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Advances in the Integration of Watershed and Lake Modeling in the Lake Winnipeg Basin

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Abstract: Estimating non-point source pollution from watersheds and the effects of mitigation measures (e.g. beneficial management practices or BMPs) is an important step in managing and protecting water quality, not only at the basin level where it originates, but also at the receiving waters such as reservoirs, lakes or oceans. Lake Winnipeg is a prime example of such land-lake interactions, where eutrophication and increased algal blooms in the lake are fueled, as evidence suggests, from agricultural sources of nutrients in the region. Over the years, simulation models at the watershed level have been applied to aid in the understanding and management of surface runoff, nutrients and sediment transport processes. Similarly, models with different degrees of complexity are used to simulate the aquatic ecology and water quality in lakes. The Soil and Water Assessment Tool (SWAT) is a widely known watershed model, which provides estimations of runoff, sediment yield, and nutrient loads at a sub-basin level. Here we examine the application of SWAT to one of three pilot watersheds on the Lake Winnipeg basin in order to investigate the impacts and uncertainties of different BMPs on nutrient loading in the targeted catchment areas. We also explore avenues for scaling and propagating such loads and uncertainties into the receiving lake models.

Keywords: Environmental models, watershed-lake models, water quality, Lake Winnipeg

Introduction

Lake Winnipeg receives surface water discharges from a large basin area ($1x10^6$ km^2), where nonpoint source pollution (NPS) from agricultural practices has being associated with an increased rate of eutrophication in the lake (Salvano et al., 2009, Jones et al., 2001). Even though the Lake Winnipeg watershed spans four provinces and four states (see insert on Figure 1), the major Canadian sources for contributing loads of nitrogen (N) and phosphorus (P) to the lake originate on the agricultural regions of southern Manitoba, in particular on the Red-Assiniboine basin, as described in Bourne et al, 2002; who based their load estimates on long-term water quality and stream flow data. Environment Canada, in a joint project with Agriculture & Agri-Food Canada, and within the framework of the Lake Winnipeg Basin Initiative (LWBI), is working on establishing a set of modeling tools to estimate sediments and nutrients generated from non-point sources in the watersheds, accounting for washed-off processes by overland flows during hydrological events, as well as simulating the final fate of these pollutants when they enter the lake. The challenge is to properly represent all these scales and interactions via an integral approach where hydrological, hydrodynamic and water quality model linkages are required to simulate such complex physical, chemical and biological processes. An immediate objective of the modeling exercise is to determine the impacts of land use change and Beneficial Management Practices (BMPs) implementation on nutrient loadings and the water quality of streams in targeted watersheds of the Red-Assiniboine basins: La Salle River (2,400 km^2), the Boyne River (1,100 km^2), both on the Red; and Little Saskatchewan River (4,000 km^2) on the Assiniboine (see Figure 1 for a schematic of the targeted watersheds). This task will be accomplished following calibration and validation of the selected model suitable for scenario testing in agricultural landscapes. Results should provide valuable information to enable prioritization of land and agricultural management actions that will effectively reduce loading of nutrients into the lake.

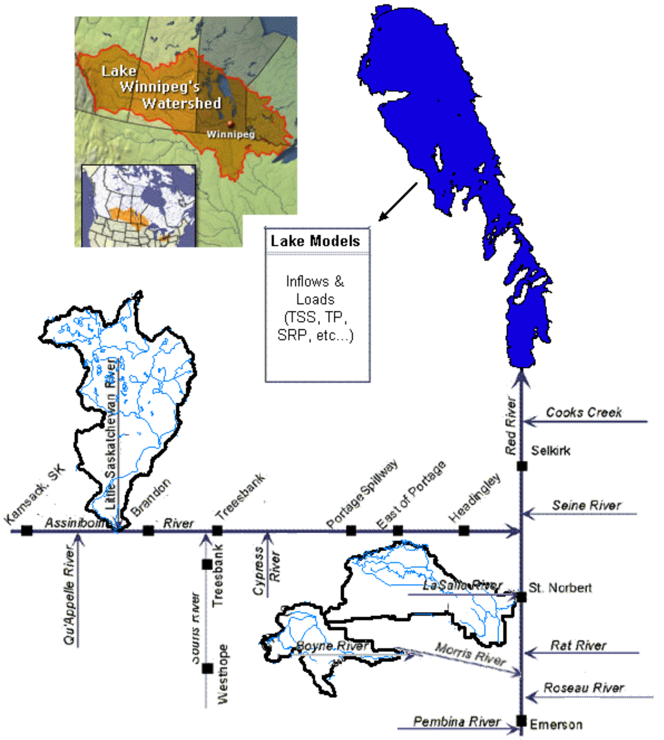

Figure 1. Lake Winnipeg targeted watersheds on top of loading schematics from nutrient loads reports (Jones and Armstrong, 2001). Note: Lake Winnipeg not shown at scale.

