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Modeling Spatial Distributions of Point and Nonpoint Source Pollution Loadings in the Great Lakes Watersheds

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Abstract—A physically based, spatially-distributed water quality model is being developed to simulate spatial and temporal distributions of material transport in the Great Lakes Watersheds of the U.S. Multiple databases of meteorology, land use, topography, hydrography, soils, agricultural statistics, and water quality were used to estimate nonpoint source loading potential in the study watersheds. Animal manure production was computed from tabulations of animals by zip code area for the census years of 1987, 1992, 1997, and 2002. Relative chemical loadings for agricultural land use were calculated from fertilizer and pesticide estimates by crop for the same periods. Comparison of these estimates to the monitored total phosphorous load indicates that both point and nonpoint sources are major contributors to the total nutrient loads in the study watersheds, with nonpoint sources being the largest contributor, particularly in the rural watersheds. These estimates are used as the input to the distributed water quality model for simulating pollutant transport through surface and subsurface processes to Great Lakes waters. Visualization and GIS interfaces are developed to visualize the spatial and temporal distribution of the pollutant transport in support of water management programs.

Keywords—Distributed Large Basin Runoff Model, Great Lakes Watersheds, nonpoint source pollution, and point sources.

I. INTRODUCTION

NONPOINT source pollution (pollutants from agriculture practices, contaminated sediments, urban runoff, and atmospheric deposition, etc) has been commonly regarded as the primary sources of impairments of the rivers, lakes, fisheries and wildlife, and aquatic ecosystems in the United States, Europe and other countries [6, 16, 37]. During the past few decades, different methods have been used to aid in the understanding and management of surface runoff, sediment, nutrient leaching, and pollutant transport. These include GIS-based procedures for risk assessment of pollutants for aquatic ecosystems [33], artificial neural network-based water quality models for prediction of concentrations of fecal indicator bacteria for beach advisories [21], statistical models for identifying highest nutrient loading areas [6]. A number of simulation models have also been developed to track the production and transport of both point and nonpoint source materials through a watershed by hydrological processes. Examples of the models include ANSWERS (Areal Nonpoint Source Watershed Environment Simulation) [3], CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) [22], GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) [23], AGNPS (Agricultural Nonpoint Source Pollution Model) [39], EPIC (Erosion Productivity Impact Calculator) [34], HSPF (Hydrologic Simulation Program in FORTRAN) [5], and SWAT (Soil and Water Assessment Tool) [2], to name a few. However, these models are either empirically based, or spatially lumped or semi-distributed, or do not consider nonpoint sources from animal manure and combined sewer overflows (CSOs). To meet this need, the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL), Western Michigan University, and Case Western Reserve University are jointly developing a spatially distributed, physically based watershed-scale water quality model to estimate movement of materials through both point and nonpoint sources in both surface and subsurface waters to the Great Lakes watersheds [7, 8, 9, 10. 13, 14, 15, 16].

This paper describes procedures for estimating potential loadings of animal manure and agricultural chemicals into surface water from multiple databases of land use/cover, animal production, fertilizer, and pesticide applications. It first gives a brief description of the distributed large basin runoff model (DLBRM) and then discusses procedures for processing and deriving loadings of animal manure and agricultural chemicals. These loading estimates are then used as input to the water quality model to quantify the transportation of combined loadings of animal manure and fertilizers to storages of upper soil zone, lower soil zone, groundwater, and surface water in the Saginaw Bay Basin and to identify critical risk areas for implementation of water management programs.

II. PROCEDURES

1. Study Area.

The study area of this research is the Saginaw Bay Basin (Figure 1) with a drainage area of about 23,200 km^2,, subdivided into four sub-watershed: the Saginaw River (16,680 km^2), and the smaller AuGres-Rifle (2,777 km^2) to the North, Kawkawlin-Pine (1,409 km^2) in the center, and Pigeon-Wiscoggin (2,425 km^2) to the East. The Saginaw Bay Basin, covering portions of 22 counties, hosts important industrial activities, crop and livestock production,, with agriculture and

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forests being the two major land uses. Soils in the watershed consist mainly of loamy and silty clays and sands, and are poorly drained in much of the area. Major crops in the watershed include corn, soybeans, dry beans, and sugar beets. Over the years, the primarily agricultural land use and associated runoff, improper manure management, and industrial pollution have led to high nutrient runoff, eutrophication in the bay, toxic contamination of fish, restrictions on fish consumption, loss of fish and wildlife habitat, and beach closures in the basin [29, 14, 16,18]. To help identify and estimate the loading potential of agricultural nonpoint sources, the DLBRM is applied to the Saginaw Bay Basin to help ecological researchers and resource managers better understand the dynamics of nutrients and chemicals for managing the NPS pollution on a regional scale.

