Red-Assiniboine Basin SPARROW Model Development Technical Document

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i) Executive Summary

Many watersheds straddle the border between Canada and the United States. Through the International Joint Commission's (IJC) International Watersheds Initiative (IWI), the Spatially-Referenced Regressions on Watershed attributes (SPARROW) model, developed by the US Geological Survey (USGS), was applied to the binational Red and Assiniboine River basins, which span portions of Manitoba, Saskatchewan, Minnesota, North Dakota and South Dakota. The impetus for this novel application was to better understand and quantify the sources of nutrients, in particular phosphorus, that contribute to the eutrophication of Lake Winnipeg.

Led by the IJC, an international team was assembled for the project, including researchers from the National Research Council of Canada (NRC), Environment Canada, Agriculture & Agri-Food Canada, Manitoba Conservation and Water Stewardship (MCWS), the Saskatchewan Watershed Authority (Saskatchewan Water Security Agency), and the USGS. The model builds on and benefits from the USGS application of SPARROW for the MRB3 (Major River Basin 3 – Great Lakes, Ohio, Upper Mississippi, and Souris-Red-Rainy) basin that includes US portions of the Red and Souris watersheds. It also takes advantage of the IWI Data Harmonization Project, which pioneered the development of interoperable hydrographic and geospatial datasets for basins along the international border.

This report documents the steps that were taken towards development of calibrated SPARROW models for the Red-Assiniboine Basin. Model output and interpretation will be made available through IJC reports and journal articles following peer review. When the binational model is considered acceptable, results from the model will be made available to key stakeholders such as the International Red and Souris River boards, provincial and state agencies, and to the public through the online tools.

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iv) List of Acronyms

AAFC	Agriculture and Agri-Food Canada
ACBIS	Aquatic Chemistry and Biological Information System
BMP	Beneficial Management Practices
CaPA	Canadian Precipitation Analysis
CDED	Canadian Digital Elevation Dataset
CFI	Canadian Fertilizer Institute
CFS	Canadian Forest Service
CMAQ	Community Multi-scale Air Quality
CS	Cropping Systems
CTI	Centre for Topographic Information
DA	Drainage Area
DSS	Decision Support System
DEM	Digital Elevation Model
EC	Environment Canada
FL	Fertilizer Loading
GPS	Global Positioning System
HNIC2P	High Nutrient Intensity Crops
HNIC1P	High to Moderate Nutrient Intensity Crops
IJC	International Joint Commission
IWI	International Watersheds Initiative
MCWS	Manitoba Conservation and Water Stewardship
MRB3	Major River Basin 3 – Great Lakes, Ohio, Upper Mississippi, and Souris-Red-Rainy
MSE	Mean Square Error
N	Nitrogen
NCA	Non-Contributing Area
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NHN	National Hydro Network
NLCD	National Land Cover Dataset
NO_2^-	Dissolved Nitrite
NO_3^-	Dissolved Nitrate
NRCan	Natural Resources Canada
NRC-OCRE	National Research Council Canada – Ocean Coastal and River Engineering
P	Phosphorus
PMIP	Planning Model Improvement Program
PPWB	Prairie Provinces Water Board
PRISM	Parameter-elevation Regressions on Independent Slopes Model
RMSE	Root Mean Square Error
SAS	Statistical Analysis Software
SE	Standard Error
SEEMS	Saskatchewan Environment’s Environmental Management System
SPARROW	SPAtially Referenced Regressions On Watershed attributes
SRTM	Shuttle Radar Topography Mission
TKN	Total Kjeldahl Nitrogen
TN	Total forms of Nitrogen

TP	Total forms of Phosphorus
USDA	US Department of Agriculture
USEPA	US Environmental Protection Agency
USGS	United States Geological Survey
WSC	Water Survey of Canada
WWTP	Waste Water Treatment Plant

1 Introduction

Many watersheds straddle the border between Canada and the United States. Through the International Joint Commission's (IJC) International Watersheds Initiative (IWI), the Spatially-Referenced Regressions on Watershed attributes (SPARROW) model, developed by the US Geological Survey (USGS), is being applied to the binational Red and Assiniboine River basins, which span portions of Manitoba, Saskatchewan, Minnesota, North Dakota and South Dakota. The impetus for this novel application is a need to better understand and quantify the sources of nutrients, in particular phosphorus, that contribute to the eutrophication of Lake Winnipeg. The lake has seen an increase in the frequency and severity of harmful algal blooms, and widespread support exists for efforts that will restore the ecological health of the system.

Led by the IJC, an international team was assembled for the project, including researchers from the National Research Council of Canada (NRC), Environment Canada (EC), Agriculture & Agri-Food Canada (AAFC), Manitoba Conservation and Water Stewardship (MCWS), the Saskatchewan Watershed Authority (Saskatchewan Water Security Agency), and the USGS. The model builds on and benefits from the USGS application of SPARROW to the Major River Basin 3 – Great Lakes, Ohio, Upper Mississippi, and Souris-Red-Rainy (MRB3) that includes US portions of the Red and Souris watersheds. It also takes advantage of the IWI Data Harmonization Project, which pioneered the development of interoperable hydrographic and geospatial datasets for basins along the international border.

Development of a binational SPARROW model presents many challenges. First, there are different conventions or styles by which the federal governments of Canada and the US and provincial and state governments collect, interpret and express data. For example, harmonization of stream networks between the two countries requires the creation of geospatial cross-walks that result in seamless hydrologic routing across the border. Another example is the reconciliation of differences between the application and reporting of fertilizers in agricultural regions. Furthermore, differences in the availability of streamflow and water quality measurements between the countries (and even across jurisdictions within countries) means that special statistical analyses are required to assess whether data from a monitoring station "qualifies" for inclusion in model calibration. In addition, this specific application of the SPARROW model, where the majority of the Red and Assiniboine River basins reside in the prairies, requires consideration of non-contributing areas or closed watersheds and the importance of the snowmelt or freshet portion of the annual hydrograph.

The objectives of the Red-Assiniboine Basin project are to:

1) Quantify the annual loads of nitrogen and phosphorus by watershed and by jurisdiction;
2) Assess the integrity of existing stream and river monitoring networks and water sampling programs for determining water and nutrient budgets;
3) Evaluate the impacts of different water resource, wastewater and agricultural practices and policies on nutrient loads and concentrations; and
4) Develop an online tool to visualize and map outputs of the binational SPARROW model.

2 Background and Purpose of Report

The objective of this study was to evaluate the nutrient loading in the Red-Assiniboine River system and to provide a modelling framework by which changes to natural and anthropogenic conditions in the basin could influence nutrient loading within the basin and to Lake Winnipeg.

The following SPARROW modelling objectives were outlined at the beginning of the study:

1. Evaluate nitrogen (N) and phosphorus (P) loading estimates at Lake Winnipeg;
2. Evaluate N and P loading estimates at border crossings, including Emerson;
3. Evaluate uncertainty in the loading estimates;
4. Identify catchments with the highest *specific* nutrient contribution; and
5. Identify total nutrient contributions to the Red River from tributary rivers.

This report documents the steps that were taken towards development of calibrated SPARROW models for the Red-Assiniboine Basin. Model output and interpretation will be made available through IJC reports and journal articles following peer review.

When the binational model is considered acceptable, results from the model will be made available to key stakeholders such as the International Red and Souris River boards, provincial and state agencies, and to the public through the online tools.

2.1 Model Extent

The SPARROW model domain covers the international Red-Assiniboine river system, which includes the Red River Basin, the Assiniboine River basin, and the Souris River Basin (see Figure 1). The system is complex in that the basin of the Souris River is a sub-basin of the Assiniboine River, which in turn is hydrographically a sub-basin of the Red River, where the confluence is within the city of Winnipeg. For consistency, the extent is referred to as the Red-Assiniboine Basin. Although the Qu'Appelle River Basin is part of the overall drainage basin, data limitations precluded its inclusion in this model. For this preliminary version of model, the Qu'Appelle River contribution to the Upper Assiniboine River is treated as a single source of nutrients (see Sections 3.1 and 7.1).

Figure 1 - Red, Souris, Assiniboine and Qu'Appelle River Basins

2.2 The SPARROW Model

The SPARROW model (SPAtially Referenced Regression On Watershed attributes) is a mass-balance watershed model developed by the USGS that relates loads of water quality parameters to human activities, climate, hydrology, geology and physiography [Schwarz et al. (2006)]. The SPARROW model has been applied in many study basins including the entire continental United States as well as New Zealand [Elliott et al. 2005]. The current application of the SPARROW model represents the first application of the model in Canada, and the first binational implementation of the model [Schwarz 2006]. The SPARROW model is typically run on the Statistical Analysis Software (SAS) platform.

2.3 Data Integration and Harmonization

As a spatially-referenced model, SPARROW requires extensive and contiguous geospatial datasets for its construction, calibration and operation. This Red-Assiniboine model is a binational model and as such requires the extra effort of harmonization of datasets both between US and Canada and among the provinces and states. The harmonization efforts followed on efforts previously conducted by the IJC data harmonization project [Laitta (2010)] whereby certain physiographic datasets in border catchments were harmonized for geospatial consistency across the US-Canada border.

2.4 Document Structure

This document covers the SPARROW model development and execution in a number of sections including:

- SPARROW Model Construction (Section 3);
- Water Quality and Stream Load Estimates (Section 4);
- Source Variables (Section 5); and
- Delivery Variables (Section 6).

3 SPARROW Model Construction

The implementation of a SPARROW model requires the assembly of a number of key geospatial and hydrological components. A SPARROW model requires a continuous stream network over the model domain, including lakes and reservoirs. Each segment of the stream network requires a delineated contributing catchment, each of which is used to characterize physiographic, climatological and other characteristics. Finally, flow-related data are required for loading, fate and transport calculations. This section outlines the approach for the development of the SPARROW model for the Red-Assiniboine SPARROW modelling project.

3.1 Stream Network

A SPARROW stream network is a geospatial line-set that describes the geographic path and connectivity of water bodies in a particular domain or watershed. The model requires a detailed and contiguous stream network that includes network segment connectivity or topology information so that flow paths and nutrient transport can be accurately assessed. Although stream networks may be derived from digital elevation model (DEM) data, the accuracy of the stream mapping from these products can suffer in areas of low topographic relief. The national DEM product available in Canada [Centre for Topographic Information (CTI)] has a very coarse vertical resolution of 1m making stream delineation in a low-relief environment like the Prairies very difficult. Consequently, the stream delineations were acquired using mapped stream network products from a number of national data sources. The National Hydro Network (NHN) product [Canadian Council on Geomatics 2009] was incorporated for the Canadian portion of the model; the National Hydrography Dataset (NHD) [USGS and USEPA 2006] was incorporated for the American side of the model; and a third product provided by the IJC Harmonization project [Laitta 2010] included the harmonized stream segment dataset across the border between US and Canada. This last dataset was available for the Souris River basin, but was not fully available for the other basins in this study.

As the US and Canadian datasets were not completely harmonized over the domain, some manual adjustments were required at the border to connect streams where appropriate. Additionally, much of the Canadian stream network required detailed investigation in the Prairies, as the available NHN network did not have a well-defined topology, with many stream segments being improperly connected. Figure 2 illustrates some of the required manual changes in the Souris River basin network, as an example. The lack of adequate topology in the NHN stream segment dataset for the Qu'Appelle River basin was considerable and would have required a substantial effort to map and digitize the missing stream segments. Consequently, the Qu'Appelle River basin was excluded from the model and represented instead by an equivalent point discharge into the Assiniboine River, which was calculated from data collected from a water quality monitoring station. The NHN is steadily being improved by Natural Resources Canada (NRCan), and although the Qu'Appelle River network is not currently prepared for integration into SPARROW, it is anticipated that improvements to the NHN will allow for inclusion in the future.

The final stream network layout for the entire model is shown in Figure 3. This stream network includes approximately 75,000 stream segments.

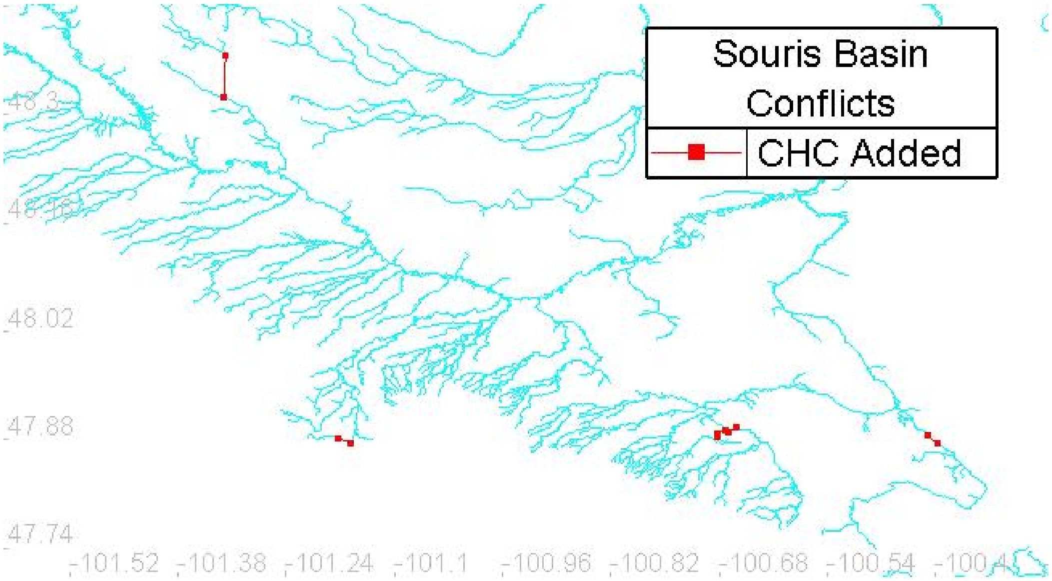

Figure 2 - Souris Basin Stream Network Corrections

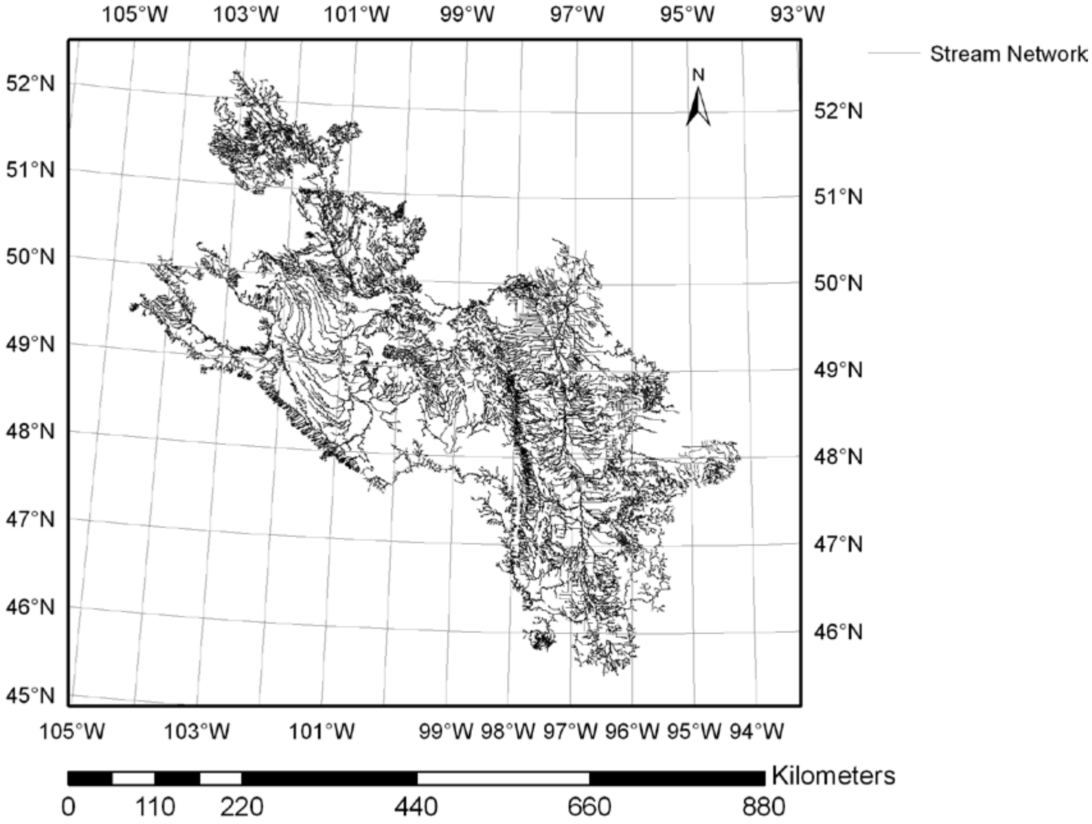

Figure 3 – Red-Assiniboine SPARROW model stream network

With the network defined and topology verified, a number of calculations were made on the stream segments themselves. Each stream segment was assigned a unique identifier, or "SPARROWID", and the relationships between upstream and downstream stream segments were explicitly defined for each segment. Additionally a "hydro sequence" number was assigned to each segment which specifies the calculation and routing sequence of the segments ensuring that contributions from the upstream segments are calculated first when the SPARROW model runs [Schwarz (2006)].

3.2 Hydraulically Connected Lakes and Reservoirs

Water bodies, such as lakes and reservoirs, hydraulically connected to the stream network require explicit definition in a SPARROW model. For each lakes associated with a stream reach, "hydraulic load" or the increase in retention time due to the presence of lakes in the network is needed to be estimated. A water body dataset was required for both the US and Canada. Thus, the NHN data were used for the Canadian portion of the model domain and NHD data were used for the US portion.

Not all lakes in the NHN and NHD datasets were hydraulically connected with the stream network. Many delineated lakes were isolated or perched with no clearly identified drainage connectivity to the stream network and therefore were not used in the model or considered in the hydraulic load calculations. Lakes were identified as hydraulically connected if a stream segment passed through them and lake polygons were linked to the streamflow network through the assignment of a SPARROWID matching the lake to the connected stream.

3.3 Non-Contributing Areas

Two potential sources of information existed for drainage areas that did not normally contribute to the runoff of the identified channels contained within the network. The first was a dataset of the previously identified isolated lakes, not connected to the stream network, and presumed to be perched lakes or so-called "prairie potholes." The second potential source was the non-contributing area map provided by (AAFC) [PFRA 2008].

The USGS approach for identifying non-contributing areas (NCAs) was to identify local low-points or "sink" locations and delineate non-contributing catchments around these points. Each lake in the isolated lake dataset could potentially represent a sink by which a non-contributing area could be delineated. This approach was investigated with the available data for this SPARROW model; however, the number of isolated lakes identified was very large and delineations of the areas that contributed to these lakes was felt to be too inclusive when representing non-contributing areas. Consequently, a hybrid approach was employed that used the isolated lake locations as sinks, but only if the lakes were located within the delineated NCA zones as identified by the AAFC.

3.4 DEM Harmonization

The DEM data was used to delineate contributing catchments for each stream segment. The DEM products available included the Canadian Digital Elevation Dataset (CDED), the US NED [USGS 2010], and the Shuttle Radar Topography Mission (SRTM) dataset [USGS (2010)]. The CDED product was provided with a relatively high horizontal resolution of 15 m, but a low vertical resolution of 1 m creating a "step" like DEM result that did not accurately describe the surface of the model as illustrated in Figure 4. The SRTM DEM product was evaluated as a potential alternative to the CDED for the Canadian domain; however, its horizontal resolution of 60m was too coarse for this study as shown in Figure 5. The NED was provided by the USGS for the US model domain and with a slightly higher resolution of 30 m. A sample of the NED is illustrated in Figure 6.

