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Urban Nonpoint Source Pollution Assessment Using A Geographical Information System

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GIS를 이용한 도심지 Nonpoint Source 오염물질 평가연구

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ABSTRACT

A geographical information systems(GIS) was a useful aid in the assessment of urban nonpoint source pollution and the development of a pollution control strategy. The GIS was used for data integration and display, and to provide data for a nonpoint source model. An empirical nonpoint source loading model driven by land use was used to estimate pollutant loadings of priority pollutant. Pollutant loadings were estimated at fine spatial resolution and aggregated to storm sewer drainage basins(sewersheds). Eleven sewersheds were generated from digital versions of sewer maps. The pollutant loadings of individual land use polygons, derived as the unit of analysis from street blocks, were aggregated to get total pollutant loading within each sewershed. Based on the model output, a critical sewershed was located. Pollutant loadings at major sewer junctions within the critical sewershed were estimated to develop a mitigation strategy. Two approaches based on the installation of wet ponds were investigated -- a regional approach using one large wet pond at the major sewer outfall and a multi-site approach using a number of smaller sites for each major sewer junction. Cost analysis showed that the regional approach would be more cost effective, though it would provide less pollution control.

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요 약

지리 정보 시스템(Geographical Information System)을 이용하여 도심지 Nonpoint Source 오염 물질의 양이 오염원 종류별로 확인되고 적절한 오염감소를 위한 대책이 마련되었다. 경험에 의한 공해물질 예측모델을 운용하기 위한 모든 입력 자료들이 도심지의 거리 구획별(Street block)별로 제공되어 각 거리 구획별 오염량이 계산되었다. 계산된 오염량은 각 우수 배출구별로 합산되어 오염량이 많은 지역이 판명되었다. 또한 오염량을 줄이기 위하여 인공호수를 만들기 위한 적지분석이 수행되었으며, 그에 따른 비용분석이 이루어졌다. 본 연구는 시형정보시스템의 도심지 공해연구에의 기여도를 입증시켜 주었다.

INTRODUCTION

By definition, nonpoint source pollution is a problem associated with extensive geographic areas. To understand the causes and impacts of nonpoint source pollution requires the integration and display of several types of geographic information, a task for which geographic information systems(GISs) are particularly suited. GISs have been used for components of the non-point pollution process, such as interpreting (e.g., Silfer et al., 1987), and modeling hydrologic response (e.g., Stuebe and Johnston, 1988) and pollutant loadings(e.g., Gilliland and Baxter-Potter, 1987). Recent federal stormwater management requirements for municipalities(US Environmental Protection Agency, 1990) make it likely that GIS will also be used for planning urban control efforts.

In urban areas, stormwater runoff is a significant nonpoint source(Peirce, 1980). Pollutants carried in urban stormwater runoff include some of the same pollutants associated with rural nonpoint source runoff, such as sediment, nutrients, oxygen demanding organic materials, bacteria, and posticides, and may also include toxic pollutants such as heavy metals and volatile organic compounds (WDNR, 1986).

Urban nonpoint source pollution is a function of land uses(e.g., amount of impervious surface and land use associated contaminant sources such as vehicles, industrial debris, leaf and animal litter, etc.), other physical properties of the land such as slope and soils, and hydrological and meteorological characteristics of an area. For urban areas, empirical models driven primarily by land use data are typically used to estimate pollutant loading.

The high degree of land use heterogeneity in urban areas means that models that can locate areas with disproportionately large pollutant loadings are extremely data intensive. It is crucial in urban nonpoint source studies to delineate the boundaries of different land uses(e.g., street blocks), even if the areas are quite small, in order to effectively target control efforts. Detailed land use data generation, integration with other geographic data, and modeling are time consuming and difficult tasks, even with automated methods. Due to the limited scope and geographic extent of previous urban nonpoint source studies, a procedure which uses a high degree of spatial resolution for land use data across extensive areas has not been demonstrated.

A procedure which facilitates nonpoint source modeling based on the aggregation of loadings from small, homogeneous areas could provide detailed information about the contribution of nonpoint pollutants from specific areas in order to identify problems. We have called such a procedure a "micro" approach. Control measures such as physical control practices, regulations, or combinations of both can be effectively targeted with a micro approch. By aggregating the pollution loading from small areas, total pollutant lodings can be obtained to estimate overall water quality impacts at sewer outfalls. Model results aggregated from small to large areas can be used for regional planning purpose, such as mitigating problems in portions of stormwater collection systems and determining or allocating costs on a per area or per land use basis.

