Estimating Nonpoint Source Pollution Loadings in the Great Lakes Watersheds

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ABSTRACT

Nonpoint source pollution (NPS) from contaminated sediments, urban runoff, storm sewers, and agriculture impairs Great Lakes shoreline waters; accurate NPS accounting is essential to effective water quality and ecosystem management. We are developing a physically based, spatially-distributed hydrology model to simulate spatial and temporal NPS distributions in the Saginaw Bay watersheds. Multiple databases of meteorology, land use, satellite imagery, topography, hydrography, soils, and agricultural statistics are used to estimate nonpoint source loading potential in the study watershed. Soil erosion and sediment yield by both wind and water are estimated based on the universal soil loss equation and vegetation indices derived from the satellite imagery. Animal manure production is computed from tabulations of animals by zip code area. Relative chemical loadings for agricultural land use are calculated from county fertilizer and pesticide estimates by crop. These estimates will be used as the input to the water quality model for simulating pollutant transport through surface and subsurface processes to the Great Lakes waters. After verification with Saginaw Bay water quality data, these simulations will help researchers better understand the dynamics of Great Lakes aquatic systems and enable agencies to target critical areas for management.

INTRODUCTION

Nonpoint source pollution is the leading source of impairment of U.S. waters (U.S. Environmental Protection Agency 2002). In the Great Lakes basin, contaminated sediments, urban runoff and combined sewerage overflows (CSOs), and agriculture have been identified as the primary sources of impairments of the Great Lakes shoreline waters (U.S. 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 (U.S. EPA 2002). Management of these problems and rehabilitation of the impaired waters to fishable and swimmable state require identifying impaired waters that are unable to support fisheries and recreational activities and tracking sources of both point and nonpoint source material transport through a watershed by hydrological processes. Such sources include sediments, animal and human wastes, 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 combined sewage overflows (CSOs) and infectious diseases. 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 2005c). The water quality model evolves from GLERL's distributed large basin runoff model (DLBRM) (Croley and He 2005a,b; He and Croley 2005). The model allows surface and subsurface flows to interact both with each other and with adjacent-cell surface and subsurface storages. Currently, it is being modified to add materials runoff through each of the storage tanks routing from upper stream downstream to the watershed outlet (for details of the model, see the companion paper by Croley and He 2005c). This paper describes procedures for estimating potential loadings of sediments, animal manure, and agricultural chemicals into surface water from multiple databases. These estimates will be used as input to the water quality model to quantify the combined loadings of agricultural sediment, animal manure, and fertilizers and pesticides to Great Lakes waters for identifying the critical risk areas for implementation of water management programs.

