Estimating Sediment and Nutrient Loads in Saginaw Bay

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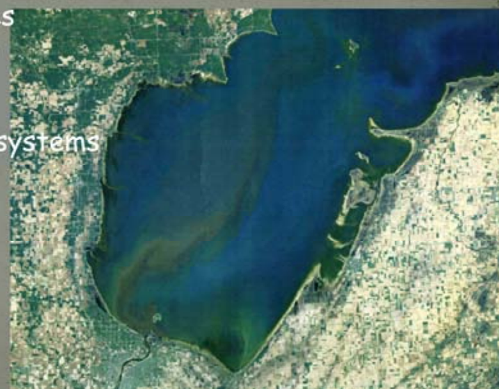

Saginaw Bay Multiple Stressors

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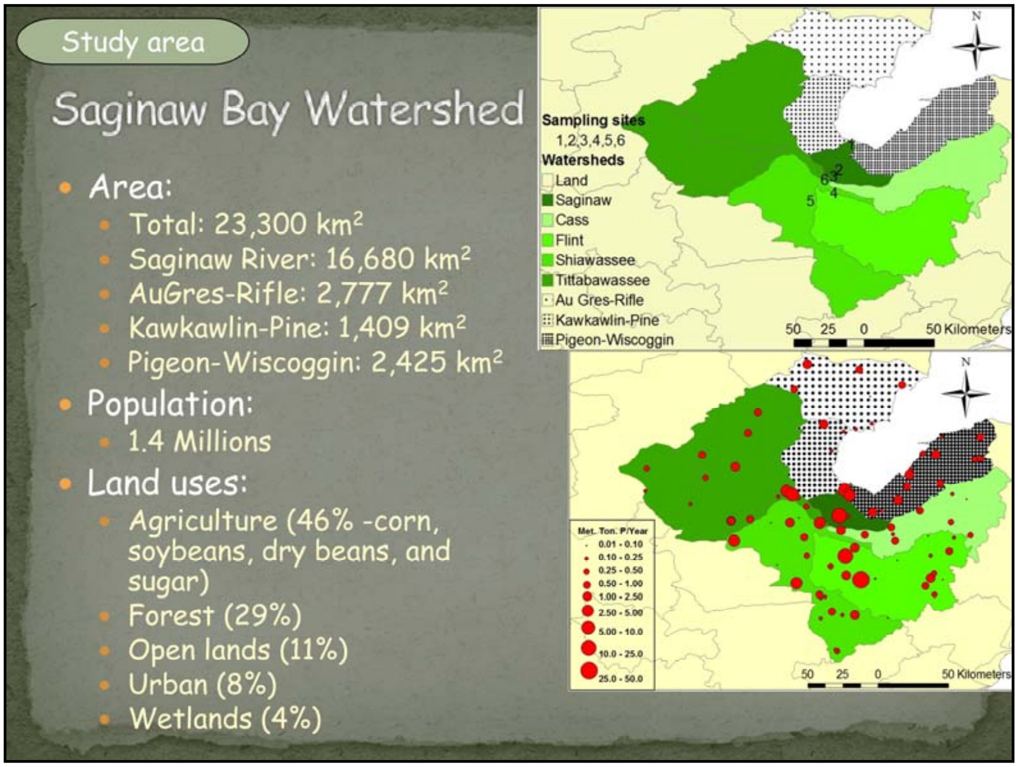
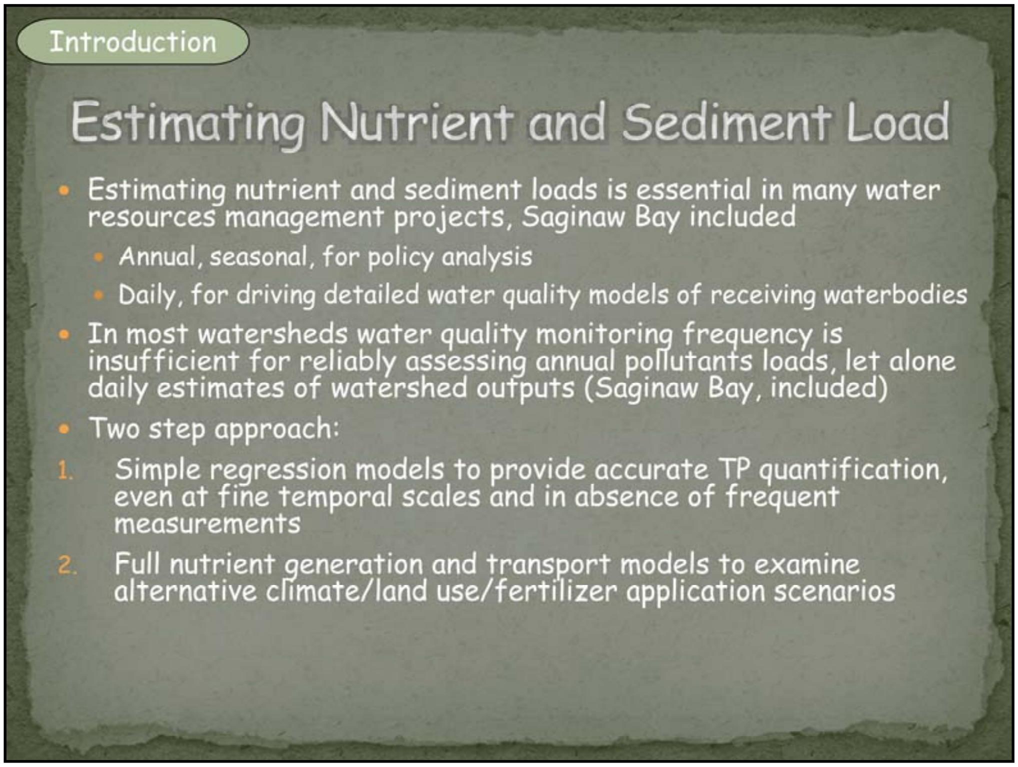


The Saginaw Bay watershed can be subdivided into four sub-watersheds. Counterclockwise in the top figure, AuGres-Riffle, Kawkawlin-Pine, Saginaw River, and Pigeon-Wiscoggin. The Saginaw River can also subdivided into five subwaterhed. Counteclockwise in the top figure, Tittabawassee, Shiawassee, Flint, Cass, and Saginaw proper.
The Saginaw River accounts around 72% of the watershed area. However, the AuGres-Riffle is occupied mostly by forests and wetlands and it is scarcely populated, and most urban areas discharge in the Saginaw River, as shown the bottom figure. Thus, the Saginaw River contributes to around 85% of the total nutrient load entering the bay.



As we all know, nutrient loads from human activities in the drainage basin are the major cause of eutrophication in rivers, lakes, or swamps. Sediment load is also a form of pollution because it may harm fish and zooplankton spawning, alter water clarity, and contribute to eutrophication through the nutrients attached to the sediments. That's why estimating nutrient and sediment loads from watersheds is essential in water resources management. For most policy analysis purposes, this analysis can be carried at the annual and seasonal scale for policy analysis. However, if we need to use these loads for driving detailed water quality models of the recipient water bodies, we need to increase the estimate resolution to daily level.

Unfortunately, water quality monitoring frequency is often insufficient for reliably assessing annual pollutants loads, let alone daily outputs.

Theoretically, building full nutrient generation and transport models is the best response to this challenge, but it is a complex and time consuming endeavor. On the other hand, simple regression models can provide accurate TP quantification, even at fine temporal scales and in absence of frequent measurements, without the costs of developing a full transport model. So it is more indicated for the initial phase and for supply inputs to the SAGinaw Environmental Model II.

Methods

Available In-Stream Water Quality Data

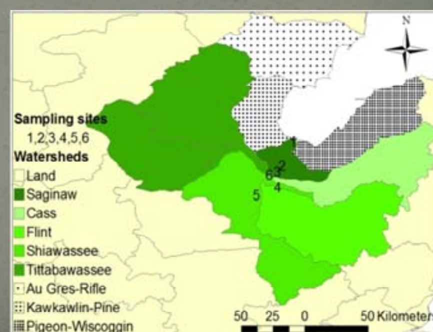
SITES	97	98	99	0	1	2	3	4	5	6	7	8
4				3	4	4	11	4	4	4	4	8
6		13		3	4	12	4	4	4	4	12	8
5		13		6	4	4	4	4	12	4	4	8
3				3	12	4	4	4	4	12	4	8
2	4	4	3	4	4	4	4	4	2	2		32
1		8			12	12	12	12	12	12	12	31

■ — USGS

■ — MDEQ

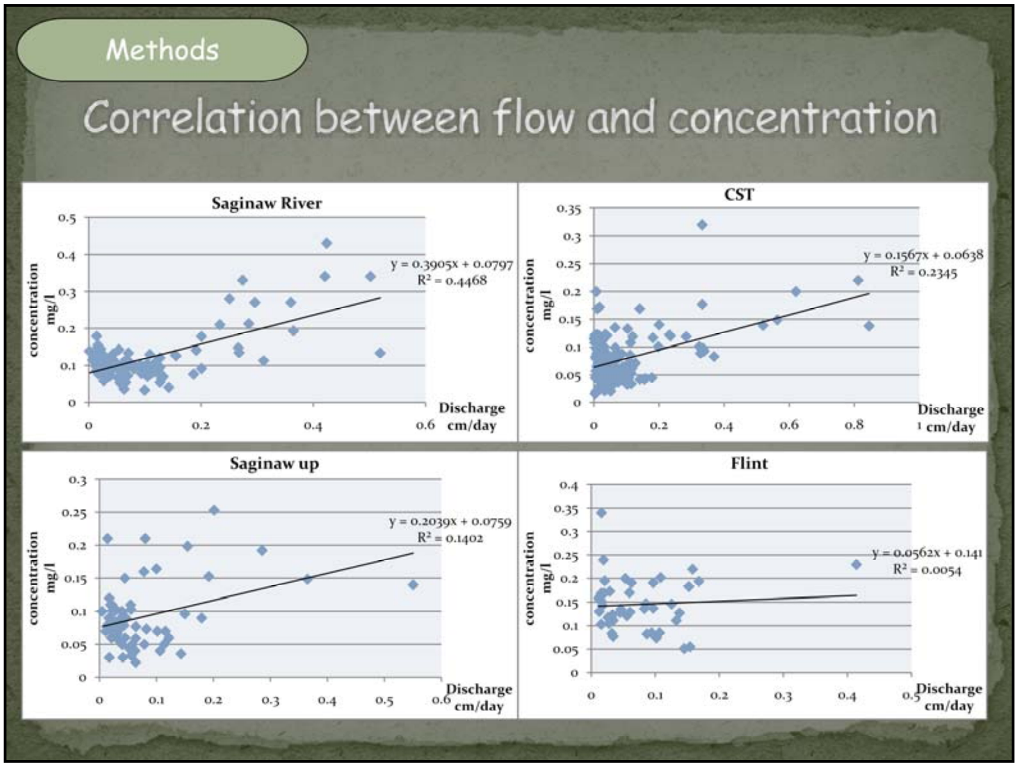
■ — CILER

Some few data for 2009 and possibly, more MDEQ data for 2008, 2009, 2010



In the last 15 years, pollutant concentration and other water parameters measured for Saginaw River and its sub-watersheds are available from Michigan Department of Environmental Quality for 1997-2007 except for the Saginaw Upstream site, for which data are available from the United States Geological Survey (USGS). In 2008 data was provided by the Cooperative Institute for Limnology and Ecosystem Research. A handful of water quality samples were collected in 2009 in Saginaw River by USGS and Limno-Tech. Also, MDEQ data should be available for 2008,2009, and 2010, but have not been made available to this study. Daily flow data at the sampling sites were obtained from the USGS database.