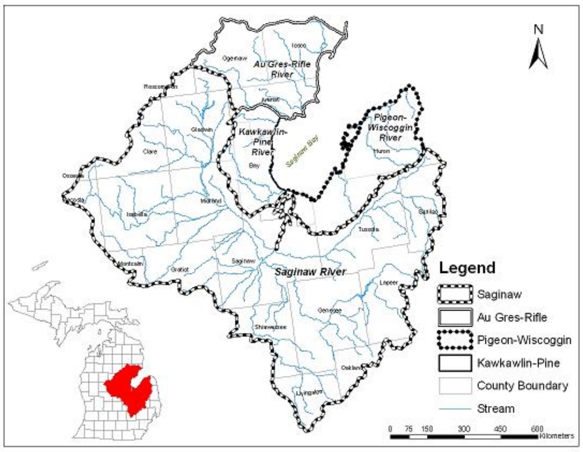

Fig. 1 Boundary of the Saginaw Bay Basin

2. DLBRM

The watershed quality model under development evolves from GLERL's DLBRM [7, 8, 13]. The DLBRM subdivides a watershed into a 1-km^2 grid network and simulates hydrologic processes for the entire watershed sequentially. Each 1-km^2 "cell" of the watershed is composed of moisture storages of upper soil zone (USZ), lower soil zone (LSZ), groundwater zone, and surface, which are arranged as a serial and parallel cascade of "tanks" to coincide with the perceived basin storage structure. Water enters the snow pack, which supplies the basin surface (degree-day snowmelt) (Figure 2). Infiltration is proportional to this supply and to saturation of the upper soil zone (partial-area infiltration). Excess supply is surface runoff. Flows from all tanks are proportional to their amounts (linear-reservoir flows). Mass conservation applies for the snow pack and tanks; energy conservation applies to evapotranspiration. The model computes potential evapotranspiration from a heat balance, indexed by daily air temperature, and calculates actual evapotranspiration as proportional to both the potential and storage. It allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. The model has been applied extensively to the riverine watersheds draining into the Laurentian Great Lakes for use in both simulation and forecasting [7, 8, 9, 10, 13, 16]. The unique features of the DLBRM include: 1) it uses readily available climatological, topographical, hydrologic, soil and land use databases; 2) it is applicable to large watersheds; 3) mass continuity equations are used to govern the hydrologic processes and solved analytically, thus, making model solution analytically tractable [7, 8]. Current model is being modified to add materials runoff through each of the storage tanks routing from upstream to downstream. The movement of pollutants through storages in a watershed is governed by continuity equations with linear loss/transformation coefficients. (mathematical equations are not shown here due to space limits; for details, see [7, 8]).