Modeling Approach

The Soil and Water Assessment Tool (SWAT) is a well known watershed model (Di Luzio et al., 2001; Neitsch et al., 2002) which provides estimates of runoff, sediment yield, and nutrient loads at a sub-basin level. SWAT is being used as the watershed scale hydrologic model in this project, due in fact to its capacity to simulate loadings to contributing streams across a wide range of scales; it also provides tools for scenario testing in agricultural landscapes. SWAT model output eventually will integrate with lake models for Lake Winnipeg. To setup SWAT on the three selected watersheds, a minimum set of data are required: i) Digital Elevation Model data or DEM, ii) soil type distribution, iii) land use coverage. Figure 2 shows the map data used in the study and the DEM for the basins derived from SRTM 90m Digital Elevation Data of NASA Shuttle Radar Terrain Mission: http://srtm.csi.cgiar.org/; http://www2.jpl.nasa.gov/srtm/. To match the resolution of land use raster manipulation, the grid was re-sampled (bi-linear interpolation) at 30m cell size. During the watershed delineation process, and after several iterations in order to make sure that the model output properly ran through the main drainage network, a number of small stream segments used to burn-in the DEM were edited at points where they commonly miss-direct flow. The resulting sub-basin delineation for the watersheds also presented in Figure 2, and is annotated with a raw measure of the mean slope (elevation drop/mean basin length) for each watershed, highlighting the flatness of the La Salle River watershed that made it the most difficult basin to delineate in this study.

Regarding soil distribution, the La Salle River watershed is dominated mainly by clays (74%) and portions of sand/silt-loams (26%); the Boyne River basin has mostly loamy-sands and sandy-loams (84%); and in the Little Saskatchewan River watershed loams (60%) and clay-loams (35%) are the dominant soil types. With respect to land use distribution, the watersheds have different degrees of agricultural land, forests, grasses, urban, wetlands and water. From the agricultural perspective, being the main nutrient source, agricultural land dominates the landscape in the La Salle River watershed with nearly 80% of the total area, followed by the Boyne River basin with 68% and the Little Saskatchewan River with 58%. Besides the evident differences in drainage areas, topography, soil type distribution and land cover between the La Salle, the Boyne and the Little Saskatchewan; these watersheds also present distinct drainage features which will need particular consideration in the model. For the La Salle watershed, there are additional point sources to simulate: a) water diversions from the Assiniboine directly into the headwaters of the basin at three locations, and b) the discharges from a dozen of sewage treatment plants located across the watershed. For its part, the Boyne watershed features the Stephenfield reservoir, right up-stream of its outlet, which calls for the model reservoir option to be used. Finally, the Little Saskatchewan watershed, which is full of natural depressions or potholes, including large non-contributing areas, will require DEM manipulation (Grimaldi et al., 2007; Lindsay et al., 2006) to identify volumetric retention by sub-basin and enable the pond function of the model.

