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SPATIALLY MODELING NONPOINT SOURCE POLLUTION LOADINGS IN THE SAGINAW BAY WATERSHEDS WITH THE DLBRM

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ABSTRACT: Accurate nonpoint source (NPS) pollution accounting is essential to effective water quality and ecosystem management. The National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory and Western Michigan University are jointly developing a physically based, spatially-distributed hydrology model to simulate spatial and temporal NPS material distributions in the Saginaw Bay watersheds, draining into Georgain Bay in the Laurentian Great Lakes. Multiple databases of meteorology, land use, topography, hydrography, soils, and agricultural statistics 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. 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. These simulations, once verified with the in situ Saginaw Bay water quality data, will provide important information to researchers and decision makers for developing the Environmental Protection Agency (EPA) mandated Total Maximum Daily Load programs to minimize the nonpoint source pollution in the watersheds.
KEY TERMS: Nonpoint source pollution; watershed modeling; Saginaw Bay Watersheds.

INTRODUCTION

Agriculture, contaminated sediments, urban runoff and combined sewer overflows (CSOs) have been identified as the primary sources of impairments of the Great Lakes shoreline waters (U.S. Environmental Protection Agency (EPA) 2002). The problems caused by these pollutants include toxic and pathogen contamination of fisheries and wildlife, fish consumption advisories, drinking water closures, and recreational restrictions (USEPA 2002). Management of these problems and rehabilitation of the impaired waters to a fishable and swimable state require identifying impaired waters that are unable to support fisheries and recreational activities and tracking both point and nonpoint source material through a watershed by hydrological processes. Such sources include sediments, animal and human manure, agricultural chemicals, nutrients, and industrial discharges, etc. While a number of simulation models have been developed to aid in the understanding and management of surface runoff, sediment, nutrient leaching, and pollutant transport processes such as ANSWERS (Areal Nonpoint Source Watershed Environment Simulation) (Beasley et al. 1980), CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) (Knisel 1980), GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) (Leonard et al. 1987), AGNPS (Agricultural Nonpoint Source Pollution Model) (Young et al. 1989), EPIC (Erosion Productivity Impact Calculator) (Sharpley and Williams 1990), and SWAT (Soil and Water Assessment Tool) (Arnold et al. 1998), to name a few, these models are either empirically based, or spatially lumped, or do not consider nonpoint sources from animal manure and CSOs. To meet this need, the National Oceanic and Atmospheric Administration (NOAA) Great Lakes Environmental Research Laboratory (GLERL) and Western Michigan 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 (Croley and He 2005a,b).

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 will then be used as input to the water quality model to quantify the transportation of combined loadings of animal manure, fertilizers, and pesticides to storages of upper

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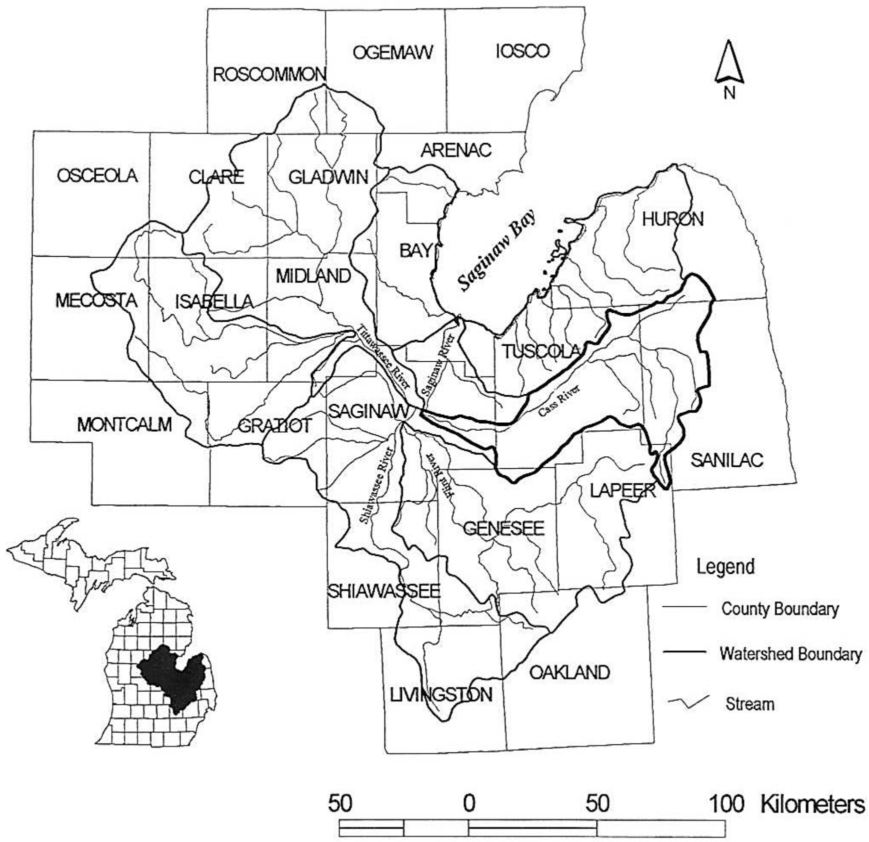