STUDY AREA

The study area of this research is the entire Saginaw Bay Watersheds with a drainage area of 22,557 km^2, accounting for approximately 15 percent of Michigan's total land (Figure 1). In this paper, we select the Cass River watershed, a sub-watershed of the Saginaw Bay watersheds to present our on-going work for estimating nonpoint source loading potential. The Cass River watershed runs cross Huron, Sanilac, Tuscola, Lapeer, Genesee, and Saginaw counties, and joins the Saginaw River near Saginaw (Fig.1) and has a drainage area of 2,177 km^2. The Cass River is used for industrial water supply, agricultural production, warmwater fishing, and navigation. Agriculture and forests are the two major land uses/covers in the Cass River watershed, accounting for 60 and 21 percent of the total land area, respectively. 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, drybeans, and sugarbeets. Over the years, the primary agricultural land use and associated runoff, improper manure management, poor municipal waster water treatment, irrigation withdrawal, and channel dredging and straightening have led to high nutrients runoff, eutrophication, toxic contamination of fish, restrictions on fish consumption, loss of fish and wildlife habitat, and beach closures in the Cass River watershed, (Michigan Department of Natural Resources, 1988). Because of dominant agricultural land use and related high soil loss potential, the Cass River watershed was selected as the study area for estimating the loading potential of agricultural nonpoint sources to assist the management agencies in planning and managing NPS pollution control activities on a regional scale.
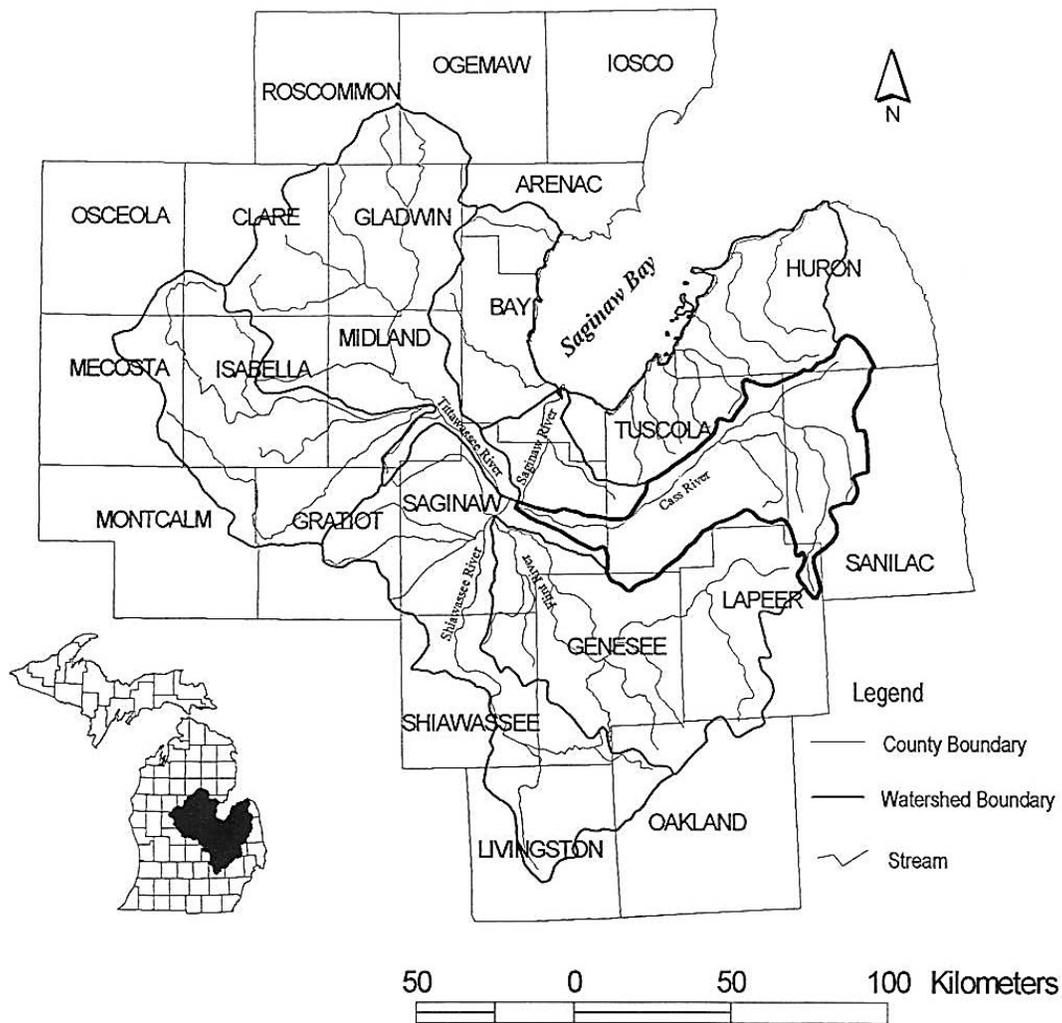
Figure 1. The Saginaw Bay watershed boundary.

ESTIMATING SOIL EROSION POTENTIAL

Soil erosion is caused by raindrops, runoff, or wind detaching and carrying soil particles away. It is the most significant nonpoint source pollution factor affecting the quality of water resources in the U.S. Soil erosion by water includes sheet and rill erosion. Sheet erosion is removal of a thin layer of soil from the surface of the land. Rill erosion is removal of soil from the sides and bottoms of small channels formed where surface runoff becomes concentrated and forms tiny streams. Sheet erosion and rill erosion usually occur together and hence referred to as sheet and rill erosion (Beasley et al. 1984). Soil erosion by wind is the removal of soil by strong winds blowing across an unprotected soil surface. This study focuses on the potential of sheet and rill erosion by both water and wind at the watershed scale.