Scope and Major Objectives

This paper presents a micro approach to establish an effective mitigation strategy to control urban nonpoint sources. The potential of using a GIS to obtain precise estimates of pollutant loads for individual sewersheds is discussed. The objectives of this study were two-fold. The first was to estimate pollutant loadings at individual sewersheds and identify the critical sewershed with a micro approach. For this, estimated pollutant loadings from individual land use polygons were aggregated to get the total amount of nonpoint sources in each sewershed. The second objective was to establish an effective mitigation strategy to decrease the amount of nonpoint pollutants from critical sewershed. To effectively target control practices and obtain adequate pollutant reduction with the least investment, pollutant loadings at major sewer junctions were estimated and different mitigation strategies were investigated.

Study Area

The study area, the City of Beaver Dam, is located at the confluence of Beaver Dam Lake and Beaver Dam River, in Dodge County, Wisconsin. Detailed street map, city limit, and polygons which were used as the collection units to calculate pollutant loadings are shown in Figure 1. Beaver Dam has an urban area of about 3060 acres(4.78 mi2) and a population of approximately 15,000. The city is part of the Wisconsin Department of Natural Resources(WDNR) Nonpoint Source Priority Watershed Program for the Beaver Dam Watershed.

Beaver Dam is typical of many smaller communities in Wisconsin. The city has experienced rapid urban development, especially in the central part of the city, which significantly affects storm sewer discharges into the Beaver Dam

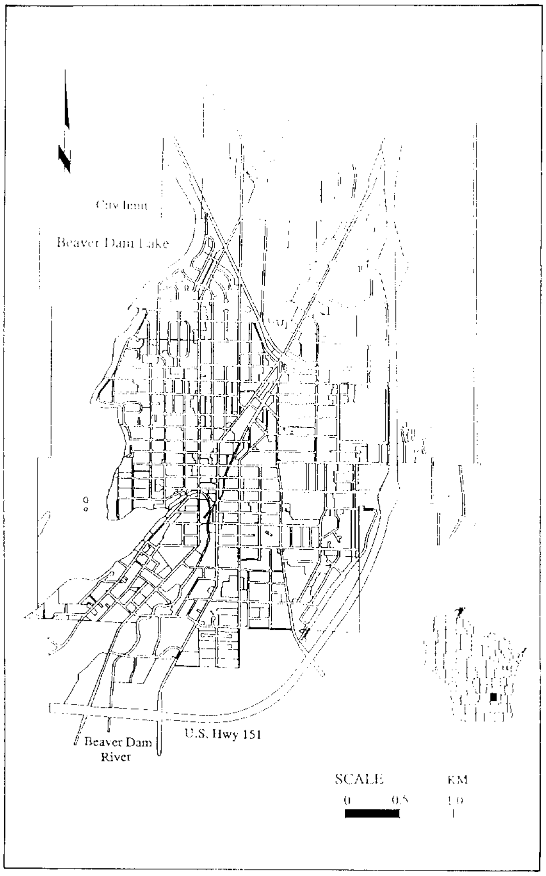

Fig. 1 Study area. A total of 517 land use polygons were generated within the city limit of Beaver Dam.

River. Also, the city has an industrial complex to the north and a sanitary sewerage treatment plant in the southeast. Soils within the city are predominantly silt loams overlying glacial till.

Beaver Dam was selected for this project for several reasons: It was selected as a Priority Watershed in Wisconsin's nonpoint program, and thus was in need of pollutant loading analysis for planning purpose ; it is representative of many other small Wisconsin communities facing similar problems ; and, it was reasonably close to both WDNR headquarters and the University of Wisconsin-Madison, permitting detailed ground-truthing and verification of results.

METHODS

Collection Units

In order to implement the micro approach, polygons representing homogeneous land uses were adopted as the smallest unit of analysis for estimating pollutant loadings. Individual land use polygons were defined from street networks, with supplemental information from zoning maps and airphotos to indicate where land uses divided street blocks. These polygons were consindered to be an elementary response area in terms of urban pollutant loadings, and so were used as the collection units.

These units can also be used to estimate pollutant discharges at major sewer outfalls or sewer junctions because individual polygons are rarely drained by more than one significant branch of a storm sewer network. By investigating the existing storm sewer network, the zones of contribution to sewer outfalls can be adequately delineated using the land ues polygons. Also, this relation between land use polygons and storm sewers can be used to aggregate pollutant loadings at major storm sewer junctions.