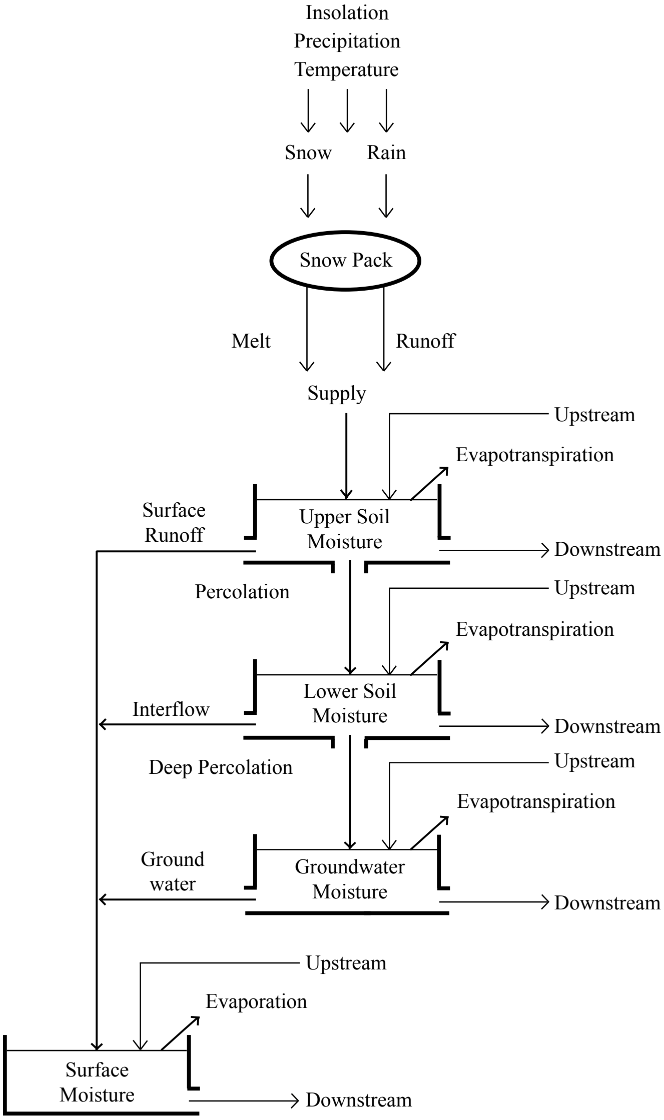

Fig. 2 Scheme of the DLBRM

The DLBRM hydrology component requires 16 input variables for each of the cells (Tables 1 and 2). The model output includes: for every cell in the watershed grid, basin outflow, surface runoff, evapotranspiration, infiltration, interflow, percolation, deep percolation, USZ and LSZ moisture storages, groundwater storage, and lateral flows between adjacent USZ, LSZ, and groundwater [13].

The DLBRM hydrology component was calibrated for the period 1950-1964, applied to the period 1999-2006, and recalibrated for this last period to reproduce the observed daily flow. Performances (Table 3) indicate that the model reproduces the flow of the Saginaw River and AuGres-Rifle Rivers well and with sufficient robustness for nutrients load assessment. Performances for the Kawkawlin-Pine and Pigeon are less satisfying, probably due to the very small portion of these watersheds contributing to the flow measured at the U.S. Geological Survey gages.

III. GIS-MODEL INTERFACE

Since the DLBRM was designed for hydrologic modeling of large scale ($>10^3$ km^2) watersheds, development of the input variables for each grid cell from multiple databases over large watersheds is a challenge.

TABLE I INPUT VARIABLES DERIVED BY THE AVDLBRM INTERFACE

Variables	Databases
Elevation	USGS digital elevation model (DEM)[a]
Flow direction	USGS DEM
Slope	USGS DEM
Land use	USGS land use database[b]
Depth of upper soil zone (USZ)	USDA STATSGO[c]
Depth of lower soil zone (LSZ)	USDA STATSGO
Available water capacity (%) of USZ	USDA STATSGO
Available water capacity of LSZ	USDA STATSGO
Permeability of USZ	USDA STATSGO
Permeability of LSZ	USDA STATSGO
Soil texture	USDA STATSGO
Manning's coefficient value	Land use, slope, and soil texture

[a] U.S. Geological Survey National Elevation Dataset (NED) http://seamless.usgs.gov/.
[b] U.S. Geological Survey National Landcover Characterization Dataset (NLCD) 1992, http://seamless.usgs.gov/.
[c] U.S. Department of Agriculture 1994. http://soils.usda.gov.

TABLE II TIME SERIES METEOROLOGICAL AND FLOW VARIABLES

Variables	Databases
Daily precipitation	National Weather Service climate databases
Daily air temperature	National Weather Service climate databases
Daily solar isolation	National Weather Service climate atlas
Daily flows	USGS discharge database

To facilitate the input and output processing for the DLBRM, an ArcView-DLBRM (AVDLBRM) interface program has been developed to assist with the model implementation. The AVDLBRM interface was written in ArcView Avenue scripts by modifying the ArcView Nonpoint Source Modeling interface by He [17].