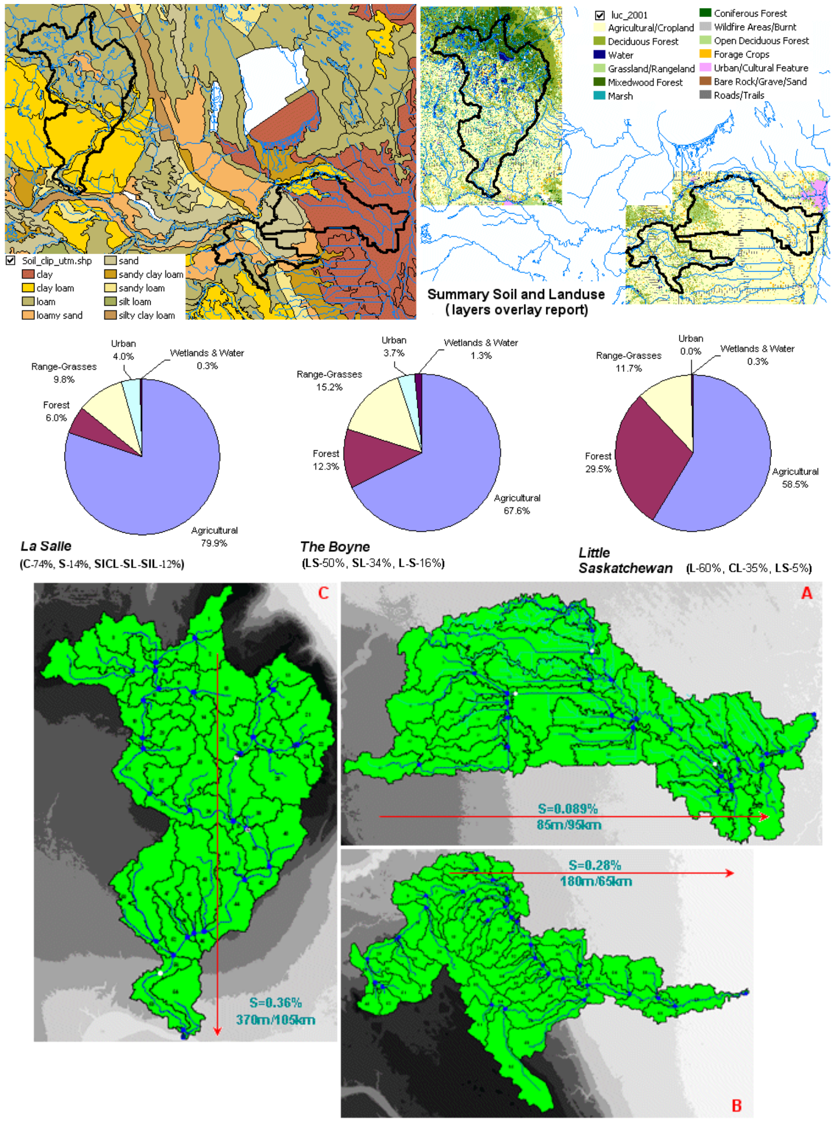

Figure 2. Digital maps and SWAT watershed delineation for pilot watersheds - top: soil and land maps; middle: land use plots and soil type percentages; bottom: DEM-delineation on targeted watersheds: A) La Salle, B) Boyne, and C) Little Saskatchewan.

Results and Uncertainties: La Salle Simulations

The remainder of the paper will centre on the La Salle watershed including simulation results and preliminary calibration/uncertainty analysis. Meteorological forcing to drive the model includes: precipitation, max and min temperatures, solar radiation, relative humidity and wind speeds. Meteorological data is available for stations neighboring the basin and Figure 3 shows sample plots of precipitation at three of the stations. It also indicates sites of interest where measured data are available (flows and water quality variables) for calibration-validation and comparison against model estimates. When working with models, calibration and validation are necessary steps and it is usually quite a challenge to get the proper setup and performance of the model. As with any model there are a number of uncertainties associated with input data, with conceptual model assumptions, parameters, and even with the same observed data used for the calibration-validation process. Note that the use of the term ‘validation’ basically intends to follow the common terminology, as a completely validated watershed model remains a subjective issue. For the La Salle watershed preliminary initial results, limited to 500 iterations and with the uncertainties aggregated to the parameters, the Generalized

Likelihood Uncertainty Estimation program GLUE (Abbaspour et al., 2007) was used on a combined calibration and uncertainty analysis. The parameter aggregation leads to estimated uncertainty in the output; quantified by the 95% prediction uncertainty band calculated at the 2.5% and the 97.5% levels of the distribution.

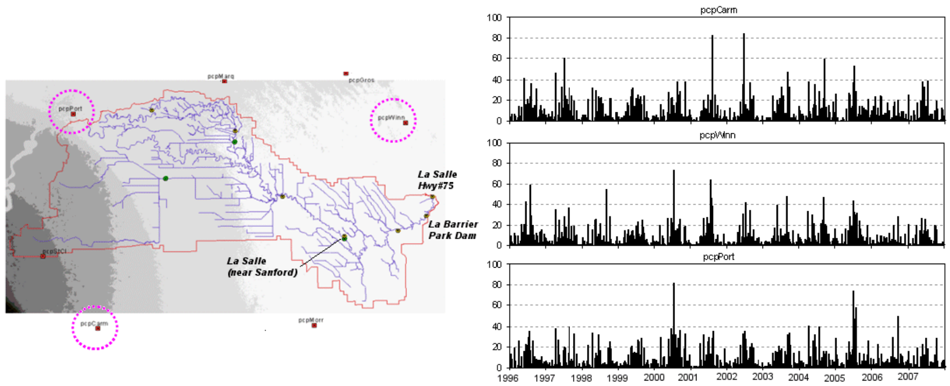

Figure 3. Precipitation at three of the rain gauges in La Salle; map indicates sites of interest where data are available for comparison with model output.

