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지리정보체계를 이용한 도시 비점원오염의 대축척 모형화

Modeling Large Scale of Urban Nonpoint Source Pollution using a Geographic Information System

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要 旨

도시하수와 관련된 비점원 오염에 대한 관심은 더 나은 수질계획을 위한 새로운 도구의 발전을 이끌어 왔다. 이 논문은 도시의 수질연구를 위해 지리정보체계가 어떻게 응용되는지를 보여준다. 지리정보체계는 비점원 오염 모형화를 위한 토지이용자료를 관리하기 위해 이용되고, 또한 여러가지 형태의 지리적 집합체내에서 오염물질을 평가하는데 이용된다. 경험적인 수질모형은 토지이용에 근본을 둔 오염물질 축적을 평가하기 위해 이용된다. 토지이용범위는 최근 사진의 판독을 통해서 구범위를 갱신함으로써 결정된다. 이러한 토지이용범위는 각각의 토지이용 다각형에 대한 오염물질 축적을 기록하는데 이용된다. 도시하수 유역과 소하수 유역의 범위를 결정하기 위해 하수지도를 수치화 시키고 해석한다. 하수구 소유역층에서 오염물질 축적을 중첩시킴으로써 주요하수의 출구에 대한 오염 축적물이 계산된다. 축적 정보를 기본으로 과다 오염 축적물의 임계지역이 어디에 위치하고 있으며, 오염 축적물을 통제하기 위한 최선의 관리기법의 효율성이 평가된다.

ABSTRACT

Concern about nonpoint source pollution associated with urban storm water has led to the development of new tools for better water quality planning. This paper presents an application of a geographic information system (GIS) for urban water quality study. The GIS was used to manage land use data for nonpoint source pollution modeling and to aggregate pollutant loadings within various types of geographic units. An empirical water quality model was used to estimate pollutant loadings based primarily on land use. A land use coverage was created by updating an old coverage through interpretation of recent photography. This land use coverage was also used to record all pollutant loadings for each land use polygon. Storm sewer maps were digitized and interpreted to create a coverage of storm sewer basins and sub-basins. By overlaying pollutant loadings with the sewer sub-basin layer, aggregated pollutant loadings for major sewer outfalls were calculated. Based on the loading information, critical areas of excessive pollutant loadings were located and the effectiveness of Best Management Practices (BMPs) to control pollutant loadings were evaluated.

1. INTRODUCTION

Nationwide, investigators show that nonpoint source pollution from urban areas is a major contributor to water quality degradation. Storm runoff and combined sewer overflows are the most significant nonpoint sources in urban areas (Peirce,1980). Establishing the best control strategy for urban nonpoint source pollution includes initial assessment of the magnitude of the nonpoint source problem. This assessment must be geographically specific to effectively target control