It consists of six modules: (1) Soil Processor, (2) DLBRM Utility, (3) Parameter Generator, (4) Output Visualizer, (5) Statistical Analyzer, and (6) Land Use Simulator. Databases required for the DLBRM include meteorological data, soil, digital elevation model (DEM), land use/cover, and hydrology and hydrography (Tables 1 and 2). The databases identified in Table 1 are used by the interface and those in Tables 1 and 2 are used to derive the DLBRM input variables and visualize the simulation results [12. 13. 15].

IV. ESTIMATING ANIMAL MANURE LOADING POTENTIAL

Differentiation of variations in animal manure production within each county requires relevant data and information at a finer scale. In this study, the animal manure loading potential within a county was estimated by using the 5-digit zip code from the Census of Agriculture for the periods of 1987, 1992, 1997, and 2002. The census data were tabulated farm counts of animal units by 5-digit zip code in three classes: 0-49, 50-199. and 200 (i.e.. number of farms with animal units up to 49, between 50 and 199, or 200 or more per zip code) for 1987 and 1992. But those classes were not available for the 1997and 2002 census data. To be consistent in determining the number of animals per farm, the weighted mean number of animals per farm was computed for each type of animal according to the percentage of three classes of animals for the 1987 and 1992 census data (The mean values of 25, 100, and 200 were used for each of the three classes of the animal units in the computation). The weighted mean number of animals per farm in the study area were computed as: 57 cattle and calves, 84 hogs and swine, 18 lamb and sheep, 2,650 chicken, and 6 horses for the census years of 1987, 1992, 1997, and 2002. These were the only data available to estimate number of animals per zip code area. It is inevitable that discrepancies exist between the actual animal number and these estimates. Users should realize the limitation of these estimates when using them for water resources planning [20].

The computed numbers of animals per zip code were matched with the 5-digit zip code boundary file and multiplied by animal manure production coefficients to estimate animal manure loading potential (tons/year) by zip code. The coefficients from the Livestock Waste Facilities Handbook MWPS-18 [30] were used in this study. As animal manure was likely applied to agricultural land, the loading potential was combined with agricultural land in the Geographic Information System to derive the animal loading potential in tons per hectare of agricultural land within each watershed. The results indicate that total amounts of nitrogen (N) and phosphate (P_2O_5) produced from animal manure ranges from 23,000 to 27,000, and from 10,000 to 11, 400 metric tons, respectively, for the periods of 1987, 1992, 1997, and 2002. These nutrients, if applied uniformly to all cropland (around 1.31 million ha) in the region, would average around 17-21 kg/ha for nitrogen, and 8-9 kg/ha for phosphate (Table 4). These amounts seem quite small on a per unit area basis. However, animal production facilities are concentrated in certain locations in the region and the manure produced from those facilities are often either applied to the adjacent cropland or disposed of locally to reduce transportation and labor cost. As shown in Figure 3, the amount of nitrogen (N) produced from manure ranges from 18 to 51 kg/ha in the east central and northwest portion of the Saginaw Bay Basin, and in certain locations, it amounts up to 153 kg/ha. Consequently, these locations can be targeted for implementation of manure management programs for minimizing the pollution potential to the surface and subsurface waters. This also indicates that agricultural statistics data at a finer scale (below county level) would reveal more useful information than would the county level data in animal manure management. Large livestock operations, difficulty to identify at the county level, could be more easily identified at the 5-digit zip code level for manure management [30, 12, 14].

TABLE IV ESTIMATED NUTRIENT LOADING IN THE SAGINAW BAY WATERSHEDS

Year	N (ton) from			$P_2 O_5$ (ton) from	
	Manure	Fertilizer	Atmos.	Manure	Fertilizer
1987	26644	97908	13950	11390	81496
1992	23754	100534	14335	11210	42229
1997	24847	108662	14208	10142	43163
2002	23257	91883	14104	10174	32186