Figure 4 - CDED DEM in a Three Dimensional View

Figure 5 - SRTM DEM in a Three Dimensional View

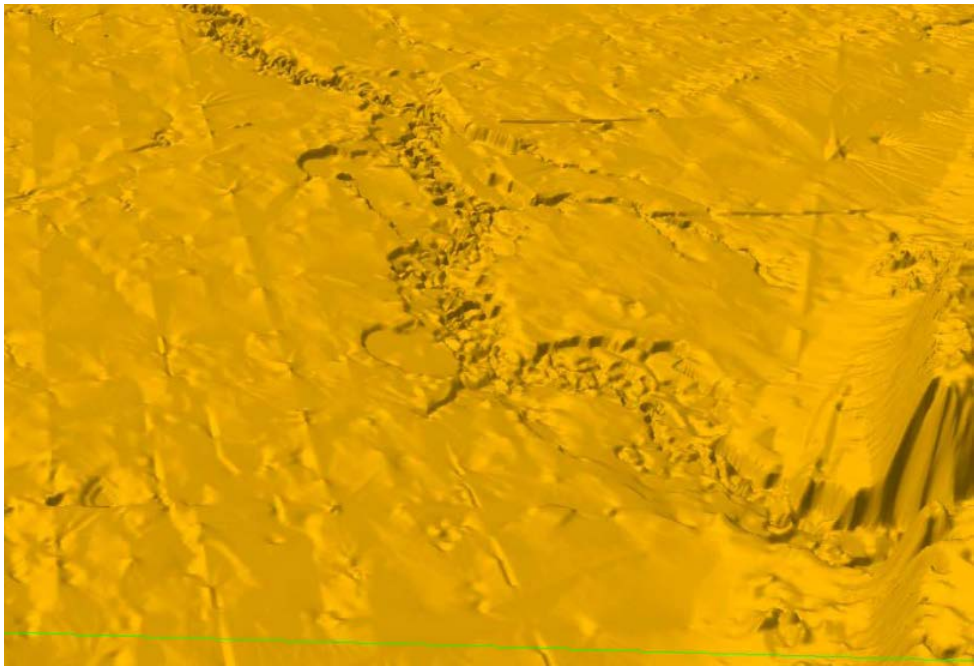

Figure 6 - NED DEM in a Three Dimensional View

Inconsistencies were observed between the CDED and NED data-sets including grid resolution, data gaps and areas of data overlap. Merging and modification of the data were performed to create a harmonized DEM usable over the entire model domain. Discrepancies were resolved using GIS tools to resample the entire product to a continuous 30 m horizontal resolution. Border data gaps were filled using a 5x5 cell averaging filter and overlapping areas were combined using the ArcGIS “blend” algorithm that combines two overlapping raster datasets using a weighted average determined by the distance from the edge of the overlapping area [ESRI 2010]. No efforts were made to vertically correct the datasets at the border, where a sharp elevation change was often observed, as the influences of catchment delineation were minimal and localized. An image of the merged elevation datasets is shown in Figure 7, which illustrates the differences between the two data products.

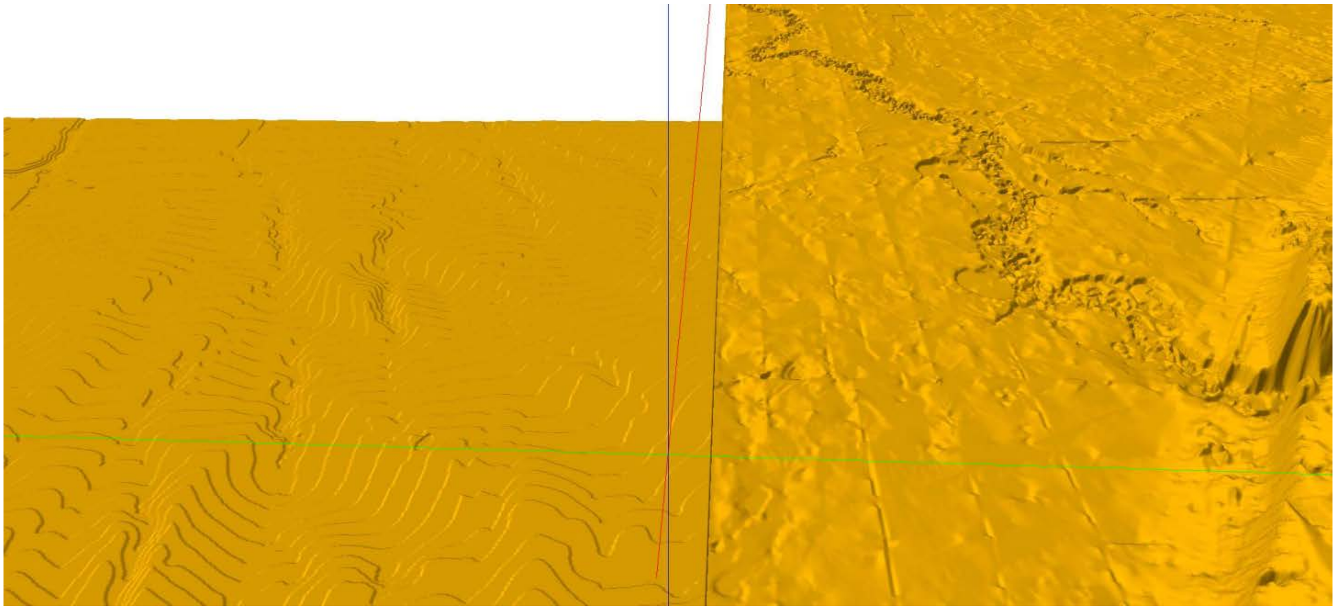

Figure 7 - Merge of the CDED (left) and NED (right) DEM datasets

3.5 Catchment Delineation

A SPARROW model requires a contributing watershed or catchment for each stream reach contained in the stream network. These catchments were delineated using a DEM data product that was harmonized over the domain using flow-direction accumulation derived from DEM slope data. Due to the relatively limited topographic relief in much of this region, the catchments could not be reliably delineated by the DEM data alone. The catchments were defined using techniques developed by the USGS with available hydrographic datasets, including the stream network itself and previously delineated sub-watershed boundaries [Johnston et al. 2009]. The flow forcing was accomplished by “burning-in” the stream network, which involves lowering the DEM elevations where the streams are identified, and by “walling” the previously delineated catchments, which involves raising the DEM at delineated catchment divides. The derived stream network (see Section 3.1) was used to burn-in the streams and a combination of available products was employed to provide walls for the known catchments. For the US portion of the domain, the HUC12 catchment delineations from the NHD were used to force catchment delineations. On the Canadian portion of the model, three products were employed: the sub-sub drainage area delineations from the Atlas of Canada [Canada 2008], unpublished watershed delineations upstream of the Water Survey of Canada (WSC) hydrometric stations [Erika Klyszejko, EC] and the IJC data harmonization project for the Souris River basin that included the harmonized HUC12 catchments across the Canada-US border for that basin [Laitta 2010]. No product merged seamlessly among sources and each required some manual adjustment to provide a consistent set of basins over the entire model domain. Figure 8 shows some of the inconsistencies between the various products employed in the walling procedure.

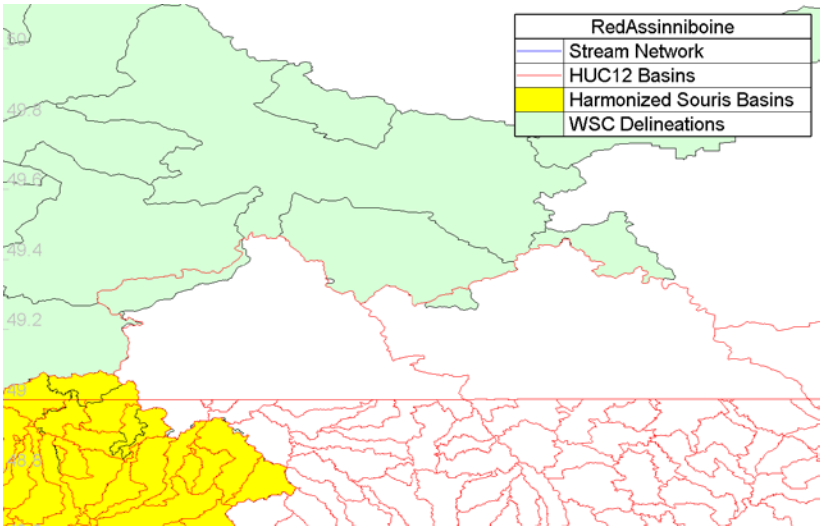

Figure 8 - Drainage Area Delineations

The final catchment delineation resulted in a series of polygons in a shapefile with each catchment polygon linked to a specific stream segment or identified sink location. Figure 9 shows a section of the stream network and catchments in the model and Figure 10 shows the catchments for the entire model domain.

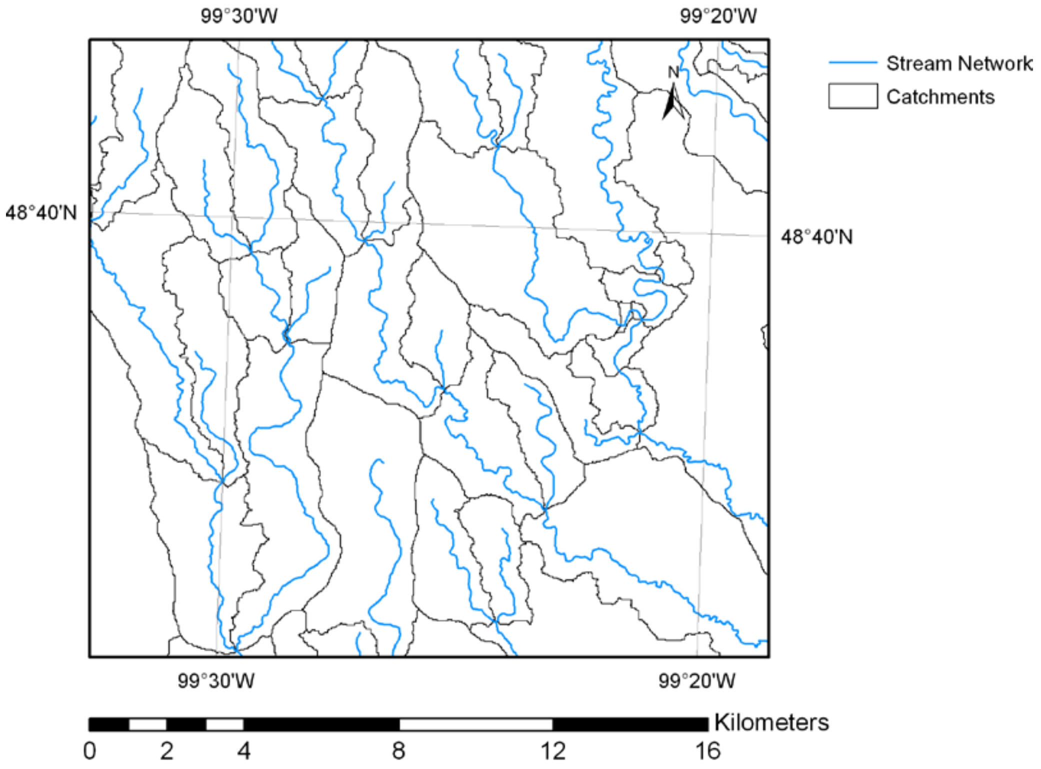

Figure 9 - Delineated Catchments Outlining Channel Network

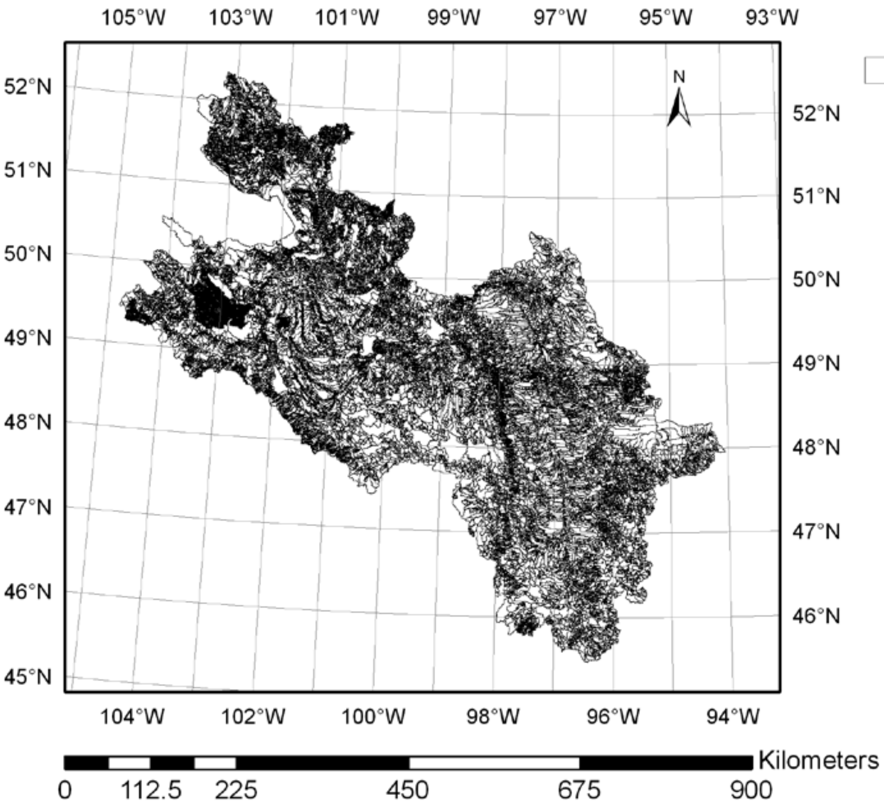

Figure 10 - Delineated Catchments for the Red Assiniboine SPARROW Model

3.6 Channel Slopes

Estimates of the slopes of all of the channels are required as an interim step in predicting channel velocities and travel times, which are ultimately used to estimate in-stream nutrient decay rates in the SPARROW model. To compute the slope of a particular channel, the upstream and downstream elevation of each stream segment along with the channel length were determined. From these data, the slope of each channel segment was calculated as:

$$S_c = \frac{E_u - E_d}{L_c} \qquad (1)$$

where

S_c = Channel Slope (m/m),

E_u = Upstream Elevation of Channel (m),

E_d = Downstream Elevation of Channel (m), and

L_c = Length of Channel (m).

The upstream and downstream channel elevations could not be determined directly from the stream network and the associated DEM, because the mapped channels did not always coincide with the DEM derived flow paths. To overcome this problem, it was assumed that the downstream channel elevation was equal to the minimum elevation in the catchment. Similarly, it was assumed that the upstream channel elevation was the minimum catchment elevation of the catchments directly upstream of the catchment for which slope was being calculated. If multiple catchments were present upstream of a catchment, the maximum of these minimum elevations was used, resulting in a modification to the slope equation:

$$S_c = \frac{Max(e_{\mathrm{d}1}, e_{d2}, \ldots, e_{dn}) - E_d}{L_c} \tag{2}$$

where

S_c = Channel Slope (m/m);

e_d = Minimum Elevation of Upstream Catchment (m);

n = Total Number of Upstream Catchments;

E_d = Minimum Elevation of Catchment (m); and

L_c = Length of Channel (m)

Channel lengths were computed using the segment length tools in the Green Kenue software [NRC-CHC (2010)]. Upstream catchments are required for all stream segments, including headwater catchments that have no delineated upstream catchments. For these headwater catchments, temporary “ghost” catchments were calculated at the headwaters of the stream segments (see Figure 11 - A Headwater Catchment), from which minimum elevation was determined for channel slope calculations.

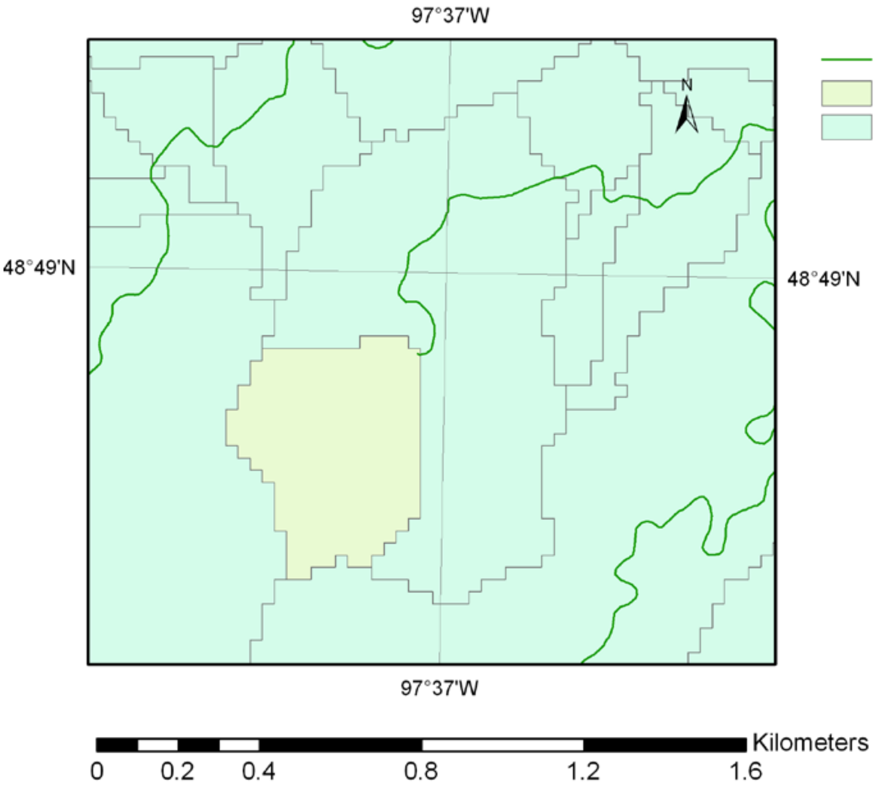

Figure 11 - A Headwater Catchment

Although most calculated slopes were physically reasonable (i.e. positive downstream slopes of reasonable magnitude) in some instances slopes were computed to be zero or negative along a stream segment due to inconsistences between the DEM data and the mapped NHN stream network (see Figure 12). Negative or zero slopes confound the velocity estimates and the associated travel time calculations in the SPARROW model; therefore, any channel with a slope value less than 0.001 m/m was assigned a value of 0.001 m/m.