SLAMM Model

An empirical urban water quality model

developed by WDNR-SLAMM(Source Loading and Management Model) (Pitt, 1988) was used to estimate the pollutant loadings of each land use polygon. This model was selected because of its familiarity to WDNR staff(it is relatively easy to run, alter, and understand) and because it has proved to be a reliable indicator of nonpoint loadings in similar Wisconsin urban watersheds.

As an urban water quality model, SLAMM calculates runoff volumes and urban pollutant loadings from individual rainfall events based on land use types. It also allows the user to estimate reductions in pollutant loadings from source areas due to control measures such as detention ponds or infiltration devices. The major parameters required for modeling are rainfall amount, soil type, existing control practices, pollutant loading coefficients, and acreages of each land use. The assumption that loadings from small cities are equivalent to similar land uses in these larger cites has been verified through testing and calibration in order watersheds.

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 on-going effort by WDNR to refine these values. At this point, predicted event mean suspended solids loadings are within 20 percent of observed values, and event mean metals(copper, lead, zinc) are within 11 percent.

GIS Implementation

In this micro appoach, nonpoint source modeling is done on a collection unit basis. This requires a well organized procedual to facilitate data lingkage between a number of collection units and the nonpoint source model. Also, each unit needs to be assigned to the appropriate sewer system branch and outfall in order to divide the urban area into individual sewershed areas. For these reasons, a geographic information system was developed for this study. Pc ARC/Info(Environmental Systems Research Institute, Redlands,CA) software was used for the GIS.

GIS was used for data entry, management, and display, including data transfer to SLAMM. As Sasowsky and Garbner(1991) described in their watershed configuration study, empirical models can be easily linked to GIS because coefficients can readily be applied to GIS layers. Physically based models are less easily linked to GIS because numerous detailed data layers need to be input and processed. In this study, GIS was mainly used to automate and transfer land use data to SLAMM, by land use polygon and by sewershed. The GIS was also used as an aid in land use classification and to generate cartographic products depicting model results(Prey et al.,1993)

Considering the importance of accurate land use boundaries and the type of model used in this study (one that analyzes polygons, not uniform cells), a vector GIS was adopted. Raster GIS have been useful for hydrologic modeling, especially for implementing finite element type models, due to the similar data structures (De Roo et al., 1989 ; Cline et al., 1989). However, as Moore et al. (1988) pointed out in their study to partition three dimensional catchment into irregularly shaped polygons, raster GIS has major drawbacks for application in hydrologic modeling : 1) it does not allow water flow from a cell to be split, leading to significant error in divergent areas ; 2) the directions of flow trajectories are matched only crudely by transitions from one grid cell to another, even in very simple planar regions.

GIS Development

Several digital layers were generated to provide input data for SLAMM. These were 1) base layer, 2) land use polygons ; 3) storm sewer network ; and 4) storm sewersheds. The base layer, primarily street blocks generated by digitizing at 1 : 4,800 city base map (Figure 1), provided a framework for other layers. From the city base map, 311 street blocks were generated within the city boundary. These blocks were further divided into 517 land use polygons using additional information from zoning maps and airphoto interpretation. The Beaver Dam city limit was digitized to delimit the project area.

Current land use was interpreted from 1 : 4,800 lithographic prints of recent panchromatic aerial photographs. The land use interpretation was verified and updated by field investigation. Land use class was entered as an attribute to individual polygons in the base layer. Results of the land use inventory in terms of input land use classes required for SLAMM are shown in Table 1. We also evaluated several other sources of land use data, including smaller scale aerial photography (1 : 40,000) and satellite imagery (Landsat TM and SPOT) (Harris et

Table 1 Beaver Dam land use inventory.

Land use category(land use identifier)	Area (acres)
Residential	**1483.4**
Low density(LR)	41.6
Medium density(MRWA)	1333.5
High density(HRWA)	9.1
-Multiple family(MF)	99.2
Commercial	**209.6**
-Strip commercial(CST)	52.8
-Shopping center(SC)	98.9
-Office park(OP)	6.6
-Downtown commercial(CDT)	51.3
Industrial	**324.9**
-Heavy industrial(MI)	221.0
-Light industrial(LI)	103.9
Institutional	**196.6**
-School(SCH)	140.2
Hospital(HOSP)	17.8
-Miscellaneous(MISC)	38.6
Open space	**768.3**
-Park(PARK)	231.1
Open space(OSUD)	496.5
-Construction(CNST)	37.6
-Cemetery(CEM)	3.1
Freeway(FREE)	**74.1**
Total area	**3056.9**

al., 1991) in terms of cost, accuracy, and land use class specificity. Satellite imagery provided data that was sufficiently accurate for modeling purposes, but was only cost effective for urban areas larger than 130 square kilometers size, assuming a single purpose for the satellite imagery.