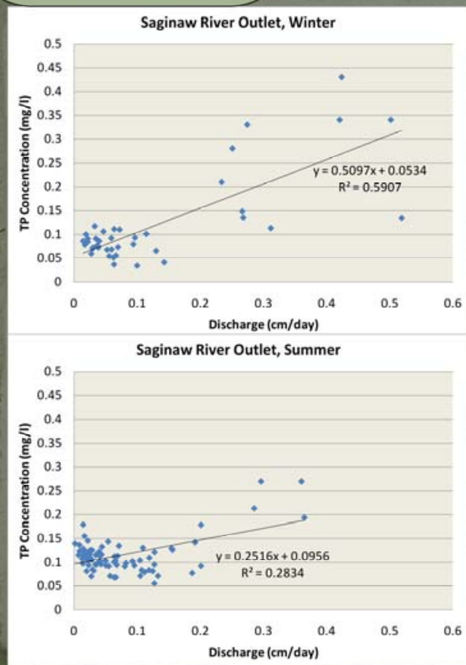
This is the satellite map showing where water quality was sampled. Note the large wetland area between sample sites 3 (Cass), 4 (Flint), 5 (Shiawasse), and 6 (Tittabawassee) and the city of Saginaw (sample site 2). Data seems to indicate that this area seriously affects sediment and nutrient loads generated in the upstream parts of the basin.



Regression methods do not require extensive data, but the quality of the predictions depends on the correlation between explanatory variables (flow) and values to be estimated (pollutant concentration). The higher the r^2 is, the better stream flow explains concentration variability. This slide shows that correlation between flow and total phosphorous concentration is so-and-so at most locations and bad for Flint. Thus, a simple relation between Q and C will not produce good results. We combined data for three sub-watersheds the Cass, the Tittabawassee, and the Shiawassee, because they show similar characteristics and performance.

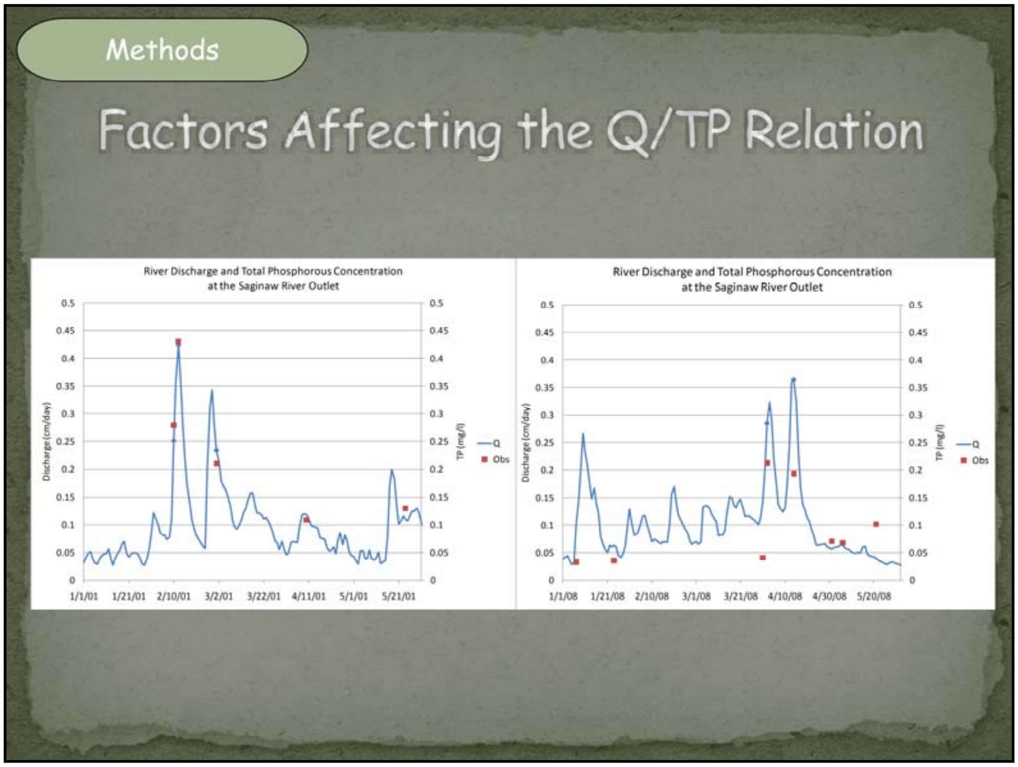
Methods

Correlation between flow and concentration.

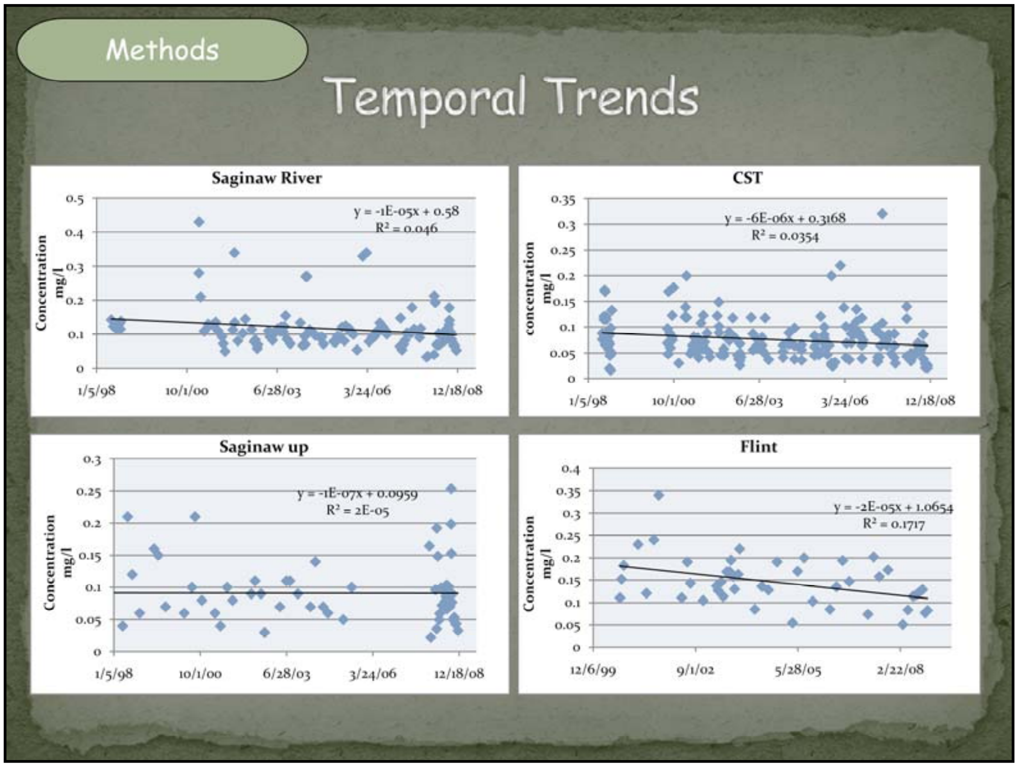


R^2	Daily flow (Q)	
	Annual	*Two seasons*
Saginaw River Basin Outlet	0.446	0.510
Flint	0.005	0.111
Cass, Shiawassee, Tittabawassee	0.234	0.270
Saginaw Upstream	0.140	0.269

A first way to improve the model is by splitting data into two seasons (Apr-Sep and Oct-Mar). This is due to the different conditions in weather (snow and frontal rain during fall and winter; convective thunderstorms during summer), landscape (barren soil during fall-winter and thicker vegetation cover during spring-summer), and fertilizer application (early spring) in the two periods. The quality of predictions improves especially for the Saginaw River Basin Outlet.

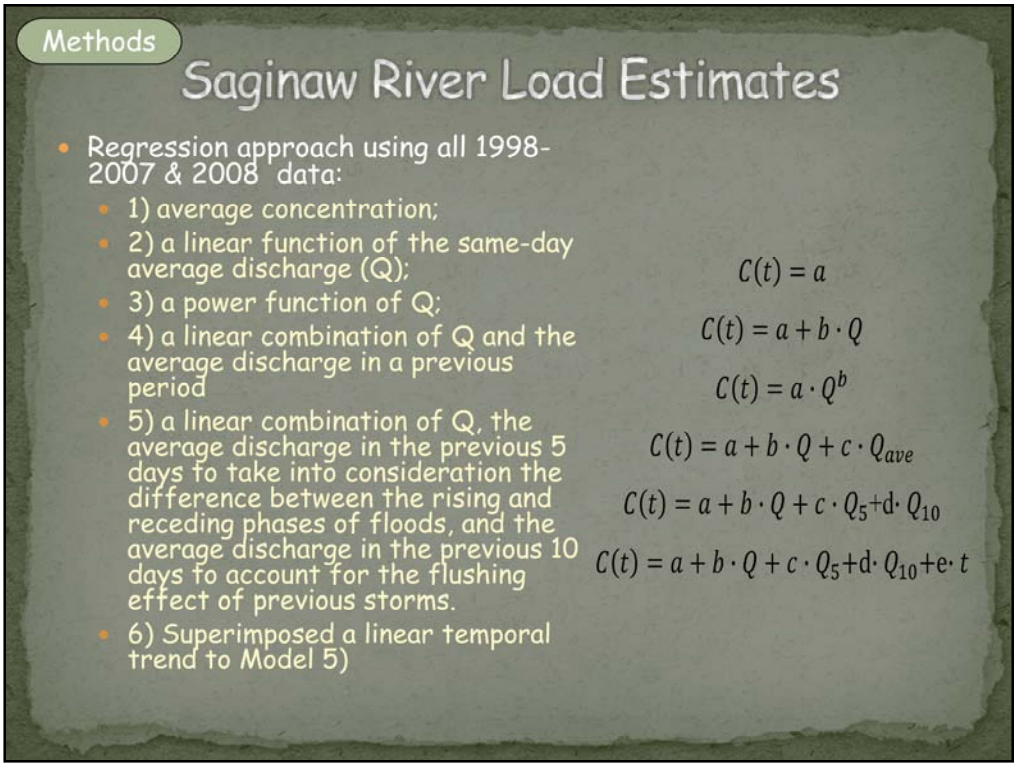


Other two factors affect the Q-C relation: 1) the difference between rising and subsiding phases of a flood; and 2) The effect of antecedent storms. The chart on the left gives an example of 1): we see that one discharge on the leading edge of a storm has a much higher concentration than a similar discharge on the trailing edge. The chart on the right is an example of 2) The concentration sampled in the second storm is lower that the concentration sampled during the first storm, despite that the discharge in the second occasion is larger than the one in the earlier storm.

