Modeling Spatial Distributions of Nonpoint Source Pollution Loadings in the Great Lakes Watersheds by Using the Distributed Large Basin Runoff Model[1]

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ABSTRACT. The NOAA Great Lakes Environmental Research Laboratory, Western Michigan University, and the University of Michigan are jointly developing a physically based, spatially-distributed hydrology model to simulate spatial and temporal nonpoint source material distributions in the Saginaw Bay watersheds, which drains into Lake Huron. 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 applications for the same periods. These estimates are to be used as the input to the distributed water quality model for simulating pollutant transport through surface and subsurface processes to Great Lakes waters. 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 Total Maximum Daily Load programs to minimize the nonpoint source pollution in the watersheds.
KEY TERMS: Nonpoint source pollution; Distributed Large Basin Runoff Model; Saginaw Bay Watersheds; Great Lakes.

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 (U.S. Environmental Protection Agency (EPA) 2002; He and Croley 2006; Bouraoui and Grizzetti 2007). 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 (Sala and Vighi (2007), artificial neural network-based water quality models for prediction of concentrations of fecal indicator bacteria for beach advisories (He and He 2008), and statistical models for identifying highest nutrient loading areas (Bouraoui and Grizzetti 2007). 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, Beasley et al. 1980), AGNPS (Agricultural Nonpoint Source Pollution Model, Young et al. 1989), EPIC (Erosion Productivity Impact Calculator, Sharpley and Williams 1990), HSPF (Hydrologic Simulation Program in FORTRAN, Bicknell et al. 1996), and SWAT (Soil and Water Assessment Tool, Arnold et al. 1998), 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 University of Michigan 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 2005, 2006, 2008; He and Croley 2006, 2007a, b, 2008).

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, and CSOs. 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 to be used as input to the water quality model to quantify the transportation of combined nutrient loadings from animal manure and fertilizers and CSOs to storages of upper soil zone, lower soil zone,

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groundwater, and surface water in the Saginaw Bay Basin and to identify critical risk areas for implementation of water management programs.

THE STUDY AREA

The study area of this research is the Saginaw Bay Basin (Figure 1) with a drainage area of about 23,300 km2,, subdivided into four sub-watersheds: the Saginaw River (16,680 km2), and the smaller AuGres-Rifle (2,777 km2) to the North, Kawkawlin-Pine (1,409 km2) in the center, and Pigeon-Wiscoggin (2,425 km2) to the East. 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 2006, and 2008). 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.