A storm sewer layer was generated by digitizing twelve 1 : 1,200 storm sewer maps(Figure 2). Due to considerable upgrading of the storm sewer network since the sewer maps were compiled, field verification was necessary to ensure that the final sewer layer was complete and correct. This was achieved through discussion with the city engineers of Beaver Darm and by field checking.

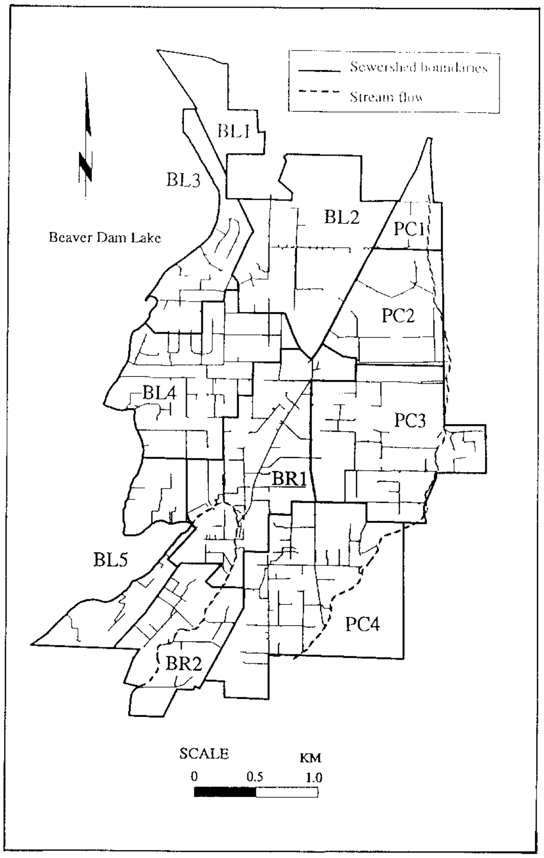

Fig.2 Storm sewer layer and sewershed boundaries. The study area was divided into 11 sewershed boundaries based on three major discharging regions : Beaver Dam Lake (BL1-BL5) ; Beaver Dam River (BR1-BR2) ; and Park Creek (PC1-PC4).

The sewershed layer, which shows the zone of contribution for individual sewer systems, was delineated from the storm sewer network in conjunction with land use polygons. It was screen digitized by assigning a sewershed code to each land use polygon while the storm sewer layer was superimposed. The Beaver Dam area was divided into three major discharging regions and each region was further divided into two to five sewersheds (Figure 2) based on the location of sewer outfalls, resulting in eleven sewersheds, ranging in size from 80 to 480 acres.

Nonpoint Source Modeling

Data about each collection unit polygon were written to an intermediate file from the GIS for use in SLAMM. Uniform values were used for the whole urban area for other SLAMM input data, such as rainfall amount, pollutant loading coefficients, and soil type. In essence, the acreage and the class of land use were the only independent variables in the modeling.

To accumulate pollutant loadings by sewershed, sewershed identifiers were assigned to each land use polygon. This was done by overlay analysis using three layers : city boundary layer, land use polygon layer, and sewershed boundary layer. The land use polygons within the city boundary (project area) were selected and assigned an additional attribute, the sewershed identification number. The polygon identifier, the land use type and acreage of each polygon were converted into text file format and read into the SLAMM model. Input data which had constant values for this exercise, were entered as global parameters(soil type, rainfall, source area pollutant coefficients). For example, average annual rainfall for the area(about 75 cm) was used to get annual pollutant loadings. Data about existing or projected management practices were entered interactively.

The model output was pollutant loadings for individual land use polygons. Major pollutants estimated were heavy metals (copper, lead, zinc, and cadmium) and other pollutants of concern—phosphorus and suspended sediments. The SLAMM output of these six pollutant loadings was converted back to GIS format. The total pollutant loadings of individual sewersheds were obtained by aggregating pollutant loadings of land use polygons within each sewershed. This was done using the sewershed identifier assigned to each polygon. The procedure of SLAMM modeling within GIS framework and the linkage of input data and model output between GIS layers and the SLAMM model are shown in Figure 3.