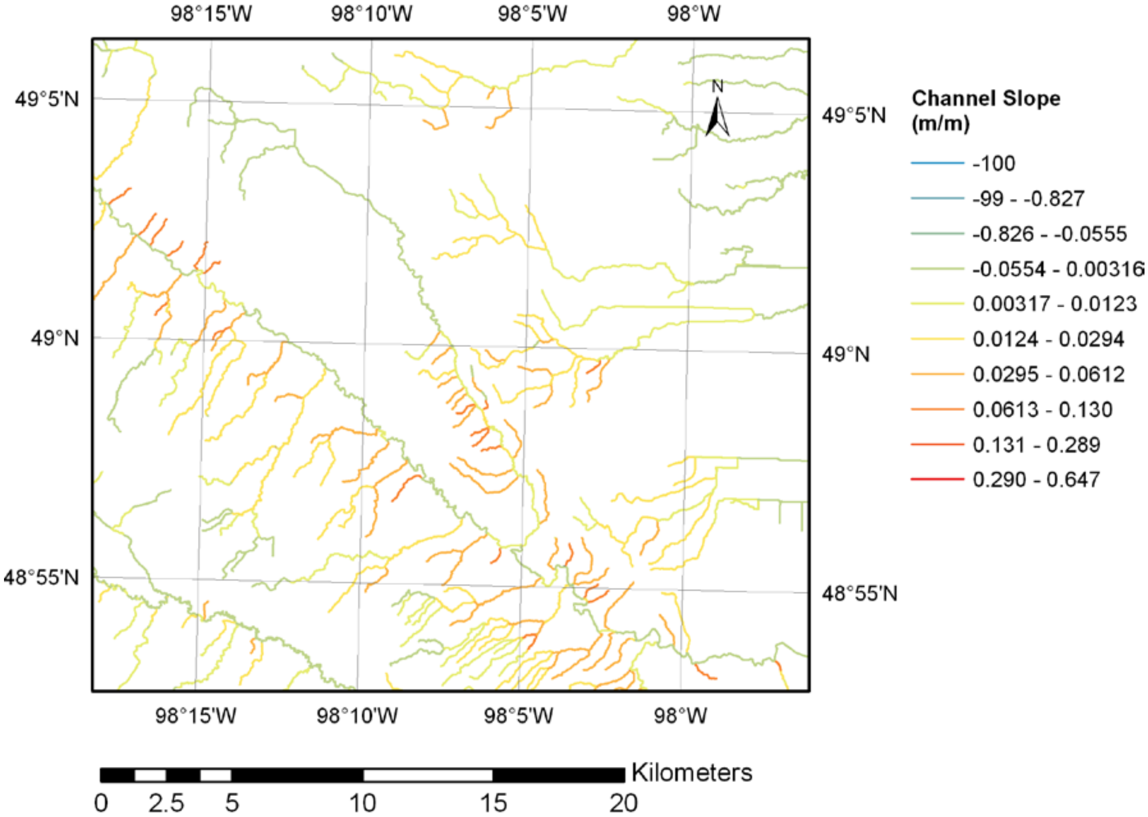

Figure 12 - Unadjusted Slope Results (m/m)

3.7 Flow Estimates

SPARROW models require flow estimates to determine flow velocity. To provide flow and runoff estimates, a 900 m runoff grid provided by the USGS [David Wolock, USGS, written communication] was employed. The runoff data were based on a water balance model employing a combination of the Parameter-elevation Regressions on Independent Slopes Model (PRISM) climatological data and the precipitation estimates from the Canadian Forest Service (CFS) climatological averages for the period of 1971 to 2000. The map of averaged runoff for each SPARROW catchment is shown in Figure 13. Border effects are visible in the runoff estimates, especially at the centre of the model domain, which is attributed to the different climatological data sources employed in the runoff model estimate. Other products were considered that may improve the runoff map, including incorporation of the Canadian Precipitation Analysis (CaPA) [Mahfouf et al. (2007)] product into the USGS water balance approach which would eliminate border issues. This is a recommended refinement step but outside the scope of this modelling effort.

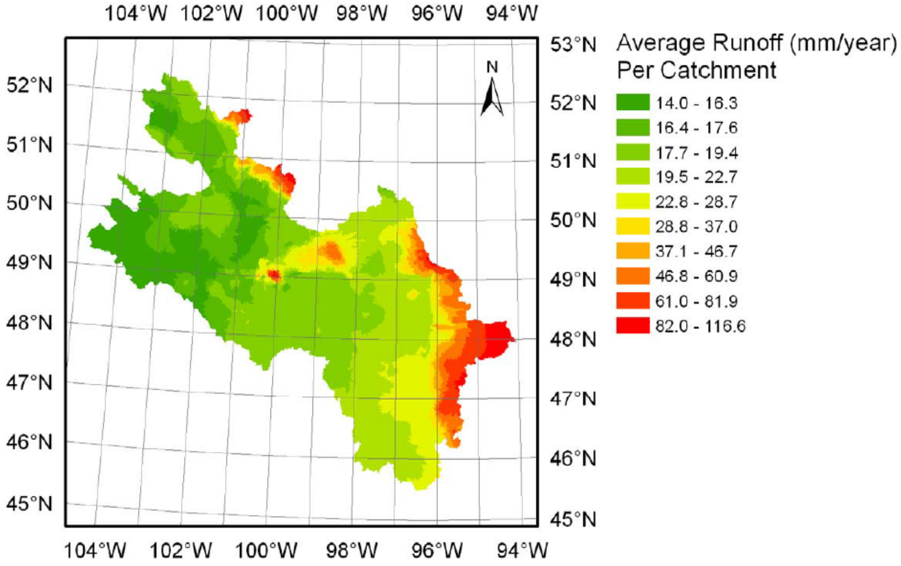

Figure 13 - USGS Runoff Map

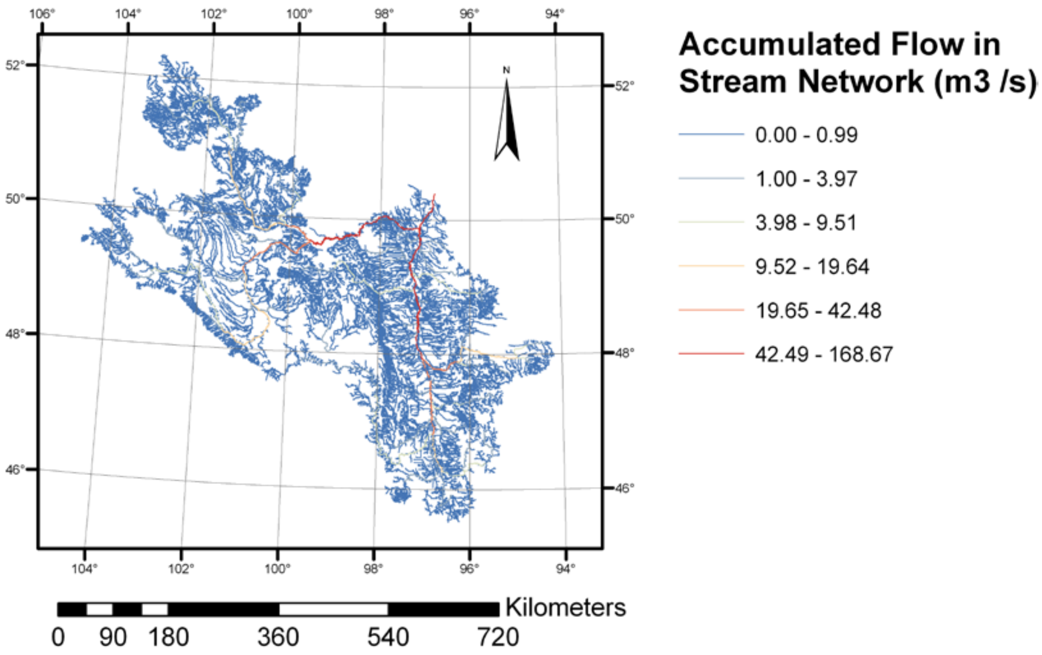

Figure 14 - Accumulated Streamflow Map

Streamflow was estimated for each stream catchment from runoff estimates for each catchment (see Figure 14). This approach is similar to that used in the development of the USGS MRB3 SPARROW model [Robertson and Saad (2011)]. The accumulated flow values were validated by comparing the estimated values with streamflow measurements from both the WSC [Environment Canada (2010)] and the USGS StreamStats (http://streamstats.usgs.gov). Hydrometric station mean daily flow data were extracted for the period of record (1971-2000) and compared with the accumulated flow used in the SPARROW model for both the US and Canada (Figure 15).

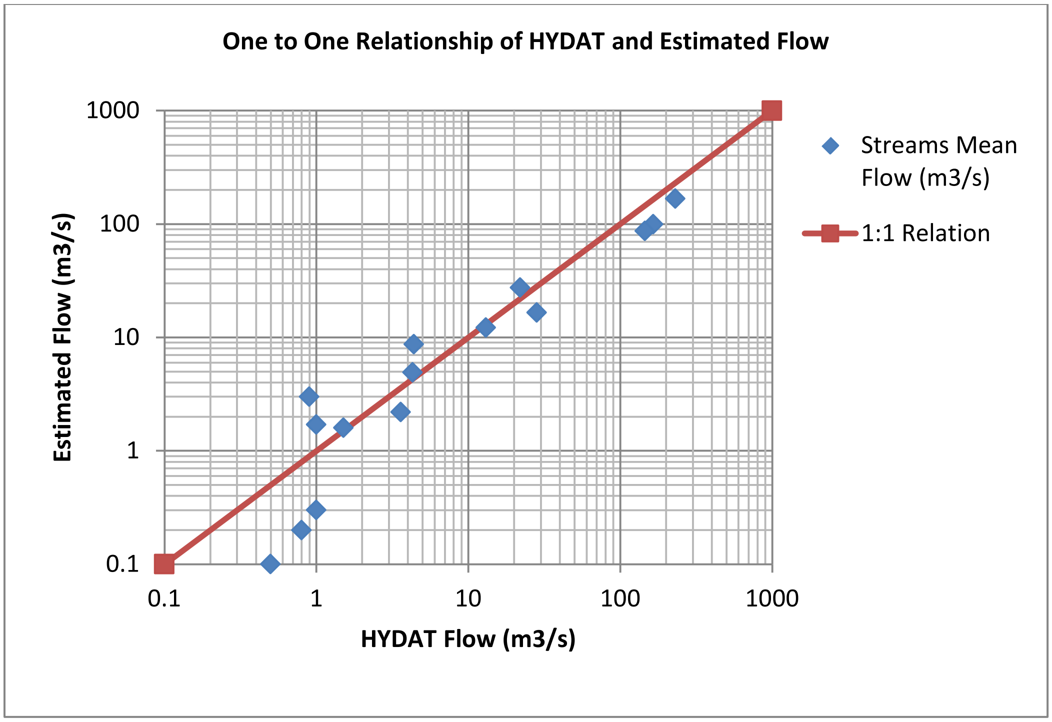

Figure 15 - Comparing Measured Flows (HYDAT) to Estimated Flows

3.8 Streamflow Velocity

Average streamflow velocity is required in SPARROW models to estimate in-stream transport and decay processes. Velocity estimates were determined using the Jobson Equation [Jobson (1997)], which was developed through measurements in over 900 rivers. The Jobson equation is a function of channel slope, drainage area and flow of the channel. The Jobson equation computes velocity:

$$V = 0.094 + 0.0143 {D_a}'^{0.919} {Q_a}'^{-0.469} S^{0.159} \frac{Q}{D_a} \tag{3}$$

$$D_a' = \frac{{D_a}^{1.25} * \sqrt{g}}{Q_a} \tag{4}$$

$$Q_a' = \frac{Q}{Q_a} \tag{5}$$

where:

D_a' = dimensionless drainage area;

Q_a' = dimensionless relative discharge;

D_a = drainage area (m^2);

Q_a = mean annual discharge (m^3/s);

Q = discharge at the time of measurement (m^3/s);

S = channel slope (m/m); and

V = velocity (m/s).

Because the velocity in SPARROW is meant to represent that at mean annual discharge, the discharge at the time of measurement (Q) was made equivalent to the mean annual discharge (Q_a):

$$Q_a' = \frac{Q}{Q_a} = 1 \tag{6}$$

The calculated velocities for the SPARROW model stream segments are shown in Figure 16.

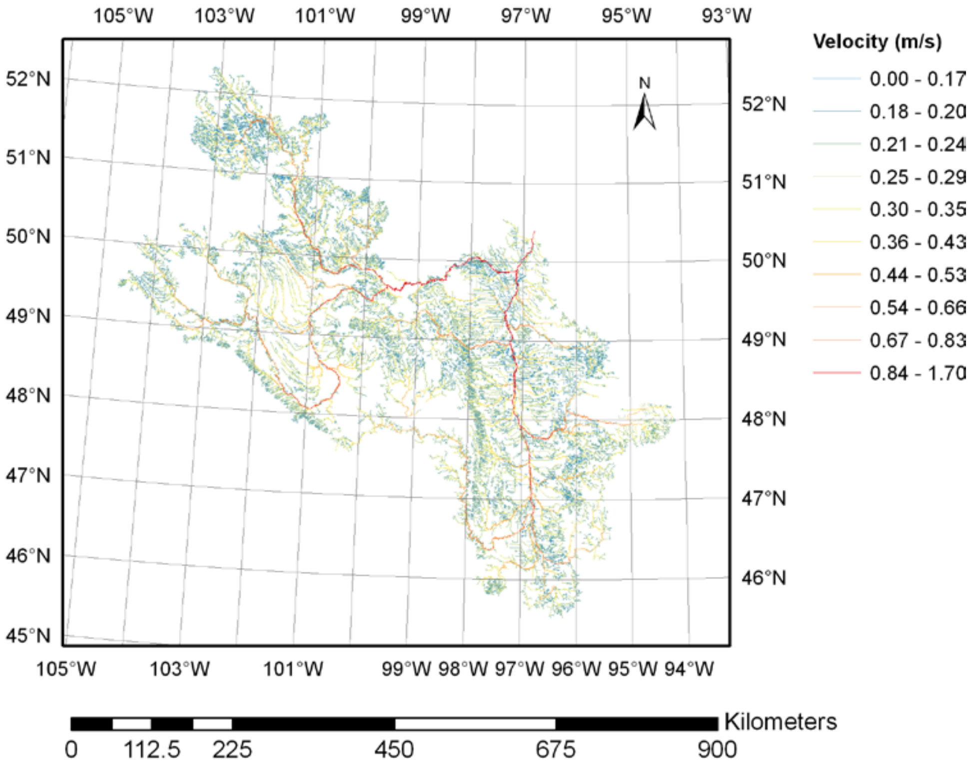

Figure 16 - Velocities of Stream Network Using the Jobson Equation

3.9 Hydraulic Load

SPARROW models account for increased residence time caused by lakes and reservoirs, by calculating an equivalent travel velocity called a “hydraulic load”. The residence times of the hydraulically connected lakes identified in Section 3.2 were estimated using the mean streamflow and the estimated lake area. Hydraulic load was computed as follows:

$$V_h = \frac{Q_C}{A_L} \tag{6}$$

where:

V_h = Hydraulic Load (m/s);

Q_C = Accumulated Flow of Upstream Channels (m^3/s); and

A_L = Total Area of Lakes in Catchment (m^2).

Hydraulic load was calculated for each stream segment with a hydraulically connected lake and stored as its inverse (in units of year/m). It was assumed that the inverse hydraulic load was non-zero in catchments containing lakes (Figure 17), and zero in catchments without lakes (Figure 18).

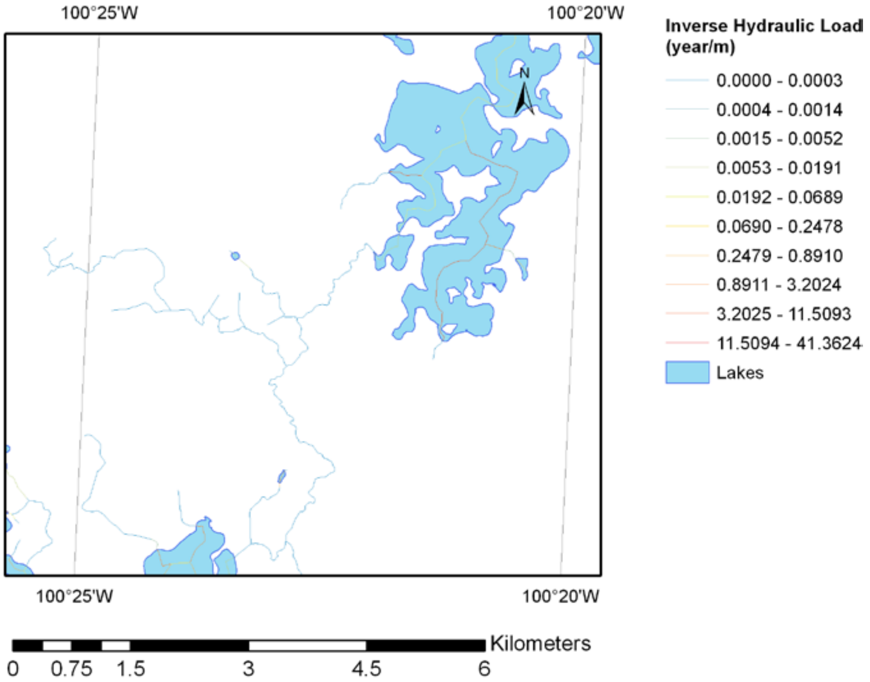

Figure 17 – Example map of inverse hydraulic load estimates with lakes shown

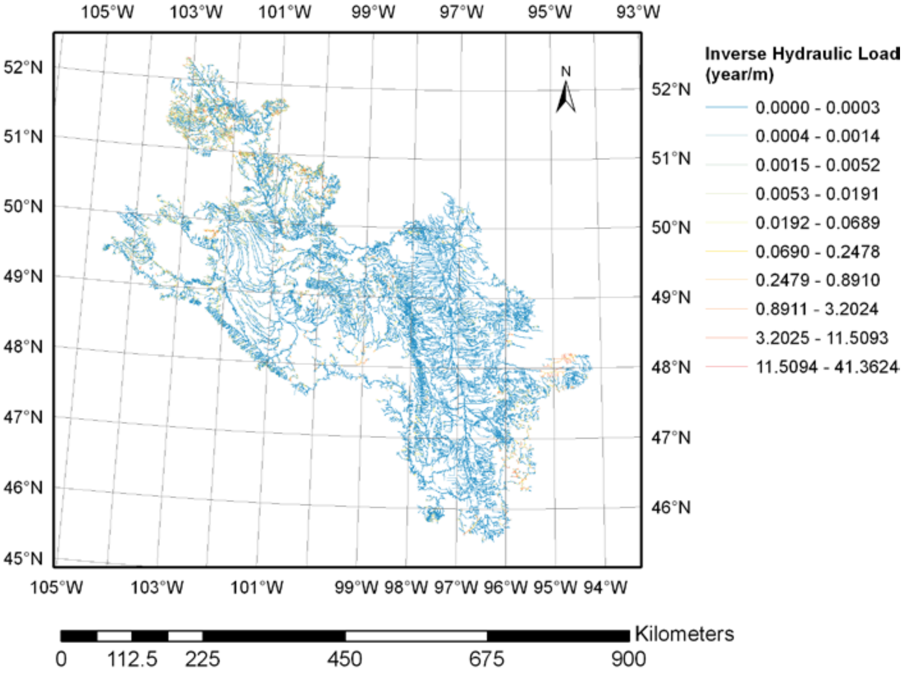

Figure 18 - Inverse hydraulic load mapped to the extent of the SPARROW model

4 Water Quality Data / Load Computation

4.1 Load Estimation

A SPARROW model relates the flux of a constituent per unit of time (referred to as "loads") to geospatial data sets that include constituent sources and watershed characteristics. All available flow gauging stations and water quality monitoring stations in the stream network were screened for inclusion in model development. Constituent loads are estimated from two sets of measurements: streamflow or discharge and water quality concentrations. Fluxmaster, which is a SAS program developed by the USGS, is used to combine these two sets of time-series data and generate a detrended mean annual load for each water quality monitoring station with sufficient data.