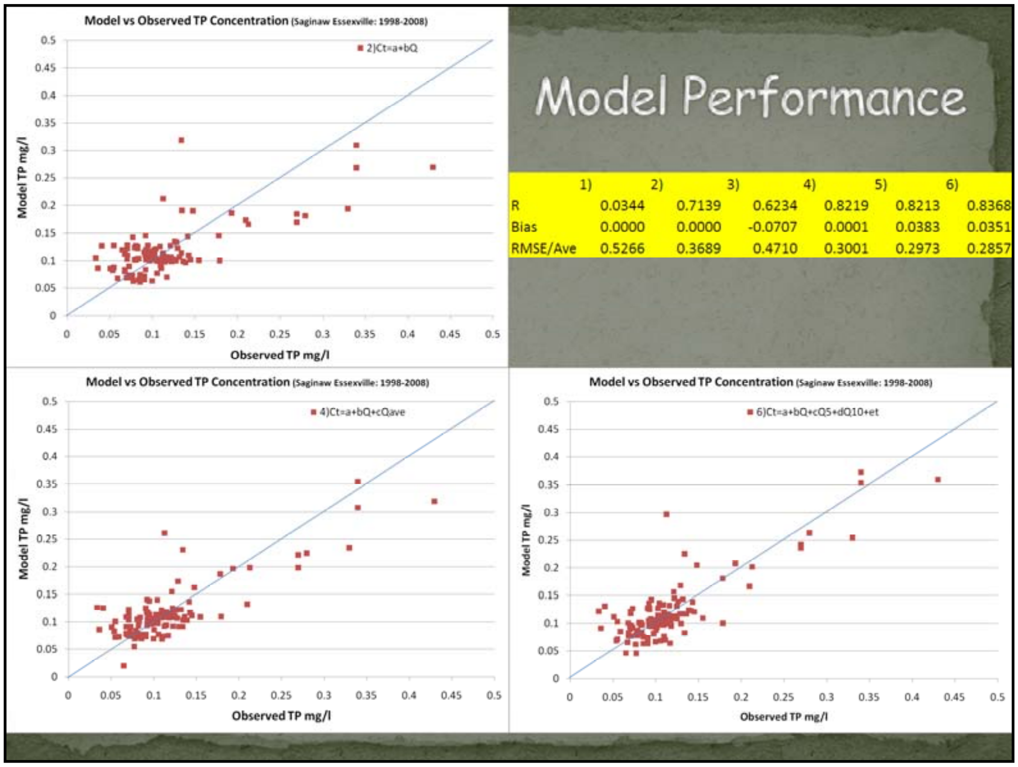


A problem affecting the Q-C relation for the Saginaw River is the fact that samples were taken over a 13-14 year period. During this time there have been many changes in watershed conditions (e.g., expansion of no-till agriculture; adoption of better wastewater treatment techniques; build-up of fertilizers in agricultural soil, decrease in population and industrial activities, etc.). The temporal trends in this slide indicate this seems to be the case, particularly for the Flint watershed, where the coefficient of determination (r^2) reaches 0.171.

Therefore, we explored the inclusion of time as explanatory variable in the TP concentration estimation model.



The regression models we considered express TP concentration as a function of the same-day discharge per unit area (Q=measured discharge/watershed area), average discharge per unit area during the previous 5 days (Q5), average discharge per unit area during the previous 10 days (Q10), and date. We also have separate models for the periods April-September and October-March.



	1)	2)	3)	4)	5)	6)
R	0.0344	0.7139	0.6234	0.8219	0.8213	0.8368
Bias	0.0000	0.0000	-0.0707	0.0001	0.0383	0.0351
RMSE/Ave	0.5266	0.3689	0.4710	0.3001	0.2973	0.2857

This slide shows the performance of different models for the Saginaw River outlet. Remarkable is the improvement due to the inclusion of Q5 (model 4) versus model 3 (just Q). The inclusion of Q10 does not seem to further improve performances (5). However, the resulting timeseries (not shown here) is much smoother than for 4). So, we prefer to use it even if it is not well supported by the data we have. Finally, the inclusion of date/time further improves model performance.

Results & discussion

TP Models (Saginaw River Outlet)

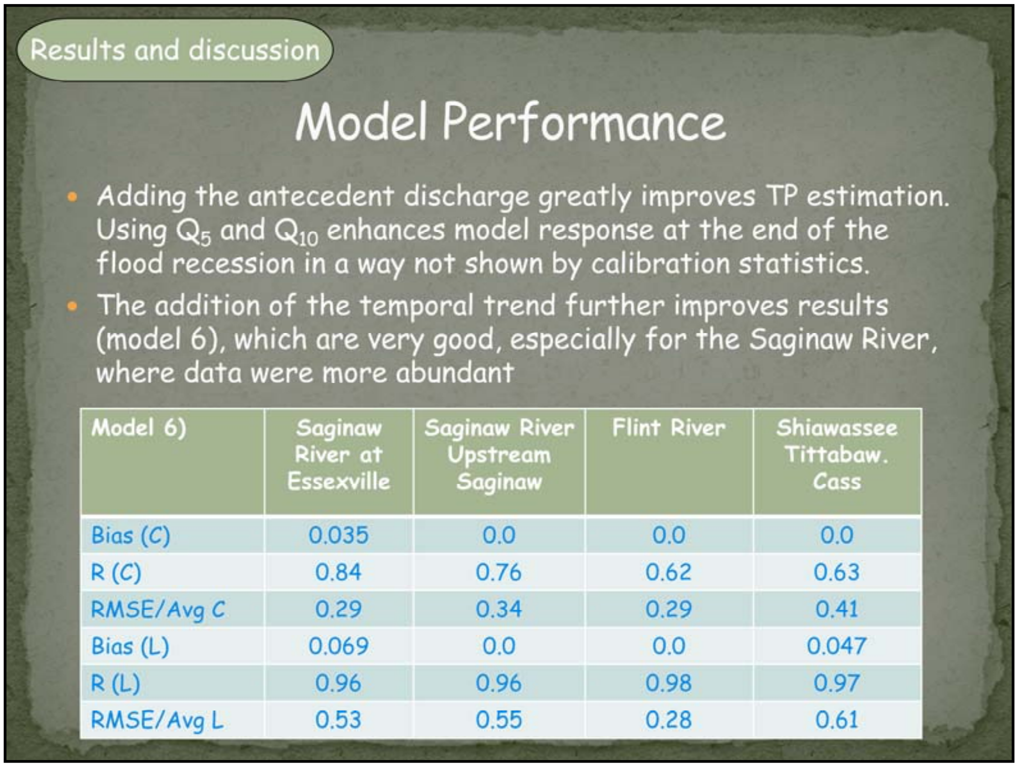
- Summer
- $C=0.435 - 0.000009\,T + 0.679\,Q - 0.908\,Q_5 + 0.261\,Q_{10}$

Coefficient	P(0.05)	Explained Variance
Q	0	64.48%
Q5	0	32.48%
Q10	0.045	1.92%
T	0	1.13%

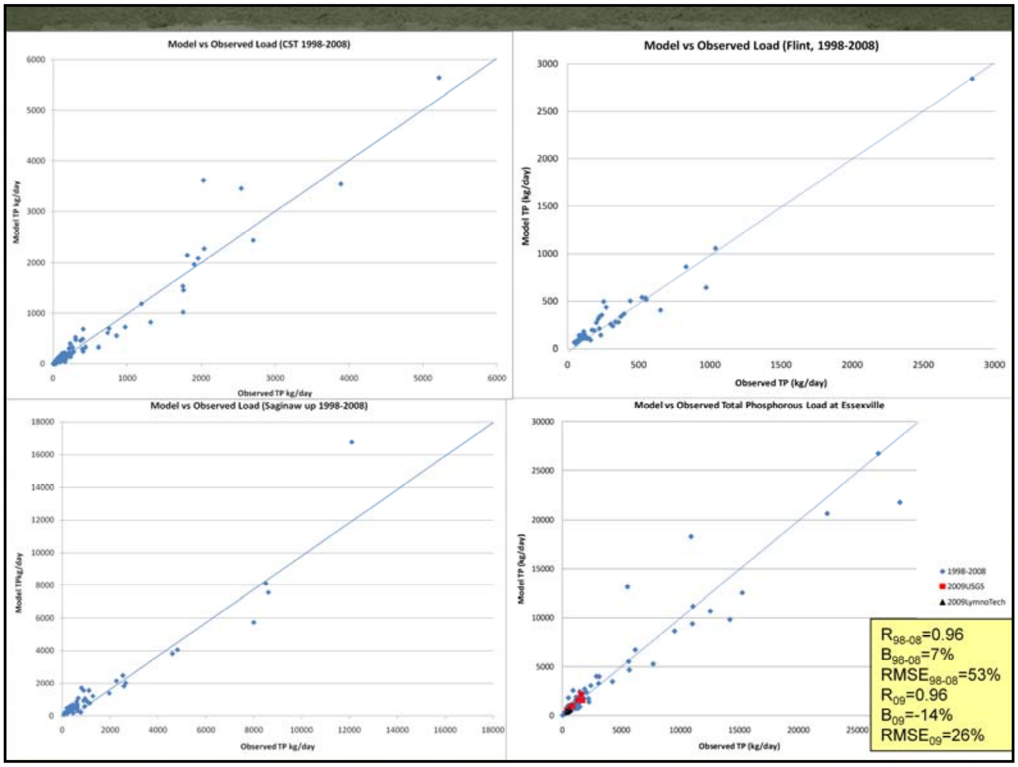
- Winter
- $C=0.590 - 0.000014\,T + 0.867\,Q - 0.740\,Q_5 + 0.363\,Q_{10}$

Coefficient	P(0.05)	Explained Variance
Q	0	62.50%
T	0.147	20.45%
Q5	0.001	15.82%
Q10	0.202	1.24%