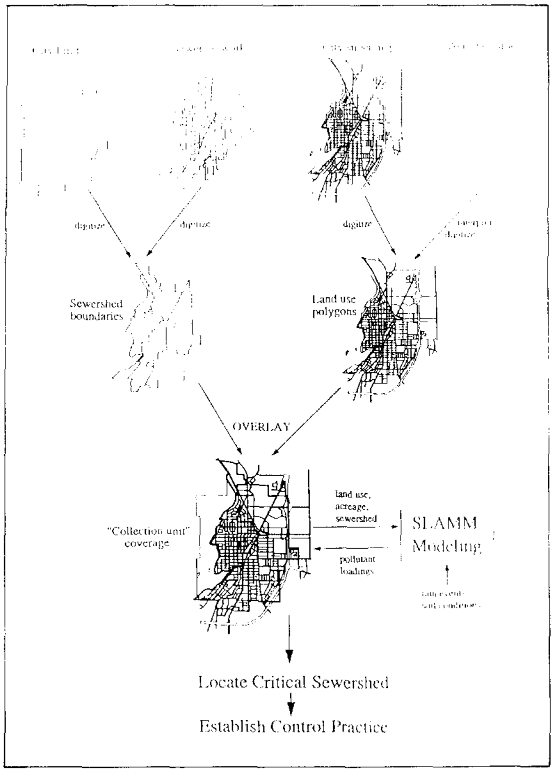

Fig. 3 Nonpoint source assessment using GIS and the SLAMM model.

Critical Area

SLAMM output was analyzed to locate the critical sewersheds—those contributing the greatest load of pollutants. Heavy

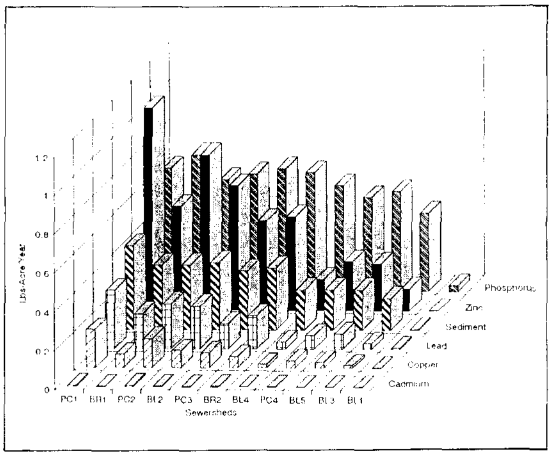

Fig. 4 Yearly Pollutant loadings for each sewershed. (See Figure 2 for sewershed locations. Sediment loadings are in units of thousands of pounds/year).

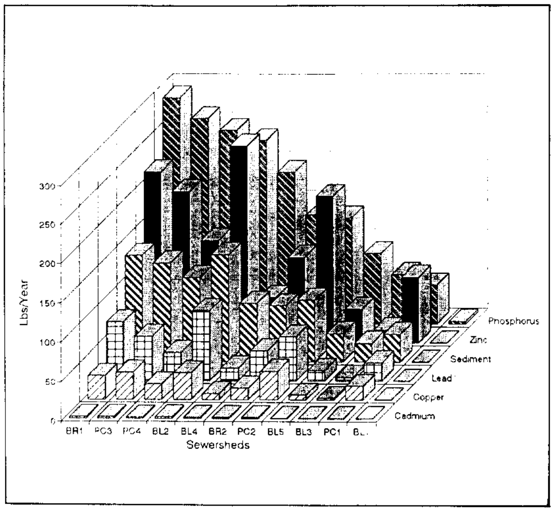

Fig.5 Yearly pollutant loadings per acre for each sewershed. (Sediment loadings are in units of thousands of pounds/year).

metal pollutants, phosphorus and sediments solids(Figure 4) were considered. Figure 5 shows loadings on a unit basis pounds of pollutants per acre per year for each sewershed, normalizing for the different sizes of sewersheds.