As part of the MRB3 model, the USGS had already generated load estimates for the US part of the basin [Robertson and Saad (2011)]. They estimated loads for total nitrogen (approximately 60 stations in the basin) and total phosphorus (approximately 85 stations in the basin). For this binational Red-Assiniboine SPARROW model, load estimates for both Canadian and US stations were combined in one seamless transboundary water quality monitoring network.

4.2 Flow and Water Quality Data

All hydrometric (or flow) and water quality monitoring stations within the model-area extent were evaluated for inclusion in load estimation (Figure 19). Overall, there were more flow stations than water quality stations and sampling frequency is much higher for flow records than for water quality measurements. Loads, expressed as detrended mean annual estimates, are composite values of multiyear time-series data. Typically several years (~20 years) of load data are desired for generating a mean-annual load in order to incorporate the hydrologic variability that occurs. SPARROW models simulate long-term mean-annual nutrient transport given nutrient inputs similar to a given base year (in this case 2002). For the Red-Assiniboine SPARROW model, the base year is 2002 was chosen because this year also corresponds roughly with census years (2001 in Canada and 2002 in the United States for the Census of Agriculture) and source input data were available for this year.

4.2.1 Streamflow data

In Canada, the vast majority of streamflow data is collected, processed and made available by EC-WSC. When WSC data are unavailable at the same location as the water quality sampling station, other options are to use flow records from reservoir outflows or transfer functions from adjacent basins.

Fluxmaster requires daily flow measurements where stations may be rejected if gaps exist in the data. When time-series are relatively robust, interpolation, smoothing functions or other approaches can be applied. In this application, winter data gaps in daily streamflow time-series for seasonal stations, whose yearly hydrograph begins and ends during periods of near-zero flows, were replaced with a daily mean streamflow value of zero m^3/s. If a particular year's time-series for a given station commenced during the spring freshet or ended on the recession curve of a major fall-time event, data gaps were not substituted. As a result, Fluxmaster would remove the water year from the statistical calculations for that station.

Small data gaps in daily streamflow time-series for all stations (continuous and seasonal) were substituted with daily values using Microsoft Excel's Autofill Series tool (linear or growth function). If nearby stations were available, the time-series from these stations were used to guide whether or not this technique was appropriate (i.e. no inflection points in neighboring stations' hydrographs during periods of missing data). In some cases, hydrograph comparisons with upstream or downstream stations indicated little change in the contributing runoff area between stations and an upstream or downstream stations' hydrograph could be used directly to fill in data gaps. Streamflow was lagged where appropriate.

Wherever possible, composite streamflow time-series were created for water quality stations where two or more upstream hydrometric stations were available to estimate streamflow. In such cases, the direct summation of streamflow hydrographs was used to estimate flow at the water quality station.

4.3 Water quality data

For the Red-Assiniboine SPARROW model, the parameters of interest were the total forms of nitrogen (TN) and phosphorus (TP). Both as concentration are expressed in mg/l. Specific nitrogen species or fractions of phosphorus may also be of interest; however, their inclusion is under consideration, as they were not incorporated in this study.

For the Red-Assiniboine basin, several databases were accessed for water quality data, including EC's ACBIS database which includes international monitoring stations and stations under the direction of the Prairie Provinces Water Board (PPWB), MCWS, Saskatchewan Environment's Environmental Management System (SEEMS), and the City of Winnipeg. Initial screening of water quality data removed all stations that were discontinued in the 1990s.

TP concentrations were available from all datasets. In contrast, TN concentrations were not always available. A significant number of water quality monitoring programs reported concentrations of various nitrogen species, but did not report total concentrations. To maximize the number of stations that could be used for TN, two numerical conventions were used. First, when total Kjeldahl nitrogen (TKN), dissolved nitrate (NO_3^-) and dissolved nitrite (NO_2^-) were available, the species were summed as TN. Second, if TKN was available and both NO_3^- and NO_2^- were below the detection limit, TKN was used as TN.

4.3.1 Co-location of flow and water quality stations

For load estimation at a specific location along a stream or river reach, flow rates or discharge and nutrient concentrations were combined using a regression. A condition of this approach is that hydrometric and water quality monitoring stations must be co-located. For the Red-Assiniboine basin, this condition was generally satisfied as most water quality sampling programs were designed around the location of hydrometric stations. Global Positioning System (GPS) coordinates were not always reliable for ascertaining co-location as different standards are employed for reporting coordinate precision. Similarly, co-located stations were sometimes located on nearby, but disconnected sections of a stream network. In low-relief prairie landscapes, which are often subject to watercourse alterations, such drainage patterns are common. In the absence of reliable GPS or mapping data, ground truthing was occasionally used to verify co-location. When two sets of time-series data were not obviously co-located, methods were used by which the flow data was adjusted or imported to match the location of the water quality data. For example, if a gauging station was located upstream or downstream of a water quality monitoring station and insignificant inflows or withdrawals existed between them, a drainage area ratio adjustment was applied to correct the flow rate.

A total of 33 stations were identified in Canada for the Red-Assiniboine SPARROW model (Table 1, Figure 20).

Table 1 – Table of Canadian flow and water quality stations.

Station Name	Station ID	Water Quality Program	Flow Station ID	Flow Station Area (km^2)	Latitude	Longitude
S Tobacco Ck (Miami)	MA05F0001	AAFCWEBs	05OF017	76.4	49.38056	-98.24861
Souris R (Coulter MB/ND)	MA05NF0001	ECHyDat	05NF012	43700	49.094	-100.948
Pembina R (MB/ND)	MA05OB0001	ECACBIS	05OB007	7500	49.03139	-98.27778
Red R (Emerson MB/ND-MN)	MA05OC0001	ECACBIS	05OC001	102000	49.008	-97.211
Assiniboine R (Shellmouth)	MB05MDS023	MWS	ShellRes	17900	50.9625	-101.4167
Assiniboine R (Russell)	MB05MES048	MWS	05ME001	19400	50.80991	-101.4338
Assiniboine R (Treesbank)	MB05MHS006	MWS	05MH013X	94344	49.694	-99.656
Assiniboine R (18th St Brandon)	MB05MHS021	MWS	05MH013	93700	49.8606	-99.9614
Assiniboine R (Happy Hollow)	MB05MHS031	MWS	05MH013	93700	49.7824	-99.7705
Assiniboine R (Portage WTP)	MB05MJS045	MWS	05MH005X	160460	49.945	-98.331
Assiniboine R (E of Portage)	MB05MJS047	MWS	05MJ003	161000	49.9692	-98.0978
Assiniboine R (Headingly)	MB05MJS053	MWS	05MJ001	162000	49.8689	-97.4047
Souris R (Treesbank)	MB05NGS003	MWS	05NG001	61100	49.627	-99.598
Red R d/s Wpg (Selkirk)	MB05OJS074	MWS	05OJ010	287000	50.141	-96.869
Qu'Appelle R (PPWB)	SA05JM0014	ECACBIS	05JM001	50900	50.484	-101.543
Assiniboine R (PPWB)	SA05MD0002	ECACBIS	05MD004	13000	51.533	-101.889
Assiniboine R (Headingly)	WPG1	Wpg	05MJ001	162000	49.85341667	-97.40811111
Red R u/s Wpg (Lockport)	WPG4	Wpg	05OJ010	287000	50.08530556	-96.94619444
Sturgeon Ck (Wpg)	WPG7	Wpg	05MJ004	556	49.92030556	-97.32327778
Assiniboine R (Miniota)	MB05MES042	MWS	05ME006	84200	50.11	-101.036
Lil Sask R (Rivers)	MB05MFS098	MWS	LWahpah	3886	50.024	-100.207
Shell R (Inglis)	MB05MDS003	MWS	05MD005	4970	50.962	-101.318
Birdtail R (Birdtail)	MB05MES034	MWS	05ME003	1100	50.421	-101.062
Antler R (Lyleton)	MB05NFS020	MWS	05NF002	3220	49.043	-101.093
Gainsborough Ck (Coulter)	MB05NFS019	MWS	05NF007	1150	49.158	-101.048
Souris R (Souris)	MB05NGS004	MWS	05NG021	59400	49.613	-100.256
Pipestone Diversion	MB05NGS026	MWS	05NG003	4240	49.68	-100.871
Pipestone Ck (Kola)	MB05NGS079	MWS	05NG024	3900	49.8422	-101.3986
Roseau R (Dominion City)	MB05ODS032	MWS	05OD001x	5245	49.146	-97.168
Rat R (Otterburne)	MB05OES026	MWS	05OE001	1420	49.502	-97.051
Boyne R (Carman)	MB05OFS060	MWS	05OF003	1135	49.5064	-98.0036
Cooks Ck (Millbrook Rd)	MB05OJS007	MWS	05OJ020	278	49.842	-96.729
Souris R (Roche Percee)	SK05NB0198	SEEMS	05NB036	6200	49.07060833	-102.8087

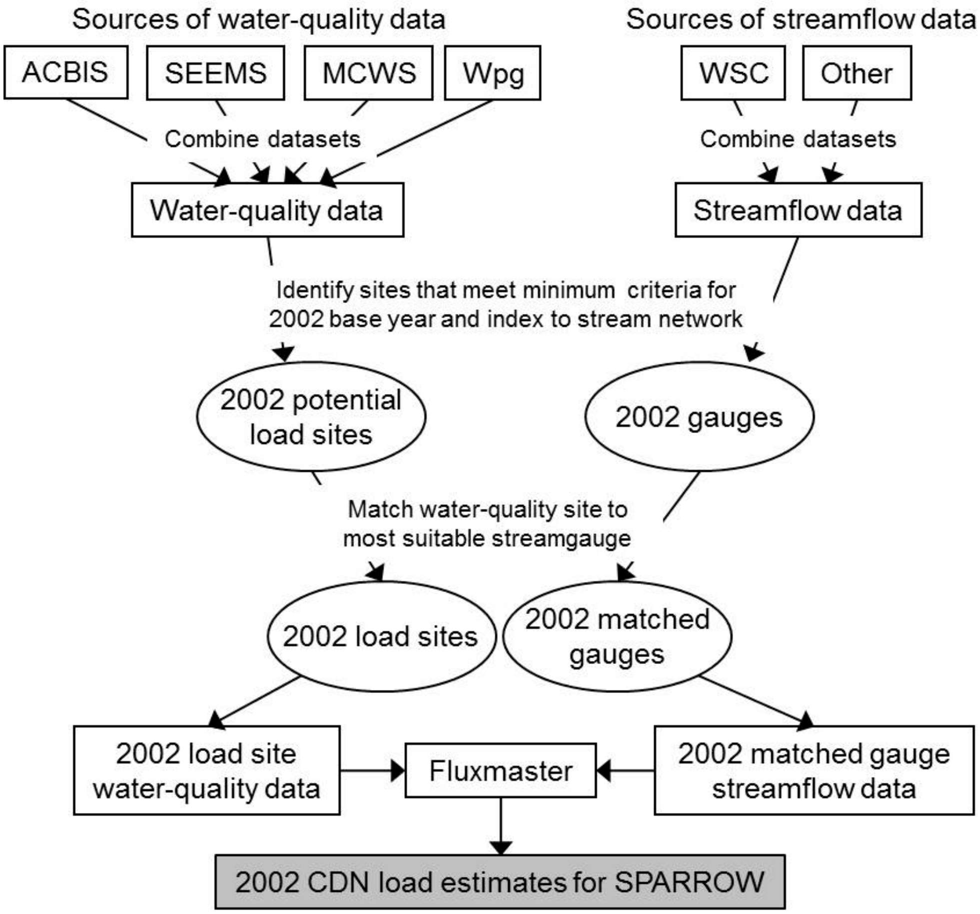

Figure 19 – Flow diagram representing the screening process for water-quality and flow data used to calculate load estimates for the Red-Assiniboine SPARROW model (Adapted from Saad et al., 2011).

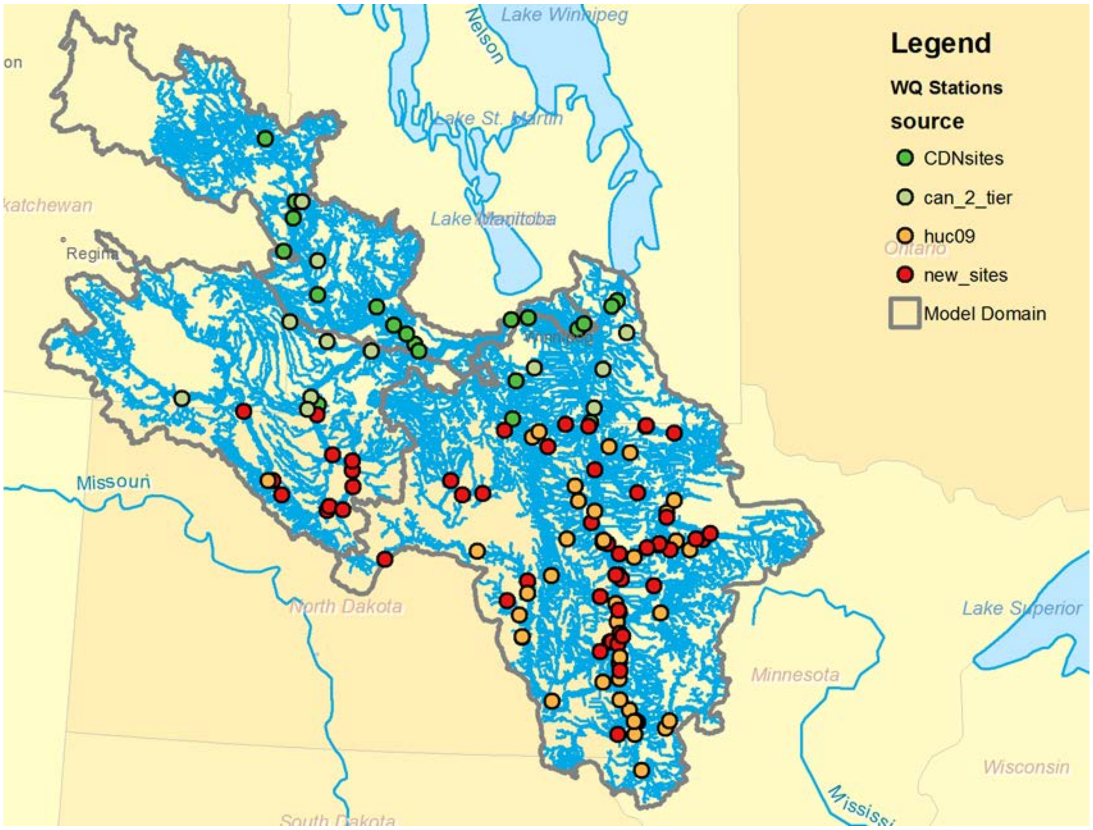

Figure 20 – Map of water quality monitoring stations from the Red and Assiniboine basins used in the SPARROW model

4.4 Load Estimation Using Fluxmaster

Fluxmaster was used to estimate loads from streamflow and water quality data. The program implements regression methods developed by Cohn [2005] and computes detrended long-term mean annual loads normalized to a base year (2002 for the Red-Assiniboine SPARROW model [Schwarz et al. (2006); Cohn (2005)]. The use of detrended mean annual loads in a SPARROW model helps compensate for differences in length of the period of record and frequency of monitoring data among sites. It also minimizes the inherent variability introduced by year-to-year variations in rainfall facilitating the identification of environmental factors that affect loading over long periods [Preston and Hamilton (2009)].

Detrended load estimates are based on detrending the water-quality model and a flow model used in Fluxmaster [Saad et al. 2011]. The water-quality model (Equation 1) relates the logarithm of concentration c_t, at time t, to: the logarithm of daily flow q_t, a decimal time term to represent trend, T_t, sine and cosine functions of decimal time to account for seasonal variation, and a model residual, e_t,

$$c_t = b_0 + b_q\, q + b_T\, T_t + b_s\, sin(2\pi T_t) + b_c\, cos(2\pi T_t) + e_t \qquad (7)$$

(1)

where b_0, b_q, b_T, b_s, and b_c are coefficients estimated for each site by a ordinary least squares method or, if some of the c_t measurements are censored, by the adjusted maximum likelihood method

[Cohn 2005], and e_t is assumed to be independent and normally distributed.

Detrended flow is then estimated using a flow model with the form

$$q_t = a_0 + a_T T_t + a_s \sin(2\pi T_t) + a_c \cos(2\pi T_t) + u_t \tag{8}$$

where a_0, a_T, a_s, and a_c are model parameters estimated using the maximum likelihood SAS Autoreg procedure (SAS Institute Inc., 2004), and u_t is a model residual that is assumed to be correlated across time according to a 30-day lag autoregressive model. For some stations, a second-order harmonic of the sine and cosine functions was included and a 10-day lag autoregressive model was used.

Final detrended flow, q^*_t, is then estimated using the relation

$$q^*_t = q_t + a_T (T_b - T_t) \tag{9}$$

where T_b is decimal time corresponding to June 30 of the designated base year (2002).

The detrended long-term mean annual load is computed by identifying the years included in the analysis period for which streamflow is continuous, summing the detrended daily load estimates for each year, and then dividing by the number of included years to obtain mean load in units of kilograms per year (Saad et al. 2011).

Several statistics are used to indicate whether a particular station was acceptable for inclusion in the SPARROW model (Table 2). They include the standard error (SE), where <50% is the threshold for inclusion, and the observed over expected (O/E), where the threshold for inclusion is 0.667 < O/E > 1.5 <50%.

Preliminary load estimates for Canadian stations included in the Red-Assiniboine SPARROW model are provided in Tables Table 2 and Table 3.

Table 2 – TN load estimates for Canadian stations included in the binational Red-Assiniboine SPARROW model.