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practices. Currently, empirical models are typically used to generate urban nonpoint source pollutant loadings. These models are based on the fact that urban nonpoint source pollution is mainly a function of land uses and associated activities (e.g., medium density residential, or highly impervious downtown commercial areas). Coefficients for pollutant loadings by land use have been developed from statistical analysis of field sampled data from the gamut of land uses found in urban areas. Therefore, the validity of model results depends on the resolution of land use data and the specificity of land use categories. Modeling urban nonpoint source pollution across extensive urban areas requires a large number of units of analysis (land use polygons) and resulting pollutant loadings because of highly heterogeneous land uses. It is crucial in urban nonpoint source studies to delineate the boundaries of different land uses, at least to the street block level, in order to effectively target control efforts. A procedure which facilitates nonpoint source modeling based on the aggregation of loadings from small, homogeneous areas provides detailed information about the contribution of nonpoint pollutants from specific areas in order to identify problems. We have called this a "micro" approach (Kim and Ventura, 1993). Such a micro-approach, using a high degree of spatial resolution for land use data across extensive areas, has only been evaluated in much smaller urban areas. A GIS provides the capabilities to integrate and display several types of geographic information in the micro-approach to urban nonpoint source modeling. This project tested three potential advantages of GIS. First, existing digital layers representing street blocks can be imported and used as base frame to collect pollutant loadings. This can also provide a framework for urban storm sewer collection area delineations. Second, parameters such as land use can be transferred between models and data bases more easily using GIS data management functions. In particular, empirical models can be easily linked to GIS layers because coefficients can readily be applied to GIS layers (Sasowsky and Gardner, 1991). This implies that modeling procedures can be simplified, with less data processing time compared to manual methods. Third, aggregated pollutant loadings can be obtained for major sewer outfalls and other geographic units of aggregation through overlay analysis. This process will identify critical areas contributing a significant amount of pollutants. With additional geographic data such as land ownership and value, the GIS and nonpoint source model can be used to evaluate the cost and effectiveness of alternative control strategies in critical areas (Prey et al., 1993). This should lead to best-fit control strategies, meeting the recent federal urban storm water regulations which require permits for certain categories of storm water discharges (U.S. Environmental Protection Agency, 1990). In a previous Wisconsin Department of Natural Resources (WDNR) sponsored pilot study using a small urban area, Harris et al. (1991) concluded that remote sensing and GIS technologies provided reliable and timely data for urban nonpoint source pollution planning. The GIS provided a detailed base layer for identifying small land use polygons, while TM satellite imagery and NHAP2 aerial photography provided an effective source of up-to-date land use data. Kim et al. (1992) reported on the development and testing of the micro-approach in this relatively small urban area. The investigators also emphasized further study, i.e., applying the results from the pilot study to larger urban areas. Based on this study, the WDNR initiated a large scale urban nonpoint source study for the Kinnickinnic River priority watershed. This study, as reported herein, was focused on developing a GIS-based nonpoint source modeling procedure to estimate pollutant loadings and establish effective mitigation strategies.

2. OBJECTIVES

The major aim of this project was to link GIS with a nonpoint source model for establishing effective BMPs based on model output of pollutants. The specific goals were to a) acquire recent land use information and develop a GIS coverage; b) generate a sewer pipe network and delineate storm sewer sub-basin boundaries for use as pollutant loading boundaries of major sewer out-

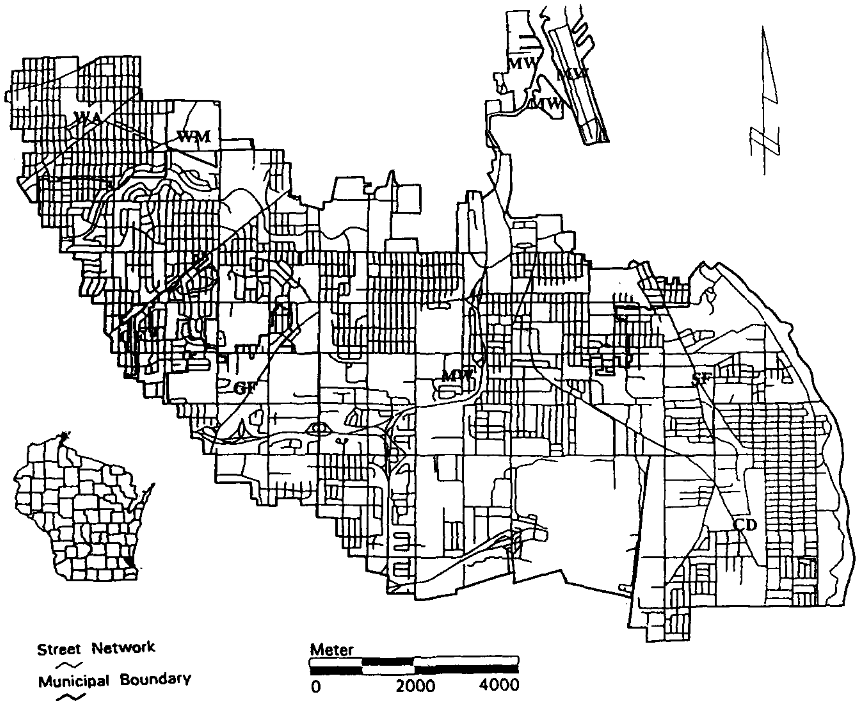

Figure 1. Street Network and Municipal Boundaries of the Study Area.