The BR1 sewershed of the downtown area and the BL2 sewershed of the major industrial complex show high total and unit pollutant loadings. A freeway, high density and multi-family residential areas, and an industrial area contributed to high unit loadings in the PC1 and PC2 sewersheds. The BL1 sewershed of the northern city park area shows the least loading. From this analysis, the BR1 sewershed, located at the central part of the Beaver Dam was ranked as the most critical sewershed requiring nonpoint source pollution control. It has commercial and industrial areas and intensive residential land use(more than 50 percent of the area). The BR1 sewershed had high loading per unit area and the highest total loadings of any sewershed. It also is a busy and noticeable part of the community, making links between physical control strategies and information and education efforts easier.

The major storm sewer sub-systems of the BR1 sewershed were analyzed to determine the pollutant loadings at major sewer junctions. The BR1 sewershed was divided into five major sections based on the storm sewer network. Ten major sewer junctions with similar pipe lengths and discharge areas were selected(percent impervious surface is included as part

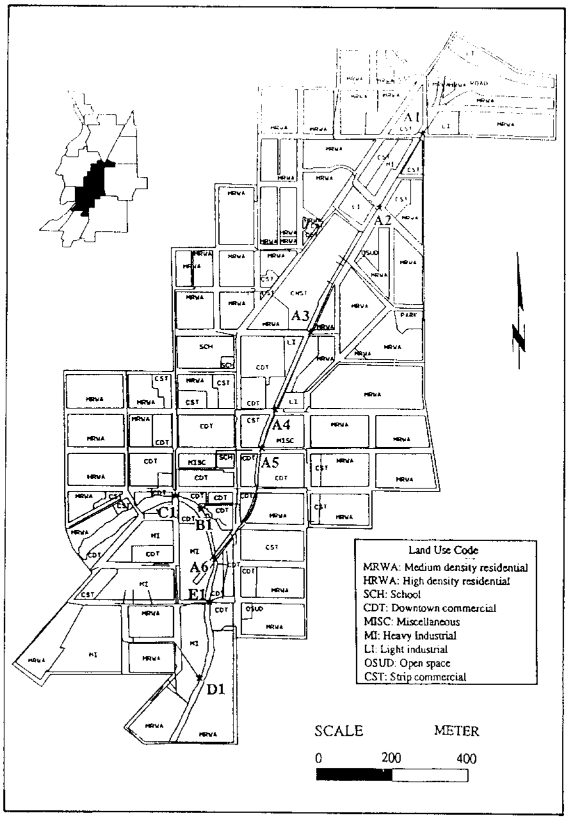

Fig.6 Selected sewer junctions of the BR1 sewershed.

of the coefficient associated with land uses). Figure 6 shows land use identifiers for each polygon, selected sewer junctions, and storm sewer sections of the BR1 sewershed. Six sewer junctions (A1 to A6) were assigned to a major sewer system which covers more than 60% of area of the sewershed. Four additional sewer junctions were assigned to four smaller sections (one each from four sections : B1, C1, D 1, and E1).

Pollutant loadings at each junction were calculated (Figure 7) and accumulated (Figure 8). Accumulation along a length of the system was based on sewer connection. The A1 to A6 junctions empty into the same system, therefore, step wise cumulative loadings were obtained at each junction. The A1 sewer junction shows high amounts of pollutant loadings due to its drainage of many polygons with land uses associated with high loadings.

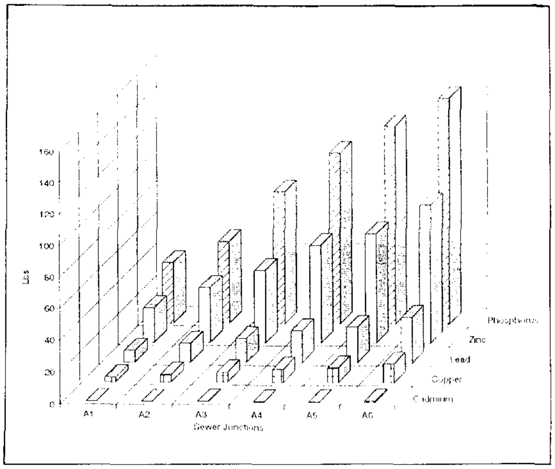

Fig.7 Heavy metal and phosphorus loadings for each sewer junction.