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Water Erosion Potential

The Universal Soil Loss Equation (USLE) (Eq.1) is one of the most fundamental and widely used methods for estimating soil erosion and sediment loading on an annual basis (Wischmeier and Smith 1978). A number of simulation models, e.g., ANSWERS, EPIC, AGNPS, and SWAT, use the USLE for erosion and sediment simulation.

$$Y=R*K*L*S*C*P*Slope\ Shape \qquad\qquad (1)$$

Where Y is the computed average soil loss per unit area, expressed in ton/acre; R is the rainfall and runoff factor and is the rainfall erosion index (EI) plus a factor for runoff from snowmelt or applied water; K is the inherent erodibility of a particular soil; L is the slope-length factor, S is the slope-steepness factor; C is the cover and management factor; P is the support practice factor; and the slope shape factor represents the effect of slope shape on soil erosion(Wischmeier and Smith 1978;Young et al. 1989).

The AGNPS, based on the USLE, simulates runoff, erosion and sediment, and nutrient yields in surface runoff from a single storm event. Basic databases required for the AGNPS model include land use/land cover, topography, water features (lakes, rivers, and drains), soils, and watershed boundary (He et al. 1993; 1994; 2001; He 2003). The model output includes estimates of runoff volume (inches), sediment yield (tons), sediment generated within each cell (tons), mass of sediment attached and soluble nitrogen in runoff (lbs/acre), and mass of sediment attached and soluble phosphorus in runoff (lbs/acre).

Digital Elevation Model (DEM) of 1:250,000 from the U.S. Geological Survey was used to derive slope and aspect. The STATSGO (State Soil Geographic Data Base) data from the U.S. Department of Agriculture Natural Resources Conservation Service were used to determine dominant texture, hydrologic group, and weighted soil erodibility. The 1979 land use/land cover data from the Michigan Resource Information System (MIRIS) and related hydrography databases were used to derive land use-related parameter values. The storm event chosen was a 24-hour precipitation of 3.7 inches occurring once every 25 years. Fallow, straight row crops, and moldboard plow tillage were assumed in the simulation.

The model was applied to the Cass River watershed with a spatial resolution of 125 ha (310 acres) (Note: the cell size was set at 310 acres to ensure the entire watershed was discretized to no more than 1,900 cells – the limit of AGNPS version 3.65). The simulated results show that the runoff volume was higher in the agricultural land (Figure 2). The soil erosion rate simulated from the single storm event generally centered around 1 to 1.5 tons per acre, with little or no erosion in the forested areas and greater rates (up to 3.5 tons per acre) in portions of the agricultural land. The sediment yield was highest (up to 45,000 tons in the 310 acre area) near the mouth of the watershed as the flatness of the area and lower peak runoff rate resulted in a higher rate of deposition. These results indicate that agricultural activity was a main nonpoint source pollution contributor under the worst management scenario (fallow, straight row crops, and moldboard plow tillage)(He et al. 1993).

Wind Erosion Potential

Wind erosion results in more than five million metric tons of soil erosion per year, accounting for 63 percent of the total soil erosion in the Saginaw Bay watersheds (Michigan Department of Natural Resources, 1988). The critical months for wind erosion are April and May in the Saginaw Bay basin. Few methods are available for estimating soil erosion by wind, such as Wind Erosion Equation developed by the USDA-Agricultural Research Service Wind Erosion Laboratory (Woodruff and Siddoway 1965;