Displays street network imported from 1983 USGS DLG (1:100,000) and boundaries of six municipalities : Milwaukee(MW), West Milwaukee(WM), Cudahy(CD), St.Francis(SF), Green Field(GF), and West Allis(WA).

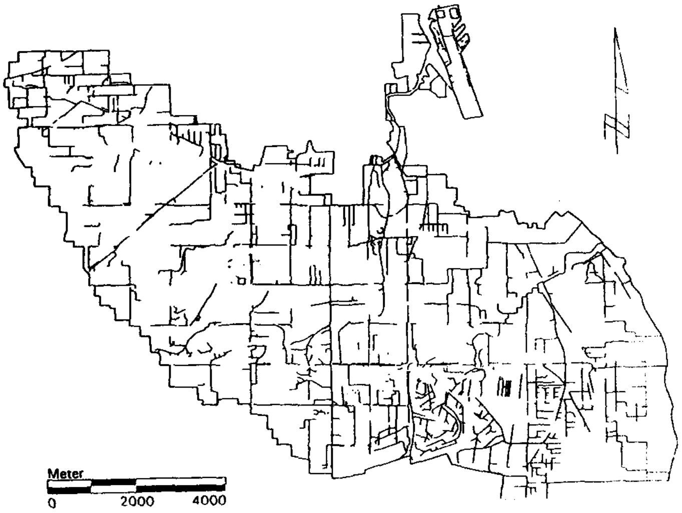

Figure 2. Digitized Storm Sewer Network

74 Sewer maps were digitized and individually registered into Universal Transverse Mercator (UTM) coordinate system and integrated into a sewer network coverage.

falls; c) estimate aggregated pollutant loadings of major sewer outfalls; and d) locate critical areas and establish BMPs for reducing pollutant loadings from these areas.

3. STUDY AREA

The study area is an urban area in the southern part of Milwaukee County, Wisconsin (Figure 1). Most of the area drains into the Kinnickinnic River, while a small portion drains directly into Lake Michigan. The area has seven major streams and an urban storm sewer basin of about 27 mi2 extending over parts of six municipalities, including the City of Milwaukee. The study area has a high density of intensive land uses, including large commercial and industrial areas, and a significant area in transportation such as freeways, railroads, and an airport.

4. METHODS

Land Use Data Sources

Several different sources of land use data were acquired for this project. In an effort to generate a recent land use layer in an effective way, they were evaluated alone and in combination.These data sources were:

a) SEWRPC land use data: 1985 land use data in hard copy plot at a scale of 1:24,000 was purchased from the Southeastern Wisconsin Regional Planning Commission (SEWRPC) and used as a baseline to generate land use data. A digital copy of these data could not be obtained in time for this study.

b) USGS DLG: 1983 USGS Digital Line Graph (DLG) transportation layer at a scale of 1:100,000 was used to delineate detailed street and railroad networks. Check plots against more accurate data showed the spatial accuracy of these data far exceeded national map accuracy standards for 1:100,000 material, and approached that of 1:24,000.

c) Aerial Photography: 1:4,800 black and white lithographic copies of 1:20,000 aerial photographs from 1990 were purchased from SEWRPC. These were used in conjunction with the 1985 SEWRPC land use coverage to generate recent land use data. It had previously been determined that satellite imagery did not have sufficient resolution to support this application (Ventura and Harris, 1993).