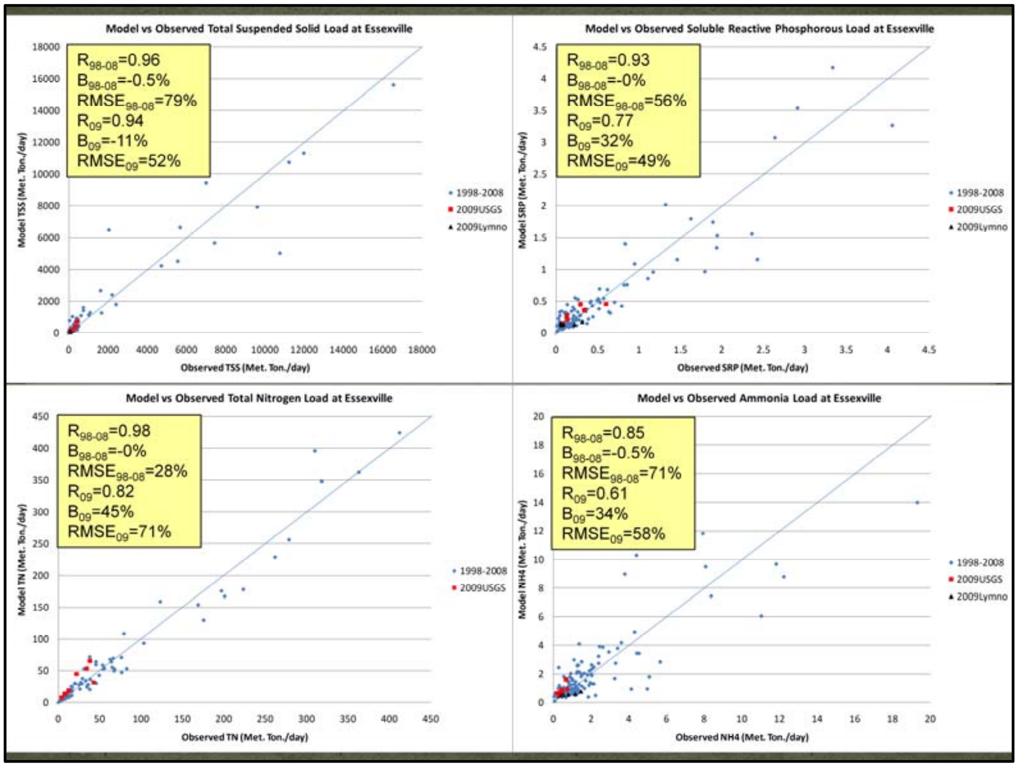
This slide shows that around 60% of observed TP variability is explained by Q, somewhere between 16 and 32% by Q5, and somewhere between 1 and 20% by temporal trends. Contribution of Q10 appears to be just 1-2%.



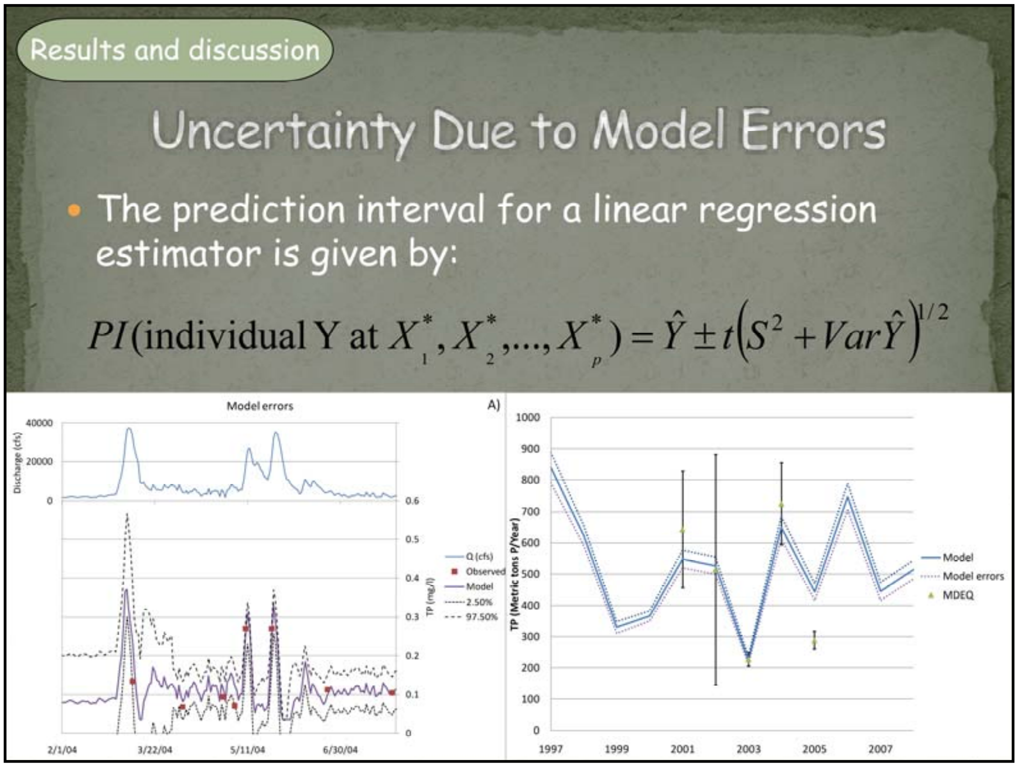
The results tell us that correlation between modeled and observed daily concentration in 1998-2008 reaches 0.84 for the entire Saginaw River watershed, 0.63 for the combined Cass, Shiawassee, and Tittabawassee Rivers, and 0.62 for the Flint River, while correlation in daily load (Q*C) is above 0.96 for all watersheds.



These figures may give a better idea of how the model performs. Note that the Chart for the Saginaw River outlet reports also a comparison with 2009 data (validation would not be the right word, given the limited range of discharge for which data are available).

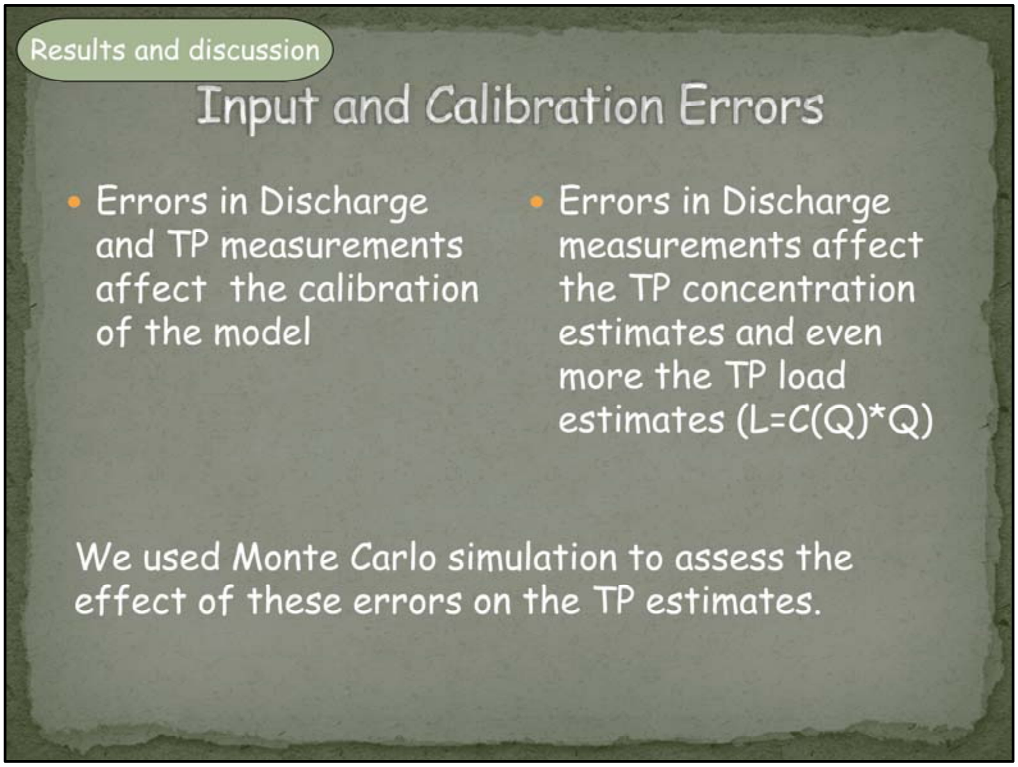


What about other pollutants? We see very good results for total suspended solids, acceptable ones for Soluble Reactive Phosphorous and Total Nitrogen, and –expectedly- not very good results for Ammonia. The reason of the poor performance with NH4 is that NH4 is released more by point sources than by non-point sources. Thus, its relation with Q is weak.



Estimations are affected by two type of uncertainty: 1) Uncertainty due to the model inability to replicate the observed data; 2) Uncertainty due to the fact that the data used for calibration and operation may also be affected by measurement errors.
Since these models are linear, the a%- prediction interval for a estimate Y as result of the specific input X* is equal to the prediction Y^ +/- Student's t of parameters (a, 3) times the residual mean square + the prediction variance.

We can see that daily prediction uncertainty during winter is larger than during summer. However, in the hypothesis that this error is temporally uncorrelated, its impact on the annual load estimate is low.



The effect of errors in discharge Q and TP concentration data used for model calibration and operation is assessed using a Monte Carlo analysis.

Results and discussion

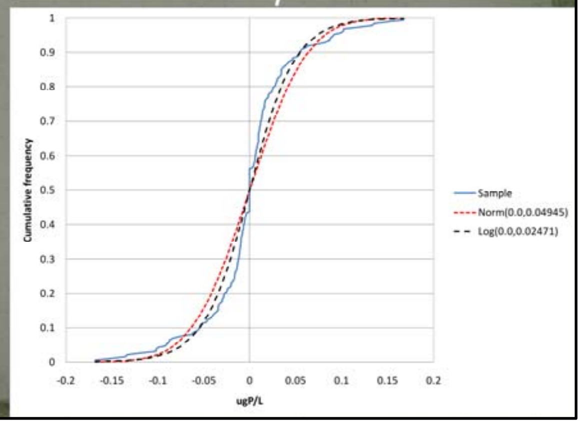
Uncertainty in Discharge Measurements

- USGS qualifies the Saginaw River Gage as "Poor" because of backwater effects and wind-driven seiches
- This means that 95% of reported values are within an interval wider than 15% from the true values
- We modeled the discharge measurement relative error as a logistically distributed random variable with 95% probability of occurrence within ±30% (that is a logistic of parameters 0.0 and 0.081887)

Results and discussion

Uncertainty in TP Measurements

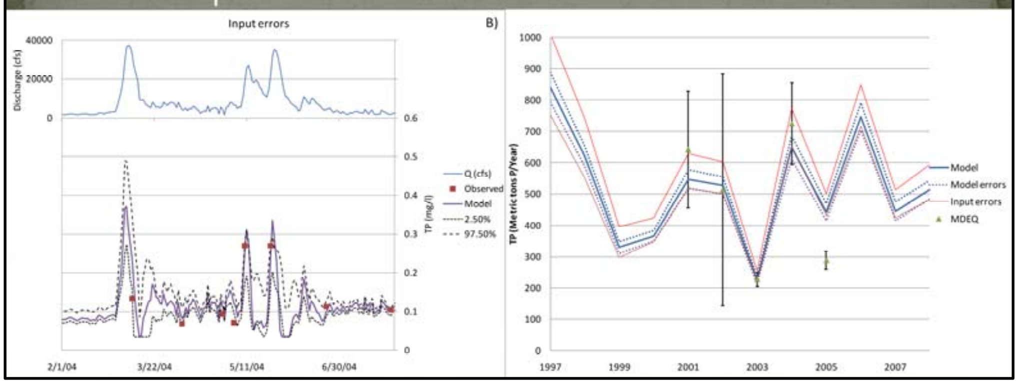
- The TP measurements are obtained as a mean of two samples. We computed the sample distribution of the differences between the single samples and their average as a measure of the uncertainty in the TP values.
- The best fit of the sample distribution was obtained with a logistic pdf with parameters 0.0 and 0.02471