Gregory1984; Presson 1986). These methods are suitable to estimate wind erosion potential at the field level but difficult to use at the watershed level. As soil erodibility, wind, and quantity of vegetative cover are the main factors affecting wind erosion (Woodruff and Siddoway, 1965), this study used soil association data and vegetation indices to estimate the wind erosion potential for the entire Cass River watershed.
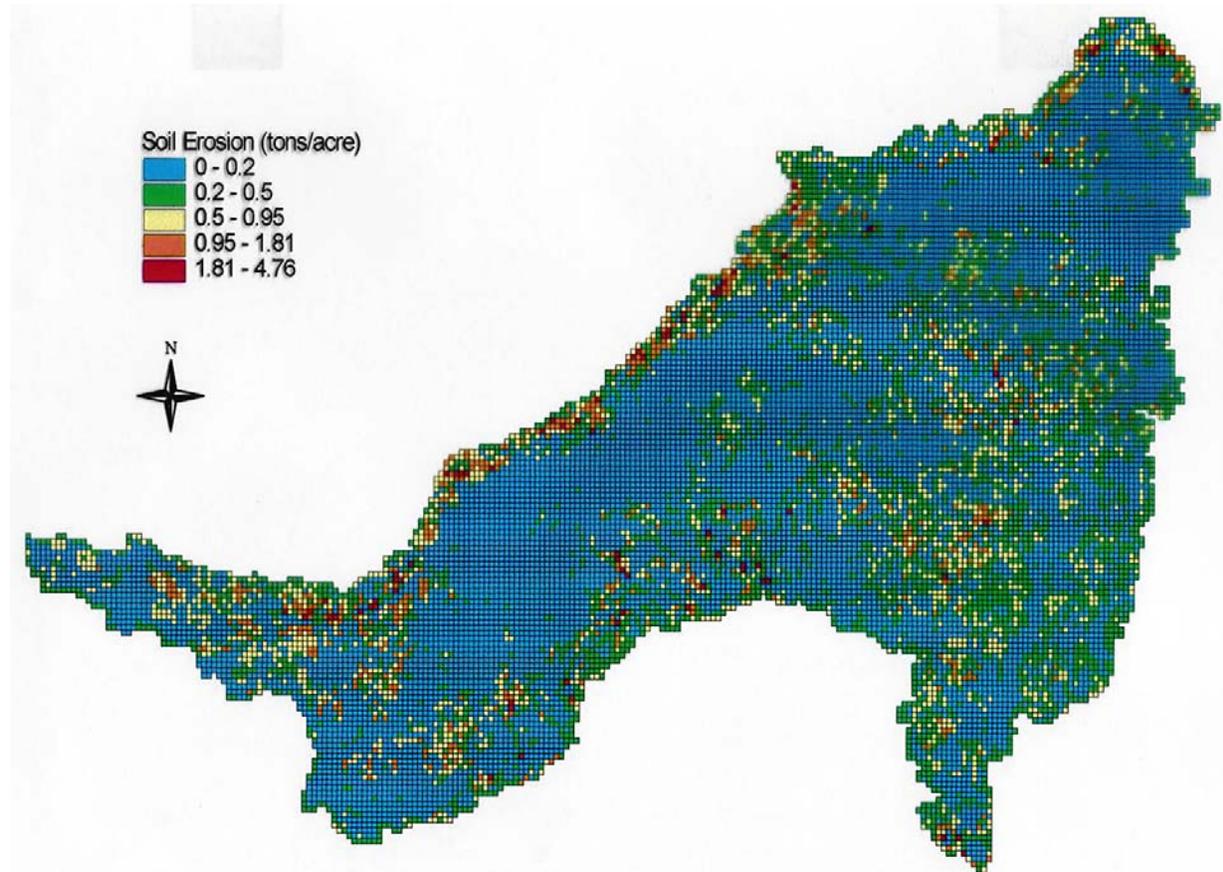

Figure 2. Simulated soil erosion rate (tons/acre) from a 24-hour, 3.7 inches of single storm event in the Cass River watershed.