Land Use Generation

Land use data have been compiled based on a version of level III USGS urban land use categories (Anderson, 1976) modified for inclusion in a nonpoint source model. Using the DLG layer, SEWRPC hard copy plot, and 1990 airphotos, a recent land use coverage was generated. The procedure used to generate land use data were:

a) import street and railroad center lines from the USGS1:100,000 DLG;

b) digitize freeway and airport polygons from SEWRPC plot, transform these polygons to overlay on street center line coverage, and "dissolve" street center lines inside freeway, railroad and airport polygons;

c) topologically structure combined street center line and freeway coverage to form a street blocks and other transportation polygon coverage. These blocks were then the initial basis for land use interpretation;

d) generate a check-plot of the land use block coverage at the scale of the SEWRPC plot. Note and add any additional line work such as when a block is sub-divided by two or more land uses of significant area.

The detailed land use classes were assigned to individual land use polygons using various sources of data in the following sequence:

a) code freeways and railroads, using primarily SEWRPC plot;

b) code open space, water bodies, and parks using primarily 1:24,000 quadrangles, supplemented by SEWRPC plot and airphotos;

c) code institutional uses such as schools and hospitals, using all three data sources;

d) code commercial, industrial, and residential areas by initially assigning land uses to broad areas according to the SEWRPC plot and then using the 1990 airphotos to validate and refine. In other words, the SEWRPC data were used to delineate major land use boundaries and then block by block interpretations were made with the photography, such as determining residential density.

Storm Sewer Sub-basin Generation

To delineate the pollutant loading boundaries of major sewer outfalls, a storm sewer pipe network coverage was generated. This was done by digitizing storm sewer pipe maps provided by individual municipalities. The 74 sewer maps obtained from municipal engineering offices were delivered in various scales and degrees of quality. These maps were individually digitized to form line coverages. The City of Milwaukee was unique in that extensive interpretation of the sewer maps had to be done before digitizing, i.e., many pipes crossed, went in and out of drainage ditches, etc. The pipes were digitized in accordance with EPA's urban storm water regulations (Environmental Protection Agency,1990). The minimum size of sewer pipes digitized was 36 inches in residential and 12 inches in commercial, industrial, and other areas. Zoning information, either on the storm sewer maps or from other sources, was used as a means to distinguish general land uses. Pipes smaller than the minimum dimension were not incorporated into the sewer network except as needed for hydrologic connectivity. These coverages were consolidated into one composite coverage to represent the sewer system of the entire study area (Figure 2). The sewer sub-basins were delineated based on a hierarchical watershed delineation in three steps. The first step was to delineate two major boundaries for the Kinnickinnic River and Lake Michigan. The Kinnickinnic River has a watershed area of 21.3 mi^2, while 5.5 mi^2 drain directly to Lake Michigan. The second step was to delineate the boundaries of major tributaries (mainly those discharging into the Kinnickinnic River). The Kinnickinnic River has six tributaries, so it was further divided into six sub-watersheds (West Milwaukee Ditch, Cherokee Park Creek, Wilson Park Creek, Ville Mann Creek, Holmes Creek, and Lyons Park Creek) based on topography, surface drainage, and storm sewer network flow. The last step was to delineate individual sewer sub-basin boundaries by interpreting the storm sewer pipe network. This resulted in a coverage showing pollutant discharge boundaries for each sewer outfall. A total of 97 sewer sub-basins, as shown in Figure 3, were delineated using the digitized sewer network, supplemented by the street coverage and topography from 1:24,000 quadrangles. The major principle in delineating the sewer sub-basins was to set the sewer sub-basin boundaries based on minimum end-pipe size to meet the EPA's requirement for storm water management. Therefore, delineation was done at a fine resolution, resulting in sewer sub-basins ranging from 11 to 1,008 acres in discharge area. This fine resolution makes it possible to establish well-suited BMPs for a variety of local urban conditions.

5. RESULTS

Land Use Interpretation Accuracy

Ground truthing by drive-by inspection was conducted to analyze the accuracy of land use interpretation. Over half the blocks (1440 out of 2789 polygons in the land use coverage) were examined. Considering the relatively homogeneous make-up of residential areas and the relatively higher ratios of interpretation errors in commercial, industrial, and institutional classes, emphasis was given to the inspection of the latter classes. The results from the ground truth were used to refine the land use data.