Station ID	Station Name	Start Date for TN	End Date for TN	Number of TN Obs.	O/E for TN	TN Load (kg/yr)	Std. Dev. of the TN Load (kg/d)
MA05F0001	S Tobacco Ck (Miami)	27/03/1993	29/06/2009	194	0.92	30389.52	741.46
MA05NF0001	Souris R (Coulter MB/ND)	09/04/1990	12/04/2006	32	0.95	544194.19	4061.61
MA05OB0001	Pembina R (MB/ND)	30/04/1990	07/12/2010	269	0.94	1060997.68	12962.88
MA05OC0001	Red R (Emerson MB/ND-MN)	10/01/1990	06/12/2010	446	0.95	15089640.63	86080.11
MB05MDS023	Assiniboine R (Shellmouth)	30/05/2001	29/07/2003	38	0.95	646352.40	5412.04
MB05MES042	Assiniboine R (Miniota)	24/01/2001	05/10/2009	50	1.05	1650226.88	12631.47
MB05MES048	Assiniboine R (Russell)	30/05/2001	28/01/2008	43	0.93	692796.14	4219.39
MB05MFS098	Lil Sask R (Rivers)	08/01/1990	05/10/2009	85	1.19	263198.53	1535.17
MB05MHS006	Assiniboine R (Treesbank)	09/01/1990	07/10/2010	247	1.08	2255987.70	9988.26
MB05MHS021	Assiniboine R (18th St Brandon)	08/01/1990	07/10/2010	247	1.04	2024628.60	9907.40
MB05MHS031	Assiniboine R (Happy Hollow)	12/01/2004	07/10/2010	71	1.05	2560035.95	11655.28
MB05MJS045	Assiniboine R (Portage WTP)	09/01/1990	07/10/2010	269	1.08	4072758.00	25729.21
MB05MJS053	Assiniboine R (Headingly)	16/08/1993	07/10/2010	171	1.04	3356122.82	12368.09
MB05NGS003	Souris R (Treesbank)	09/01/1990	07/10/2010	182	1.01	976444.17	7663.76
MB05OJS074	Red R d/s Wpg (Selkirk)	10/01/1990	02/09/2010	279	1.06	27310541.90	126847.70
SA05JM0014	Qu'Appelle R (PPWB)	15/01/1990	13/12/2010	214	1.04	465338.65	2076.52
SA05MD0002	Assiniboine R (PPWB)	15/01/1990	15/12/2010	259	0.93	574375.61	5689.92
WPG1	Assiniboine R (Headingly)	25/01/1995	10/11/2010	216	0.95	3822537.14	24006.69
WPG4	Red R u/s Wpg (Lockport)	11/01/1995	10/11/2010	220	1.04	24350837.27	160683.03
WPG7	Sturgeon Ck (Wpg)	14/10/1998	20/10/2010	90	0.19	206642.80	
MB05MDS003	Shell R (Inglis)	15/05/1973	21/09/2010	104	1.12	3859.50	23.88
MB05MES034	Birdtail R (Birdtail)	13/06/2001	21/01/2009	35	1.12	1843.52	19.01
MB05NFS019	Gainsborough Ck (Coulter)	14/04/1998	22/04/2008	24			
MB05NFS020	Antler R (Lyleton)	14/04/1998	08/05/2007	26	0.58	2508.06	
MB05NGS004	Souris R (Souris)	22/03/1978	10/07/2010	165	0.94	20742.47	165.63
MB05NGS026	Pipestone Diversion	07/07/1997	13/01/2009	56	1.06	3256.87	42.66
MB05NGS079	Pipestone Ck (Kola)	24/04/2001	21/10/2008	30	1.05	2396.93	26.83
MB05ODS032	Roseau R (Dominion City)	03/10/1973	21/06/2010	84	0.92	15429.17	94.54
MB05OES026	Rat R (Otterburne)	03/10/1973	14/07/2010	97	1.08	4149.37	31.44
MB05OFS060	Boyne R (Carman)	17/05/1973	23/06/2010	71	1.29	2521.80	34.00
MB05OJS007	Cooks Ck (Millbrook Rd)	07/05/1990	05/07/2010	72	1.19	500.06	6.46
SK05NB0198	Souris R (Roche Percee)						

Table 3 – TP load estimates for Canadian stations included in the binational Red-Assiniboine SPARROW model.

Station ID	Station Name	Start Date for TP	End Date for TP	Number of Obs. for TP	O/E for TP	TP Load (kg/yr)	Std. Dev. of the TP Load (kg/d)
MA05F0001	S Tobacco Ck (Miami)	27/03/1993	29/06/2009	200	0.95	6454.98	180.85
MA05NF0001	Souris R (Coulter MB/ND)	09/04/1990	12/04/2006	33	0.93	102009.85	689.75
MA05OB0001	Pembina R (MB/ND)	30/04/1990	07/12/2010	280	1.18	197895.80	1951.71
MA05OC0001	Red R (Emerson MB/ND-MN)	10/01/1990	06/12/2010	461	1.05	2551668.49	14346.07
MB05MDS023	Assiniboine R (Shellmouth)	30/05/2001	29/07/2003	38	1.02	40577.20	151.60
MB05MES042	Assiniboine R (Miniota)	24/01/2001	05/10/2009	50	1.22	305717.57	2187.77
MB05MES048	Assiniboine R (Russell)	30/05/2001	28/01/2008	43	0.98	43069.74	166.11
MB05MFS098	Lil Sask R (Rivers)	08/01/1990	05/10/2009	105	1.41	35464.41	245.26
MB05MHS006	Assiniboine R (Treesbank)	09/01/1990	07/10/2010	248	1.03	403614.66	2612.59
MB05MHS021	Assiniboine R (18th St Brandon)	08/01/1990	07/10/2010	247	0.98	386621.18	2715.52
MB05MHS031	Assiniboine R (Happy Hollow)	12/01/2004	07/10/2010	71	1.02	476674.30	3527.80
MB05MJS045	Assiniboine R (Portage WTP)	09/01/1990	07/10/2010	269	1.20	794243.66	5958.37
MB05MJS053	Assiniboine R (Headingly)	16/08/1993	07/10/2010	172	1.07	664017.32	2689.68
MB05NGS003	Souris R (Treesbank)	09/01/1990	07/10/2010	245	0.92	213093.83	1909.86
MB05OJS074	Red R d/s Wpg (Selkirk)	10/01/1990	02/09/2010	355	1.03	4573080.49	23094.13
SA05JM0014	Qu'Appelle R (PPWB)	15/01/1990	13/12/2010	221	1.02	74127.01	338.91
SA05MD0002	Assiniboine R (PPWB)	15/01/1990	15/12/2010	270	1.01	61232.93	626.71
WPG1	Assiniboine R (Headingly)	25/01/1995	10/11/2010	214	1.11	554720.80	2509.97
WPG4	Red R u/s Wpg (Lockport)	11/01/1995	10/11/2010	218	1.25	4350908.05	26955.34
WPG7	Sturgeon Ck (Wpg)	01/08/1995	20/10/2010	102	1.19	22578.51	472.72
MB05MDS003	Shell R (Inglis)	15/05/1973	21/09/2010	135	1.44	378.04	3.63
MB05MES034	Birdtail R (Birdtail)	30/05/2001	21/01/2009	42	1.07	175.32	1.52
MB05NFS019	Gainsborough Ck (Coulter)	29/04/1997	22/04/2008	27	1.14	64.30	1.27
MB05NFS020	Antler R (Lyleton)	29/04/1997	08/05/2007	29	0.83	170.02	3.62
MB05NGS004	Souris R (Souris)	22/03/1978	10/07/2010	165	0.85	4610.35	44.16
MB05NGS026	Pipestone Diversion	03/04/1989	13/01/2009	68	1.03	339.21	4.72
MB05NGS079	Pipestone Ck (Kola)	04/04/1991	21/10/2008	48	1.20	230.18	2.93
MB05ODS032	Roseau R (Dominion City)	10/05/1973	21/06/2010	110	1.06	1699.33	11.62
MB05OES026	Rat R (Otterburne)	10/05/1973	14/07/2010	123	1.14	744.71	7.89
MB05OFS060	Boyne R (Carman)	17/05/1973	23/06/2010	95	1.47	281.05	4.11
MB05OJS007	Cooks Ck (Millbrook Rd)	07/05/1990	05/07/2010	116	1.15	55.39	1.09
SK05NB0198	Souris R (Roche Percee)	21/06/2004	19/10/2010	27	0.66	281.82	5.07

5 Source Variables

A SPARROW model requires the definition of all of the important sources of the constituent being modeled. A series of geospatial data sources were processed in this study for use as source variables including:

1. Atmospheric Deposition;
2. Land Use;
3. Inorganic Fertilizer Loading;
4. Manure Loading;
5. Cropping System by Nutrient Intensity; and
6. Waste Water Treatment Plants (WWTP) Point Loading.

5.1 Atmospheric Deposition

Atmospheric deposition of nitrogen has been identified as a significant source of nitrogen in previously developed SPARROW models for the continental US. The data source employed to estimate nitrogen deposition over the area was provided by Community Multi-scale Air Quality (CMAQ) in a grid format at a 14 km resolution [Byun and Ching (1999)]. Two attributes were extracted from this data set: oxidized and reduced dry deposition of nitrogen. Units were in kg/ha/year for both attributes.

The dataset was converted to a raster, resampled to a 25 m resolution and the zonal statistics for the deposition values were determined over each catchment. The total deposition values for all forms of nitrogen were assembled for entry into the SPARROW model. For each catchment, the resulting averages of oxidized and reduced nitrogen values were added together in order to obtain the total nitrogen deposition attribute. The combined total nitrogen deposition estimates are shown in Figure 21.

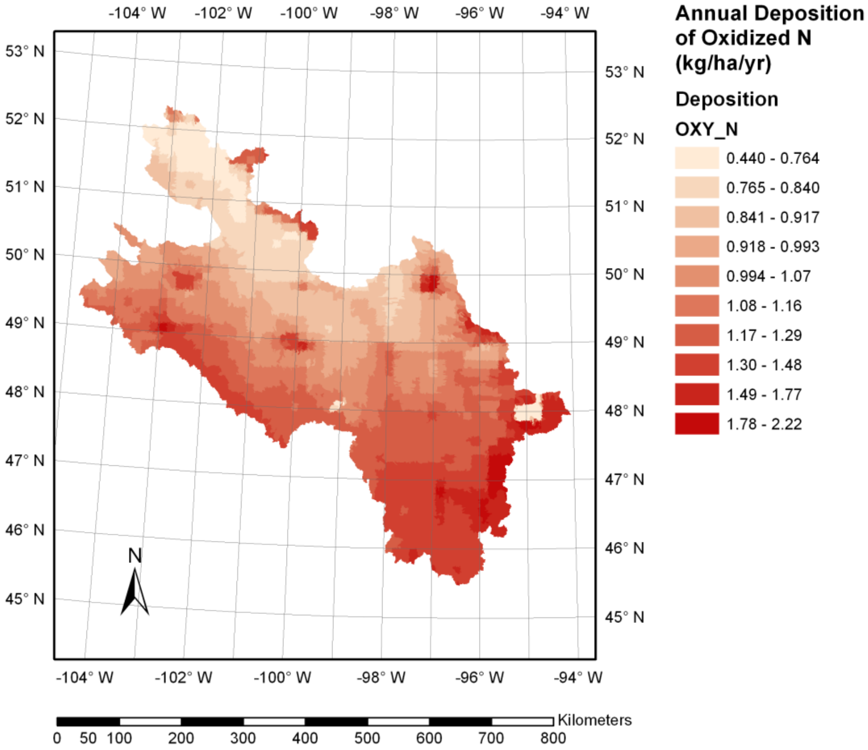

Figure 21 - Map of Dry Deposition of Oxidized Nitrogen

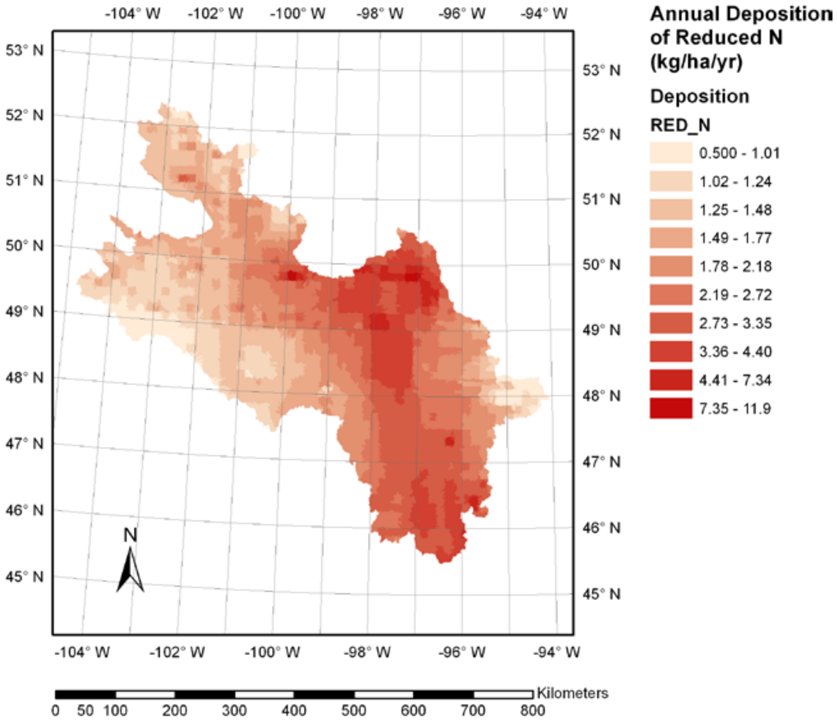

Figure 22 - Map of Dry Deposition of Reduced Nitrogen

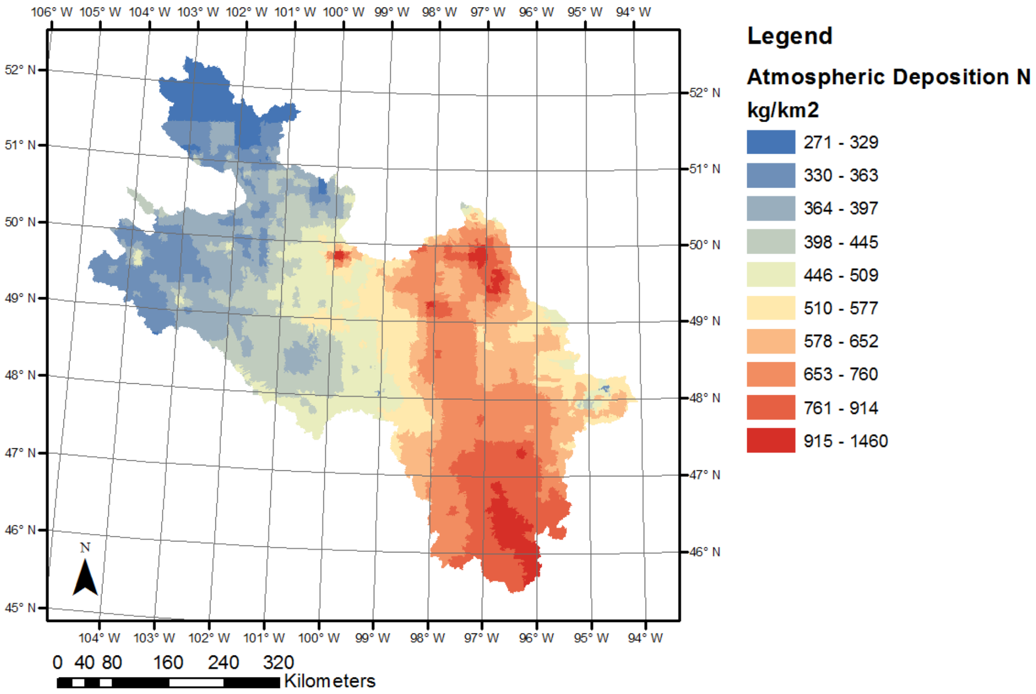

Figure 23 - Map of Dry Deposition of Total Nitrogen

5.2 Land Use

Different land uses may be used as source variables in some SPARROW model whereby loading is linked to specific land use classes. Previous SPARROW models have been developed using land use data, such as forested and urban areas [Robertson and Saad (2011)]. In order for the land use data to be incorporated in the SPARROW models for the entire Red-Assiniboine River Basin, a harmonized data set needed to be developed using data products from both US and Canada. The land use data provided for the Canadian portion of the model domain was the Land Cover data circa 2000 from NRCan's Geobase [Centre for Topographic Information (CTI)]. The land use data for the US portion was taken from the National Land Cover Dataset (NLCD) circa 2001 [Homer and Wickham (2007)]. These two land use data products were harmonized using a set of cross-walk tables shown in Table 4 and Table 5 to produce a common harmonized land use product over the domain. The final harmonized land use product is shown in Figure 24.

Table 4 - Mapping of AAFC LULC Classes

AAFC Code	AAFC Description	Target Code	Target Description
1	NA		
20	Water	1	Water
30	Non-Vegetated Land	3	Barren
34	Developed	2	Urban
50	Shrubland	5	Grassland/Shrub
80	Wetland	7	Wetland
110	Grassland	5	Grassland/Shrub
120	Agriculture	6	Agriculture Crop
121	Agr-Annual Cropland	6	Agriculture Crop
122	Agr-Pasture/Forage	8	Agriculture Pasture
210	Coniferous	4	Forest
220	Broadleaf	4	Forest
230	Mixedwood	4	Forest

Table 5 - Mapping of NLCD Classes

NLCD Code	NLCD Description	Target Code	Target Description
0	Unclassified		
11	Open Water	1	Water
12	Perennial Snow/Ice	9	Snow / Ice
21	Developed, Open Space	2	Urban
22	Developed, Low Intensity	2	Urban
23	Developed, Medium Intensity	2	Urban
24	Developed, High Intensity	2	Urban
31	Barren Land	3	Barren

41	Deciduous Forest	4	Forest
42	Evergreen Forest	4	Forest
43	Mixed Forest	4	Forest
52	Shrub/Scrub	5	Grassland/Shrub
71	Herbaceous	5	Grassland/Shrub
81	Hay/Pasture	8	Agriculture Pasture
82	Cultivated Crops	6	Agriculture Crop
90	Woody Wetlands	7	Wetland
95	Emergent Herbaceous Wetlands	7	Wetland

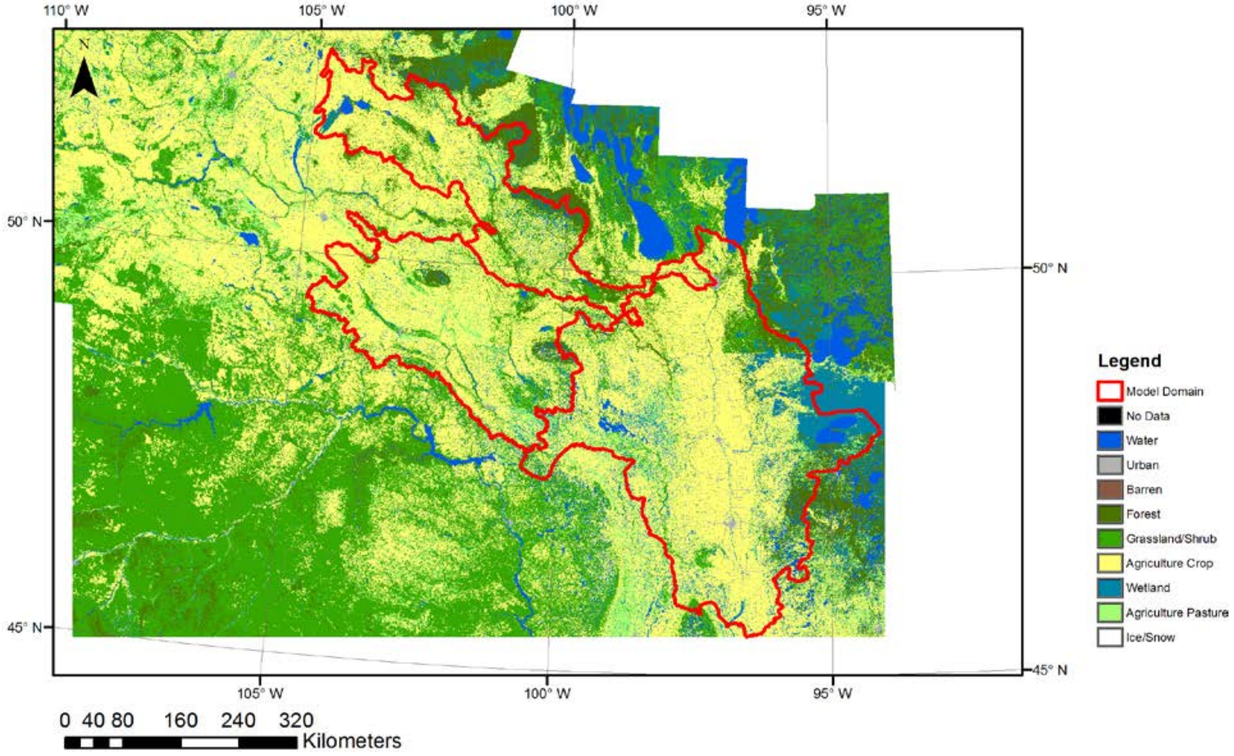

Figure 24 - Harmonized Land Use

The land use classifications were incorporated into datasets available for SPARROW model development by taking zonal statistics for each land use classification and storing the proportional fraction of the area covered by each land use type for each catchment.

