GIS to Estimate Storm-Water Pollutant Mass Loadings

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Abstract: In order to develop a monitoring program for the Santa Monica Bay, Calif., watershed, a land-use runoff model was developed using a geographic information system (GIS) coupled with an empirical runoff model. The GIS/model has simple data requirements as compared to more complex models that require routing information; and it is useful for predicting receiving-water loading on an annual basis or for single-storm events. Its approach can also be used to graphically present model results in simple and intuitive ways that provide better insight to managers and planners in evaluating pollution sources and control strategies. The GIS/model was used to locate monitoring stations in the most economical way. The model predictions can be used to improve the evaluation of best management practices to control pollutant discharges. Receiving-water pollutant contributions from point and nonpoint sources can be compared to develop more economical strategies for overall pollutant minimization.

INTRODUCTION

In many locations nonpoint sources of water pollution have been recognized as being of greater importance than point sources. This is due in part to the continuing efforts to reduce pollution from point sources (e.g., increasing treatment requirements for both municipal and industrial wastewaters) over the past two decades (NOAA 1991), as well as recognition that nonpoint sources, such as storm water, may contain harmful toxic contaminants (Lau et al. 1993, Bay et al. 1996). Other studies have also shown nonpoint sources to be the major cause of surface water quality degradation in many areas of the United States, surpassing pollutant loadings to receiving waters from point sources such as treated municipal and industrial wastewaters (Gilliland and Baxter-Potter 1987; Driscoll et al. 1990; National 1990).

Pollution from treated wastewater discharges through the two major outfalls from the City of Los Angeles's Hyperion and Los Angeles County's Joint Water Pollution Control plants has decreased by more than an order of magnitude during the past 20 years. As a result nonpoint sources now contribute an increased fraction of the total pollutant mass to Santa Monica Bay (SMB). Treatment-plant expansion is currently under way to provide full secondary treatment for the foreseeable future. In addition, with a Los Angeles County population estimated at more than 9,000,000 in 1993, there is an increasing probability for pollutants to be discharged to the receiving water through spills, illicit dumping, atmospheric fallout, storm-water runoff from increased paving, storm-water conveyance, and activities such as automobile use and maintenance.

Nonpoint pollution processes such as storm-water runoff are inherently difficult to model due to their stochastic nature in both time and space domains (Corbitt 1989). Furthermore, nonpoint source pollution modeling generally requires organizing and processing large amounts of spatially referenced data that is either not feasible or difficult to implement without the aid of computer automation.

Geographic information system (GIS) technology has matured over the last 10 years and has gained widespread acceptance as a valuable tool because of its ability to carry out complex spatial operations and to link spatial and descriptive information (Sabins 1997; Marsalek 1991). Ventura and Kim (1993) used an urban water quality model, source loading and management model (SLAMM), and coupled it with a vector-based GIS to estimate the pollutant loadings of each land-use polygon in their studied sewershed. Gilliland and Baxter-Potter (1987) demonstrated the application of a GIS to predict nonpoint source pollution potential from agricultural sources. Other studies have also shown the application of a GIS to either predict or estimate the pollutant loads from agricultural sources (Engel et al. 1993; Heidtke and Auer 1993; Xu et al. 1993). The GIS facilitates the handling of voluminous quantities of data, which have impeded traditional modeling approaches, and allows the fine discretization of watershed data that is required for detailed analysis. The example presented in this paper is for a greater and more complex site with more parameters than previously used.

The goal of this study is to estimate the annual pollutants emission to SMB so that catchments with the largest contribution of each pollutant can be identified and prioritized for developing a monitoring program and applying best management practices (BMPs). An empirical model generally does not require an extensive data-gathering effort to model the annual events; in addition, the relatively large area of the SMB watershed makes a vector-based GIS particularly well suited as a back-end database management tool to handle both the spatial and attribute database. Therefore, an empirical model coupled with a vector GIS was used in this investigation. A physical process model could also be used in this study, but the data and time requirements are prohibitive and not required to achieve the stated goals. There are certain advantages of using a raster-based GIS, but they are not significant at the limited detail and precision of this work.

An empirical urban runoff model is described in this paper. After briefly discussing the model structure, the implementation of a GIS with the model and its application to the SMB watershed are discussed in detail. The mass emission rates from different size subbasins in the watershed are presented. This information was used to develop a monitoring program to estimate mass emissions to SMB (Stenstrom and Strecker 1993b). Two hypothetical scenarios are shown to illustrate the utility of the GIS/model in predicting the impact of BMPs. Finally, a summary and conclusion are presented based on the model's predictions, along with their implications for future management of the SMB watershed.

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METHODOLOGY

The modeling procedure is divided into two parts. The first part is an empirical runoff model—described previously by Stenstrom et al. (1984) and Stenstrom and Strecker (1993a)—which uses data on local rainfall, land-use, drainage, and local and national water quality to estimate pollutant loadings to the receiving waters. The second part involves the implementation of a vector GIS, which is utilized as a back-end database management tool and spatially interfaces the empirical urban runoff model. Fig. 1 is an overview of the modeling process.