Table 1 presents a set of meaningful parameters and bracketed ranges for each model process, selected from an extensive literature review on the calibration of SWAT in a wide variety of watersheds and scenarios. In order to evaluate model output related to the runoff component, simulated river discharge is compared to the measured stream flow using indices such as the root mean square error (R^2), and the Nash-Sutcliffe (*NS*) coefficient of efficiency (Nash and Sutcliffe, 1970). Additionally, the *P-factor* and the *R-factor* are two indices commonly used to compare predicted output by uncertainty bands and evaluate the strength of the calibration and uncertainty analysis (Schuol et al., 2006). *P-factor* gauges the degree to which measured data are bracketed in the 95% band of the predicted uncertainty (95PPU). The larger the *P-factor*, the more measured data are contained in the range (max *P-factor*=1 implies all measured data are within the 95% bracket). The *R-factor* is a ratio between the thickness of the 95PPU band and the standard deviation of the measured data (Yang et al., 2008), indicating the width of the uncertainty interval. *R-factor* indicates the strength of the calibration and should be close to or smaller than a practical value of 1.

Table 1. Parameter Selection and Ranges for Calibration of SWAT in the La Salle River.

Model Process	Parameter *	Description	Default [range]*	Value
Hydrology	SFTMP	Snow fall temperature (C)	1 [-5 : 5]	0
	SMTMP	Snowmelt base temperature (C)	0.5 [-5 : 5]	0.8
	SMFMX	Max snowmelt rate (mm/C-day)	4.5 [0 : 10]	2.5
	SMFMN	Min snowmelt rate (mm/C-day)	4.5 [0 : 10]	2.5
	TIMP	Snowpack temperature lag factor	1 [0.01 : 1]	0.2
	SNCOVMX	Snow amount for 100% cover (mm)	1 [0 : 500]	10
	ESCO	Soil evaporation compensation factor	0.95 [0.01 : 1]	0.05
	SURLAG	Surface runoff lag time	4 [0 : 24]	0.8
	ALPHA_BF	Base flow recession constant	0.048 [0 : 1]	0.141
Sediment	SPCON	Factor for channel sediment routing	0.0001 [0 : 0.01]	0.0002
	CH_N2	Main channel Manning's roughness	0.014 [0 : 0.3]	0.05
	CH_EROD	Channel erodibility factor	0 [0 : 0.6]	0.3
Nutrients	RCN	Nitrogen in rainfall (mg N/l)	1 [0 : 15]	1.5
	NPERCO	Nitrogen percolation coefficient	0.2 [0.01 : 1]	0.6
	PPERCO	Phosphorus percolation coefficient	10 [10 : 17.5]	10

*(references): Green et al., 2007; Santhi et al., 2001; Georgas et al., 2009; Arnold et al., 1998; Santhi et al., 2008; Cho et al., 2009; Kumar and Merwade, 2009; Arabi et al., 2007;

Model results for La Salle River watershed are preliminary with a basic selection of parameters and a limited number of iterations for the calibration and uncertainty analysis. The results and comparisons of SWAT output against measured values for flow and nutrients in the La Salle River basin are shown in Figure 4 for daily flows near Sanford and nutrients at the watershed outlet (see locations in Figure 3). Calculated and measured flows and nutrients are compared on a daily and monthly basis; including the basic statistics of the GLUE program as shown in Figure 5. It should be noted that at the desktop level, only 500 iterations where performed as initially. In the SWAT-CUP manual suggest a number of runs for GLUE around 10,000 iterations. Research is being done to implement the intensive computational task in multi-processor high speed parallelized servers.