The STATSGO was used to extract six wind erodibility indices for all the soil associations in the Cass River watershed. The wind erodibility indices of these six groups are determined based on the surface texture and percent aggregates. These groups are: Group 1: 310 ton/acre/year; Group 2: 134 ton/acre/year; Group 3: 86 ton/acre/year, Group 4: 86 ton/acre/year, Group 5: 56 ton/acre/year, and Group 6: 48 ton/acre/year (USDA Soil Conservation Service, 1993). The higher value of the indices, the more vulnerable the particular soil associations to wind erosion. For example, Group 1 represents the soil associations with a very fine or fine sand and 1 percent of aggregates and has a wind erodibility of 310 ton/acre/year, the most vulnerable group of the six to wind erosion (USDA Soil Conservation Service 1993).

The LANDSAT 5 Thematic Mapper data of June 1, 1992 was used to derive the Normalized Differential Vegetation Indices (NDVI). These indices give a relative quantification of vegetation amount, with vegetated areas yielding high values, and nonvegetated areas yielding low or zero values. The formula for calculating the NDVI is:

$$NDVI = (TM\ Band\ 4 - TM\ Band\ 3) / (TM\ Band\ 4 + TM\ Band\ 3) \qquad (2)$$

The TM Bands 3 and 4 represent the red and near-infrared spectrum respectively. The differential values between the two help us determine vegetation type, vigor, and biomass content (Lillesand and Kiefer 1987).

The wind erodibility group indices from the STATSGO were combined with the Normalized Difference Vegetation Indices to delineate the potential wind erosion areas. The criteria for classifying the wind erosion based on soil and vegetative factors were as follows:

Table 1. Classification of Wind Erosion Potential based on the Soil Erodibility and NDVI Values.

Wind Erosion Potential	Classification Criteria	
	NDVI	Wind Erodibility Group Indices (tons/acre/year)
No Wind Erosion	>0.60	Any Group Indices (1-6)
Subtle Wind Erosion	0.40-0.60	134-300
Little Wind Erosion	0.40-0.60 or 0.20-0.39	>300 or <140
Medium Wind Erosion	0.20-0.39 or 0.10-0.19	>140 or <140
High Wind Erosion	0.10-0.19 or <0.10	>140 or <100
Severe Wind Erosion	<0.10	>100

Wind speed and direction were not considered in identifying the potential wind erosion areas because such variables were not available in the four second order weather stations within or adjacent to the Cass River watershed. The closest first order weather station which collects wind speed and direction data (Flint Weather Station) is about 50 miles south of the watershed. Soil moisture data was not considered in the delineation process because wind erosion occurs in the Saginaw Bay basin including the Cass River watershed during the period of April to May when soil moisture is usually high in the region (Merva, 1986).

The wind erodibility of the soil groups in the Cass River watershed ranged from 48 to 310 ton/acre/year based on the properties of soil associations from the STATSGO. The normalized differential vegetation indices (NDVI) derived from the LANDSAT TM data showed that about 33 percent of the Cass River watershed had NDVI value of between 0.01-0.20, 23 percent of the area with NDVI 0.21-0.40, 39 percent of the land with NDVI value of 0.41-0.60, and about 6 percent of the land with dense vegetation cover (NDVI value of 0.61-1.00). As soil and vegetation are two of the most important factors affecting the wind erosion potential, the wind erodibility and NDVI were combined to produce a wind erosion map for the Cass River watershed. The results indicate that about 25 percent of the Cass River watershed had a medium wind erosion potential (Table 2) and most of the area was in agricultural land.

Table 2: Distribution of Wind Erosion Potential in the Cass River Watershed

Wind Erosion Potential	Acres	Percent
No Wind Erosion	257756	44.3
Subtle Wind Erosion	57069	9.8
Little Wind Erosion	120131	20.7
Medium Wind Erosion	143951	24.8
Severe Wind Erosion	2155	0.4
Total	581,063	100.0