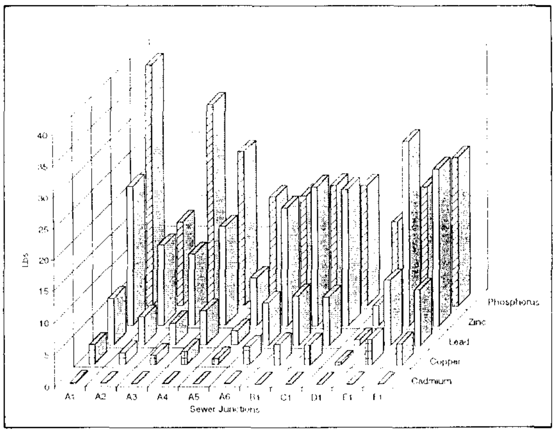

Fig.8 Accumulated pollutant loadings for A1 through A6 junctions.

Mitigation Strategy

Control practices to reduce the pollutant discharges from the BR1 sewershed were considered, based on the analysis of the component areas of the sewer system. The established goal for pollutant reduction was 65% for zinc and copper, and 5% for lead. This is based on the relatively higher magnitude of zinc and copper loadings compared to lead. Due to its minimal loading, cadmium was excluded from pollutant reduction goals.

The control practice selected for this area was wet detention ponds, because they are able to decrease pollutant loadings up to 90% through sedimentation (WDNR, 1991). The minimum size of the wet pond required for the BR1 sewershed to achieve the 65% pollutant reduction was 2.2 acres. This is based on sedimentation of 60% of particles 20μm or larger("20 micron control").

The siting of these ponds is critical when determining installation cost. To decide the most cost effective site selection, two approaches were used--a multi-site approach and a one-regional site approach. In the multi-site approach, one wet pond site was selected for each sewer junction. A total of ten wet pond sites were selected. The major advantages of the multi-site approach are 1)there is no need to purchase a large area and, 2)minor installation of storm sewer pipes will be needed to change the sewer flow path into the detention ponds. The one-regional site approach is more cost effective when a large open space can be secured near a major sewer outfall. However, it may incur higher installation costs from re-configuring sewer pipes around outfalls. Since the BR1 sewershed has an intensively developed urban area, both approaches were examined to determine the most cost-effective approach. Sites chosen for the scenarios are shown in Figure 9.

Table2 Cost analysis for detention pond siting.

	Multi-sites	One-regional site
Area obtainable	4.2 acres	2.5 acres
Land value	$143,000	$101,700
Building value	$287,400	$208,800
Sewer pipe cost	$ 42,500	$137,200
Pipe installation cost	$120,000	$120,000
Wet pond construction cost	$236,500	$137,500
Total cost	$829,400	$705,200

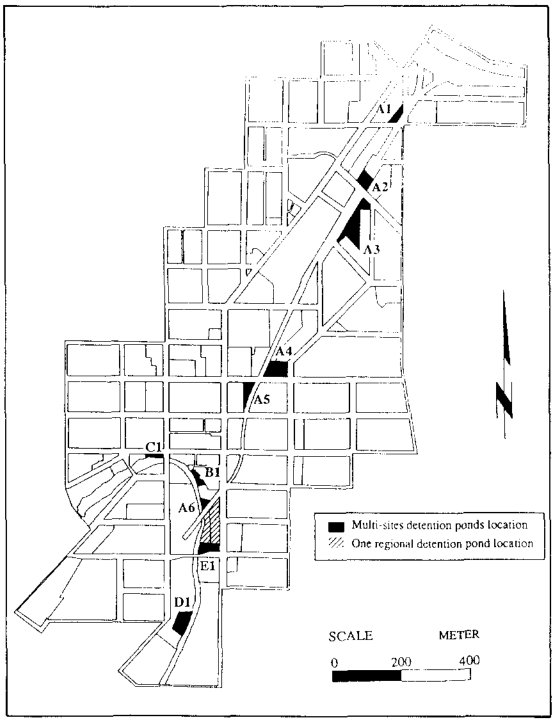

Fig.9 Selected sites of detention ponds in the BR1 sewershed.

Cost analysis was carried out for both approaches. Major cost categories (Table 2) included were property value, sewer installation cost, and wet pond construction cost. To get property values for the potential sites, assessed value of land and buildings was considered (market values for these were not available, though by law, municipalities should be assessing at 100 percent of market value). For the existing open space, construction costs were the primary consideration. For some open space(e.g.,A2), no property value was counted, since it was owned by the city government. Pipe and construction costs were totaled to determine sewer installation cost. For new paths into the detention ponds, a minimum path was delineated and the length and dimension of the required sewer system were calculated. Costs for sewer and wet pond materials and construction were based on Southeast Wisconsin Regional Planning Commission cost sharing for previous installations in similar areas. For example, the average cost of wet pond construction was $55,000/acre.