Watershed Description

SMB, shown in Fig. 2, is a major receiving water for one of the largest population centers in the United States. It is bounded on the northwest by Point Dume and on the southeast by Palos Verdes Point, a linear distance of about 60 km. The bay extends from the shoreline of Los Angeles and the adjacent cities of Santa Monica, El Segundo, Redondo Beach, and Malibu westward to water depths greater than 500 m. The total area of the SMB watershed as defined by Fig. 2 is 1,072 km^2, of which 464 km^2 are urban areas and the remainder are either classified as nonurban (open, parks, etc.) or unknown areas (less than 0.2%). The bay serves 9,000,000 people as a major recreational resource, providing fishing, boating, and swimming activities. The watershed contains the largest commercial center on the West Coast for manufacturing, aerospace, and petrochemical industries (NOAA 1991). In addition, Los Angeles International Airport (LAX) in El Segundo is one of the busiest airports in the nation, with hundreds of flights daily directly over the SMB watershed. The opportunities for pollutants to be discharged to the bay from local drainage systems or aerial fallout are great.

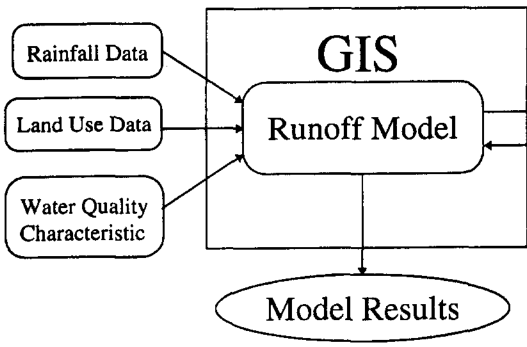

FIG. 1. Overview of Modeling Process

Land Use

Three sets of land-use data from the Southern California Association of Governments (SCAG) were used in this study. They were interpreted and derived from aerial photographs taken in 1987, 1990, and 1993. The original goal of using these three data sets was to compare the pollutant loading results caused by urbanization. Due to limited growth over the six-year period, and to improved interpretation from aerial photography, very few changes in the data sets due to growth were found. Therefore, only the most recent (1993) land-use data were utilized. The land-use definitions and descriptions in this study are a slightly modified version of Anderson land-use classification (Anderson et al. 1976), where level II classification (which represents land-use categories by two-digit codes) is used to describe the predominant geographic attributes of the watershed. The eight land-use categories utilized in this study are shown in Table 1. The minimum level of accuracy in identifying land-use and land-cover categories from remote sensing data should be at least 85%, as stated by Anderson et al. (1976). Therefore, a minimum of 85% accuracy of the two land-use data sets shown in Table 1 was assumed in this study.