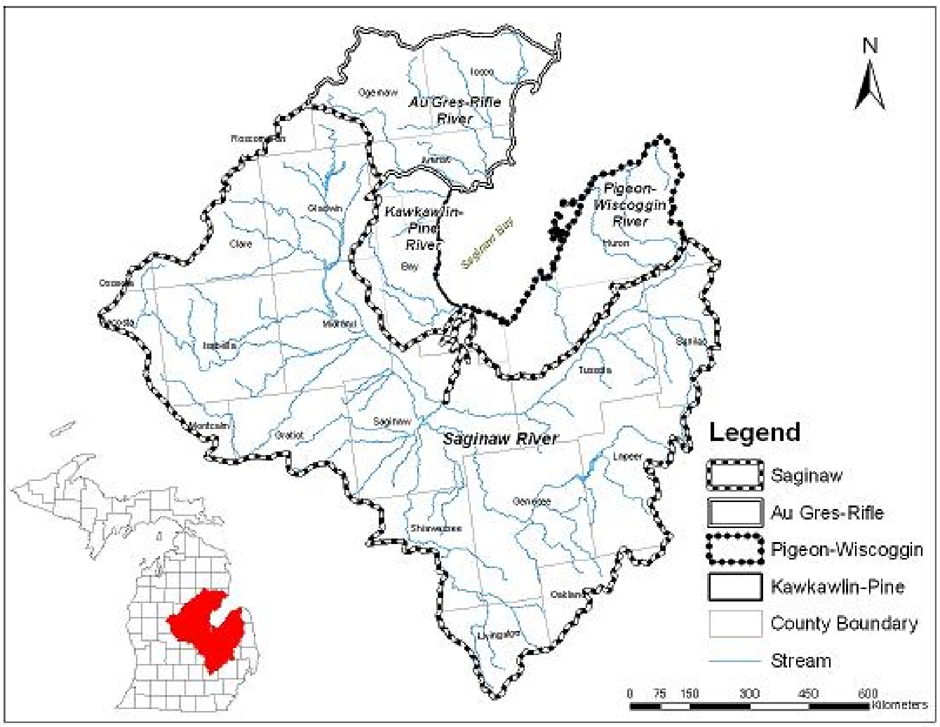

Figure 1. Boundary of the Saginaw Bay Basin.

DLBRM

The watershed quality model under development evolves from GLERL's DLBRM (Croley and He 2005, 2006; and He and Croley 2007a). The DLBRM divides a watershed into a 1-km2 grid network and simulates hydrologic processes for the entire watershed sequentially. Each 1-km2 "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 2005, 2006, 2008; Croley et al. 2005; He and Croley 2006, 2007). 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 2005, 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 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 Croley and He 2005, 2006).

The DLBRM hydrology component requires 16 meteorological, topographic, hydrological, land use and soil related input variables for each of the cells. 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 2007a,b).

Calibration of the DLBRM hydrology component was done 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 1) 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-Wiscoggin are less satisfying, probably due to the very small portion of these watersheds contributing to the flow measured at the USGS gages.

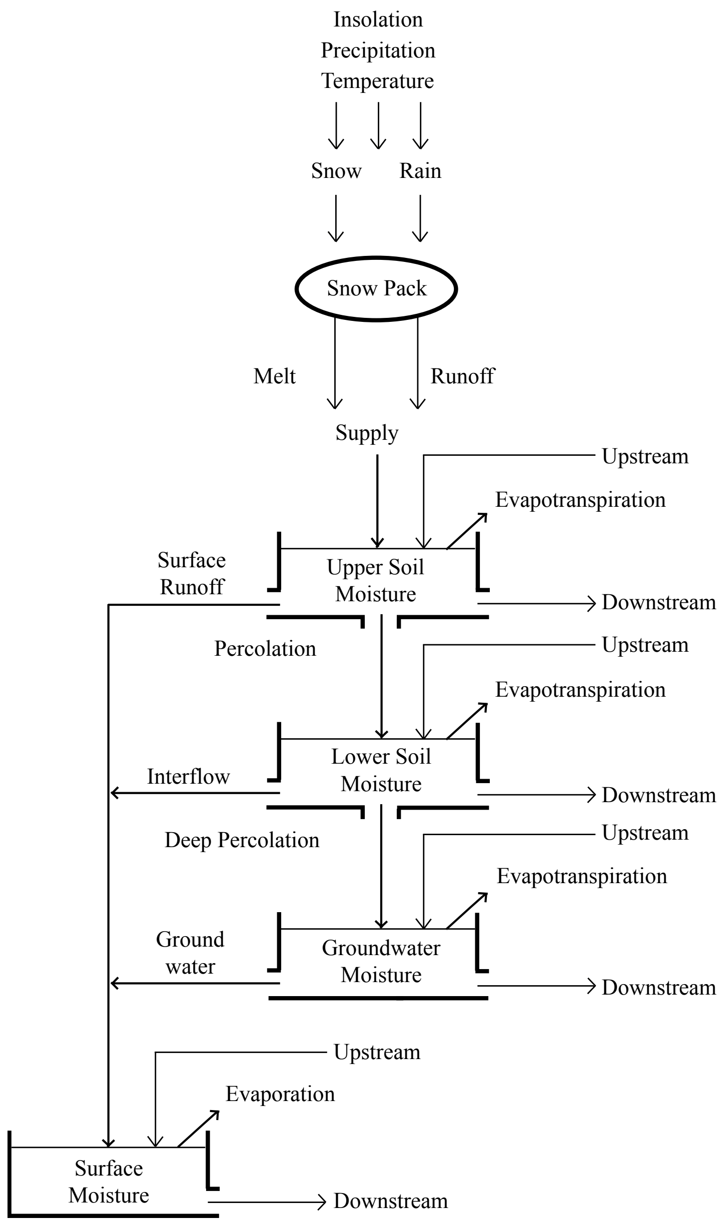

Figure 2. Schematic of Distributed Large Basin Runoff Model (DLBRM) for One Cell.