V. AGRICULTURAL CHEMICAL LOADING POTENTIAL

Large quantities of fertilizers and pesticides are used to enhance agricultural production each year. These chemicals, if improperly applied, also represent a potential threat to both surface and groundwater. Estimating loading potential of such chemicals, however, is challenging because no fertilizer and pesticide information is collected at county level on an annual basis [35, 38]. The U.S. Geological Survey estimated the county level manure and fertilizer application rates for the period of 1982-2001 based on the state level fertilizer sales data and agricultural statistics data [1, 32]. The results show that approximately 92,000 to 109,000 metric tons of nitrogen (N) fertilizer and 32,000 to 81,000 metric tons of phosphate were applied to cropland in the study area each year, averaging about 24 to 83 kg/ha per year (Table 4). Comparison of the manure nutrient estimates from the USGS (1987, 1992, 1997) with those estimates from zip code level computations for Michigan indicates that the N estimates differences were only about 3% and P differences were about 25 to 28 percent. These estimates only show amounts of fertilizers applied to the study area each year and do not consider uptake of the fertilizer by crops. Lack of soil testing, plant uptake of nutrients, and mineralization and volatilization information makes it very difficult and speculative to estimate nutrient budget and excessive nutrients remaining in the soil each year. Thus no attempt was made to estimate excessive nutrients in the soil each year. Instead, only fertilizer loading potential was estimated in the study area.

Information on restricted-use pesticide (RUP) (pesticides that could cause environmental damage, even when used as directed) was acquired from Michigan Department of Agriculture Pesticides and Plant Pest Management Division [31]. The RUP sales database contains all RUP sales in the State of Michigan, including name of reporting county, over 880 chemical names, percentage of active ingredient, amount applied, and name of applied county since 2000. Since Atrazine accounts for more than 80 percent of the RUP sales in Michigan, the sales (amount of active ingredient) of Atrazine were extracted from the database by year and county for the Saginaw Bay Basin [31]. The uncertainty associated with the RUP sales based estimates is that the locations of sales and applications of pesticides may not be the same. The estimates of Atrazine applications by county were spatially overlain with the land use data in GIS to derive the Atrazine application rates per ha of cropland (kg/ha) at the county level. Approximately 149 metric tons of Atrazine were used in the Saginaw Bay Basin in 2002. While a majority of applied Atrazine may be used by plants, some portions of it could be transported either through surface runoff or drainage tiles to the surface waters or leached to groundwater in the watershed. Thus, implementing best management practices in applying agricultural chemicals is crucial for reducing the pollution potential in the study area [12, 14, 19].

VI. CRITICAL NONPOINT SOURCE POLLUTION AREAS

The loading potential of pesticides (Atrazine) and nutrients (N and P_2O_5 from manure and fertilizers) were assigned to each 1-km^2 cell of the watershed study area (the watersheds were divided into 1-km^2 grid cells) by using the AVDLBRM interface [7, 8, 12, 14, 16]. These data layers will be used with other input variables to simulate transportation of the nutrients and Atrazine in the storages of upper soil zone, lower soil zone, groundwater, and surface water. Additionally, soil erosion and sedimentation will be estimated by adapting the Revised Universal Soil Loss Equation methodology to daily simulation. Eventually, the DLBRM will simulate loading potential and transport of nutrients, pesticides, and soil erosion and sedimentation in the Saginaw Bay Basin and other watersheds.

VII. POINT SOURCE POLLUTION

Nutrient and sediment loads generated by municipal and industrial wastewater treatment plants (WWTP) and by combined sewer overflows (CSOs) and sanitary sewer

