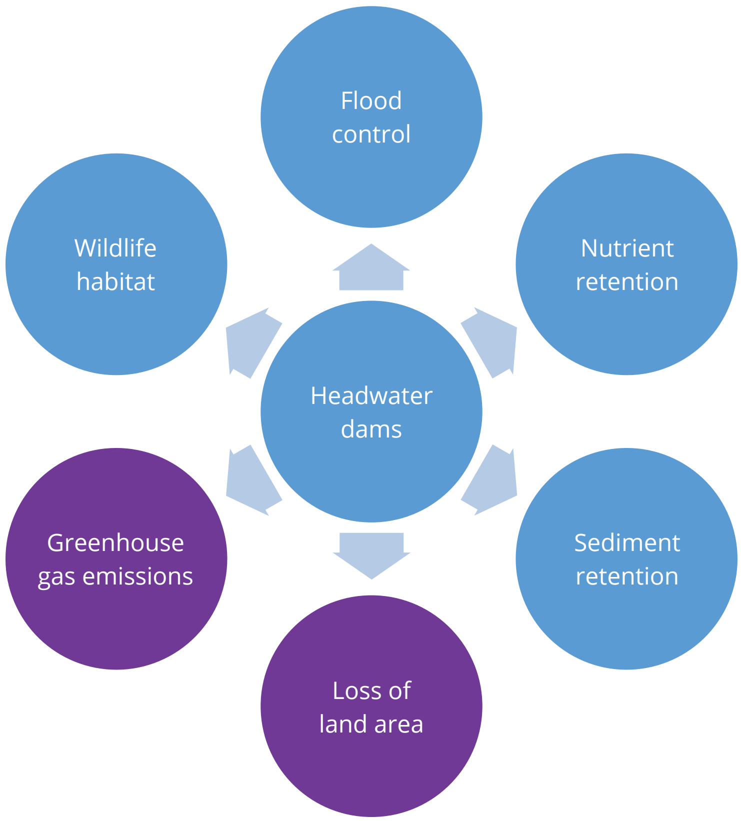


Figure 5. Tradeoffs in dam design and siting.

SUMMARY OF TOBACCO CREEK MODEL WATERSHED MONITORING RECOMMENDATIONS

- Nutrient loads and concentrations in the Canadian prairies depend on complex cold region hydrological processes. To understand and model these process controls requires comprehensive hydrological as well as water quality monitoring. For example, convective storms can only be quantified with a high density of rainfall gauges. Our recommendation is an additional 20 gauges in the upland, 20 in the lowland, and 10 along the escarpment.

- Because individual years can show very different behavior, multiple years of comprehensive observations are required for a monitoring system to capture the natural variability in response.

- Nutrient concentrations show high spatial variability, and can exhibit different behavior at different scales. It is important to monitor in sufficient detail both at field scale (to capture hydrological and nutrient states and fluxes) and at nested catchment scales (to determine the spatial integration of response and channel controls on nutrient response). The escarpment is a critical feature in understanding nutrient fluxes at Tobacco Creek. Monitoring work at scales that are unimpacted by the escarpment (i.e., above, or below in small catchments like individual drains) is required to isolate the effects of changes in land management.

- Snowmelt nutrient concentrations show low variability as compared to hydrology for the field-scale sites studied. This suggests cost savings can be attained by reducing sampling frequency with limited effects on estimates of nutrient export. This does not apply to rainfall generated response. However, additional years of data are required to confirm this result.

- If testing BMP efficacy is the goal, then monitoring programs should focus on a small-scale comparative approach, where business-as-usual or reference subwatersheds are compared to experimental watersheds where BMPs are installed. This helps control for the impact of variable hydrology, if watersheds that are similar in other attributes like slope, soils, land uses can be identified. Because eutrophication control necessitates reduced loads at the scale of the largest catchments, and complex spatial dynamics may lead to surprises in terms of net results, monitoring at the larger watershed scale would be beneficial, particularly as the aggregate response of BMPs has received little attention through monitoring or analysis. A paired approach may be best, where small scale efficacy can be assessed, combined with larger scale research to understand aggregate impacts of all activities in the watershed.

- Nutrient sensors are a valuable tool in developing accurate estimates of short-term changes in nutrient concentration. However, the flashy hydrology of the prairies contributes to significant risk in their deployment.

- While changes in loads and concentrations are the factor of greatest interest in efforts to mitigate eutrophication, insights into ecosystem health and attenuation capacity can be gained with other lower-cost indicators. Tests for nitrate-saturation are a sensitive indicator reflective of human activities. Sediment equilibrium phosphorus concentrations are too heavily impacted by variable geology to reliably reflect human activities.

- Data integrity at the existing Environment Canada monitoring stations has been compromised in recent years and there is significant risk in relying on these data. Options to develop parallel systems will need to be explored.

- Where BMPs are of interest in terms of hydrological effects and effects on water chemistry, detailed data regarding stubble height and residues is required.

- Snow survey distances should be extended. Current 125 m transects show evidence of autocorrelation.

- Dry deposition/wet deposition data is lacking and/or sparse in the prairies. This is critical in understanding lake nutrient budgets and may be important at the catchment scale, particularly for snowmelt.

- Gravimetric soil moisture measurements in fall are required to constrain hydrological models and understand snowmelt infiltration/runoff.

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FUNDING

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GLOBAL INSTITUTE FOR WATER SECURITY

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