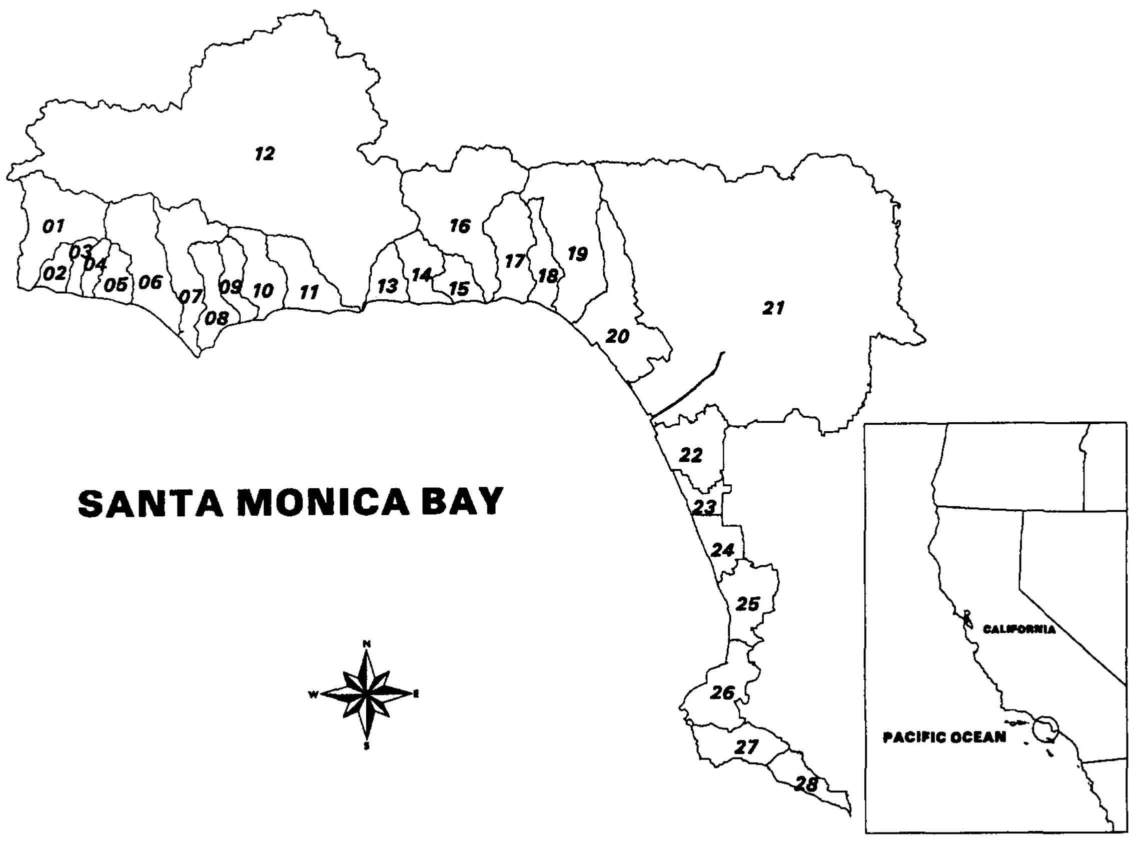

FIG. 2. Santa Monica Bay Watershed and Subbasin Boundaries

TABLE 1. Land-Use Characteristics[a]

Land-use category (1)	Impervious surface area[b] (%) (2)	Runoff coefficient[c] (3)
Single-family	42	0.39
Multiple-family	68	0.58
Commercial	92	0.74
Public	80	0.66
Light industrial	91	0.74
Other urban	80	0.66
Open	0	0.10
Unknown	65	0.56

[a]Adopted from Stenstrom and Strecker (1993a).
[b]Based on Los Angeles County Department of Public Works, NPDES Permit No. CA0061654, Attachment 1, Santa Monica Bay Drainage Basin, drainage area characterization.
[c]Estimates based on percent imperviousness and runoff coefficient relationship given in Driscoll et al. (1990).

An important characteristic of land use is the expected storm-water runoff rate. Previous investigators, through analysis of a large set of rainfall-runoff data from many studies on urban areas and highways, have shown that the runoff coefficient, RV (defined as the overall average ratio of runoff to rainfall), is highly correlated to impervious surface area (IMP) (EPA 1983; Driscoll et al. 1990). This assumption was adopted in this study and is shown as

$$RV = 0.007\ IMP + 0.1 \quad (1)$$

where IMP is expressed as a percentage. In this study the IMP percentage for a given land-use category area was based upon the SMB drainage area characteristics (Los Angeles County Department of Public Works, Alhambra, Calif.). The Driscoll et al. (1990) relationship between the IMP and RV in (1) was used to determine the value of the runoff coefficient for each land-use type. The values of IMP and RV utilized for the eight land-use categories modeled in this study are shown in Table 1. The GIS is used to implement the foregoing procedures and will be discussed in more detail in the later sections. Subsequently, after the determination of runoff coefficients for each catchment, annual average storm runoff volume can then be estimated for the whole watershed using the equations discussed in the next paragraph.

Rainfall

Rainfall data have been collected from 10 gauges in the watershed over a 42-yr period, including at the LAX gauge station. The Synoptic Rainfall Analysis Program (SYNOP) (Woodward-Clyde Consultants, Inc. 1989) was used to compute the mean, standard deviation, and the coefficient of variation for all of the rainfall-event statistics. To facilitate the modeling process, rainfall correction factors (CF) were derived from both the 50-yr, 24-h rainfall and the 1990–91 seasonal total isohyetal map. These were used in conjunction with the average storm rainfall (ASRF) at the LAX rain gauge station to scale the rainfall for each catchment to reflect spatial variations within the watershed. Based on the rational method (Viessman et al. 1989), annual average storm runoff volumes (ASV) for each catchment were then calculated by multiplying the CF, the ASRF at LAX, the area, and the runoff coefficient (RV) as shown in the next equation. The annual average storm runoff (AASV) of each catchment was calculated by multiplying ASV from the next equation and the average number of storms per year (NSTORM) as shown in the one following it. Since this study was only concerned with rainfall events that produce runoff, all those of less than 2.5 mm were discarded from the statistical analysis. For the SMB watershed, the average time between storms varies from 198 to 258 h (8 to 11 d) during the wet season. The coefficient of variation of the time between storms ranges from 1.10 to 1.36 in the rainfall records of 10 selected rain gauges in the SMB watershed (Stenstrom and Strecker 1993a). Therefore, NSTORM is approximately equal to 16 storm events in each wet season. The average storm rainfall and the annual average storm runoff were calculated as follows:

$$ASV_i = RV \cdot AREA \cdot CF \cdot ASRF_{LAX} \quad (2)$$

$$AASV_i = ASV_i \cdot NSTORM \quad (3)$$

where ASRF is expressed in meters (m); AASV in cubic meters per year (m^3/yr); ASV in cubic meters (m^3); and NSTORM in [$year^{-1}$]; and where AREA = area of catchment i (m^2). The GIS/model can be used for different periods or for single events.