ESTIMATING ANIMAL MANURE LOADING POTENTIAL

Improper management of animal manure can result in eutrophication of surface water and nitrate contamination of groundwater (He and Shi 1998). Differentiation of variations in soil and animal manure production within each county requires relevant data and information at the finer scale. The animal manure loading potential was estimated by using the 5-digit zip code from the 1987 Census of Agriculture (He and Shi 1998). Farm counts of animal units by 5-digit zip code were tabulated for cattle and hogs only in three classes: 0-49, 50-199. and 200 or more per zip code area (we used 49, 199, and 200 to represent the three classes of animals per zip code in our calculation). These data were matched with the 5-digit zip code boundary file and multiplied by animal manure production coefficients to estimate animal manure loading potential (tons/per year) by zip code. The coefficients from Livestock Waste Facilities Handbook MWPS-18 (Midwest Plan Service, 1985) were used in this study: for a 1,000 lb dairy cow, the annual manure production is 15 tons, nitrogen 150 lbs, and phosphate 60 lbs; for a 150 lb pig, the annual manure production is 1.8 tons, nitrogen 25 lbs, and phosphate 18 lbs. As the animal waste was likely applied to agricultural land, the loading potential was combined with agricultural land to derive the animal loading potential in tons per acre of agricultural land.

The results indicate that Huron and Sanilac Counties produced the greatest animal waste loading potential per acre of land (over 30 tons/acre/year), Tuscola and Lapeer Counties had second highest loading potential (20-30 tons/acre/year) in the Cass River watershed (Figure 3). Portions of the Sanilac and Tuscola Counties had animal loading potential of over 40 tons per acre of land annually. Distribution of nitrogen and phosphate from animal manure by zip code shows similar patterns. Huron, Sanilac, and Lapeer Counties had the highest nitrogen and phosphate loading potential, Tuscola County had the second highest amount, and Saginaw and Genesee Counties had the lowest loading potential in the Cass River watershed. At the zip code level, four zip code areas (48465, 48426, 48729, and 48464) had animal manure nitrogen production rates greater than 150 lb/acre/year. Consequently, these locations can be targeted for implementation of manure management programs. This also indicates that agricultural statistics data at the 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 easily identified at the 5-digit zip code level for manure management (He and Shi 1998).

Table 3. Estimated Total Amounts of Animal Waste, Nitrogen, and Phosphate from Animal Waste in the Cass River Watershed based on the 1987 Census of Agriculture Data

Animal Waste (tons)	Nitrogen (N)(tons)	Phosphate (P_2O_5)(tons)
9,632,000	25,700	21,180