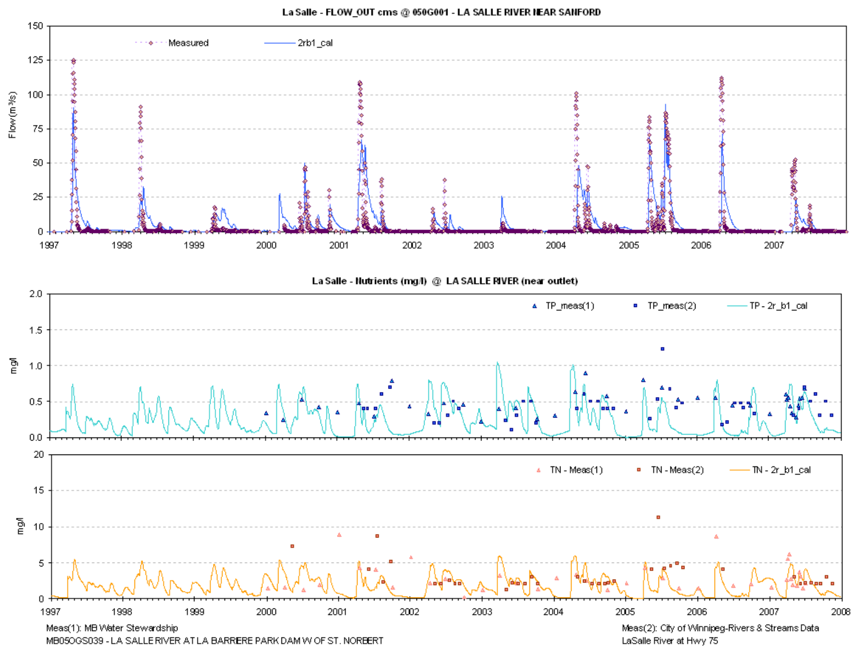

Figure 4. Daily SWAT output against measured values for flow and nutrients in the La Salle River basin (top: daily flows near Sanford; bottom: nutrients at the watershed outlet)

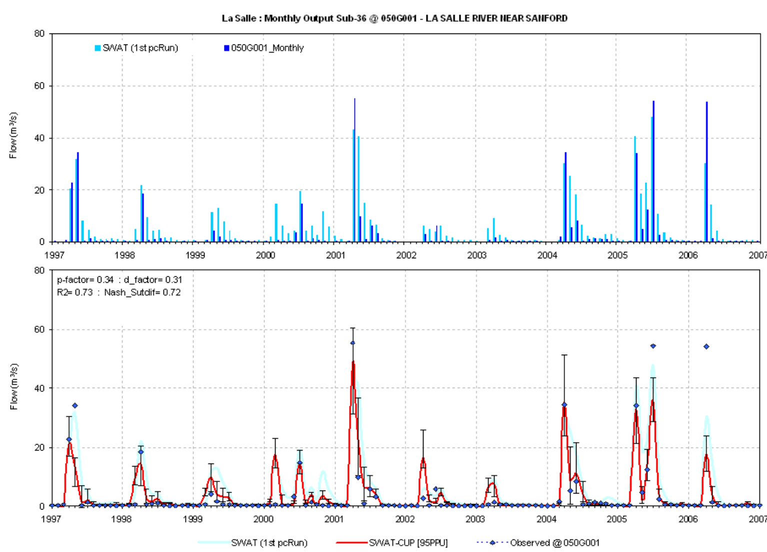

Figure 5. Monthly SWAT output calibration with GLUE from SWAT-CUP (top: daily flows and nutrients with 1st set of parameters; bottom: monthly values-95% uncertainty brackets)

Scaling-up Inflow Loadings to the Lake

The effects of watershed BMPs on Lake Winnipegs water quality requires the scaling-up of the loadings from the selected 3 pilot sub-watersheds to represent the whole Red River watershed loadings in this land-lake model integration. This scaling-up is required since the

Red River watershed is too large to model in its entirety for this project. This first approach uses statistical analysis to attempt to relate the TSS (total suspended solids) and nutrients in the pilot sub watersheds to the total loading for the Red River entering the lake. The resulting relationships can be used to scale up simulated sub-watersheds runoff and loading to the lake.