5.3 Inorganic Fertilizer Inputs

To determine the inorganic fertilizer application of N and P, a similar approach was taken on each side of the international border. The AAFC agricultural census of 2001 reports fertilizer purchase quantities, but does not provide a break-down in the type of fertilizer purchased by the census reporting area. However, the Canadian Fertilizer Institute (CFI) reports fertilizer expenditures by fertilizer type at the provincial level. Thus, the N and P loadings can be estimated at the provincial level (see Table 6).

Table 6 - Fertilizer Expenditures and Application, Canadian Fertilizer Institute and AAFC Census of Agriculture

Commercial Fertilizer	**Commercial Fertilizer Area Applied (ha)** Census of Agriculture 2001 - area receiving commercial fertilizer in 2000	**Expenditures on Commercial Fertilizer** Census of Agriculture 2001 - expenditures on commercial fertilizer in 2000	**Amount Applied** (fertilizer year ending June 30, 2002 courtesy Canadian Fertilizer Institute)	
			Nitrogen (Metric Tonnes)	**Phosphorous (Metric Tonnes)**
MB	3,531,168	$ 291,214,275	308,261	105,299
SK	9,908,558	$ 575,891,622	499,362	204,182

For inorganic fertilizer application at the catchment level, it was assumed that the N and P proportions would be maintained at the provincial level. The fertilizer application for each catchment was pro-rated based on reported expenditures in the AAFC reporting area.

The data obtained for the US portion of the model were obtained from the data sources employed by the MRB3 model [Robertson and Saad (2011)]. The inorganic fertilizer loading by catchment for this SPARROW model N and P are shown in Figure 25 and Figure 26 respectively. The estimated applications show reasonable consistency across the international border.

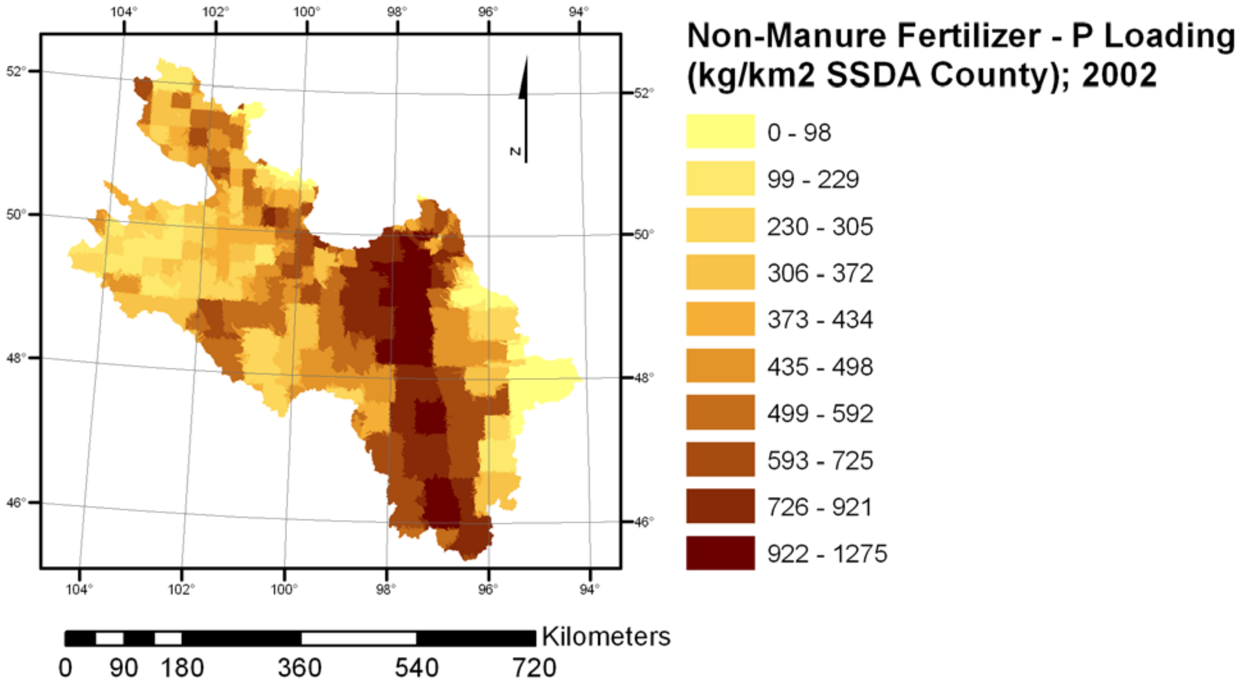

Figure 25 - Inorganic Fertilizer Loading – Phosphorus

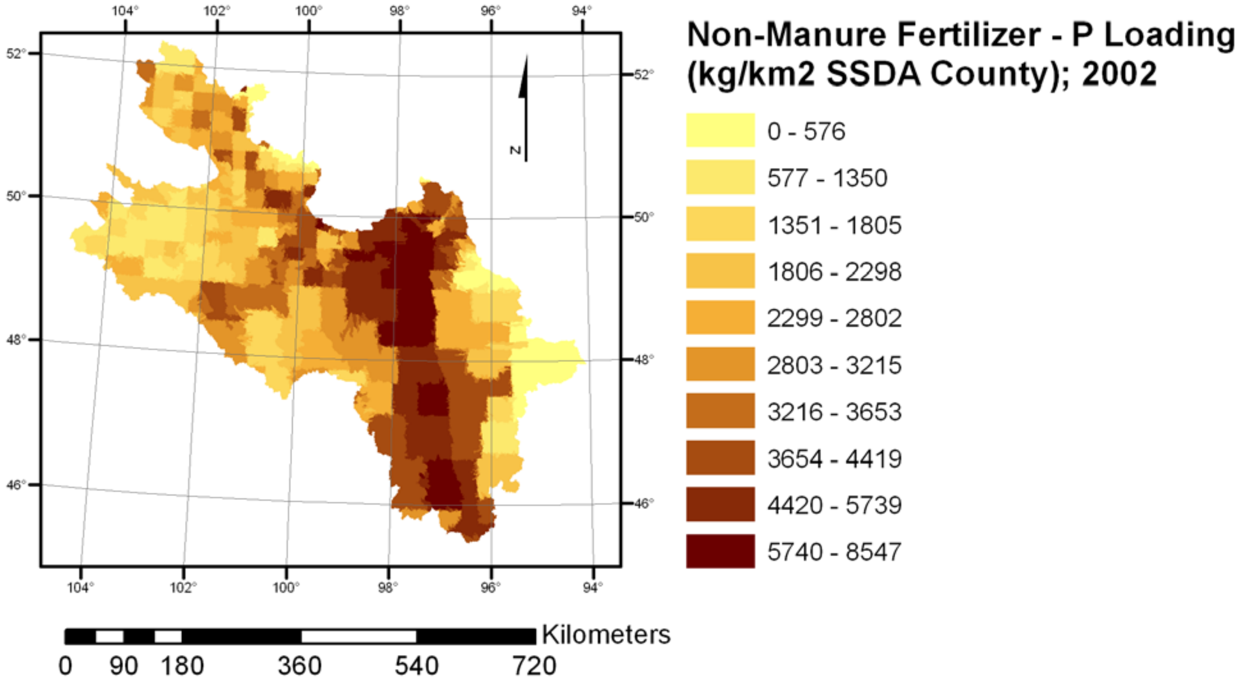

Figure 26 - Inorganic Fertilizer Loading - Nitrogen

5.4 Manure Inputs

Livestock manure is considered an important source of phosphorus and nitrogen. Livestock manure data were obtained from the Statistics Canada agricultural survey data for Canada and US Department of Agriculture (USDA) agricultural survey data for US. US data were estimated from total livestock headcounts by county, using data for the year closest to the target base year, which was 2002. Canadian data included livestock headcounts by sub-sub drainage area, which was available for 2001 [AAFC (2001)]. To harmonize the data, both surveys of livestock headcounts were combined to common classes of livestock using the cross-walk information outlined in Table 7. Manure loading estimates by reporting area were calculated by determining head counts in each reporting area and applying a multiplier supplied by AAFC [AAFC (2001)]. Total SPARROW catchment manure inputs were determined by calculating the mean total loading rate for each catchment by converting the manure loading shapefile to a 25 m raster and employing a zonal statistics tool. Figure 27 and Figure 28 illustrate the manure loading rates as phosphorus and nitrogen respectively. Although overall manure input rates appeared consistent between the US and Canadian border, inconsistencies are visible in these two datasets. This was partially explained by known differences in livestock farming practices between the US and Canada near the border.

Table 7 - Manure Nitrogen and Phosphorus multipliers by Cattle Head-count

Canadian Data	**US Data**	**Selection for SPARROW**	**N Multiplier [kg N/animal/yr]**	**P Multiplier [kg P/animal/yr]**
Beef Cattle	Beef Cattle	Beef Cattle	78.81	21.32
Milk Cows	Milk Cows	Milk Cows	25.33	6.85
Bulls	-	Not Included	-	-
Calves	-	Not Included	-	-
Heifer	Other Cattle	Heifer	52.19	14.12
Steers	Steers	Steers	56.29	15.23
Boilers	Broilers	Broilers	0.36	0.1
Laying Hens	Layers	Laying Hens	0.55	0.2
Pullets	Pullets	Pullets	0.36	0.1
Turkeys	Turkeys	Turkeys	1.54	0.57
Boars	-	Hogs and Pigs	9.93	3.31
Hogs	Breeding Hogs	Hogs and Pigs	-	-
-	Other Hogs	Hogs and Pigs	9.93	3.31
-	Hogs Sold	Hogs and Pigs	9.93	3.31
Nursing Pigs	-	Hogs and Pigs	9.93	3.31
Sows	-	Hogs and Pigs	9.93	3.31
Sheep	Sheep	Sheep	6.95	1.44
Goats	-	Not Included	-	-
Horses	Horses	Horses	49.28	11.66
Other Large Livestock	-	Not Included	-	-

Other Small Livestock	-	Not Included	-	-

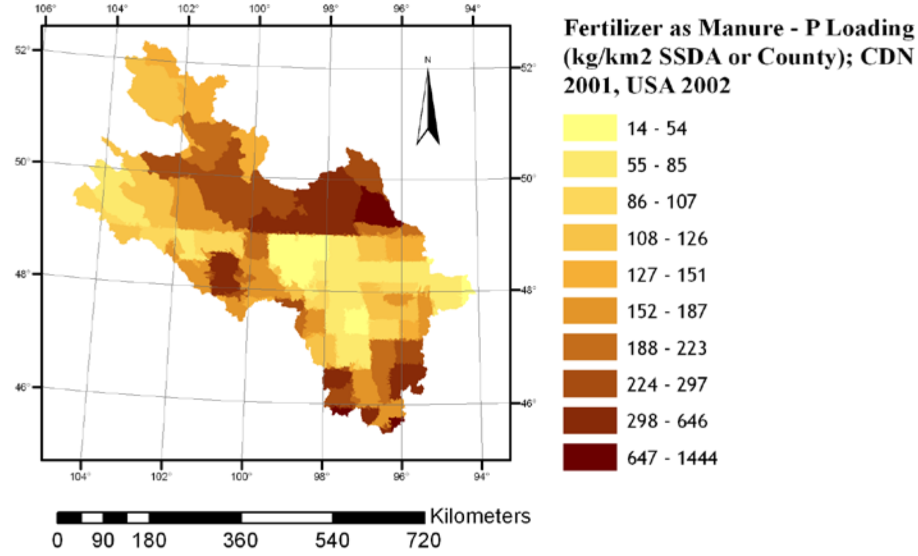

Figure 27 - Manure loading as P

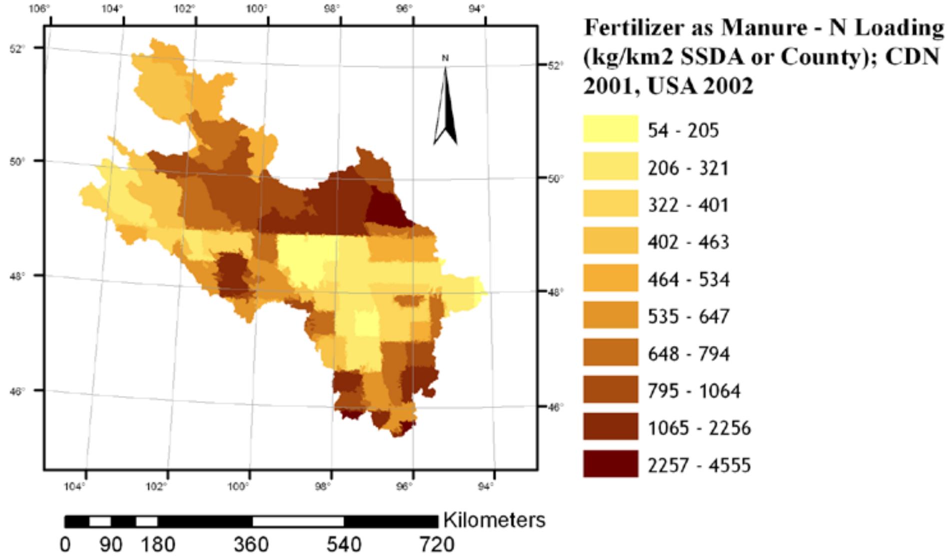

Figure 28 - Manure Loading as N

5.5 Cropping Systems

In order to describe the nutrient loading intensity, a map of "cropping systems" data was developed to describe which catchments were supporting high intensity crops and which were not. This data product served as a potential source input variable in the SPARROW models. This coverage was developed using agriculture survey data from both countries. For Canada, the 2001 Canadian Census of Agriculture was employed providing the reported crop types by census reporting area. For the US, the 2002 Census of Agriculture was employed for identifying crop types by county. The crop types were divided into High and Moderate intensity crop groupings as indicated in Table 8, by absolute area and by relative area as a fraction of the total cultivated (agricultural) land.

Table 8 - Cropping Systems Harmonization by Nutrient Intensity

Category	**Description**	**GIS code**	**2001 Canadian Census of Agriculture By Consolidated Census Subdivision**	**2002 US Census of Agriculture By County**	**Units**
Annual Cropland	Area of Cultivated / Non-perennial Crops	CultAc	[CROP_ACRE_] -([ALFALFA_AC]+ [HAY_ACRE_A])	[Cropland]- [Forage]	Acres
High to Moderate Nutrient Intensity Crops	Area of High Nutrient Intensity Row Crops, Horticulture Crops, and Low Residue Pulse Crops	HNIC1ac	[CORN_GRA_1]+ [CORN_SIL_1]+ [SOY_ACRE_A]+ [BEAN_ACRE_]+ [LENTIL_ACR]+ [PEA_ACRE_A]+ [SUNFLOWER1]+ [VEG_ACRE_A]+ [POTATO_ACR]	[CornGrain]+ [CornSilage]+ [Potato]+ [Sgrbeet]+ [Soybean]+ [DryBean]+ [Vegtbl]+ [Sunflwr]	Acres
High to Moderate Nutrient Intensity Crops	High Nutrient Intensity Row Crops, Horticulture Crops, and Low Residue Pulse Crops - Proportion of Annual Cropland	HNIC1P	([CORN_GRA_1]+ [CORN_SIL_1]+ [SOY_ACRE_A]+ [BEAN_ACRE_]+ [LENTIL_ACR]+ [PEA_ACRE_A]+ [SUNFLOWER1]+ [VEG_ACRE_A]+ [POTATO_ACR])/ [CultAc]	([CornGrain]+ [CornSilage]+ [Potato]+ [Sgrbeet]+ [Soybean]+ [DryBean]+ [Vegtbl]+ [Sunflwr])/ [CultAcre]	Ratio
High Nutrient Intensity Crops	Area of High Nutrient Intensity Row Crops and Horticulture Crops	HNIC2ac	[CORN_GRA_1]+ [CORN_SIL_1]+ [SOY_ACRE_A]+ [SUNFLOWER1]+ [VEG_ACRE_A]+ [POTATO_ACR]	[CornGrain]+ [CornSilage]+ [Potato]+ [Sgrbeet]+ [Soybean]+ [Vegtbl]+ [Sunflwr]	Acres
High Nutrient Intensity Crops	High Nutrient Intensity Row Crops and Horticulture Crops - Proportion of Annual Cropland	HNIC2P	([CORN_GRA_1]+ [CORN_SIL_1]+ [SOY_ACRE_A]+ [SUNFLOWER1]+ [VEG_ACRE_A]+ [POTATO_ACR])/ [CultAc]	([CornGrain]+ [CornSilage]+ [Potato]+ [Sgrbeet]+ [Soybean]+ [Vegtbl]+ [Sunflwr])/ [CultAc]	Ratio

Maps of High to Moderate nutrient intensity crops as a ratio of the total cultivated area (HNIC1P) and High nutrient intensity crops as a ratio of total cultivated area (HNIC2P) are shown in Figure 29 and Figure 30 respectively.