Interpretation accuracy was analyzed based on six major land use categories and 22 detailed land use classes. Due to the use of reference data provided by SEWRPC and large scale airphotos, the final coverage had a high interpretation accuracy. The six major categories show 98 percent average and overall accuracies (Table 1). The residential and transportation classes were almost 100 percent correct. The lowest accuracy was obtained from the industrial class. A relatively high confusion between the industrial class and commercial and open space classes was observed. For 22 detailed land use

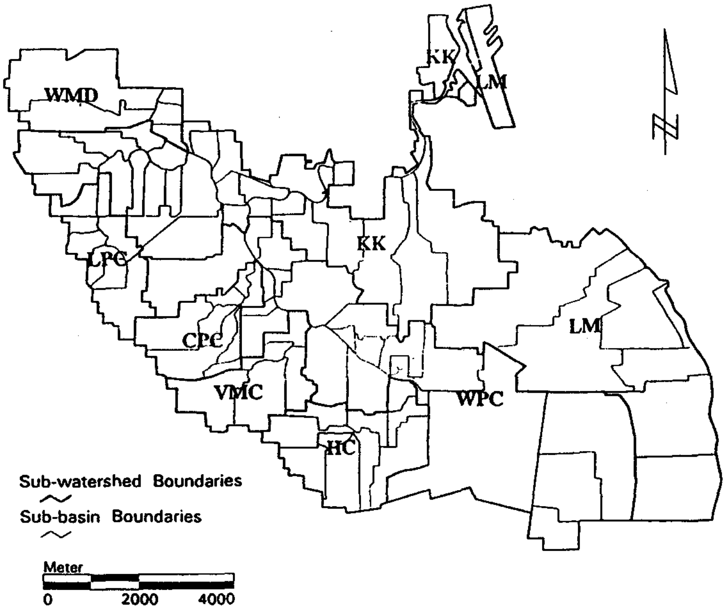

Figure 3. Sub-watershed and Storm Sewer Sub-basin Boundaries.

Displays boundaries of 97 storm sewer sub-basins and eight sub-watersheds: West Milwaukee Ditch (WMD), Lyons Park Creek(LPC), Cherokee Park Creek (CPC), Ville Mann Creek (VMC), Holmes Creek (HC), Wilson Park Creek (WPC), Lake Michigan (LM), and Kinnickinnic River (KK).

Table 1. Land Use Interpretation Accuracy of Six Major Categories.

Displays interpretation accuracy of land use in six major categories. Also shown are detailed land use classes of each category and their classification accuracies.

Known Land Use Classes Sub-classes (% accuracy)	Number of Polygons	Accuracy (%)	Number of polygons classified into classes					
			Residential	Commercial	Industrial	Open space	Institutional	Transportation
Residential High density (96) Medium density (95) Low density (75) Multi-family (74) Mobile home (100)	556	100	555	1				
Commercial Strip commercial (95) Downtown commercial (93) Shopping center (80) Office park (70)	299	96	8	287	2		2	
Industrial Manufacturing (99) Light industry (82) Airport (100)	266	93		9	247	10		
Open Space Undeveloped (99) Construction (88) Park (84) Water (100) Cemetery (100)	125	99			1	124		
Institutional School (100) Miscellaneous (88) Hospital (100)	113	98		1	1		111	
Transportation Railroad (100) Freeway (100)	81	100						81