RESULTS

The most critical sewershed was successfully located using the SLAMM model in conjunction with a GIS. The linkage with GIS provided an effective tool for locating small areas making substantial contributions to water quality degradation. The validity of the modeling results was verified by limited in-field grab sampling.

Cost comparison of the two control approaches is shown in Table 2. The multi-site approach costs 18% more than the one-regional site approach. The higher cost of the multi-site approach($829,400 compared to $705,000) is derived from additional property values ($120,000 more) and pond construction costs ($99,000 more). These are offset by reduced pipe costs($94,700 less for the multi-site approach). The regional site needs pipes with larger dimensions as the sewer systems converge into one or two major systems at the outfall.

Because whole parcels would have to be purchased at each sewer outfall, the acreage for the mult-site approach (4.2 acres) exceeded that required for minimal control(2.2 acres). Either approach must be fit into existing land use patterns, so additional pollutant control must also be considered in cost comparisons. The multi-site approach provided more acres of detention ponds and hence finer particle control. It could provide about 72% pollution reduction--14 m control. On a cost per acre basis, the multi-site approach was cheaper(approximately $200,000 compared to $280,000). The average price of pollutant reduction was $5,200 per pound for zinc and $37,500 per pound for copper.

The multi-site approach also provides greater flexibility in control strategies. By eliminating one or two "expensive" ponds(high land values or construction costs, or reluctant land owners), the total price could be brought below the one-regional cost while still maintaining an adequate level of control.

CONCLUSIONS

The procedure introduced in this paper documents a micro approach for urban nonpoint pollution assessment which takes into consideration the high degree of land use heterogeneity in urban areas. Individual land use polygons were used as the unit-of-analysis. A GIS was implemented to generate and manage digital layers, conduct overlay and other spatial analysis, and transfer data to an empirical nonpoint source model to estimate total pollutant loadings for each sewershed or sewer junction. The volume and complexity of these analyses could have not been conducted at a reasonable cost without GIS.

No major problems existed in the linkage of model parameters between GIS data and the nonpoint model--SLAMM. The model output, transferred back to the polygons, was effective for graphical display to find a critical pollution area. The mitigation strategy discussed in this paper concentrated on cost analysis of a physical control practice--wet detention ponds. This study demonstrates that GIS technology is effective for urban nonpoint source control, using its data automation, overlay analysis, database management, and cartographic display capabilities.

This micro approach will assist a community in meeting the federal Environmental Protection Agency's(EPA) stormwater requirements. The permit applications require the assimilation and integration of various spatial data, including storm sewer outfall locations, storm sewer drainage areas, present and projected land use, estimated pollutant loadings and concentrations, and receiving water resources. The micro approach should provide most of the data and techniques to satisfy these requirements.

Future Directions.

Though much of this study was conducted using computer-based technologies, considerable manual effort was still needed. Further research toward more effective nonpoint assessment is required in the following areas : 1)delineating discharging boundaries and sewer junctions in an automated way by using GIS's spatial modeling capability ; and, 2)developing an automated methodology to generate urban land use inventory using remote sensing technology. In this study, the discharging boundaries for the sewersheds and major sewer junctions were delineated through on-screen digitizing by examining the storm sewer layer. For large urban areas, this would take considerable time. Further research is needed to delineate discharging boundaries in a more effective way. One such technique could be the use of GIS capabilities such as network processing. This can assign flow direction, and link other information to individual sewer pipe nodes as attributes, and trace flow direction over the entire sewer System. Therefore, the area covered by a branch of a storm sewer system could be delineated.

Developing an automated methodology to generate an urban land use inventory is also critical. The generation of a land use inventory is a considerable effort in urban nonpoint source studies. As the model specificity and resolution get finer, the number of land use polygons for nonpoint source modeling will increase. It would be ideal to use very small polygons in urban areas, as the land use is highly heterogeneous. The critical question is how land use can be generated at fine resolution. Extracting land use data from small areas manually can require highly trained personnel and many months of effort, especially for large urban areas. Without an automated procedure, it is almost impossible to adopt the micro approch in large urban areas. Developing an automated methodology to generate a land use inventory using an alternative data source such as digital imagery is worth investigating. The digital imagery can be analyzed using numerical processing algorithms to extract certain land use features. This could produce a cost effective methodology to inventory land uses. It could be one of major benefits of remote sensing technology for future urban water quality studies.

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