Water Quality

Eleven water-quality parameters are of concern to urban nonpoint source runoff and were modeled in this study. They are: total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), nitrite and nitrate (NO23), Total Keldahl nitrogen (TKN), total phosphorus (TP), soluble phosphorus (SP), total copper (Cu), total lead (Pb), Total zinc (Zn), and total oil and grease (O&G).

These parameters were chosen for their general tendency to be indicators of problems in urban runoff, and because sufficient data were available from national and/or local data to estimate land-use contributions.

To use the empirical model it is necessary to know the site median event mean concentration (EMC) of each pollutant for each land-use type. To determine the EMCs for different land uses, all agencies that monitor storm-water discharge to SMB were surveyed. No one agency has this responsibility and 15 sources of data were found that were collected from 47 monitoring locations for a variety of water quality parameters. A total of 43,015 data points were collected. Unfortunately, much of the data were not particularly useful since they were collected by different agencies using different methodologies for varying purposes.

Most of the water quality data were grab samples that represent instantaneous values of pollutant concentrations. In most cases a single instantaneous value cannot be used to represent average conditions; furthermore, it does not describe the variability of the pollutant concentrations (Wanielista and Yousef 1993). In addition, much of the data were collected during dry weather conditions and are not useful for assessing storm-water pollutant discharges. To improve estimates of site median EMCs, the SMB data were compared to the EPA's Nationwide Urban Runoff Program (NURP) database, which were composite samples collected from known land uses (Driscoll et al. 1990). A comparison of the appropriate subset of the water quality data collected in the SMB watershed to the corresponding NURP data showed that the SMB watershed concentrations are generally much higher, and median SMB concentrations approximate 90th percentile NURP concentrations (Stenstrom and Strecker 1993a). The higher concentrations may occur because of the reduced rainfall of the SMB watershed, as compared to NURP sites, as well as from potentially larger urbanization in the Los Angeles area. No O&G data were collected in the NURP study, and O&G concentrations were estimated from previous findings by Stenstrom et al. (1984), Fam et al. (1987), and Silverman, et al. (1988).

Previous researchers have shown the variable EMCs in storm-water runoff from urban areas can be adequately described by a lognormal distribution (Driscoll et al. 1990). If the EMCs are lognormally distributed, site median EMCs can be transformed to the mean runoff event concentrations (ME), using

$$ME = SM\sqrt{1 + COV^2} \quad (4)$$

where SM = site median EMC (mg/L); ME = event mean concentration (mg/L); and COV = coefficient of variation. A typical value for the COV of pollutant concentrations is 0.71 for urban areas (Driscoll et al. 1990). Therefore, event mean concentration is approximately 23% greater than the site median EMC. The estimated annual loading for individual pollutants (APL) is expressed as:

$$APL_i = AASV \cdot ME_i \cdot CF \quad (5)$$

where APL = annual pollutant loadings (kg/yr); ME = event mean concentration (mg/L); *CF* = conversion factor for runoff volume to liters; and i = pollutant i.

GIS IMPLEMENTATION

A UNIX-based GIS, ARC-INFO 7.0.4 (*ARC/INFO* 1992) was used for the GIS on an IBM RISC/6000 POWERstation Model 550E. The database for this GIS/model consists of three spatial coverages: a land-use coverage, a subbasin coverage, and a catchment coverage. All three coverages were available in ARC-INFO native format, and were originally developed by scanning U.S. Geological Survey (USGS) maps with drainage data provided by the Los Angeles County Department of Public Works. The land-use, subbasin, and catchment coverages are related with rainfall and runoff attribute data to form an integrated GIS/model to estimate the pollutant loadings from the watershed. Land-use polygons are adopted as the smallest unit for analysis. These three spatial coverages have the following general characteristics: Subbasin coverage (BA) contains 28 polygons; catchment coverage (CA) contains 500 polygons within the 28 BA polygons; 1993 land-use coverage (LU93) contains 6,498 polygons within the 500 polygons of CA.

Fig. 3 shows the distribution of land-use pattern in the SMB watershed in 1993. Tables 2 and 3 illustrate the land-use pattern of LU93 land-use coverage and the land use by subbasins, respectively. Open, single-family, and multiple-family are predominant land uses, accounting for close to 85% of the total land use in the SMB watershed. The majority of the open and single/multiple family land uses are located in subbasin 12 (Malibu drainage) and subbasin 21 (Ballona Creek drainage), respectively.

Fig. 2 shows the distribution of 28 subbasins in the SMB watershed. The subbasins are lumped into three major regions and are categorized in the following way: subbasins 1–19 make up the North Bay; subbasins 20–22 make up the West Los Angeles; and subbasins 23–28 make up the South Bay.