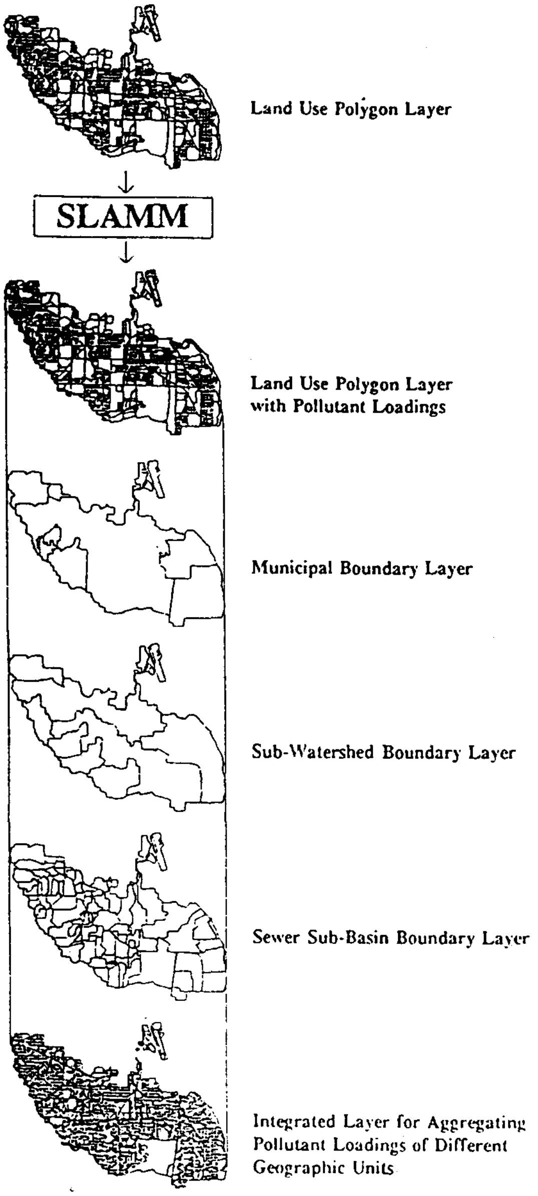

Figure 4. Overlay Analysis for Pollutant Loading Accumulation.

For accumulated pollutant loadings within different geographic units and the boundaries of major sewer outfalls, the land use polygon layer which stores loadings for individual land use poly- gons were overlayed with other layers including municipal boundary, sub-watershed boundary, and sewer sub-basin boundary.

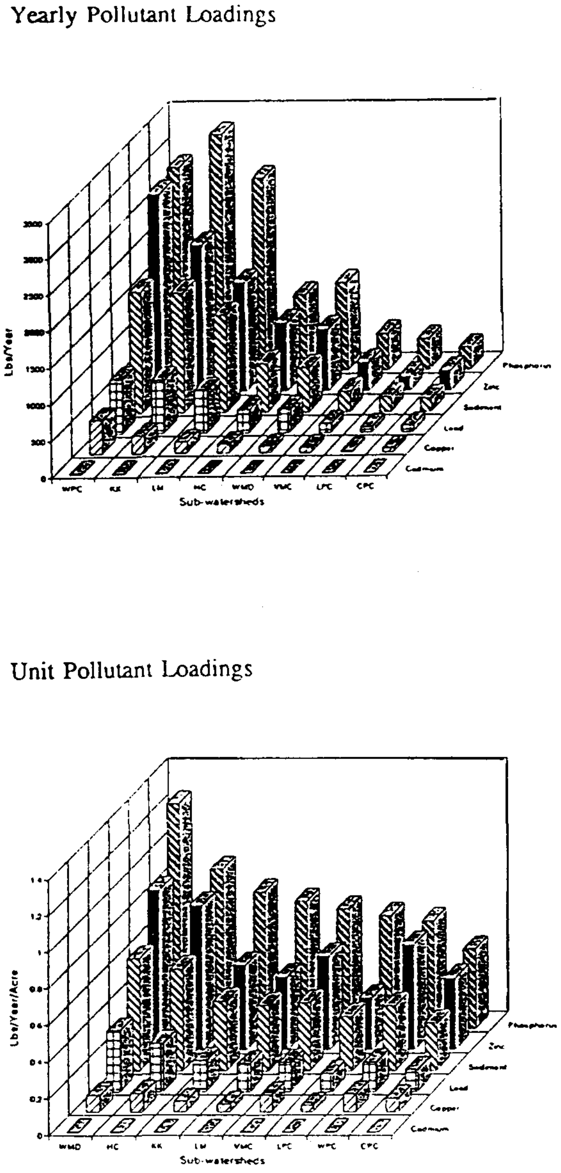

Figure 5. Pollutant Loadings for Sub-watersheds.