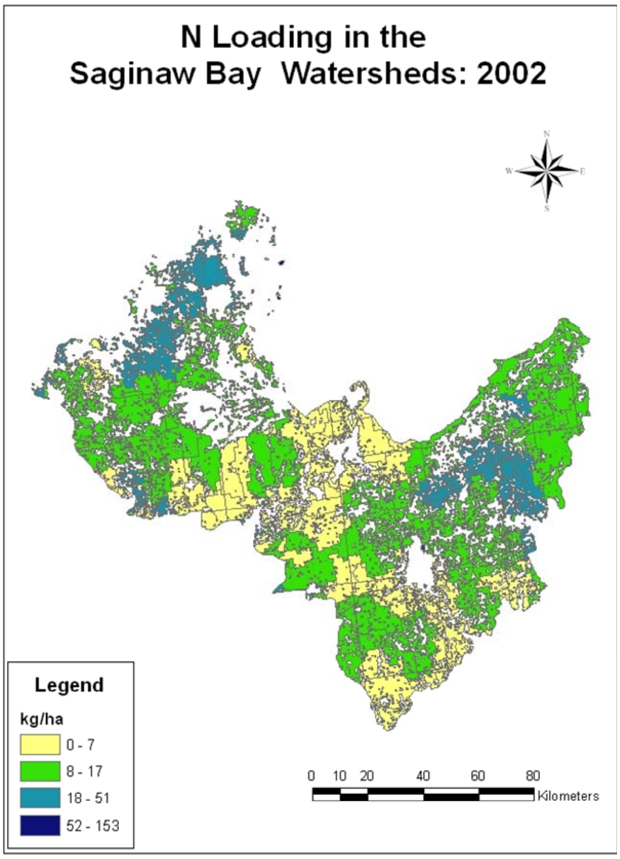

Fig. 3 Distribution of nitrogen (N) from animal manure (kg/ha) by zip code in the Saginaw Bay Basin (data source: www.census.gov).

overflows (SSOs) have been estimated from the National Pollutant Discharge Elimination System permits and verified with the management of some of the sources. Table 5 shows that the phosphorous load generated by point sources accounts for about 16% of the total load exported by the Saginaw River during wet years and 38% of the load during dry years (Table 5). The estimates seem to indicate that the CSO's contribution to the total load entering the bay is negligible. Consequently, CSOs will not be modeled at least initially. Loads from other municipal and industrial sources will vary only at the monthly scale.

TABLE V ESTIMATED TOTAL PHOSPHOROUS LOAD (METRIC TON PER YEAR) EXPORTED BY THE POINT SOURCES IN THE SAGINAW RIVER

	CSO/SSO	WWTP	Total Load*	CSO fraction of load (%)	WWTP fraction of load (%)
2001	2.43	--	642.00	0.38	--
2002	3.02	--	513.00	0.59	--
2003	0.59	--	345.00	0.17	--
2004	2.98	116.00	724.00	0.41	16.0
2005	--	110.00	288.00	--	38.2

*Michigan Dept. of Environmental Quality, 2003-2006.

A suite of simple models relating Total Phosphorous (TP) concentration at day ***t*** to the river discharge at day ***t*** and antecedent average 10-day discharge were built using concentration data reported by the Michigan Department of Environmental Quality [25, 26, 27, 28] and river discharge data at the related monitory sites. Combining these models for the period 1997-2006, it was possible to estimate the annual TP load produced by different parts of the Saginaw River watersheds (Figure 4 and Figure 5). A first point to notice is that point sources in the Saginaw River as well as possible river erosion produce almost one quarter of the load reaching the Bay. The TP dynamics in the Flint River is also heavily influenced by waste water treatment plant (WWTP) discharges, suggesting that a large fraction of this loads is of point source origin. On the other hand, the similarity of TP behavior in the more rural Tittabawasse, Shiawasse, and Cass watersheds suggests that most of these loads are of agricultural origin (Flint, Tittabawasse, Shiawasse, and Cass all flow into Saginaw River and then to Saginaw Bay). Further, of notable importance appears the role of the National Wildlife Refuge (NWR), an area of wetlands and swamps upstream the City of Saginaw, which acts as a sink for almost 10% of the load coming from the upper part of the watershed.

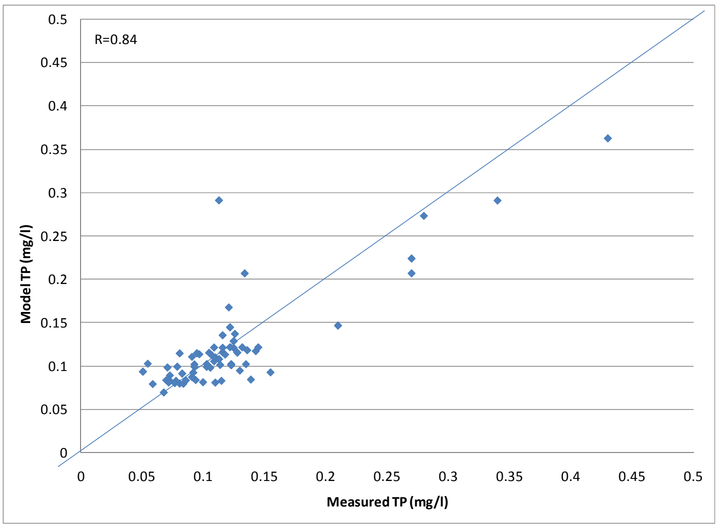

Fig. 4 Model calibration results for TP concentration at Essexville, MI.