The GIS modeling work can be divided into three main steps. The first is to link the land-use coverage with rainfall and runoff coefficient information [(1)–(3)], and also to link CA with the corresponding rainfall correction factor (CF), which is used to reflect the spatial variation of rainfall pattern. The second step is to the overlay BA with the two new coverages created in the first step to form the final coverage, which will be used to estimate the pollutant loadings. The last

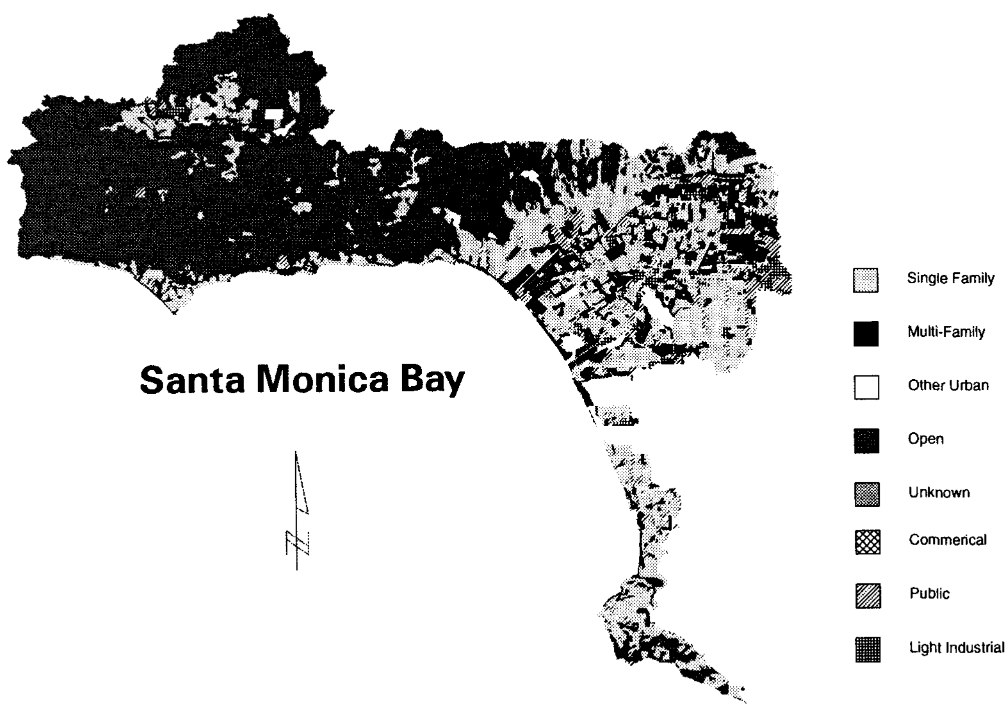

FIG. 3. Land-Use Pattern in SMB Watershed (Based on 1993 Land-Use Data)

TABLE 2. Areal Distribution of Land-Use Coverage

Land-use coverage (1)	Land-Use Area [ha (% of total)]								
	Unknown (2)	Single-family (3)	Multiple-family (4)	Commercial (5)	Public (6)	Light industrial (7)	Other urban (8)	Open (9)	Total (10)
LU93	9 (0.01)	26,102 (24.4)	8,070 (7.5)	4,902 (4.6)	2,526 (2.4)	2,213 (2.1)	2,845 (2.7)	60,509 (56.5)	107,178 (100)

TABLE 3. Land-Use Distribution in 28 Subbasins (Based on LU93)

Subbasin (1)	Land-Use Area (%) Single-family (2)	Multiple-family (3)	Commercial (4)	Public (5)	Light industrial (6)	Other urban (7)	Open (8)	Unknown (9)	Total area (ha) (10)
1	1	0	0	0	0	0	98	0	2,915
2	3	0	0	0	0	0	97	0	578
3	11	1	0	0	0	0	88	0	449
4	8	0	0	0	0	0	92	0	477
5	9	0	0	0	0	0	91	0	815
6	9	0	0	1	0	0	89	0	2,777
7	9	1	0	0	0	0	88	0	2,469
8	21	2	0	0	0	0	76	0	1,371
9	10	0	0	0	0	1	88	0	902
10	5	1	0	0	0	0	94	0	1,525
11	4	1	1	4	0	0	90	0	1,741
12	9	2	1	1	0	2	85	0	28,444
13	11	1	1	0	0	0	86	0	912
14	12	2	0	0	0	0	86	0	1,281
15	3	0	0	0	0	0	96	1	837
16	10	0	0	0	0	0	90	0	5,102
17	12	2	0	1	0	2	83	0	2,016
18	23	3	1	2	0	2	69	0	1,149
19	21	1	0	1	0	0	77	0	4,266
20	41	22	11	4	4	3	16	0	3,622
21	42	17	11	5	4	3	18	0	33,692
22	26	6	3	5	1	41	19	0	2,037
23	6	5	7	0	62	13	7	0	665
24	64	12	9	6	1	1	7	0	1,103
25	52	21	8	9	1	2	7	0	1,750
26	67	5	2	3	0	1	22	0	1,993
27	37	3	2	2	1	3	53	0	1,521
28	45	4	1	5	0	0	45	0	948

step is to link the 11 water quality characteristics [(4)] with the final coverage.