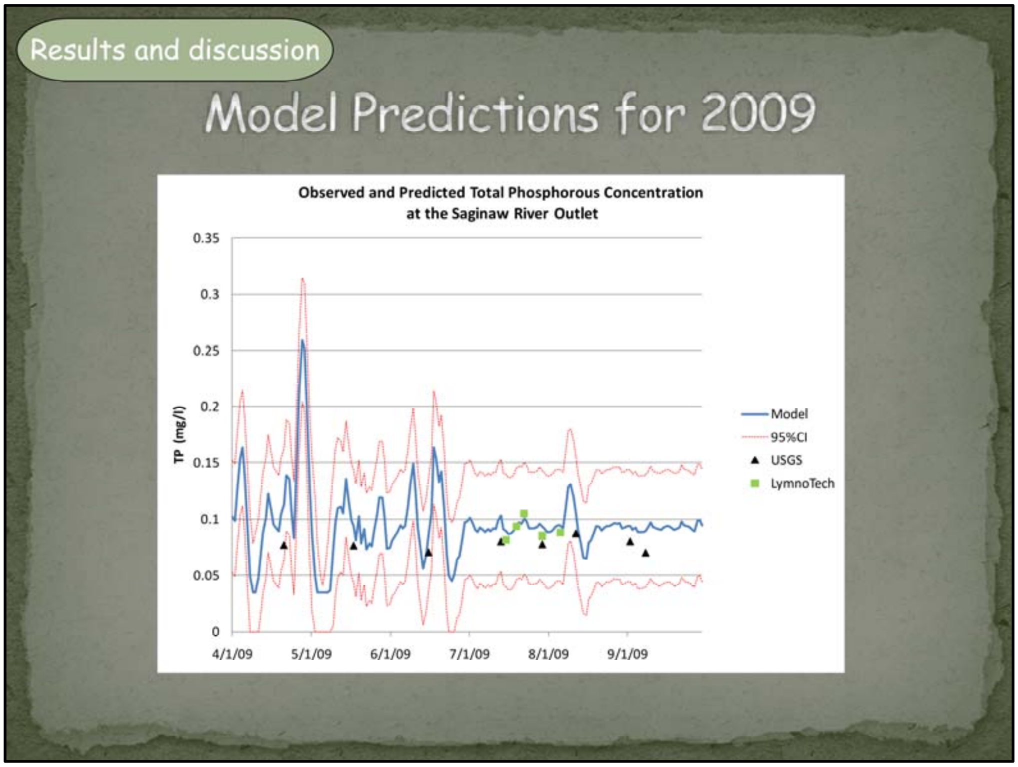


Results and discussion

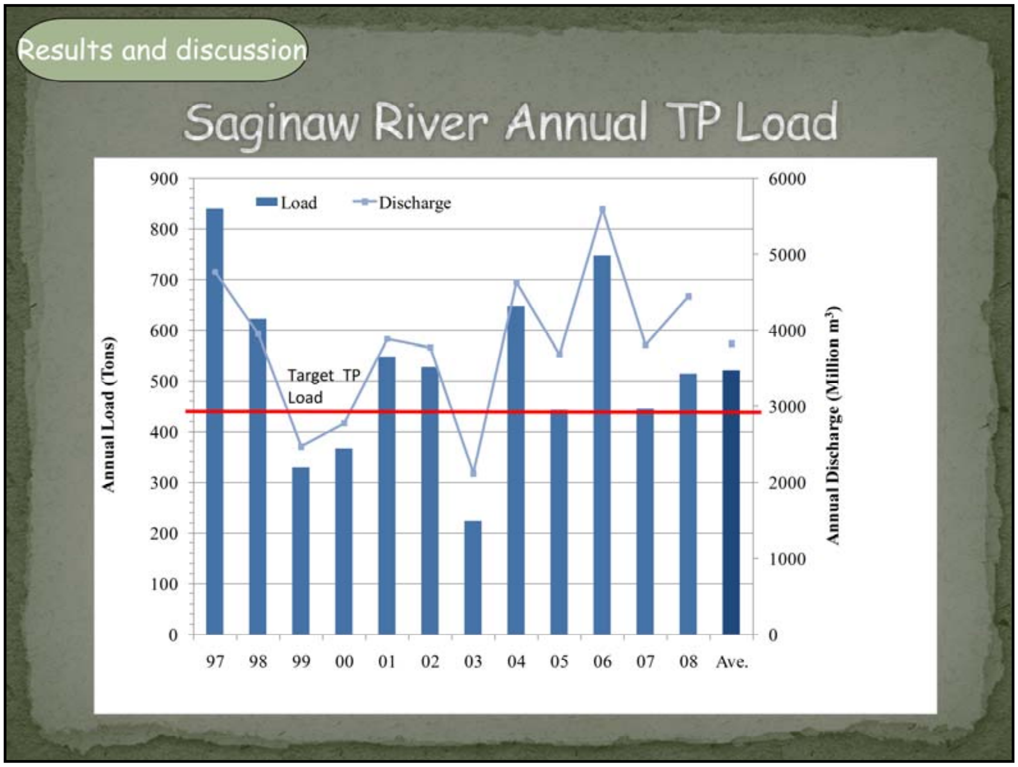
TP Estimate Uncertainty Due to Measurement Errors

- Uncertainty at the daily TP concentration is much smaller than that caused by model errors
- However, the uncertainty in annual load is higher because changes in calibration parameters induce shifts in model behavior that are persistent.

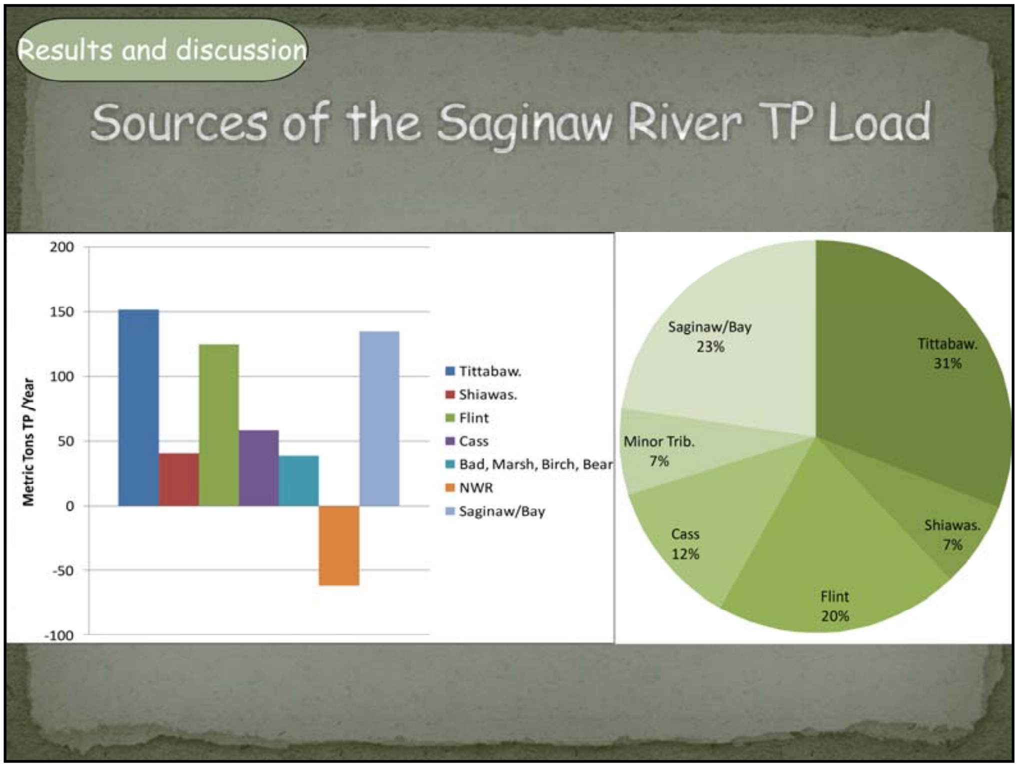




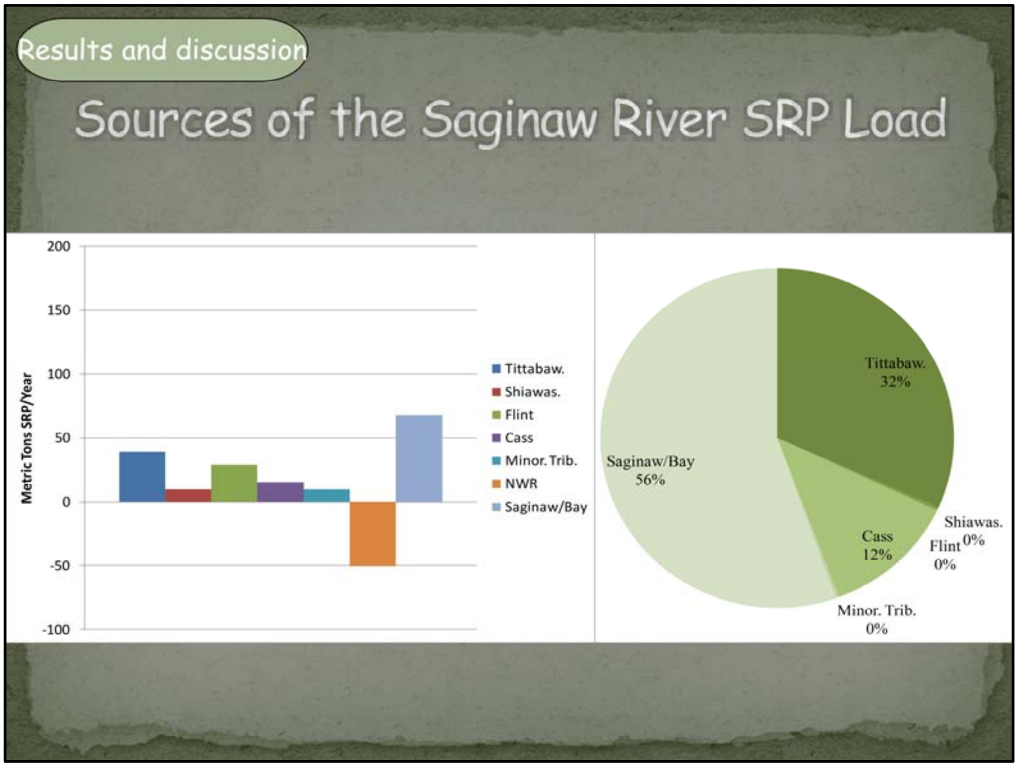
When applied 2009, we see that all the few available data fall in the prediction uncertainty band of the model