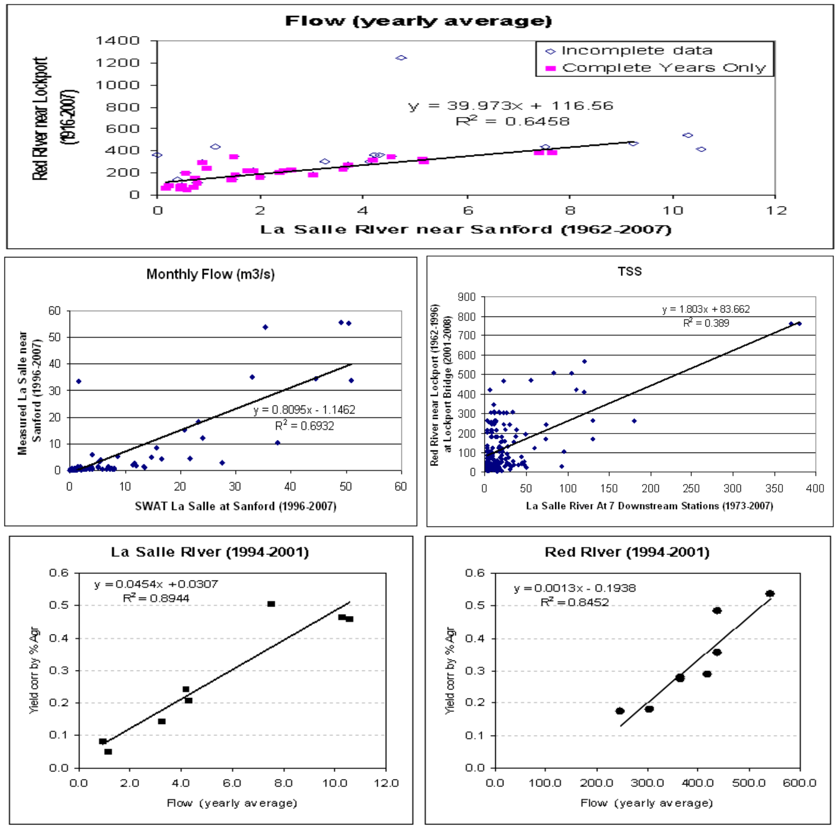

Figure 6. La Salle and Red rivers regressions: top) yearly average flow; mid) monthly flows and TSS; bot) yearly average TP yield (kg/ha AGR/yr)

The daily flow rate for the most downstream flow station on La Salle, La Salle near Sanford, was correlated with the most downstream flow station on the Red River, Red River near Lockport, using a linear relationship. The R^2 value is reasonable given the size of upscaling. Using monthly average values results in a R^2 of 0.61 which is better than when using daily values (R^2=0.50). It should be noted that La Salle experiences many periods of zero flow, especially during the winter when there is ice cover, which makes it harder to establish a trend. The linear trend: y = 36.474x + 152.7, (R^2=0.6116) was estimated for monthly averages (months with missing values not included). Figure 6-top shows yearly average flows for the Red River versus La Salle River observations. Those years with no missing data have a linear regression R^2=0.65. Also plotted are years with some missing data which tend to be further from the regression line. The plot in Figure 6-mid shows measured and model results (SWAT). For flows, it is close to a 1:1 relationship. Due to the model imperfections it might be better to estimate the measured from the SWAT results then use the estimated measured to get the Red River. TSS was compared between downstream La Salle stations (1973-2007) and Red River near Lockport (1962-1996) and Red River at Lockport Bridge (2001-2008). The seven La Salle stations are: La Salle River Rock Dam SW 34-8-2 E; La Salle River at La Barriere Park Dam W of St. Norbert; La Salle River at Pr 330 at La Salle WQ0069; La Salle River at PTH #75 in St. Norbert; La Salle River Bridge NE 35-8-2 E; La Salle River End of Mile Road East of SE 34-8-2 E; La Salle River Riverbank Farms SE 34-8-2 E. R^2 is 0.51 for highway 75 station (most downstream La Salle station) versus 0.39 when using all 7 stations. The La Salle stations have similar linear slopes from 0.9-4.9 compared to the Red River near Lockport. This downstream regression is encouraging but there could be backwater influence from the Red River on this site, especially during high flow and low flow periods which could account for the good correlation. City of Winnipeg measurements were added to the plots for Red River at Lockport Bridge (2001-2008). For nutrients, and as a first attempt, TP (total phosphorus) is compared between La Salle and Red River. For the Selkirk area of Red River, we obtained data from the City of Winnipeg at Red R. at Lockport Bridge 2001-2008. In the La Salle basin, La Salle River at La Barriere Park Dam W of St. Norbert (MB05OGS039) is the only site with data in this time period. Unfortunately there are only a few dates matching between stations, so monthly values were estimated first. With such limited data, a good correlation is not expected. Regression between observed values at the two sites was weak, with very low values of R^2. Additional analysis produced better results using yearly averages. TP values were compared using the data from Bourne et al. (2002) for 1994-2001. The TP yield was compared to the average flow rate in Figure 6-bot for La Salle River and Red River and linear regression line was fitted for both resulting in R^2 of 0.89 and 0.85, respectively.