There are two basic ways of linking an attribute table to a table of geographic records. A relational join command is used to perform the relational join operation, which expands the geographic file to permanently include the attribute file. A relate operation temporarily links the attribute file with the geographic file in which the two links are separately stored. There are advantages to each method that depend on the data storage requirements, the speed of the computer, and other miscellaneous factors (*ARC/INFO* 1992). Since there are only four equations (variables) needed to link with LU93 and CA spatial coverages, and also because join operations are generally faster to manipulate than relate operations, the relational join is used in the first step. The first "join" operation is a "one to many" relationship (one land-use or runoff coefficient is related to many different polygons) between the land-use coverage and the runoff coefficient attribute table [(1)]. The second "join" operation is a "one to one" relationship between the catchment coverage and the rainfall correction factor attribute table.

After the superimposing the land-use, catchment, and subbasin coverages, (2)–(5) can then be implemented in the GIS/model. This process is a union, which creates an output coverage by overlaying the three spatial coverages. All polygons and attributes from these three spatial coverages are combined and preserved at the output coverage. The order of the union operation is important because all duplicate parameters except the one in the first input coverage are deleted. Therefore, the spatial union operation between the land-use coverage and the catchment coverage must precede the operation between the output coverage and the subbasin coverage in order to preserve the variable "AREA" of the land-use coverage. The variable "AREA" of LU93 represents the "AREA" term in (2) and (3). Fig. 4 depicts the overall spatial union operations of the second step.

The estimated pollutant loading formula from (5) is then linked with the resultant output coverage (or table) to calculate the 11 pollutant loadings from each catchment polygon and also from each subbasin polygon. This process is facilitated if the GIS has built-in statistics commands. The following two equations are used to estimate the pollutant loadings from catchment i (C_i) in subbasins j and j (B_j), respectively:

$$C_i = \sum_{k=1}^{8} \sum_{n=1}^{N} \mathrm{AASV}_{n,k,i} \cdot \mathrm{ME}_{n,k,i} \cdot \mathrm{G} \tag{6}$$

$$B_j = \sum_{i=1}^{M} C_i \tag{7}$$

where AASV = average annual storm volume (m^3/yr); ME = event mean concentration (mg/L); G = conversion factor [($m^3 \cdot$mg/L to kg) $\times 10^{-3}$]; C_i = estimated annual pollutant loading of catchment i (kg/yr); B_j = estimated annual pollutant loading of subbasin j (kg/yr); N = total number of land-use polygons with land-use type k within catchment i; M = total number of catchment polygons within subbasin j; k = land-use type; and n = land use polygon n within the catchment i.

RESULTS

The GIS/model was used to determine the areas (basins) and land uses producing the most polluted runoff. The annual pollutant loadings and the annual unit pollutant loadings from each land-use category are shown in Tables 4 and 5, respectively. In Table 4 the annual pollutant loadings for each land use are in metric tons per year (t/yr), whereas in Table 5 the annual unit pollutant loadings for each land use are in metric tons per hectare per year (t/ha/yr), which are calculated by normalizing for the different land-use areas. As shown in Table 4, the single-family land use produces the highest loading of