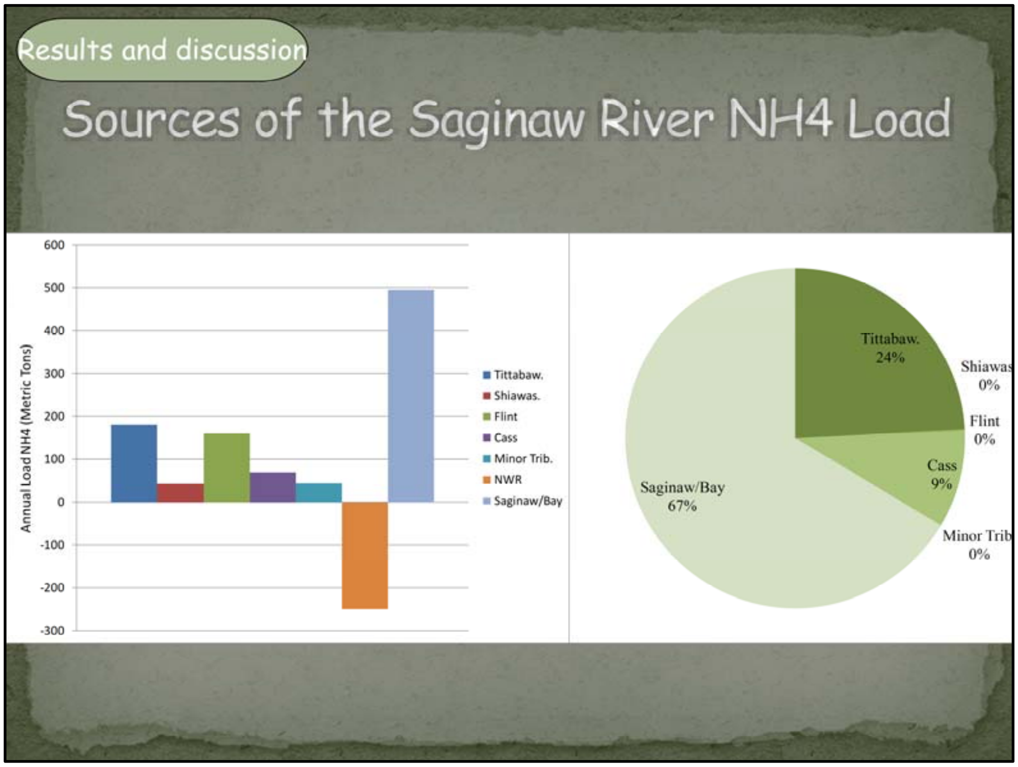
This figure indicates that the TP load from the Saginaw River has been higher than the target TP load to the bay most of the years. Considering that Saginaw River carries around 80-90% of the TP load to the Bay with the rest contributed by some minor Rivers as well as the atmospheric deposition, it is clear that the target TP load has been met only during the driest years and that the average TP load is well above 500 metric tons P per year.



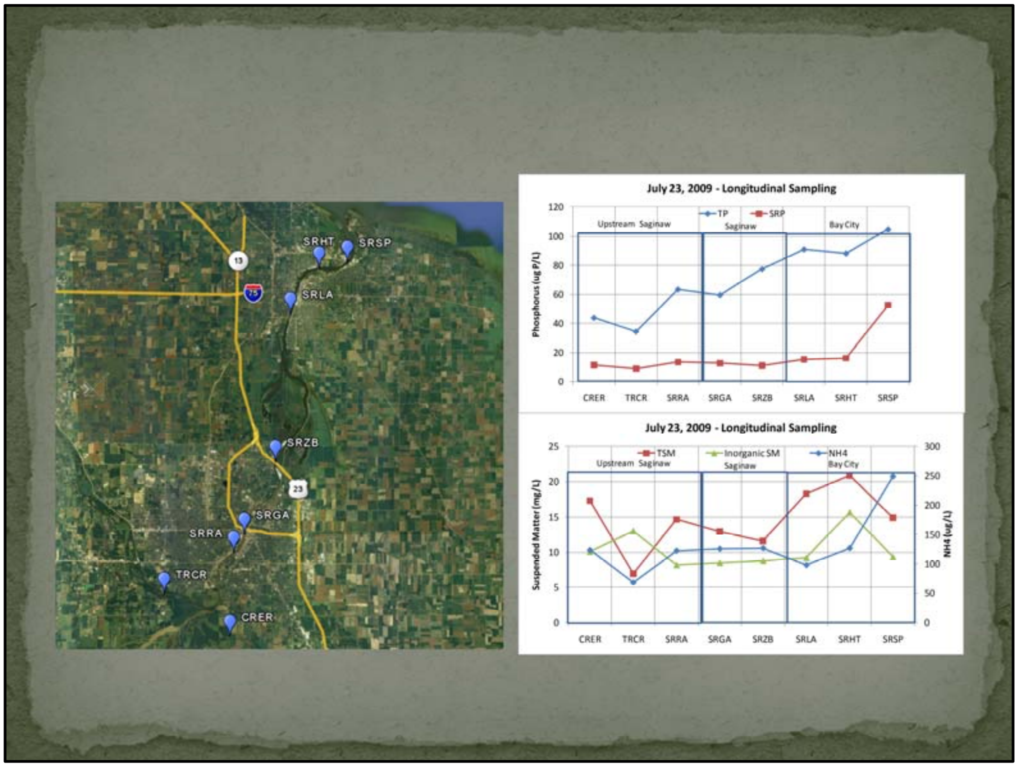
By considering the difference between the TP loads passing through the six sampling points in Saginaw River basin is possible to determine the contribution of different portions of the basin to the TP load entering the Bay. While the largest fraction of Saginaw River TP load originates in the largest sub-basin (Tittabawassee), these two figures highlight the importance of the urban discharges at the coastal cities of Saginaw and Bay as TP sources (in average 23% of the total). This portion of the watershed features a TP load per square kilometer (not shown here) four times higher than the average level of other sub-watersheds, showing the preponderance of pollution from urban sources. The figure shows also the sink effect of the National Wildlife Refuge. When this is taken into account and assuming that it affects mostly discharges from the Shiawassee, Flint, and minor tributaries (Bad, Marsh, Birch, and Bear), we see that near one fourth of TP exported by the Saginaw River is generated by Saginaw and Bay and 30% in the Tittabawassee watershed. We need to stress that load estimations are affected by uncertainty and that the uncertainty affecting the difference between two load estimates could be equal to the sum of the uncertainty of the single components.



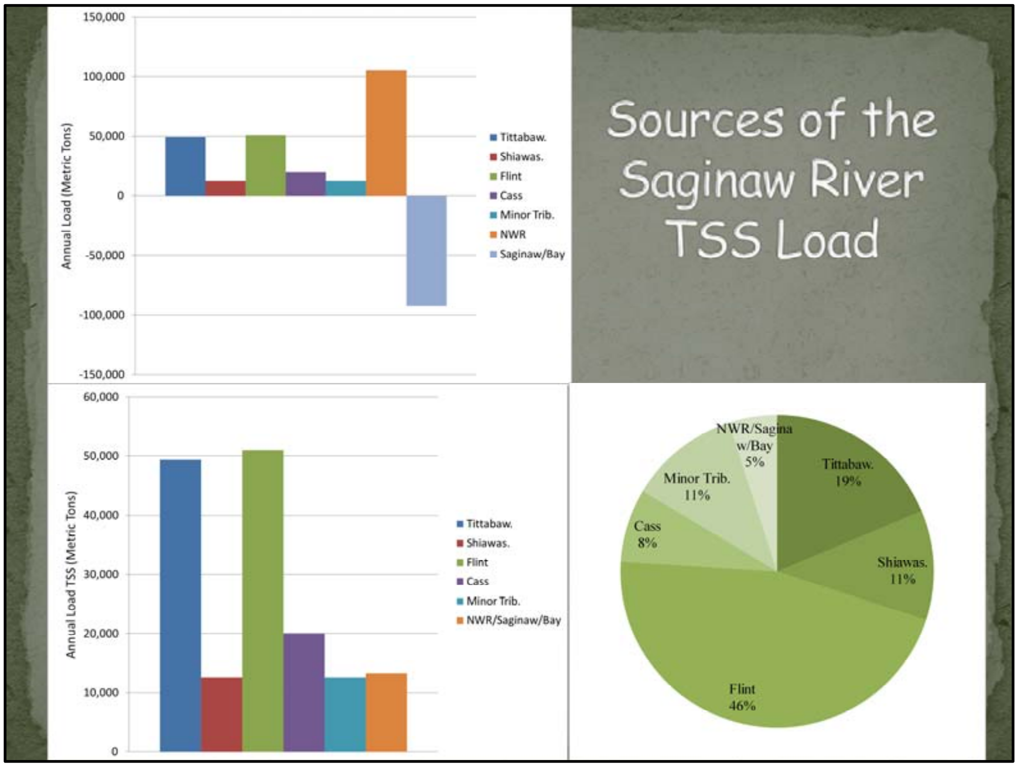
When considering SRP, we see that more than half the SRP exported by the Saginaw river is generated by Saginaw and Bay and 30% in the Tittabawassee watershed.



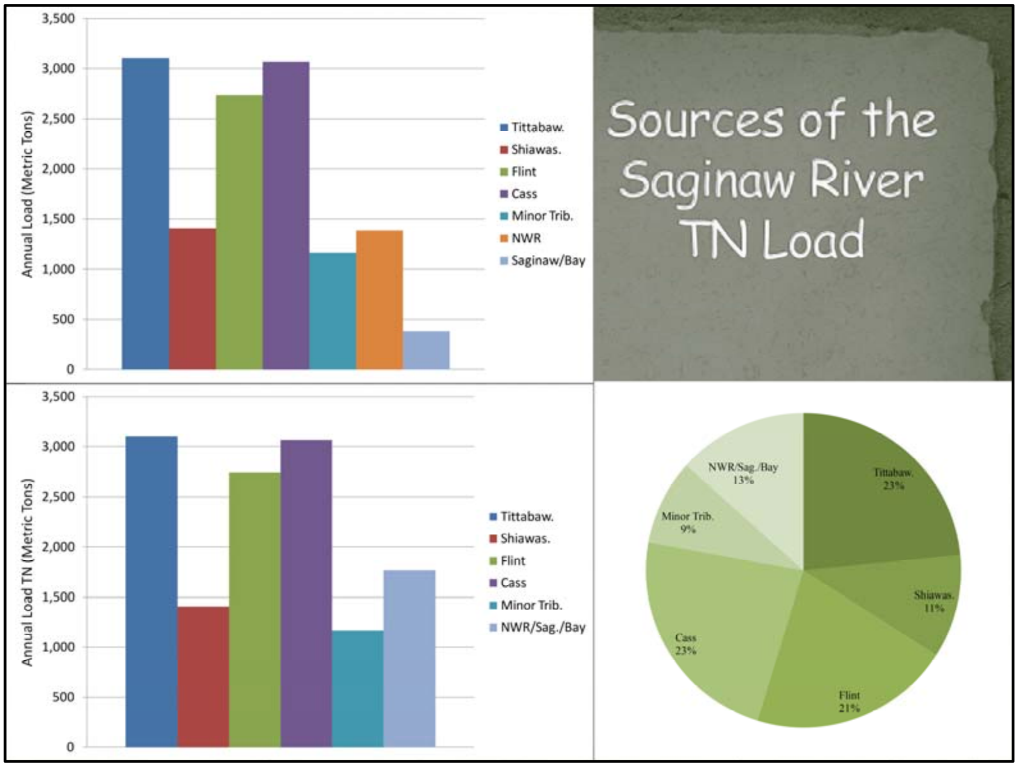
When considering NH4, we see that more than 65% of NH4 exported by the Saginaw river is generated by Saginaw and Bay and 24% in the Tittabawassee watershed.