Displays yearly and unit pollutant loadings for eight sub-watersheds (refer to Figure 3 for sub- watershed codes).

classes, 92 percent average accuracy was obtained (Table 1). Relatively lower accuracy was obtained in low density and multi-family residential, and office park. Low density residential was often confused with medium density residential, and multi-family was confused with high density residential areas, as expected. The general land use pattern of office parks is similar to strip commercial. This caused lower accuracy for office parks. The mobile home park, schools, airport, hospitals, water, cemetery, freeways, and railroad were 100 percent correct. This is mainly due to the use of topographic maps, which indicated the locations of several of these classes.

Nonpoint Source Modeling

An empirical urban water quality model developed by WDNR--Source Loading and Management Model (SLAMM)--was used to estimate the pollutant loadings of each land use polygon. This model calculates runoff volumes and urban pollutant loadings from individual rainfall events for each land use type (Pitt, 1988). This model also allows the user to estimate reductions in pollutant loadings from source areas due to control measures such as detention ponds or infiltration devices (WDNR, 1991). The major parameters required for modeling are annual rainfall amount, soil type, existing control practices, pollutant loadings coefficients, and the acreage of each land use. In practice, acreages and land use classes are the only independent variables in the modeling. Uniform values were used for the whole area for the other input data. The strength of the SLAMM model is the small storm hydrology algorithms and source area pollutant coefficients (WDNR, 1991). The small storm hydrology verification took place in Toronto, Ontario and Milwaukee, Wisconsin on 185 random rainfall events. The observed runoff volume was within 2 mm of model predicted runoff in most cases. The source area coefficients have been developed through extensive field calibration and verification, including an ongoing effort by WDNR to refine these values. The model was run for 97 sub-basins of eight sub-watersheds. Loadings of six pollutants of concern were obtained from the model. Results from the sub-basin analyses were used to calculated total and unit (per acre) loadings for sub-watersheds and municipalities. Loadings from individual land use polygons were stored as an additional attribute in that coverage. Through overlay analysis, it was possible to determine loadings within any larger division of the area (Figure 4). Figure 5 shows the yearly and unit pollutant loadings of each sub-watershed. For heavy metals (e.g., lead, copper, zinc, and cadmium), Wilson Park Creek showed the highest loadings except phosphorus, followed by the Kinnickinnic and Lake Michigan sub-watersheds. This is explained by the large industrial area, including an airport, in Wilson Park Creek. The Kinnickinnic sub-watershed has the highest loadings of phosphorus, followed by Wilson Park Creek sub-watershed, due to its large residential area. The unit pollutant loading--the yearly pollutant loadings per acre--were highest for West Milwaukee Ditch. This was expected given the relatively high proportion of heavy industrial land use, the balance being largely residential with little open space. This area also has the highest unit loadings of sediment solids. For individual municipalities, the City of Milwaukee shows the highest total pollutant loadings followed by the cities of Cudahy and West Allis. This was expected since the contributing area of Milwaukee is much larger than any other municipality. The unit pollutant loading analysis showed that the City of West Milwaukee had the highest per acre loadings of all types of pollutants. This is due to its small area and relatively high portion of industrial land uses.

Best Management Practices

Based on the pollutant loading analysis, a critical sub-basin was selected for evaluation of BMPs. The KK26 sub-basin was selected in the east central part of Kinnickinnic sub-watershed because of its high pollutant loadings and relatively large portion of residential area. Wet ponds were the BMPs selected to decrease pollutant loadings. KK26 sub-basin has open spaces around major sewer outfall which provide potential sites for wet