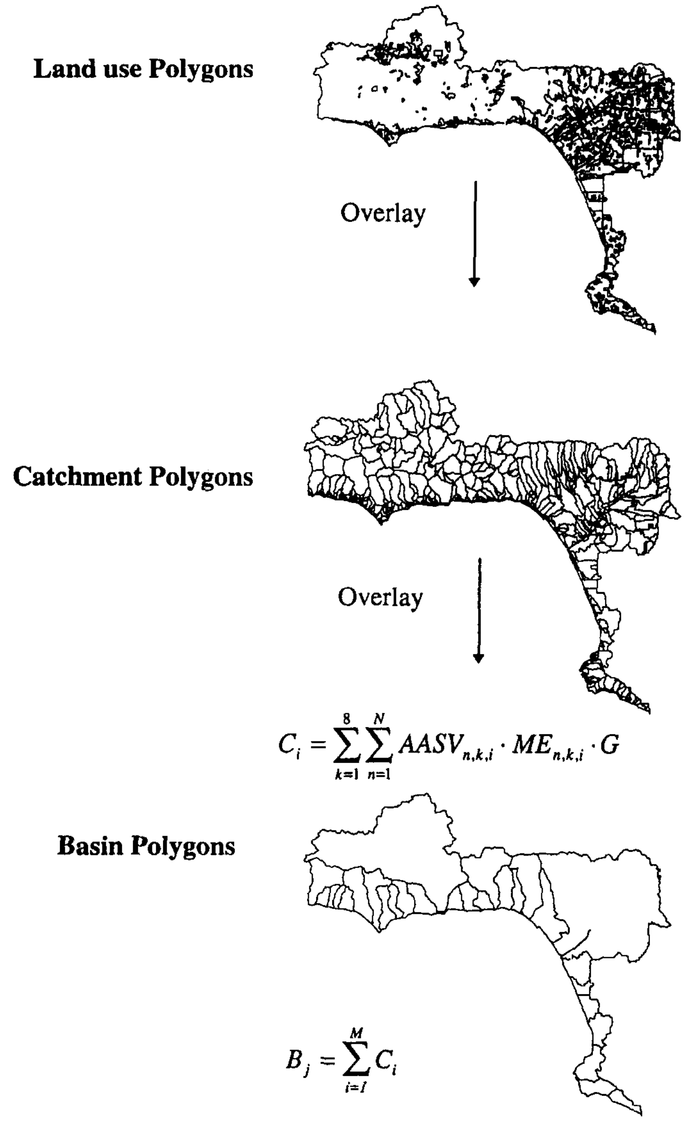

FIG. 4. Spatial Union Operation Using GIS and Nonpoint Source Modeling: (a) Land-Use Polygons; (b) Catchment Polygons; (c) Basin Polygons

all pollutants among all land uses except for open, which has a higher TSS load. This results because the single-family and open land uses together account for more than 80% of the total area (see Table 2). Table 4 shows the oil and grease contributions from commercial, public, and light industrial areas, which are approximately 46% of the total oil and grease emissions, even though the overall area size accounts for only 9% of the total area in SMB watershed (see Table 2). The normalized land-use loadings in Table 5 show commercial, public, and light industrial areas have the highest per unit area contributions. High loadings can be produced from relatively small areas within the watershed. Oil and grease runoff is strongly correlated with land use, resulting in a large variation in emission rates (Fam et al. 1987).

It is not possible to calibrate the GIS/model because data are not available. (One of the purposes of this project was to develop the GIS/model in order to develop a monitoring program.) The only estimates for discharge to the bay were performed by the Southern California Association of Governments (SCAG) (1988), and only for subbasins 12 and 21. A detailed comparison was presented by Stenstrom and Strecker (1993a), but is too lengthy to repeat here; however, the comparisons were generally good, considering the challenging nature of monitoring wet weather pollutant flow. For subbasin 21, which is highly developed, the model generally predicted higher emissions for six contaminants and a higher flow rate than estimated by SCAG; the model averaged 83% higher. For subbasin 12, which contains a large fraction of open or undeveloped land, the model's predictions were 32% lower than SCAG's estimates for the same pollutants. Emissions (or lead were quite different between the model and SCAG's estimates, which may be due to total versus dissolved measurement differences. The writers consider this is good agreement. One possible source of the differences is that the model is calibrated using water quality data collected over the 1972–91 period, as opposed to a single year.

Fig. 5 shows the annual and unit pollutant loadings from the 28 subbasins in the watershed. For all 11 pollutants, the Ballona Creek drainage (subbasin 21), which drains the greater part of the Los Angeles metropolitan area, shows the highest loadings, followed by the Malibu drainage (subbasin 12). The remaining 26 subbasin watersheds only contribute 35% of the total loading. Subbasin 21 shows the largest percentage loadings of oil and grease. These observations are explained by the land use and the total areas in subbasin 21, as shown in Table 3. This subbasin includes four major Interstate freeways, networks of complicated transportation systems, and a heavy concentration of multifamily residences and other miscellaneous urban structures. Freeways and major roads are lumped into the "other urban" land-use category.) The unit pollutant loadings were highest for subbasin 23, followed closely by subbasins 21, 20, and 22. This is expected because of their high proportions of industrial areas, utility facilities, and other urbanized areas. These subbasins also have the highest loadings and unit loadings of oil and grease. The ability to rank pollutant emissions will be useful if problems associated with specific pollutants are identified in the bay. The GIS/model results are a starting point to look for ways of reducing emissions.

The GIS/model results were used to design a monitoring program (Stenstrom and Strecker 1993b) that has become the structure for the Los Angeles County Department of Public Works monitoring program for the areas draining into Santa

TABLE 4. Annual Pollutant Loadings for Each Land Use (Based on LU93)

Land use (1)	Annual Pollutant Loadings (T/yr) TSS (2)	BOD_5 (3)	COD (4)	TP (5)	SP (6)	TKN (7)	NO23 (8)	Total Cu (9)	Total Pb (10)	Total Zn (11)	O&G (12)
Single-family	12,316	722	5,946	36	11	183	79	4	15	15	127
Multiple-family	3,985	285	2,467	12	2	46	19	2	8	7	417
Commercial	2,683	209	1,342	6	3	30	18	1	3	10	328
Public	1,215	94	607	3	1	13	8	0	2	5	148
Light industrial	1,127	88	564	3	1	13	8	0	1	4	138
Other urban	1,603	114	992	5	1	18	8	1	3	3	168
Open	14,383	59	2,789	15	4	82	43	2	4	13	0
Unknown	0	0	0	0	0	0	0	0	0	0	0