Figure 1. The boundary of the Saginaw Bay Basin..

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.

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. The Saginaw Bay Basin, covering portions of 22 counties, is an important base for industrial supply, food production, warm water fishing, and navigation, with agriculture and 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 (Michigan Department of Natural Resources 1988; He et al. 1993; He and Croley 2005b). 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.

DLBRM

The watershed quality model under development evolves from GLERL's DLBRM (Croley and He 2005a, 2006). Each 1-km^2 "cell" of the watershed is composed of moisture storages of upper soil zone, lower soil zone, 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 (Croley and He 2005a, 2006; Croley et al. 2005). 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 (Croley and He 2005a, 2006). Currently, the model is being modified to add materials runoff through each of the storage tanks routing from upstream to downstream. The movement of conservative pollutant through storages in a watershed is governed by the continuity equations (mathematical equations are not shown here due to space limits; for details, see Croley and He 2005a, 2006).

The DLBRM operates on a grid network basis and requires 16 input variables for each of the cells (see 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 (He and Croley 2005a).

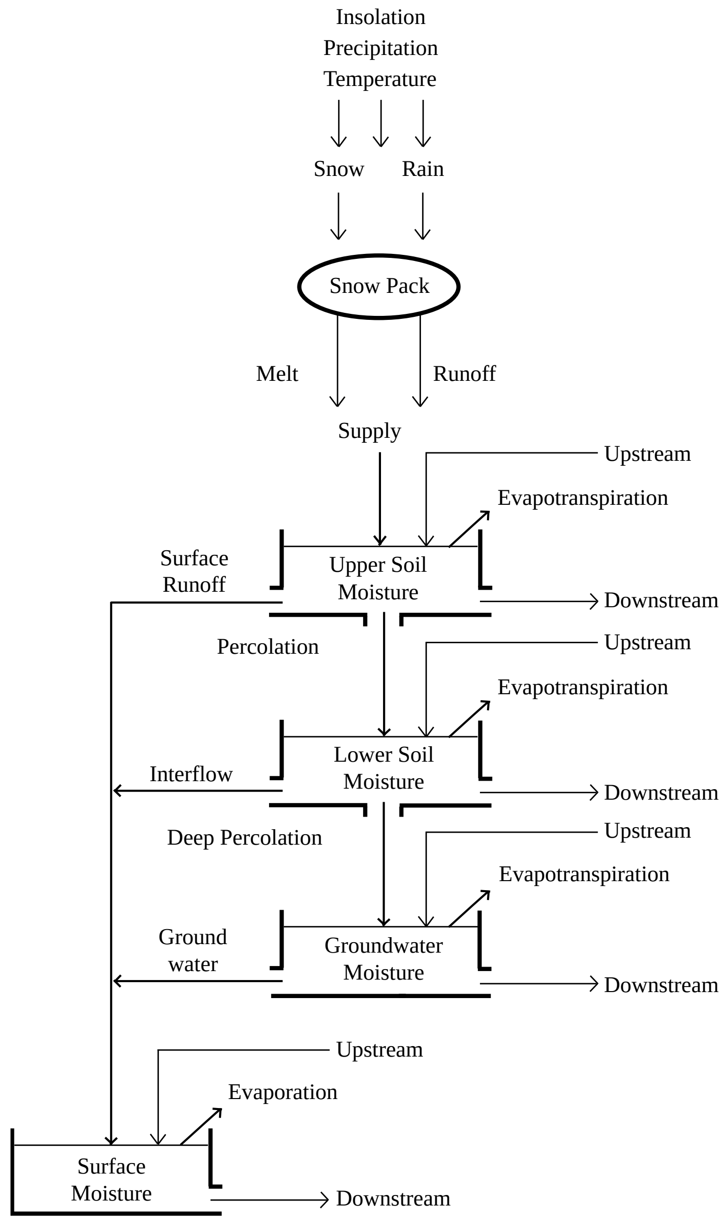

Figure 2. Tank cascade schematic of Distributed Large Basin Runoff Model.