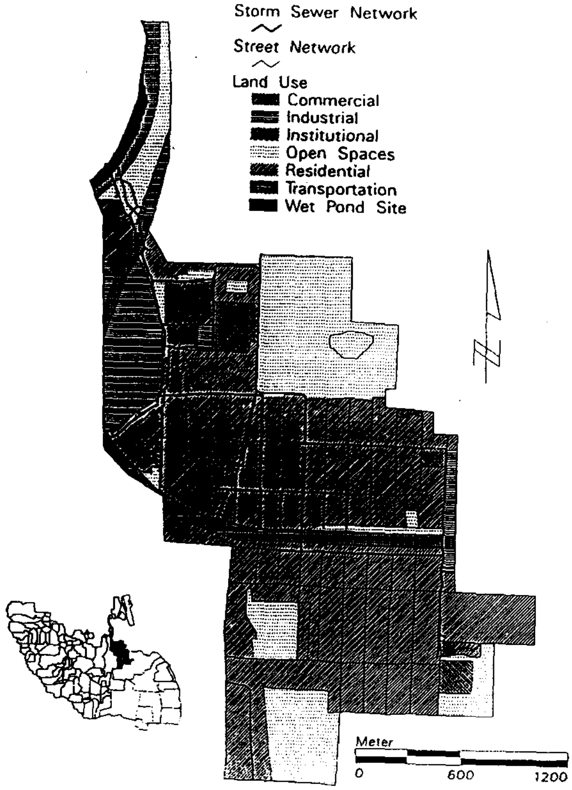

Figure 6. Critical Sub-basin: KK26 Sub-basin

Displays land use inventory and storm sewer network of KK26 sub-basin selected as critical sub-basin. 5.4 acre open space around outfalls were used as potential wet pond site for reducing suspended solids by 90 percent.

ponds with minimal disturbance to existing land use (Figure 6). To meet a goal of 90 percent sediment reduction, DNR planners calculated a wet pond size of 5.3 acres. Fortuitously, about 5.4 acres of open space was located near the outfall of this sub-basin, making the siting and implementation of BMPs a straight-forward task. This example demonstrated that planners now have the tools and data to effectively target and evaluate BMPs.

6. CONCLUSION

This study demonstrates the potential application of GIS for modeling purposes in water quality studies in a large urban area. The methods from this study should be applicable to other urban areas for establishing BMPs. The micro-approach can identify the magnitude of pollutant loadings from any size land use polygon and provide the basis for aggregation to larger areas. This procedure will assist communities in meeting the EPA's storm water requirements. No major problems existed in the linkage of model parameters between GIS data and the nonpoint source model. The model output, transferred back to individual land use polygons, was effective for graphical display and for accumulating pollutant loadings to find critical pollution areas. This study demonstrates that GIS technology is effective for urban nonpoint source pollution control, using its data automation, overlay analysis, data base management, and cartographic display capabilities. Up-to-date, accurate data that was specific enough to support urban nonpoint source pollution modeling was generated from aerial photography in conjunction with other data. The aerial photography was used with existing DLG data to delineate individual urban street blocks. More specific land use boundaries within street blocks were delineated using a 1985 SEWRPC land use map. Considering the high accuracy of the land use interpretation (over 90 percent using aerial photography), the procedure to generate land use data demonstrated in this micro-approach should be further used for large scale urban nonpoint source pollution modeling for other urban areas. The micro-approach has two time-consuming components--manual land use interpretation and boundary delineation of sewer sub-basins. The more these tasks can be automated, the more efficient the approach will be. Automated urban land use generation using scanned imagery and computerized land use classification methods is feasible (Kim, 1993). However, the cost of scanning and the high degree of technical expertise needed to classify images may preclude routine use by municipalities. Head-ups (on-screen) digitizing may be an effective way to realize some advantages of a GIS approach to land use generation using known interpretation techniques. For the delineation of sewer sub-basin boundaries, a more automated procedure could save time and effort. However, the initial automation of storm sewer maps will require a great deal of skilled interpretation if the variety and reliability of maps in the Milwaukee area is any indication. After initial data capture, it should be possible to develop rules based on topography, flow direction, and connectivity to automate the delineation of drainage basins. If these efforts are done in conjunction with the development of facilities management systems for storm sewers, additional benefits beyond water quality planning will accrue.

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