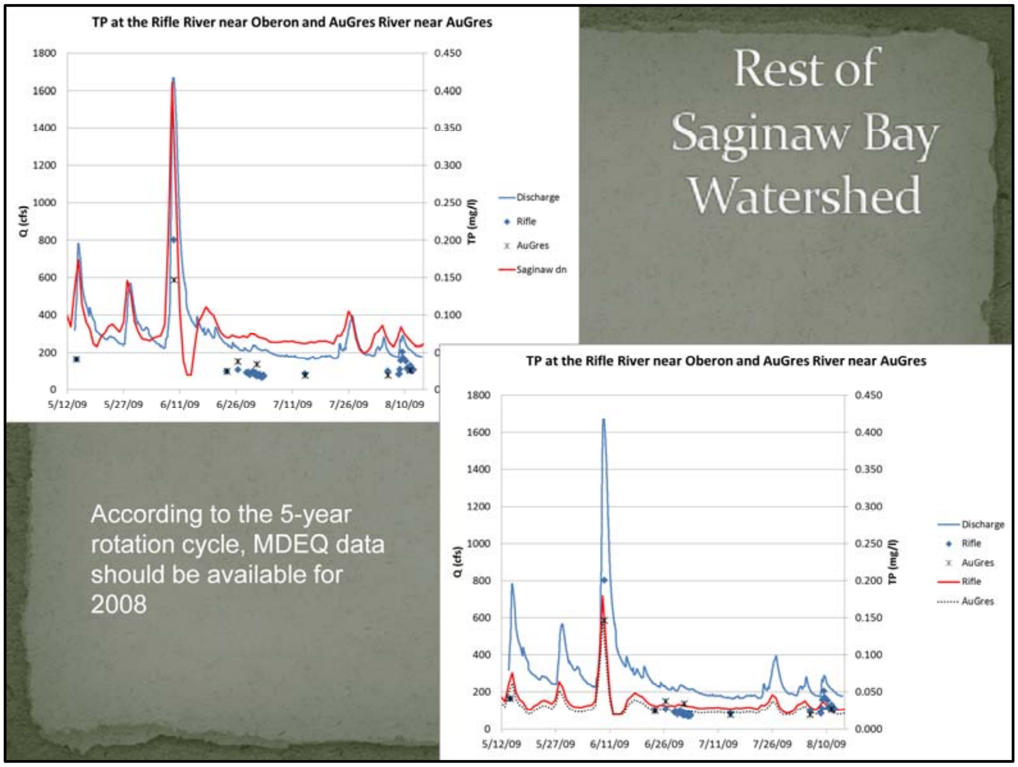
A sampling cruise done in 2009 supports this analysis: We see the TP steadily increasing from upstream Saginaw down to Essexville possibly by resuspension/scouring, while SRP is just slightly increasing along the river, but spikes downstream the Bay and Essexville WWTP outlets (downstream SRHT).



The behavior of TSS is not so clear. In this case, the NWR behaves like a source, while the segment between Saginaw and the outlet as a sink. The latter could be explained by deposition along the wide and flat channel between these two points (the US Army Corp of Engineers needs to regularly dredge the river to maintain navigability). The former is not so easy to understand. A possible explanation is that the data upstream Saginaw were collected by USGS using a different procedure than that used by MDEQ for sampling the tributaries. A second possible explanation is that the NWR area is seasonally flooded for creating a habitat for migratory birds and that this creates an area for strong sediment scouring (the prevalent soil is highly erodible loess).

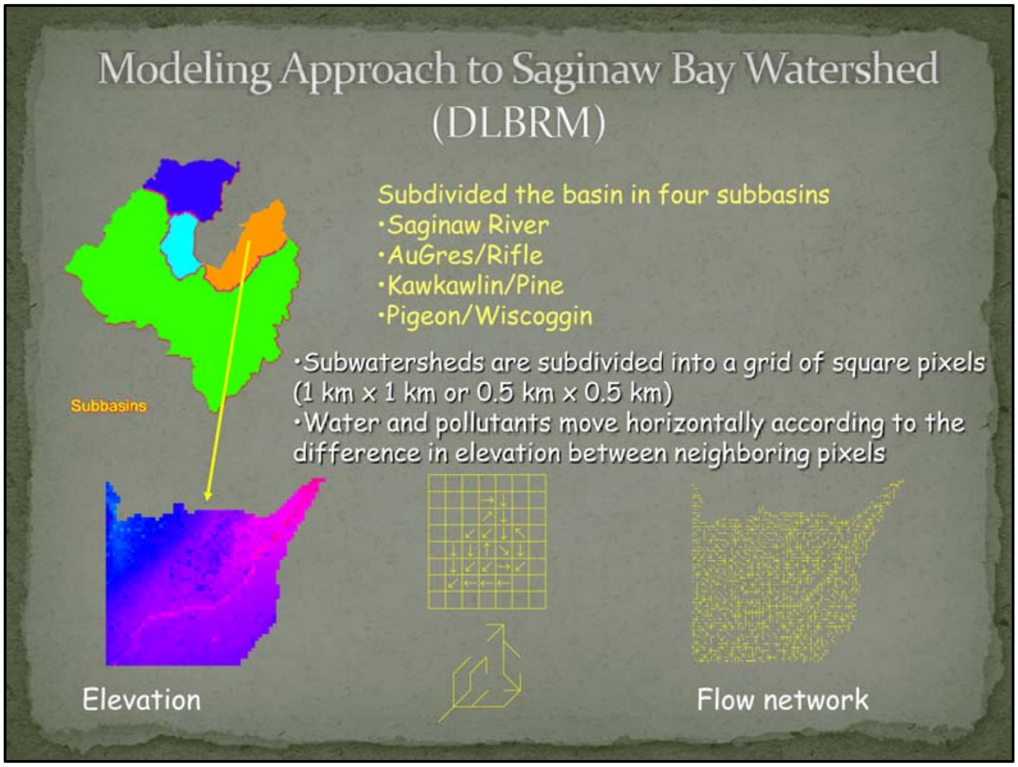


The behavior of TN is not so clear. Also in this case, the NWR behaves like a source, while the segment between Saginaw and the outlet as a small source. The latter could be easily explained by point source contribution (see NH4), but the former is not so easy to understand. A possible explanation is that the data upstream Saginaw were collected by USGS using a different procedure than that used by MDEQ for sampling the tributaries. A second possible explanation is that the bacterial activity in the NWR area generates Nitrogen by oxidizing organic matter or fixing atmospheric N.



We have seen that the models proposed here can be applied to the Saginaw River and that should account for nearly 80-90% of TP entering Saginaw Bay. Could we apply it to other tributaries to Saginaw Bay? The first thing to consider is that the model uses discharge per unit area, which is easily scalable to other watersheds. The second aspects to consider is that the Saginaw is different from the other tributaries, both for size, and for the presence of large urban discharges noear the watershed outlet. This means that an application this model to other watershed needs to be checked against locally sampled data.

In the top figure, we see the application of the Regression model developed for Saginaw River to the smaller and less populated AuGres and Rifle Rivers. As input data, we used the discharge per unit area recorded at USGS gage 04142000 (Riffle river). As expected, TP concentration is much higher than the recorded data. However, when we adjust model estimates by multiplying them by the ratio between the average observed values and the average model prediction, we se that we can trace observed TP values very well. Unfortunately, observations in 2009 were taken only during summer, limiting the usefulness of this approach. Such situation could be improved when the MDEQ monitoring data for 2008 are made available.



The ultimate objective is to create a full sediment and nutrient generation and transport model of the Saginaw Bay watershed. The approach outlined here is based on a modification of the existing Distributed Large Basin Runoff Model, a watershed hydrology model which has been applied to the Saginaw Bay watershed.

Hydrology Calibration 1950-64

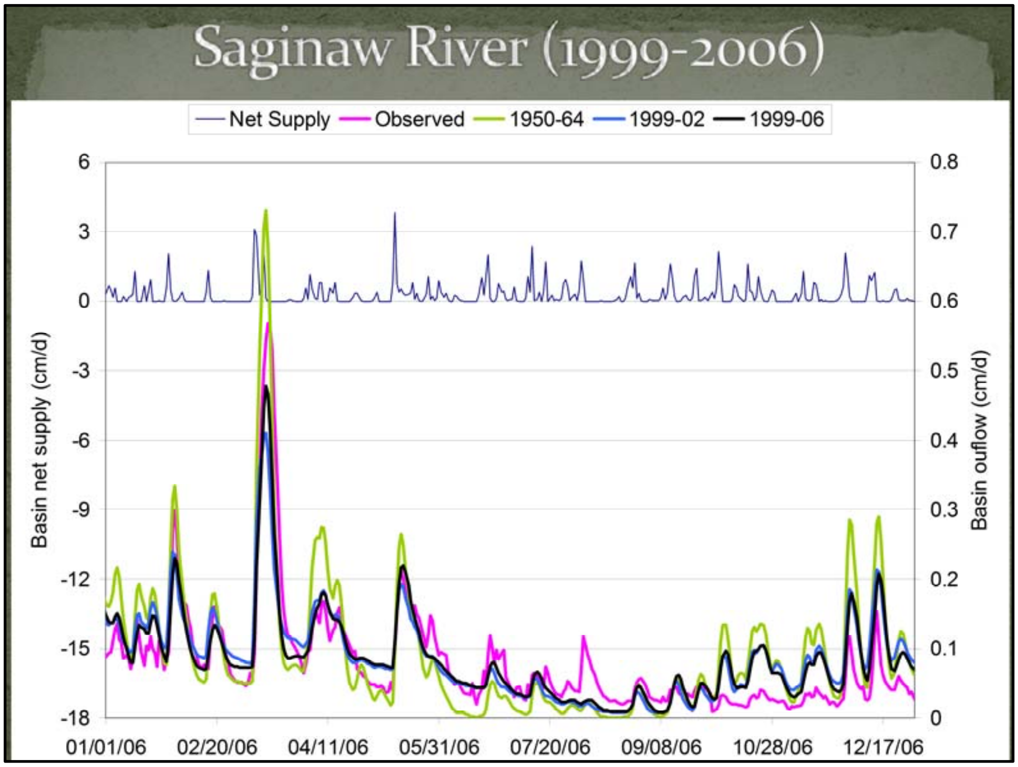
	Saginaw River	AuGres- Rifle	Kawkawlin-Pine	Pigeon-Wiscoggin (1986-93)
1 x 1 km				
Relative Bias	-5.0%	-1.7%	7.5%	6.9%
Correlation	0.90	0.86	0.79	0.79
RMSE/Q_{Ave}	61%	55%	148%	128%
0.5 x 0.5 km				
Relative Bias	--	-3.7%	7.1%	7.7%
Correlation	--	0.86	0.79	0.80
RMSE/Q_{Ave}	--	55%	146%	126%

The DLBRM hydrology component as been calibrated for the four Saginaw Bay subwatersheds both at the 1.0 and 0.5 km resolution during 1950-1964 (1986-1993 for Pigeon-Wiscoggin). This table reports the statistics of the comparison between predicted and recorded daily discharge. Performance is quite good in Saginaw and AuGres, but not very good in the other two watersheds. However, the gages used for comparison covered just 20% of the Kawkawlin watershed and just 15% of the Pigeon-Wiscoggin, decreasing their capability of representing the dynamics in the entire watershed.