The total annual loading potential for the animal manure, nitrogen, and phosphate was 10 million tons, 26 tons, and 21 tons, respectively, in the Cass River watershed, averaging 30 tons of animal waste, 160 lbs. of nitrogen, and 130 lbs of phosphate per acre of agricultural land annually (Table 3). The high loading potential makes optimal management of animal manure in the Cass River watershed necessary for minimizing the pollution potential to surface and subsurface waters. These estimates, of course, do not include manure produced by other animals such as sheep and poultry. Thus, it is inevitable that discrepancies exist between the actual animal manure amount and these estimates. Users should realize the limitation of these estimates when using them for water resources planning.
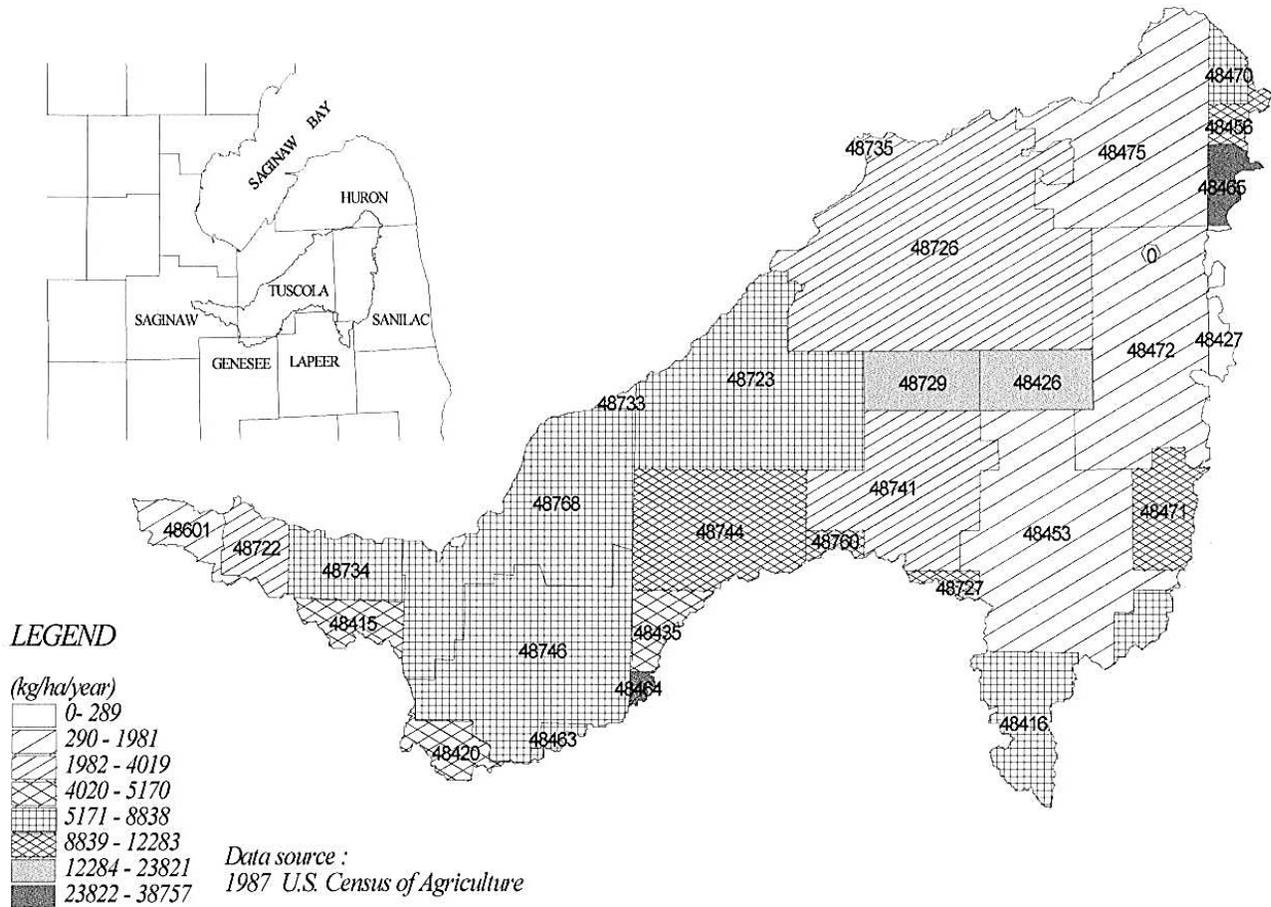

Figure 3. Distribution of animal manure (in kg/ha) by zip code in the Cass River watershed.

AGRICULTURAL CHEMICAL LOADING POTENTIAL

Agricultural chemical data from the Michigan Department of Agriculture (MDA) were used to estimate the loading potential of agricultural chemicals (including both fertilizers and pesticides) in the Cass River watershed. The MDA Pesticide and Plant Pest Management Division (PPMD) maintains two databases for tracking pesticide use: (1) Restricted-Use Pesticide (RUP) (pesticides that could cause environmental damage, even when used as directed) Sales Based Estimates, which records all RUP sales in the state of Michigan; and (2) Survey Based Estimates, which provides estimates of pesticide use associated with each production type in a county by multiplying crop acreage by percentage of area treated and average

application rates based on the 1990 and 1991 agricultural chemical usage survey data. Nitrogen fertilizer usage data were also estimated from the agricultural chemical usage survey data at the county level (USDA National Agricultural Statistics Services, 1990, 1991). The uncertainty associated with the RUP sales based estimates is that the locations of sales and applications of pesticides may not be same. The problem with the survey based estimates is that crop production estimates and pesticide application estimates are not available for all crops (Michigan Department of Agriculture, 1993). We used the survey based estimates for pesticides and nitrogen fertilizer for estimating agricultural chemical loading potential in the Cass River watershed. The estimates were further adjusted by consulting the MSU Cooperative Extension Service pesticide expert (Renner, Personal Communication 1994). These estimates were lumped together to derive the average usage of pesticides per acre of cropland at the county level. They were not differentiated by their toxic level as this project focused on estimating the loading potential of total agricultural chemicals. Similarly, the usage of nitrogen fertilizers were divided by the total acreage of application cropland to derive the average usage of nitrogen fertilizer per acre of cropland. Average phosphate application data for all the cropland were based on the USDA National Agricultural Statistical Service's 1990 and 1991 field crops survey results at the state level (Table 4).