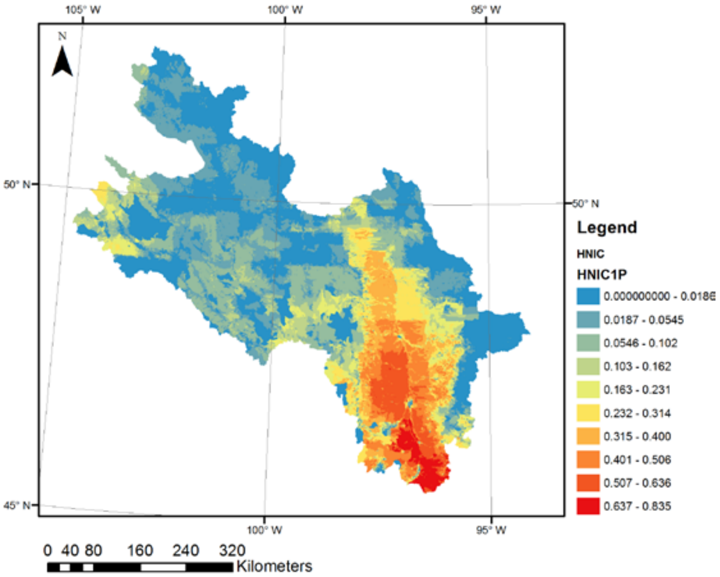

Figure 29 - High to Moderate Nutrient Intensity Crops (HNIC1P)

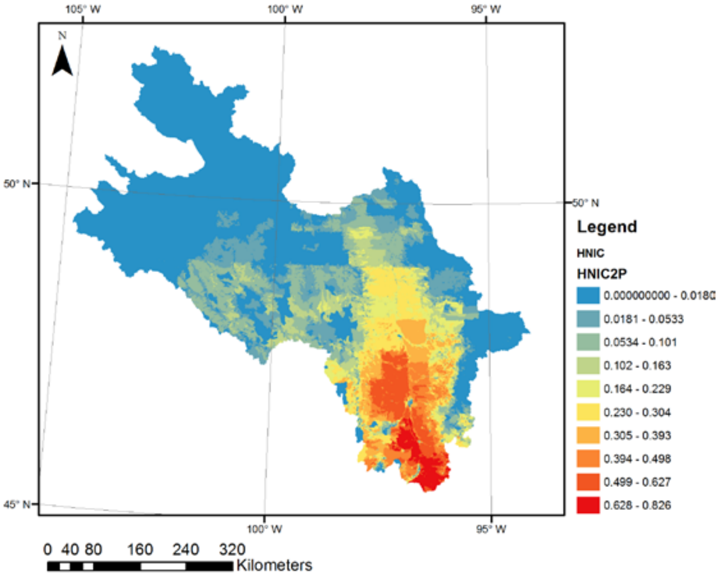

Figure 30 - High Nutrient Intensity Crops (HNIC2P)

5.6 Wastewater Treatment Plants (WWTP) Inputs

Input from wastewater treatment plants can be an important source of phosphorus and nitrogen. These inputs are often referred to as point sources because they can be defined as an input at a specific location. US data were obtained from the previously developed MRB3 model [Robertson and Saad 2011]. For the Canadian portion, the WWTP inputs were obtained from the MCWS and the Saskatchewan Water Security Agency. In total 351 point discharges were identified in the model domain and are shown in Figure 31. Each WWTP was linked to a particular catchment.

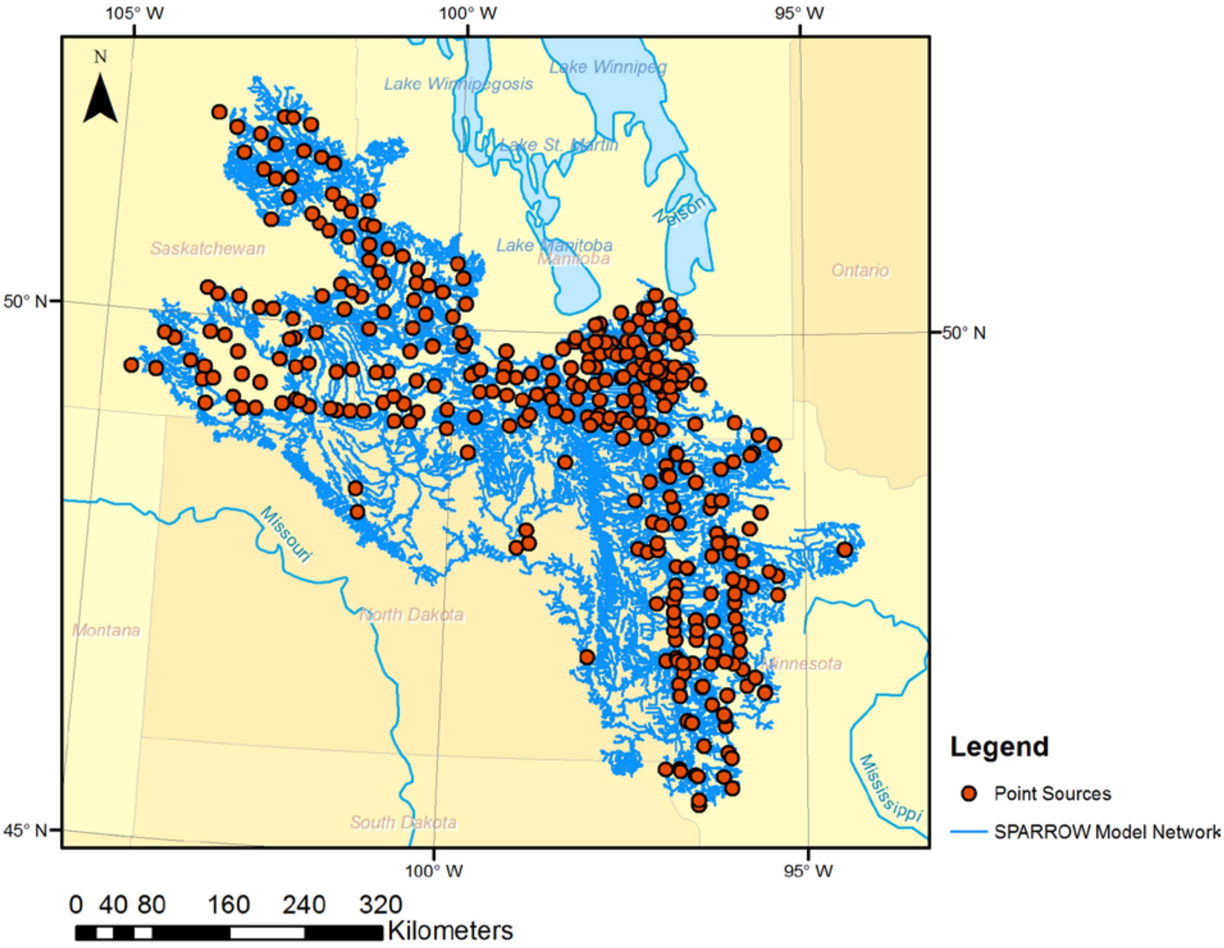

Figure 31 - Wastewater Treatment Plant Point Loading

Point source inputs were compared between state and provincial jurisdictions to ensure that estimates generated in Manitoba and Saskatchewan were representative. State and provincial point source inputs for N and P are shown in Figure 32 and Figure 33, respectively. Manitoba and Saskatchewan inputs appear similar to those of Minnesota, although Manitoba had a few very large sources, which may be due to the inclusion of the City of Winnipeg. North Dakota and South Dakota only had the “major” point sources identified making their distributions somewhat less representative.

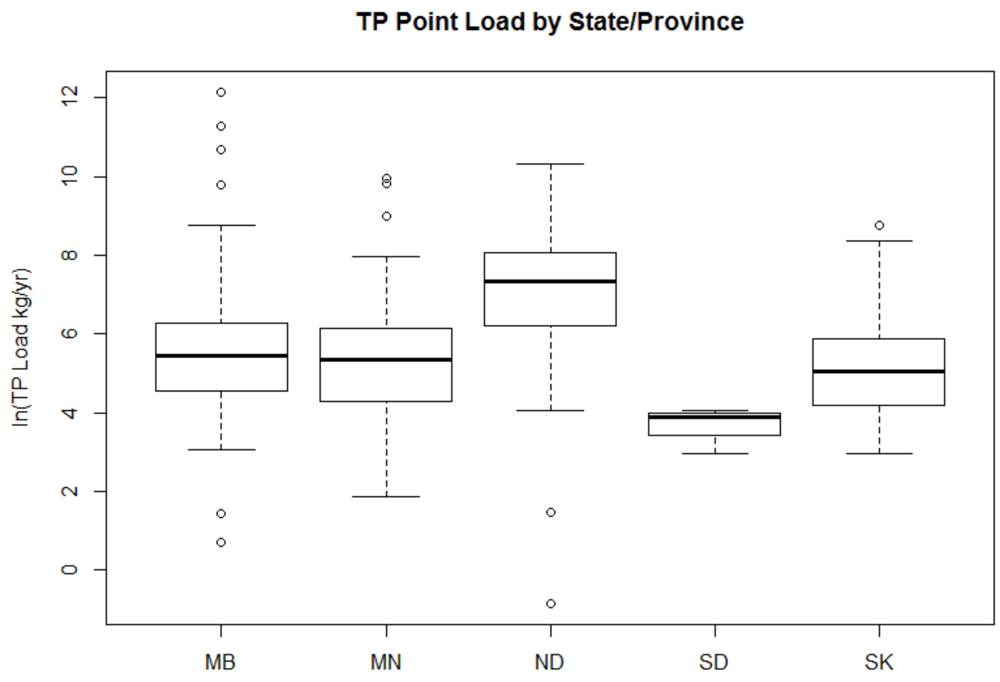

Figure 32 - Point Load Values by Province / State, Phosphorus

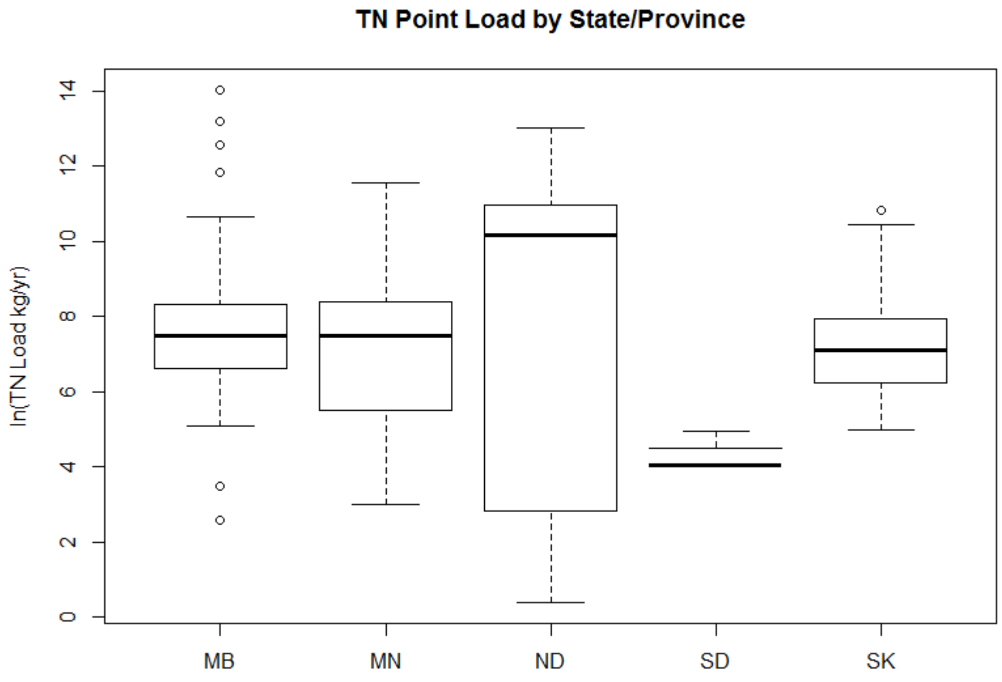

Figure 33 - Point Load Values by Province / State, Nitrogen

6 Land-to-Water Delivery Variables

SPARROW models usually include important land-to-water delivery variables which can be included in the model to explain or describe variability in nutrient transport from the source to the stream network. A series of geospatial data sources were processed in this study for examination as potential land-to-water delivery variables including:

1. Climate Data;
2. Catchment Slope;
3. Flow Path Length; and
4. Soil Permeability.

6.1 Climate Data

PRISM [Daly and Phillips (1994)], CFS and CaPA [Mahfouf et al. (2007)] data were used in this model to describe the precipitation and temperature patterns, respectively throughout the study area. Data were provided as monthly and annual averages over the period from 1971 to 2000 including precipitation and temperature data. Monthly and annual averages were provided as separate rasters with grid resolution of 900 m. CaPA precipitation data seamlessly covered all of North America. It was converted from daily measurements to monthly and annual averages over the period from 2002 to 2010. Each monthly and annual average was provided as a separate raster with grid resolution of 1000 m. CaPA contained only precipitation estimates and had no temperature data. Air temperature data were obtained from merged data from PRISM and CFS, and processed similar to precipitation.

Each of the two climate datasets were clipped to the model extent, resampled to a 25 m resolution and processed with the delineated SPARROW model catchments using a zonal statistics tool. Mean values for temperature or precipitation rates were preserved for each catchment in one shapefile for precipitation data and, in the case of the PRISM/CFS dataset, an extra shapefile for temperature containing average values for monthly and annual totals was added. The CaPA precipitation dataset is shown in Figure 35.

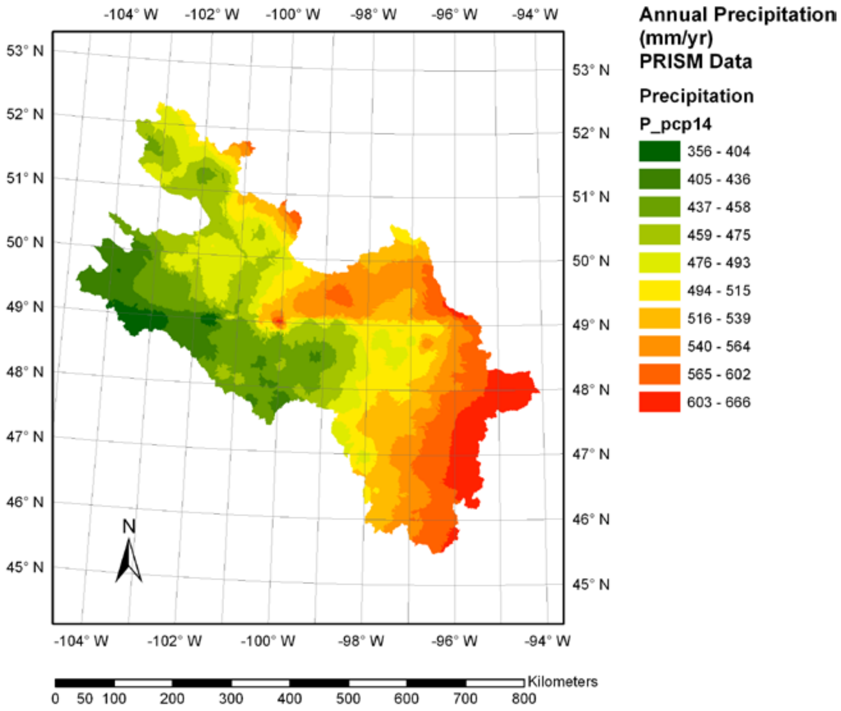

Figure 34 – PRISM/CFS Mean Precipitation Mapped to Catchments (1971-2000 Averages)

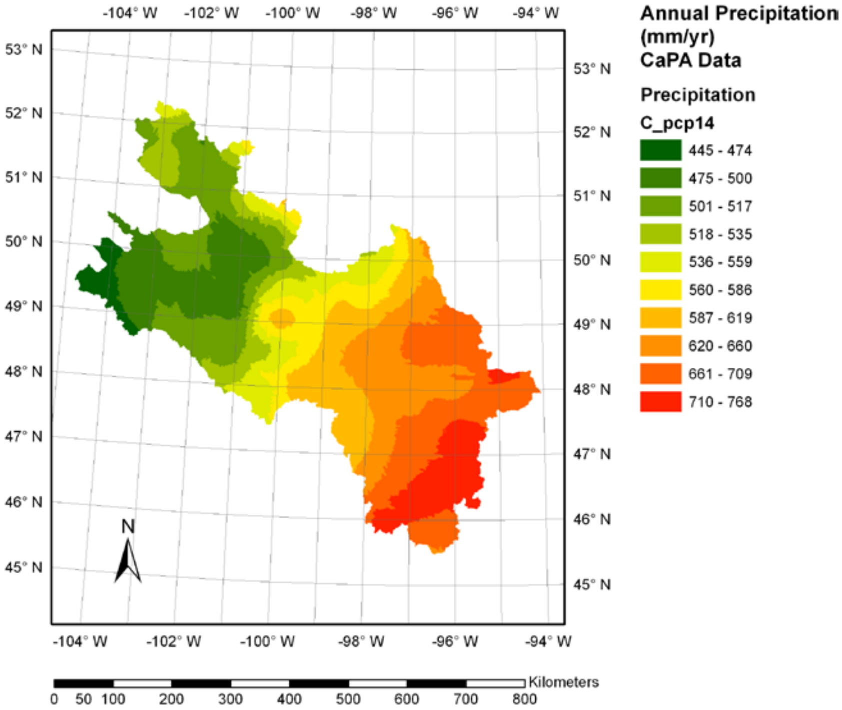

Figure 35 - CaPA Mean Precipitation Mapped to Catchments (2002-2010 Averages)

The PRISM and CFS datasets were used to describe air temperature over the model domain. The mean annual temperature estimates are shown in Figure 36, where few border effects can be visible.

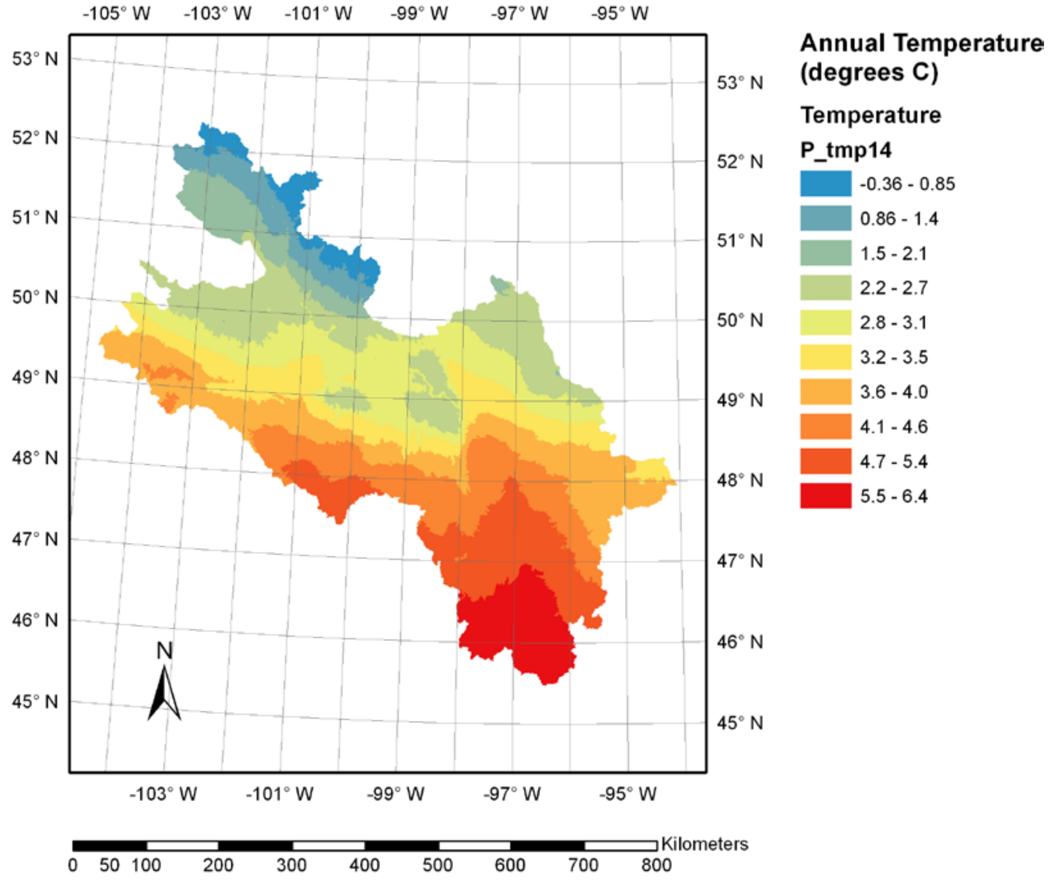

Figure 36 – PRISM/CFS Mean Temperature Mapped to Catchments (1971-2000)

6.2 Catchment Mean Slopes

Catchment mean slopes may be useful as a predictive land-to-water delivery variable for the SPARROW model. They help describe the gradient of the catchment, which may influence the transport of nutrients from surface of the land to the stream network. The slopes were derived from the DEM dataset. For each DEM cell, the slope was calculated as the maximum rate of change between the target cell and each of its neighbours. Subsequently, the slope raster derived from this calculation was averaged over each catchment using a zonal statistics tool. The average slopes are shown in Figure 37, in units of degrees.