GIS-MODEL INTERFACE

The DLBRM divides a watershed into a 1-km^2 grid network (to match the spatial coverage of meteorological data) and simulates hydrologic processes for the entire watershed sequentially. It requires 16 input variables for each of the 1-km^2 grid cells (see Tables 1 and 2). Since the DLBRM was designed for hydrologic modeling of large scale (>10^3 km^2) watersheds, development of the 16 input variables for each grid cell from multiple databases over large watersheds is a challenge. 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 et al. (2001) and He (2003). 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 (He and Croley 2005a).

Table 1. 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 2. 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

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(http://www.nass.usda.gov/Census_of_Agriculture/index.asp). 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 1997 and 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 (He and Shi 1998).

The computed numbers of animals per zip code were matched with the 5-digit zip code boundary file (obtained from the Census of Bureaus website: http://www.census.gov/geo/www/cob/z52000.html#shp) 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 (Midwest Plan Service 1985) were used in this study. For example, a 1,000 lb dairy cow produces 13 metric tons of manure in a year (20-25 percent solids content and 75-80 percent moisture content) with 150 lbs of nitrogen and 60 lbs of phosphate; a 150 lb pig produces 1.6 metric tons of manure in a year with 25 lbs of nitrogen and 18 lbs of phosphate (Table 3). 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 20,000 to 23,000, and from 10,000 to 13, 000 metric tons, respectively, for

Table 3. Estimates of Annual Animal Manure Loading Potential per Livestock.

Animal	Weight	Manure		N		P_2O_5		K_2O	
	(lb)	(lb/day)	(kg/yr)	(lb/day)	(kg/yr)	(lb/day)	(kg/yr)	(lb/day)	(kg/yr)
Cattle	1000	82.0	13588	0.41	68	0.166	28	0.325	54
Swine	150	10.0	1657	0.068	11	0.050	8	0.054	9
Sheep	100	4.0	663	0.045	8	0.015	3	0.039	7
Poultry	4	0.21	35	0.0029	0.5	0.0025	0.4	0.0014	0.2
Horse	1000	45.0	7457	0.27	45	0.105	17	0.205	34

Source: Midwest Plan Service , 1985.

Table 4. Estimated Nutrient and Pesticides Loading (ton/year) in the Saginaw Bay Basin[a].

Year	N (ton) from		P_2O_5 (ton) from		Atrazine (ton)
	Manure[b]	Fertilizer	Manure[b]	Fertilizer	
1987	22944	196235	12054	148362	
1992	22430	198595	13353	148375	
1997	20332	187180	14118	143810	
2002	19277	184900	10628	146093	179

[a]About 1.31 million ha of cropland (3.24 million acres) is available in the Saginaw Bay Basin.

[b]Estimated total amounts of nitrogen and phosphate from animal manure were based on the Census of Agriculture Data of 1987, 1992, 1997, and 2002.

[c]Atrazine data were acquired and processed from the Michigan Department of Agriculture Restricted Use Pesticides database.

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 15-17 kg/ha for nitrogen, and 8-10 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 (He and Shi 1998; He and Croley 2005b).

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 (U.S. Geological Survey 2000; USEPA 2004). The U. S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) provides state summaries of fertilizer and pesticide use annually for selected major field crops (e, g., corn, wheat, soybeans, cotton, potatoes, etc.). For Michigan, fertilizer application rates are only available at the state level for corn, potatoes, and soybeans for selected years (USDA NASS 2004). To compute the average fertilizer application rates in the study area, the average application rates of each of six major crops [corn, dry beans, oats, soybeans, sugar beets, and wheat, collectively representing over 97 percent of the harvested crop acreage in the Saginaw Bay Basin (USDA NASS 2004)] were compiled from a number of sources (Christenson et al. 1992; Michigan Department of Agriculture 2004, 2005; USDA NASS 2004, 2005). The fertilizer application rates of these crops were multiplied by the crop mix in the Saginaw Bay Basin to derive the amount of fertilizer applied to cropland. The results show that approximately 185,000 to 200,000 metric tons of nitrogen (N) fertilizer and 144,000 to 150,000 metric tons of phosphate were applied to cropland in the study area each year, averaging about 110 to 153 kg/ha per year (Table 4). 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 difficulty 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 (Rowe 2005). 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 (Rowe 2005). 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 179 metric tons of Atrazine were used in the Saginaw Bay Basin in 2002 (estimates of Atrazine were also available for 2000, 2001, 2003, 2004, and 2005 but not shown in Table 4). Although these numbers represent the amounts applied to the crops and a major portion of these may be used by plants, some portions of these 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 (He and Shi 1998; He and Croley 2005b).