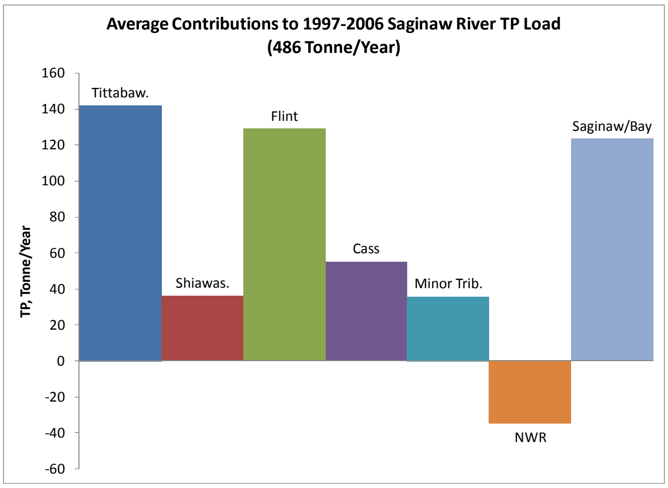

Fig. 5 TP annual loads for different parts of the Saginaw River Basin.

VIII. SUMMARY

The NOAA's Great Lakes Environmental Research Laboratory, Western Michigan University, and Case Western Reserve University are developing a spatially distributed, physically-based watershed-scale water quality model to estimate movement of materials through point and nonpoint sources in both surface and subsurface waters to the Great Lakes watersheds. This paper, through a case study of the Saginaw Bay Basin, estimates loading potential of nutrients from animal manure and fertilizers and point sources . The animal industry produces approximately over 25,000 tons of nitrogen and 10,000 tons of phosphate in the Saginaw Bay Basin, averaging 19 kg of nitrogen, and 8 kg of phosphate per ha of agricultural land annually. About 100,000 tons of nitrogen fertilizer, 40,000 tons of phosphate, and 149 tons of Atrazine are used annually in the agricultural land of the study area. Point sources contribute over 110 metric tons of phosphorous load in the study watersheds, accounting for about 16 to 38 percent of the total phosphorous load annually. Work is underway to modify and refine the current model for simulating pollutant transport in both surface and subsurface water in the Saginaw Bay watersheds in support of water quality programs.

The analysis shows that both point and nonpoint sources are major contributors to the total nutrient load in the study watersheds, with nonpoint source pollution being the largest contributor, particularly in the rural watersheds. Agricultural statistics data at the finer scale (below county level) would reveal more useful information than the county level data in estimating multiple sources of pollutant loading potential. Governmental agencies should consider collecting and tabulating relevant information at the township or zip code level to aid environmental planning and management.

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TABLE III HYDROLOGIC SIMULATION PERFORMANCES FOR THE SAGINAW BAY WATERSHEDS

Basin	Size (km^2)	Period	Calib. Param.	Bias (%)	Corr.	Avg flow (cm/d)	RMSE/ Flow (%)	Nash Sutcliffe
Saginaw	16,680	011950-121964	011950-121964	-5.0	0.90	0.056	61.4	0.77
		011999-092006	011950-121964	-2.4	0.80	0.062	71.8	0.63
		011999-092006	011999-092006	0.1	0.84	0.062	60.0	0.48
AuGres-Rifle	2,777	011950-121964	011950-121964	-1.7	0.86	0.079	54.5	0.66
		011999-122006	011950-121964	-0.8	0.85	0.088	42.6	0.70
		011999-122006	011999-122006	-1.7	0.89	0.088	36.6	0.72
Kawkawlin-Pine	1,409	011950-121964	011950-121964	9.7	0.79	0.048	147.9	0.25
Pigeon-Wisgoggin	2,425	011986-121993	011986-121993	6.9	0.79	0.072	125.0	0.30