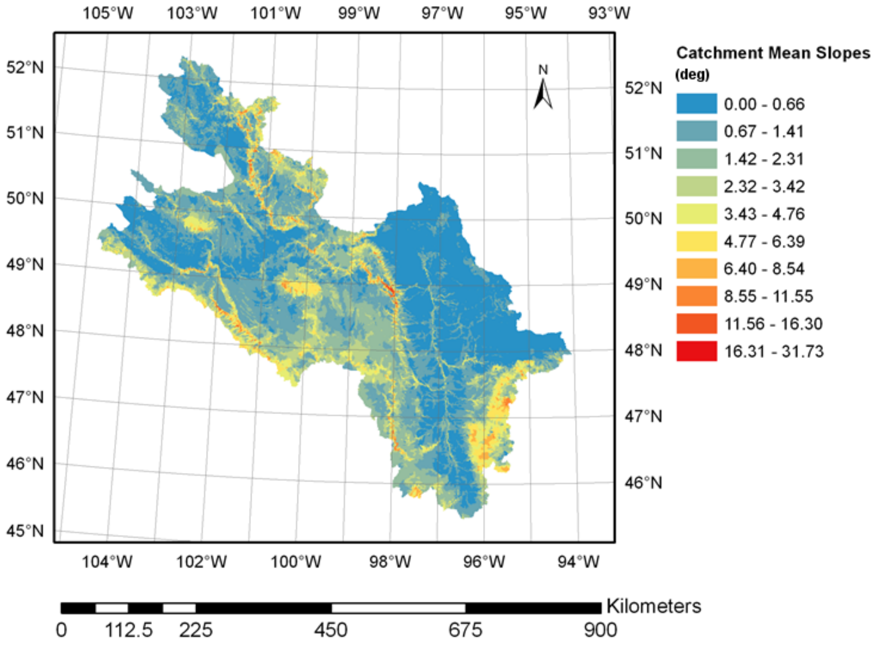

Figure 37 - Catchment Mean Slopes Mapped to the Extent of the Model

6.3 Average Flow Path Lengths

The average flow path length is the average distance a particle of water travels within the catchment before it arrives to a stream network. This was identified as a potentially important land-to-water delivery variable for the SPARROW model because nutrient fate can be influenced by travel time. Flow path lengths were calculated for each pixel in the catchment by first determining the flow direction grid from the DEM dataset, then accumulating the distance for the flow path from each pixel to the catchment stream. Subsequently, the flow path lengths for each pixel within each catchment were averaged. The flow path lengths for each catchment are shown in Figure 38.

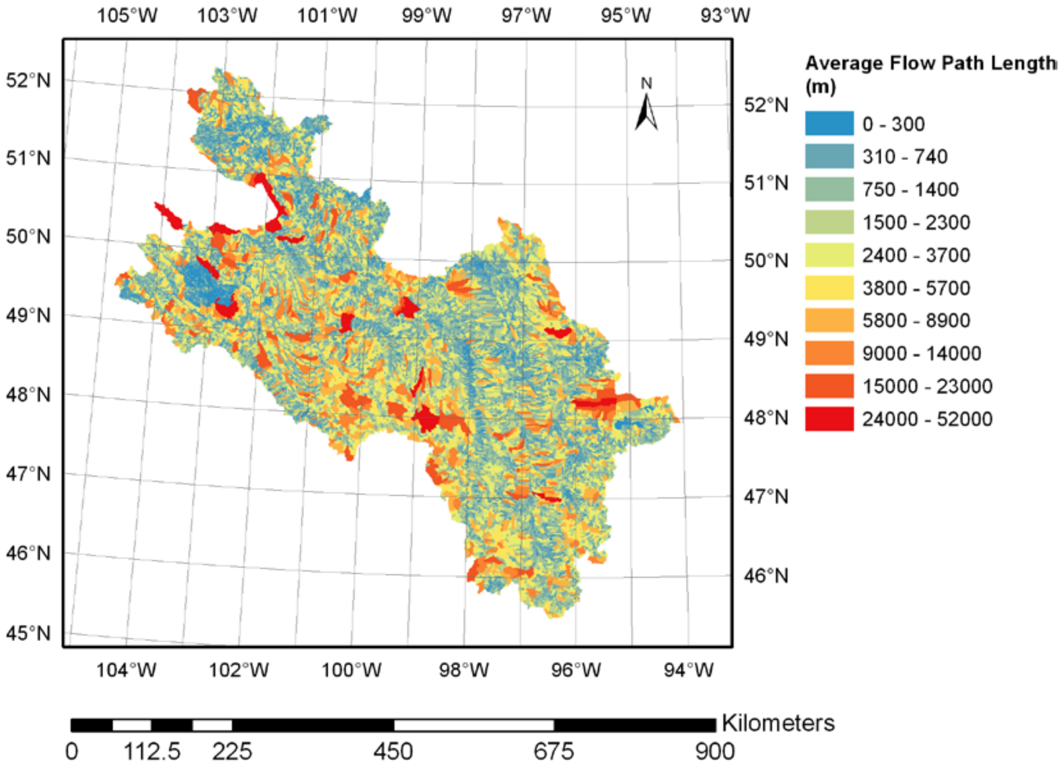

Figure 38 - Flow Path Lengths on a Catchment Basis

6.4 Soil Permeability

Soil permeability has been identified previously as a significant land-to-water delivery variable in SPARROW models, with higher soil permeability leading to a potential reduction in runoff [Robertson and Saad (2011)]. A harmonized soil permeability data set was developed by merging the Canadian AAFC Soils data [AAFC 2000] with US STATSGO data [Schwarz and Alexander 1995]. The Canadian AAFC dataset field defined as the saturated hydraulic conductivity in inches per hour was harmonized with the US STATSGO permeability field employing the same units. The results are shown in Figure 39.

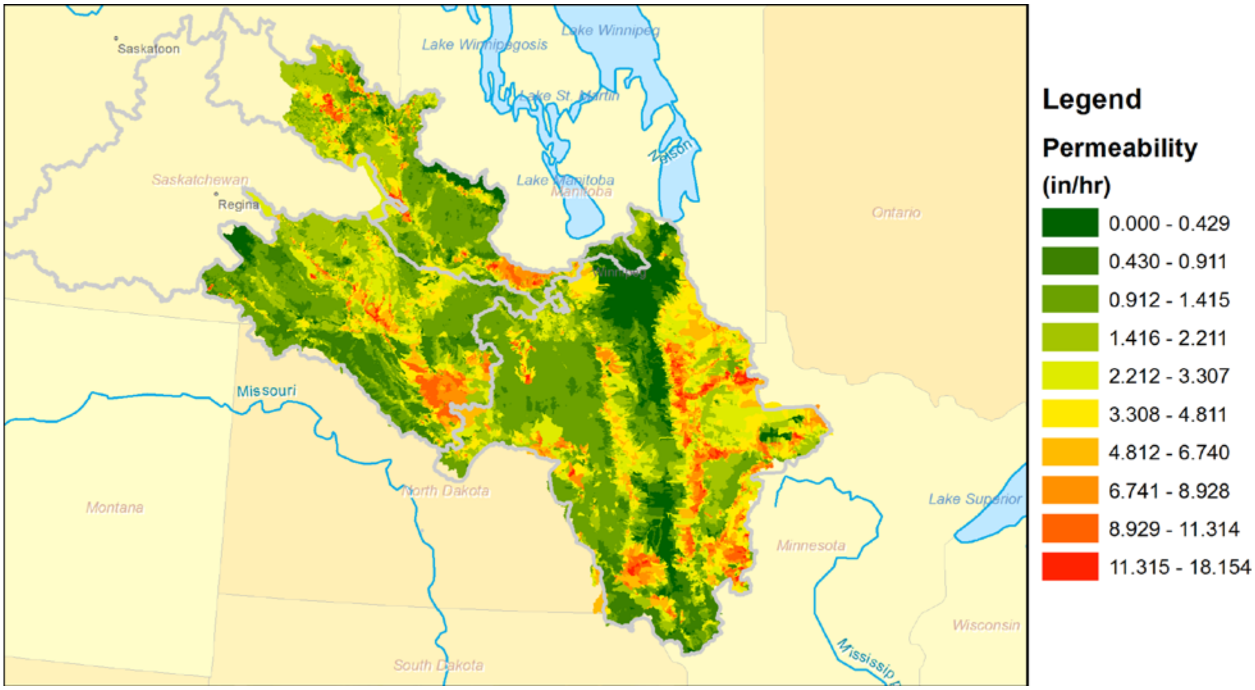

Figure 39 - Harmonized Soil Permeability Dataset

7 Next Steps: SPARROW Model Setup and Calibration

SPARROW models are GIS-based, regional, non-linear regression water quality models that simulate nutrient sources, transport and in-stream losses under steady-state conditions [Smith et al. (1997), Schwarz et al. (2006)]. The model can be used to predict annual nutrient loads for an identified representative base year to which all temporal input data have been detrended. There are three types of variables used in SPARROW models that vary spatially over the model domain: source variables, land-to-water delivery variables and in-stream loss (or in-stream source and sink) variables. Source variables quantify nutrient inputs to the model domain and typically include inputs from fertilizers, manure, atmospheric deposition, point discharges, and specific land-use types for which inputs are difficult to quantify. Land-to-water delivery variables are typically landscape or climactic properties that cause variability in the amount of nutrients that are transferred from the land to the nearby stream. These variables may describe variability in surface- or ground-water flow. In-stream variables are source or sink parameters that represent temporal net decay, deposition, source or resuspension processes in the stream channel.

7.1 Qu'Appelle River as a single point source

Due to difficulties in developing the stream network in the region of the Qu'Appelle River, it was determined that the model would be developed to exclude that portion of the drainage network (see Section 3.1). To account for the nutrient loads entering the Assiniboine River from the Qu'Appelle River, the load from this area was input as a constant (FORCE). This estimated load was obtained from the load computed for a water quality station on the Qu'Appelle River upstream of the confluence with the Assiniboine River.

7.2 SPARROW Variables

The three variable classes were calculated and included in the SPARROW data file for use in model calibration. Table 9 summarizes the variables that were calculated for use in this model. All source variables that explicitly include nutrient loads are determined as elemental nutrients (e.g. as N or P).

Table 9 - Red-Assiniboine SPARROW Variable List

Variable Code	Description	Variable Type
DEMIAREA	Catchment Drainage Area (km^2)	Source
POINT	Point nutrient discharges (kg/yr)	Source
FORCE	Point nutrient discharge for the Qu'Appelle River (kg/yr)	Source
FERT	Inorganic Fertilizer Loading (kg/yr)	Source
MAN	Manure Loading (kg/yr)	Source
WETWOOD	Portion of catchment that is Wetland or Forest (km^2/km^2)	Source
HNIC	Fraction of catchment that contains a high nutrient intensity cropping system (km^2/km^2)	Source
URBAN	Fraction of catchment containing urban land use class (km^2/km^2)	Source
CMAQ	Atmospheric deposition of N (kg/yr)	Source
PRECIP	Mean annual precipitation rate (mm/yr)	Land-to-water delivery
TEMP	Mean annual temperature (deg C)	Land-to-water delivery
KSAT	Soil permeability (in/hr)	Land-to-water delivery
FLOWLEN	Mean catchment flow path length (m)	Land-to-water delivery
RCHDECAY1	Reach nutrient decay rate for flows less than 1.3 m^3/s	In-stream decay
RCHDECAY2	Reach nutrient decay rate for flows greater than 1.3 m^3/s	In-stream decay

8 Conclusions

A SPARROW model requires development of an operational stream network, load estimates of water quality parameters throughout the network, geospatial data layers that describe all of the important sources of the constituent being modelled, and geospatial data layers for environmental characteristics that cause variation in the delivery of the sources to the stream and losses in downstream transport. Binational SPARROW modelling requires an additional phase of effort, which entails harmonizing or combining datasets from multiple jurisdictions and their data collection and management agencies.

9 References

[AAFC (2000)] AAFC. *Canadian Soil Information System: National Soil Database*. Agriculture and Agri-Food Canada, 2000.

[AAFC (2001)] AAFC. Interpolated Census of Agriculture to Soil Landscapes, Ecological Frameworks, and Drainage Areas of Canada. Technical report, Agriculture and Agri-Food Canada, 2001.

[Byun and Ching (1999)] Daewon W Byun and JKS Ching. *Science algorithms of the EPA Models-3 community multiscale air quality (CMAQ) modeling system*. US Environmental Protection Agency, Office of Research and Development Washington, DC, USA, 1999.

[Canada (2008)] Natural Resources Canada. Atlas of canada 1,000,000 national frameworks data, hydrology - drainage network. Online, 2008.

[Canadian Council on Geomatics (2009)] Canadian Council on Geomatics. National Hydro Network (NHN). Internet, 2009. http://www.geobase.ca/geobase/en/data/nhn/index.html.

[Centre for Topographic Information (CTI)] Centre for Topographic Information (CTI). Canadian Digital Elevation Data (CDED). Internet, September 2000. http://www.geobase.ca/geobase/en/data/cded/index.html.

[Centre for Topographic Information (CTI)] Centre for Topographic Information (CTI). Land cover, circa 2000-vector data product, edition 1.0. Technical report, Natural Resources Canada, 2009.

[Cohn (2005)] Timothy A Cohn. Estimating contaminant loads in rivers: An application of adjusted maximum likelihood to type 1 censored data. *Water Resources Research*, 41 (7): W07003, 2005.

[Daly and Phillips (1994)] R.P. Neilson Daly, C. and D.L. Phillips. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. *Journal of Applied Meteorology*, 33: 140–158, 1994.

[Elliott et al. 2005] Elliott, A.H., R.B. Alexander, G.E. Schwarz, U. Shankar, J.P.S. Sukias and G.B. McBride. 2005. Estimation of nutrient sources and transport for New Zealand using the hybrid mechanistic-statistical model SPARROW. J. Hydrology (NZ). 44:1-27.

[Environment Canada (2010)] Environment Canada. *EC Data Explorer Reference Manual - Version 1.2*, September 2010. URL http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=0A47D72F-1. http://www.ec.gc.ca/rhc-wsc/default.asp?lang=En&n=0A47D72F-1.

[ESRI (2010)] ESRI. *ArcGIS Help Library - ArcGIS 10*. ESRI, 2010.

[Homer and Wickham (2007)] Dewitz J. Fry J. Coan M. Hossain N. Larson C. Herold N. McKerrow A. VanDriel J.N. Homer, C. and J. Wickham. Completion of the 2001 national land cover database for the conterminous united states. *Photogrammetric Engineering and Remote Sensing*, 73 (4): 337–341, 2007.

[Jobson (1997)] Harvey E. Jobson. Predicting travel time and dispersion in rivers and streams. *Journal of Hydraulic Engineering*, 123: 971–978, 1997.

[Johnston et al. (2009)] C.M. Johnston, T.G. Dewald, T.R. Bondelid, B.B. Worstell, L.D. McKay, Alan Rea, R.B. Moore, and J.L. Goodall. Evaluation of catchment delineation methods for the medium-resolution national hydrography dataset:. Investigations Report 2009–5233, U.S. Geological Survey Scientific, 2009. URL http://pubs.usgs.gov/sir/2009/5233/.

[Laitta (2010)] Michael Laitta. Canada-U.S. Transboundary Hydrographic Data Harmonization Efforts Gain Momentum - International Joint Commission (IJC). Online, October 2010. URL http://www.ijc.org/-rel/boards/watershed/Canada-US_Hydro_Harmonization_e.pdf.

[Mahfouf et al. (2007)] Jean-François Mahfouf, Bruce Brasnett, and Stéphane Gagnon. A canadian precipitation analysis (capa) project: Description and preliminary results. *Atmosphere-ocean*, 45 (1): 1–17, 2007.

[NRC-CHC (2010)] NRC-CHC. *Green Kenue Reference Manual*. National Research Council Canada - Canadian Hydraulics Centre, Ottawa, Ontario, September 2010.

[PFRA (2008)] PFRA. PFRA watershed project – areas of non-contributing drainage. Online, March 2008.

[Preston and Hamilton (2009)] R.B. Alexander M.D. Woodside Preston, S.D. and P.A. Hamilton. Sparrow modeling—enhancing understanding of the nation's water quality. Survey Fact Sheet 2009-3019, U.S. Geological, 2009.

[Robertson and Saad (2011)] Dale M Robertson and David A Saad. Nutrient inputs to the laurentian great lakes by source and watershed estimated using sparrow watershed models1. *Journal of the American Water Resources Association*, 47 (5): 1011–1033, 2011.

[Saad et al. (2011)] Saad, D.A., G.E. Schwarz, D.M. Robertson and N.L. Booth. 2011. A multi-agency nutrient dataset used to estimate loads, improve monitoring design, and calibrate regional nutrient SPARROW models. Journal of the American Water Resources Assocation, 47 (5): 933-949.

[Schwarz (2006)] G.E. Schwarz. The SPARROW surface water-quality model: Theory, application, and user documentation. 2006.

[Schwarz and Alexander (1995)] G.E. Schwarz and R.B. Alexander. Soils data for the conterminous united states derived from the nrcs state soil geographic (statsgo) data base. Online, September 1995.

[Schwarz et al. (2006)] G.E. Schwarz, A.B. Hoos, R.B. Alexander, and R.A. Smith. The SPARROW Surface Water-Quality Model: Theory, Application and User Documentation. In *U.S. Geological Survey Techniques and Methods - Book 6, Section B*, chapter Chapter 3. USGS, 2006.

[Smith et al. (1997)] R.A. Smith, G.E. Schwarz, and R.B. Alexander. Regional interpretation of water-quality monitoring data. *Water Resources Research*, 33 (12): 2781–2798, 1997. ISSN 0043-1397.

[USGS (2010)] USGS. Shuttle radar topography mission. Internet, 2010. URL http://dds.cr.usgs.gov/-srtm/version2_1/SRTM3/.

[USGS (2010)] USGS. National elevation dataset (ned). Online, 2010. URL http://ned.usgs.gov/.

[USGS and USEPA (2006)] USGS and USEPA. *NHDPlus User Guide*. US Geological Survey and US Environmental Protection Agency, June 2006.

Appendix A

9.1 Coordinate System

The Albers Equal-Area Projection was used as a standard coordinate system for the entirety of the project.

Table 10 - Albers Equal-Area Projection

Central Meridian	-96
Latitude of Origin	23
1st Standard Parallel	29.5
2nd Standard Parallel	45.5
Ellipsoid	NAD83