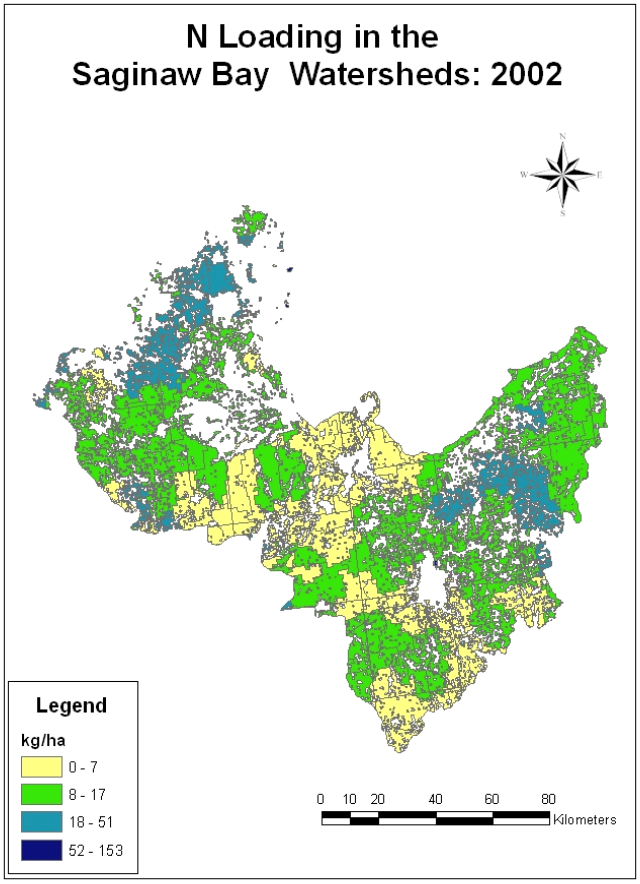

Figure 3. Distribution of nitrogen (N) from animal manure (kg/ha) by zip code in the Saginaw Bay Basin (data source: www.census.gov).

CRITICAL NONPOINT SOURCE POLLUTION AREAS

The loading potential of nutrients (N and P_2O_5) from manure, fertilizers, and pesticides (Atrazine) 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 (Croley and He 2005a, 2006; He and Croley 2005b). 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. This work is underway, and once completed, will help ecological researchers and resource managers better understand the spatial and temporal distribution of nonpoint source pollution, and identify the critical NPS pollution areas for implementation of best management practices. Additionally, we are incorporating the Revised Universal Soil Loss Equation, version 2.0, into the DLBRM to estimate soil erosion and sedimentation. 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.

SUMMARY

The National Oceanic and Atmospheric Administration's Great Lakes Environmental Research Laboratory and Western Michigan 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 animal manure and nutrients, and agricultural chemicals. The animal industry produces approximately over 20,000 tons of nitrogen and 10,000 tons of phosphate in the Saginaw Bay Basin, averaging 15 kg of nitrogen, and 8 kg of phosphate per ha of agricultural land annually. About 200,000 tons of nitrogen fertilizer, 140,000 tons of phosphate, and 176 tons of Atrazine are used annually in the agricultural land of the study area. These estimates will be input to the distributed large basin runoff water quality model for simulating pollutant transport in both surface and subsurface water in the Saginaw Bay watersheds. The results, once verified with the Saginaw Bay water quality data, will help management agencies and ecosystem researchers for identifying critical pollution areas for implementing water quality control programs to rehabilitate critical fisheries and wildlife habitat and recreation areas.

Agricultural statistics data at the finer scale (below county level) would reveal more useful information than would 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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