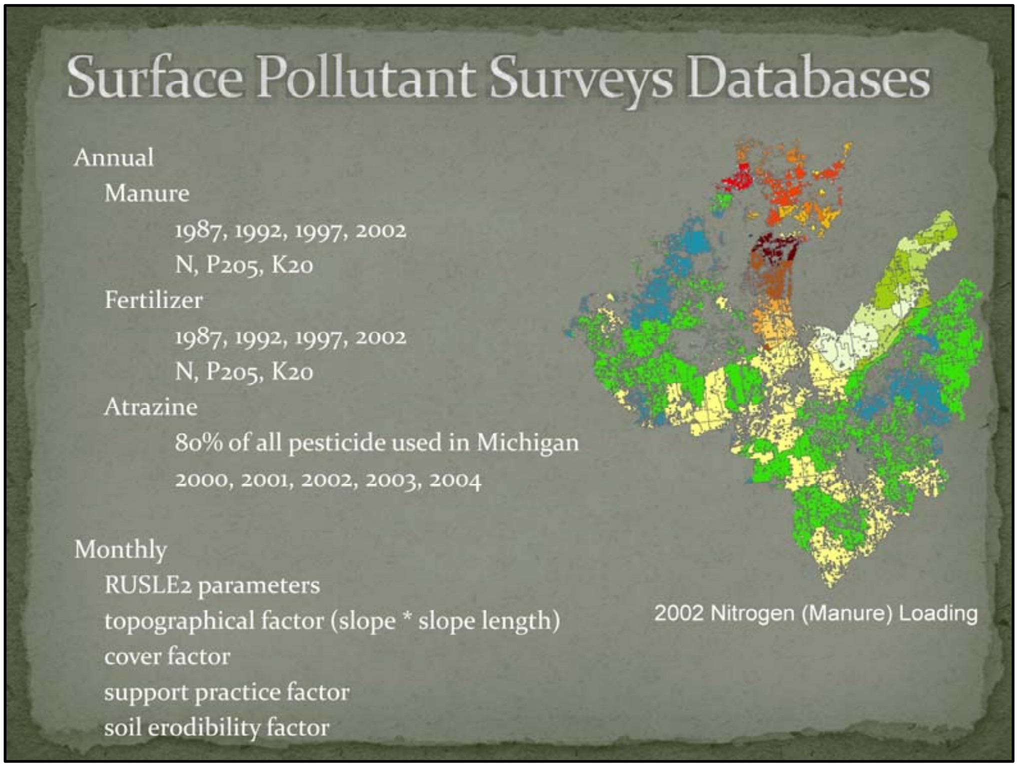
Robustness Test (1999-06)

	Saginaw River	AuGres- Rifle	Kawkawlin-Pine (1974-82)	Pigeon-Wiscoggin
1 x 1 km				
Relative Bias	-0.2%	0.2%	-7.1%	--
Correlation	0.79	0.85	0.79	--
$RMSE/Q_{Ave}$	73%	50%	131%	--
0.5 x 0.5 km				
Relative Bias	--	-1.3%	-11%	--
Correlation	--	0.87	0.80	--
$RMSE/Q_{Ave}$	--	41%	132%	--

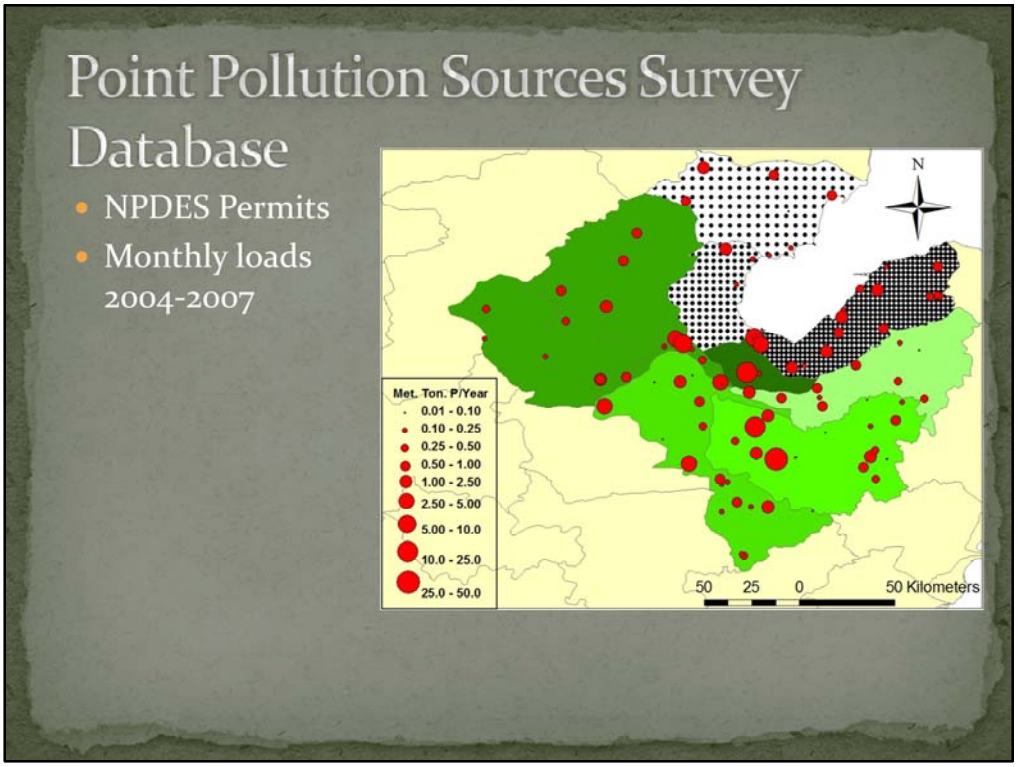
The models calibrated for 1950-1964 were then applied to the 1999-06 period. Despite the 35 years interval between the calibration and validation periods, model performance is still good, showing a good model robustness. DLBRM has then been recalibrated for this latter period.



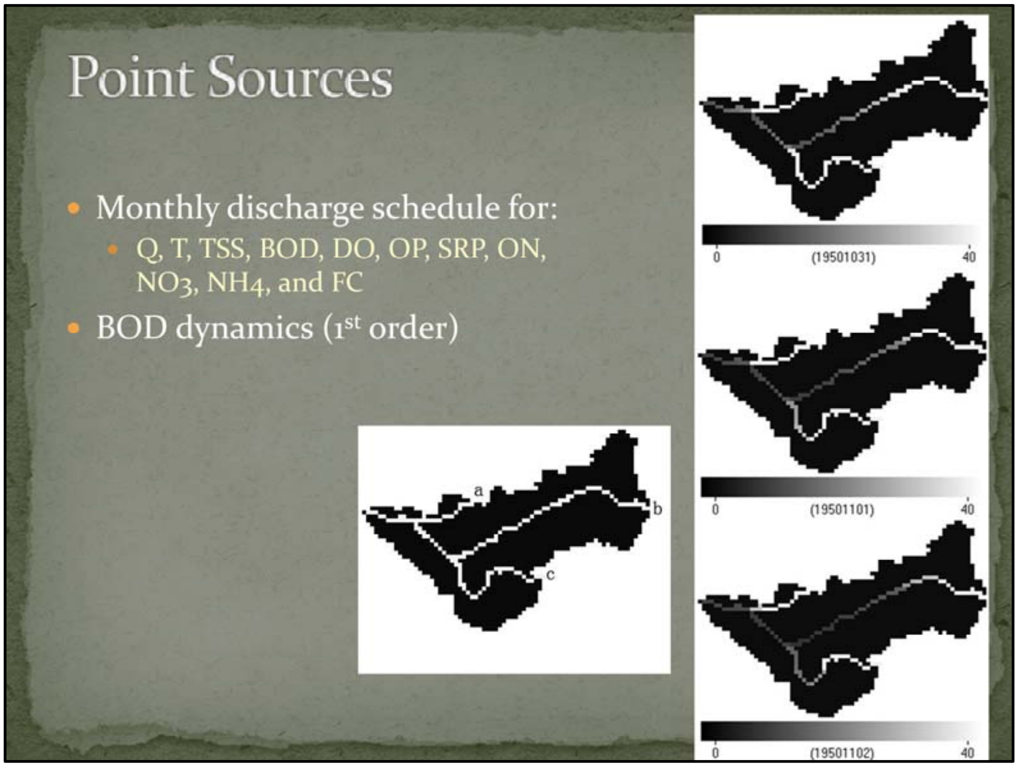
A figure is often better than a table. Here we have the observed discharge (purple line) and the model response to the input net supply (rainfall + snowmelt, top blue thin line) for the original (1950-1964, green line) and recalibrated (1999-06, black line) DLBRM models.



We developed input layers for manure and fertilizer applications and for erosion parameters



We created a layer for the point source discharges using NPDES permit monitoring data



We have modified the DLBRM to allow the transport of non conservative substances (BOD)

Erosion/Transport Models

- Sediment Transport:
  - Daily version of RUSLE/RUSLE2 approach. For each pixel i and each (average) day j:

$a'_{ij}=(r'(Pr_{ij}))/(r'_{im(j)})\ r_{im(j)}\ k_i\ l_i\ S_i\ c_{ij}\ p_{ij}$

$r'(Pr_{ij})=a_i Pr_{ij}^{bi}$ (Richardson et al., 1983;Hollinger et al., 2002)

$r'_{i,m(j)}$ = long term average of r' during month m(j)

  - Erosion/deposition along river system simulated with carrying capacity concept

$$\frac{dX_i}{dt} = e_i + q_i - r_i = e_i + q_i - \min(X_i, \alpha_s Sc_{\max})$$

The sediment erosion model is being implemented and it is based on a daily version of the RUSLE model.

Conclusions

- Although the relation between discharge and TP concentration is not very accurate, the approach shown here takes advantage of infrequent, but long-term, water quality samples to produce reliable estimates at high temporal resolution
- In particular we showed the advantage of including the temporal trend, splitting data into two seasons, taking into consideration the difference between the rising and receding phases of floods, and accounting for the flushing effect of previous storms
- We showed that this approach substantially reduces model error. However, users should be aware of the potential impact of the uncertainty in the data used for calibrating and deploying the model
- We also showed that such models can provide the answers to several policy questions as well as supply reliable inputs to models simulating the water quality in the recipient waterbodies
- We are now finally working to implement the sediment and nutrient transport model

Thanks for the Attention!

Questions?
Comments?
Suggestions?

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