Integration with Lake Models

Scaled up watershed loadings are integrated with a lake model capable of simulating their fate. Important parameters include TSS and TP which can affect eutrophication and algal blooms in the lake. The impacts and uncertainties of different BMPs on the loadings can in turn be determined in the lake. Two models were selected to simulate circulation and transport in the lake: OneLay and PolTra (Simons and Lam, 1986); which combined form a 2-D horizontal vertically mixed lake model. The models are based on a rectangular grid representation of the lake. OneLay is the hydrodynamic program that uses lake depths, river inflow/outflow, and wind vector to simulate horizontal currents and water levels. PolTra is the pollutant transport model that includes river loading and uses the bathymetry and water transport computed by OneLay to simulate water and sediment concentrations. These two models were selected because, compared to 3-D models, they are relatively simple and fast running, which is desirable during the preliminary testing stages. Also the two models are "in house" models so the source code is readily available and familiar. OneLay and PolTra for this study included the addition of resuspension from the sediments based on orbital velocity as well as modifications to implement in OpenMI. Modelled inflows include the Saskatchewan River, Dauphin River, Red River and Winnipeg River, which make up 80 to 90% of the inflow to the lake. Winnipeg River contributes approximately 45% of the inflow but the Red River tends to be the dominant contributor of water quality loads such as nutrients. Figure 10 shows the TSS observations in the fall of 2002 and the PolTra simulated values for October 20, which is the median date of the fall cruise measurements. The cumulative average root mean square error for the entire simulation was approximately 9 ppm.

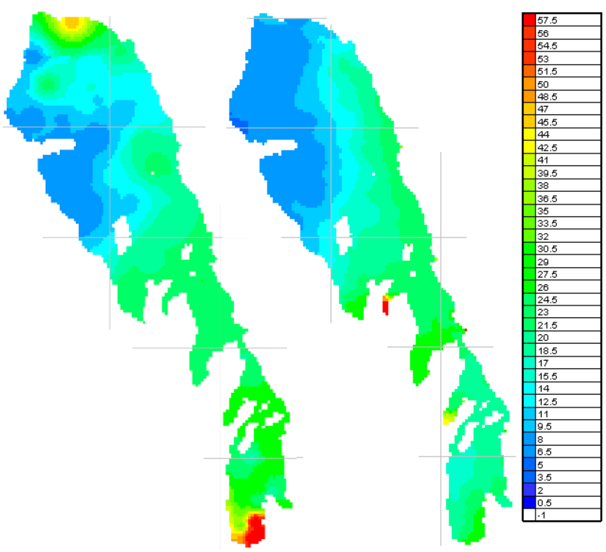

Figure 10. Lake Winnipeg TSS October 2002 Observed and PolTra simulation (ppm)

Conclusions

Even though the results shown in this paper are a preliminary attempt at evaluating flow, nutrient and sediment transport from selected watersheds in the Lake Winnipeg basin, all the models have been individually calibrated with the best available data at this time. By manipulating the available model input through hypothetical alteration of land-use and other input, the research team will be able to produce integrated results that will enable watershed planners and federal and provincial policymakers to prioritize land and agricultural management actions that will most effectively reduce loading of nutrients into tributaries of the Lake Winnipeg Basin. Because of the extremely large size of the watersheds draining into Lake Winnipeg, together with the scaling methodology of the output, there are still many technical challenges to deal with in this application. For example, all the necessary data, including model results, had to be collated into databases accessible by the modelers and to support scenario selection. The data had to be summarized or processed in order to be useful for the model and for easy viewing of input data and output results. In most cases, both the data and model results require special temporal and spatial alignment methods to make meaningful comparison among them. In parallel a Lake Winnipeg Basin Initiative Information Portal is being developed with a consistent look and feel to help in the visualization and animation of data and models input and output. It is an ideal platform for integrated environmental modeling to investigate error propagation among the models.

References

Abbaspour, K.C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J., Srinivasan, R., 2007. Modelling of hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J. Hydrol*. 333, 413–430.