Table 4. Estimated Agricultural Chemical Loading Potential in the Cass River Watershed

County	Cropland (Acres)	Nitrogen Amount (lbs)	Phosphate Amount (lbs)	Pesticides Amount (lbs)
Huron	10,164	579,348	426,888	8,284
Genesee	4,932	247,093	207,144	3,290
Lapeer	11,713	585,650	491,946	7,567
Saginaw	21,729	956,076	912,618	15,428
Sanilac	136,114	6,669,586	5,716,788	83,030
Tuscola	137,389	6,182,505	5,770,338	88,341
Total	322,041	15,220,000	13,526,000	206,000

As shown in Table 4, approximately 15 million pounds of nitrogen and 13.5 million pounds of phosphate fertilizers and 206,000 pounds of pesticides were applied to cropland in the Cass River watershed annually. 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 Cass River watershed.

CRITICAL NONPOINT SOURCE POLLUTION AREAS

Taking into account the loading potential of soil erosion, animal manure, and agricultural chemicals, it seems that the overall noinpoint source pollution potential is highest in the Huron, Sanilac, and eastern Tuscola portions of the Cass River watershed. These areas, located in the upper stream of the Cass River watershed, are mainly cropland with relatively high slope and close proximity to drains and tributaries. The high fertilizer and pesticide application rate, and large amount of animal manure from concentrated livestock industry, and intensive cropping activities make these areas a major source of potential contamination to the surface and subsurface waters in the Cass River watershed. In addition, as these

areas are located in the upper stream, activities in these areas will have a greater impact on the water quality downstream.

The simulated sediment yield from the AGNPS appears to be greatest in the mouth of the Cass River near Saginaw due to the flatness of the area. The larger amount of sedimentation in the area is likely to have negative impact on aquatic habitat. It could also lead to elevated streambed and increased flooding frequency and damage in the surrounding areas. These areas could be targeted for future water quality management programs for minimizing nonpoint source contamination potential.

SUMMARY

The National Oceanic and Atmospheric Administration 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 Cass River watershed, estimates loading potential of soil erosion and sediment by both water and wind, animal manure and nutrients, and agricultural chemicals. The results suggest that the Cass River watershed introduces large amounts of nutrients and sediment into the Saginaw River and Bay. Soil erosion was up to 3.5 tons per acre in some agricultural land area after a single 24-hour storm of 3.7 inches with frequency of one in 25 years. The sediment yield was up to 145 tons per acre at the outlet of the watershed. Total nitrogen and phosphorus runoff was higher in agricultural land. About 25 percent of the total land area in the Cass River watershed was subject to medium wind erosion. The concentrated animal industry produces approximately 10 million tons of manure, 26 tons of nitrogen and 21 tons of phosphate in the Cass River watershed, averaging 30 tons of manure, 160 lbs of nitrogen, and 130 lbs of phosphate per acre of agricultural land annually. About 15 million lbs of nitrogen fertilizer, 13 million lbs of phosphate, and 206,000 lbs of pesticides were used annually in the agricultural land of the Cass River watershed. Portions of these fertilizer and pesticides could be transported either through surface runoff or drainage tiles to the streams and groundwater in the watershed.

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.

This paper estimates the loading potential of multiple sources of pollutants but does not consider the pollutant transport through runoff processes in the entire watershed. Work is underway to provide these estimates to the distributed large basin runoff water quality model for simulating pollutant transport in both surface and subsurface water in all of the Saginaw Bay watersheds. Such information, once verified with the Saginaw Bay water quality data, will help management agencies and ecosystem researchers for prioritizing water quality control programs and protecting critical fisheries and wildlife habitat.

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