ESTIMATING MANURE NUTRIENT 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; He and Croley 2008).

Table 1. Hydrologic simulation performances for the Saginaw Bay Tributaries

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

Flow for 1999-2006 was not available for Kawkawlin-Pine and Pigeon-Wiscoggin.

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. The animal manure production was combined with agricultural land in the Geographic Information System (GIS) 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 (P2O5) 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 2). 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. Consequently, these locations can be targeted for implementation of manure management programs for minimizing the pollution potential to the surface and subsurface waters.

AGRICULTURAL CHEMICAL LOADING POTENTIAL

Estimating loading potential of fertilizers and pesticides 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. Geological Survey estimated the county level nutrient inputs from livestock manure and fertilizer applications and atmospheric deposition for the period of 1982-2001 (Ruddy et al. 2006). The county level fertilizer applications were estimated from the state-level fertilizer sales and county level fertilizer expenditures and human population data for both farm and nonfarm uses. The results show that approximately 90,000 to 109,000 metric tons of nitrogen (N) fertilizer and 32,200 to 81,500 metric tons of phosphate (P2O5) were applied to cropland in the study area each year, averaging about 69 to 83 kg/ha per year (Table 2). The county level estimates of manure nutrients by the USGS were determined using the Census of Agriculture livestock data while taking into account confined and unconfined animal facilities. Comparison of the county level manure nutrient estimates from the USGS (1987, 1992, 1997) with those estimates on the zip code level for Michigan indicates that the N estimates differences were only about 3% and P differences were about 25 to 28 percent. Since the zip code level data show detailed spatial variation, the manure nutrient estimates at the zip code level were used in this study The atmospheric deposition of inorganic nitrogen at county level was estimated from the monitory data of National Atmospheric Deposition Program for all land cover types (Ruddy et al. 2006). These estimates only show amounts of nutrients applied to the study area each year and do not consider uptake of the nutrients 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 nutrient loading potential was estimated in the study area.

Table 2. Estimated Nutrient and Pesticides Loading (ton/year) in the Saginaw Bay Basin.

Year	N (Ton) from			P_2O_5 (Ton) from		Atrazine (Ton)
	Manure	Fertilizer	Atmosphere	Manure	Fertilizer	
1987	26644	97908	13950	11390	81496	
1992	25754	100534	14355	11210	42229	
1997	24847	108662	14208	10142	43163	
2002	23257	91883	14104	10174	32186	149

Information on restricted-use pesticide (RUP) (pesticides that could cause environmental damage, even when used as directed) was acquired from the 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 149 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 2). 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 2008).

CRITICAL NONPOINT SOURCE POLLUTION AREAS

The loading potential of pesticides (Atrazine) and nutrients (N and P2O5 from manure and fertilizers) were assigned to each 1-km2 cell of the watershed study area (the watersheds were divided into 1-km2 grid cells) by using the ArcView DLBRM interface (Croley and He 2005, 2006; He 2003; He and Croley 2006, 2007a,b). 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 (RUSLE) 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.

SUMMARY

The NOAA's Great Lakes Environmental Research Laboratory, Western Michigan University, and University of Michigan 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 23,000 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 100,000 tons of nitrogen fertilizer, 40,000 tons of phosphate, and 150 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. While the development of the water quality model is well underway, lack of long term, systematic water quality data makes calibration of the DLBRM difficult and in turn hinders the modeling of the watershed processes. A coordinated effort between governmental agencies, research institutions and private organizations needs to be initiated to systematically collect long term, water quality data with adequate temporal and spatial coverages to support watershed research and management programs.

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