Ahl, Robert S., Scott W. Woods, and Hans R. Zuuring, 2008. Hydrologic Calibration and Validation of SWAT in a Snow-Dominated Rocky Mountain Watershed, Montana, U.S.A. *J. of the American Water Resources Association*, 44(6):1411-1430.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling assessment–Part 1: Model development, *J. A. Water Resour. Assoc*. 34 (1), 73–89.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Allen, P.M., 1999. Continental scale simulation of the hydrologic balance. *J. Am.Water Resour. Assoc.* 35 (5), 1037–1051.

Bourne, A., Armstrong, N., Jones, G., 2002. A preliminary estimate of total nitrogen and total phosphorus loading to streams in Manitoba, WQM Section. Manitoba Conservation Rep#. 2002-04.

Cho, H., Olivera, F., 2009. Effect of the spatial variability of landuse, soil and precipitation on streamflows in small watersheds. *Jr. American Water Resources Association*, 45(3):673-686.

Di Luzio, M., Srinivasan, R., Arnold, J.G., 2001. *ArcView Interface for SWAT2000 – User's Guide*. Blackland Research Center, Texas Agricultural Experiment Station and Grassland, Soil and Water Research Laboratory, USDA Agricultural Research Service, Temple, Texas.

Green, C. H., Arnold, J. G., Williams, J. R., Haney, R., Harmel, R. D., 2007. Soil and Water Assessment Tool Hydrologic and Water Quality Evaluation Of Poultry Litter Application To Small-Scale Sub-watersheds in Texas, *Transactions AASABE*, Vol.50(4) 1199-1209.

Georgas, N., Srinivasan R., Farley, K., Jagupilla, S.C., 2009. AVGWLF Based Estimation of Nonpoint Source Nitrogen Loads Generated Within Long Island Sound Subwatersheds. *Jr..American Water Resources Association*, 45(3):715-733.

Grimaldi S., Nardi F., Benedetto F., Istanbulluoglu E., Bras R.L., 2007. A physically-based method for removing pits in digital elevation models, *Advances in Water Resources 30*, p.2151-2158

Jones, G., and Armstrong, N., 2001. *Long-Term Trends in Total Nitrogen and Total Phosphorus Concentrations in Manitoba Streams*, Manitoba Conservation Report No. 2001-07, Water Quality Management Section, December 2001, 175p.

Lindsay J.B., Creed I.F., 2006.Distinguishing actual and artifact depressions in digital elevation data, *Computers & Geosciences* 32, p.1192-1204.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., King, K.W., 2002. *Soil and Water Assessment Tool–Theoretical Documentation.* Soil and Water Research Laboratory, Agricultural Research Service and Blackland Research Center, Texas Agricultural Experiment Station, Temple, Texas.

Salvano E, Flaten DN, Rousseau AN, Quilbe R., 2009. Are current phosphorus risk indicators useful to predict quality of surface waters in southern manitoba, Canada? *Jr. Env. Qual.,* 24;38(5):2096-105.

Sanjiv, K. and Merwade, V, 2009. Impact of Watershed Subdivision and Soil Data Resolution on SWAT Model Calibration and Parameter Uncertainty. *Journal of the American Water Resources Association* (JAWRA) 45(5):1179-1196.

Santhi, C., N. Kannan, J.G. Arnold, and M. Di Luzio, 2008. Spatial Calibration and Temporal Validation of Flow for Regional Scale Hydrologic Modeling. *J. of the American Water Resources Association* (JAWRA) 44(4):829-846.

Schuol, J., Abbaspour, K.C., Srinivasan, R., and Yang, H., 2008. Estimates of freshwater availability in the West African sub-continent using the SWAT hydrologic model, *Jr. of Hydrology*, 352, 30– 49.

Simons, T.J. and Lam, D.C.L., 1986. *Documentation of a 2-Dimensional X-Y Model Package For Computing Lake Circulations and Pollutant Transports in Physics-based modeling of lakes, reservoirs, and impoundments.* Report Environmental Effects of the Energy Division, ASCE, U.S. EPA through the Oak Ridge National Laboratory; edited by William G. Gray.

Yang, J., Abbaspour K.C., Reichert P., Yang H., 2008. Comparing uncertainty analysis for a SWAT application to the Chaohe Basin in China, *Jr. Hydrology*, 358(1-2):1-23.