TABLE 5. Unit Pollutant Loadings for Each Land Use (Based on LU93)

Land use (1)	Annual Unit Pollutant Loadings (t/ha/yr) TSS (2)	BOD_5 (3)	COD (4)	TP (5)	SP (6)	TKN (7)	NO23 (8)	Total Cu (9)	Total Pb (10)	Total Zn (11)	O&G (12)
Single-family	5.E-01	3.E-02	2.E-01	1.E-03	4.E-04	7.E-03	3.E-03	2.E-04	6.E-04	6.E-04	5.E-03
Multiple-family	5.E-01	4.E-02	3.E-01	1.E-03	3.E-04	6.E-03	2.E-03	2.E-04	1.E-03	9.E-04	5.E-02
Commercial	5.E-01	4.E-02	3.E-01	1.E-03	5.E-04	6.E-03	4.E-03	2.E-04	7.E-04	2.E-03	7.E-02
Public	5.E-01	4.E-02	2.E-01	1.E-03	5.E-04	5.E-03	3.E-03	2.E-04	6.E-04	2.E-03	6.E-02
Light industrial	5.E-01	4.E-02	3.E-01	1.E-03	5.E-04	6.E-03	3.E-03	2.E-04	6.E-04	2.E-03	6.E-02
Other urban	6.E-01	4.E-02	3.E-01	2.E-03	3.E-04	6.E-03	3.E-03	3.E-04	1.E-03	1.E-03	6.E-02
Open	2.E-01	1.E-03	5.E-02	3.E-04	7.E-05	1.E--3	7.E-04	3.E-05	7.E-05	2.E-04	0.E+00
Unknown	9.E+00	7.E-01	6.E+00	3.E-02	6.E-03	1.E-01	5.E-02	5.E-03	2.E-02	2.E-02	1.E+00

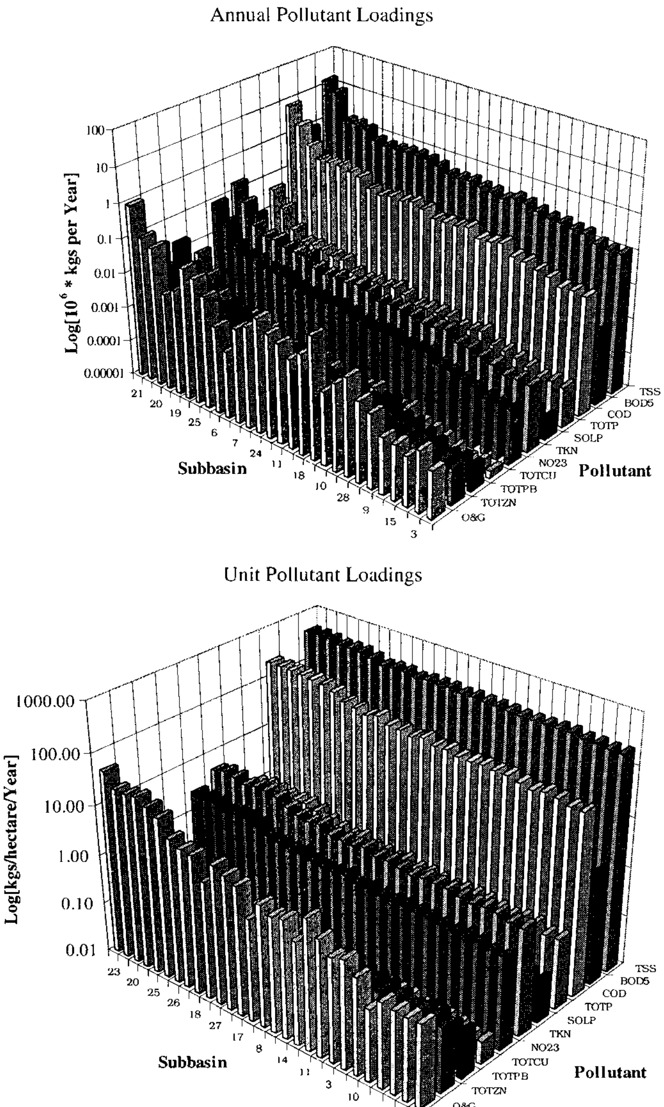

FIG. 5. Pollutant Loadings for 28 Subbasins (Based on 1993 Land-Use Coverage): (a) Annual Pollutant Loadings; (b) Unit Pollutant Loadings

Monica Bay. Using the GIS/model it is easy to position monitoring stations at locations that will sample a minimum fraction of the runoff. For example, selecting subbasins 12 and 21 will sample approximately 65% of the total runoff, based upon flow rate. It is also possible to select monitoring locations based upon other criteria, such as the anticipated mass loadings of some particular pollutant. Another possibility is to use the GIS/model to select small land parcels that are predominately composed of single land uses. In this way, stations are selected to be used to collect data for additional model calibration and validation. For the SMB monitoring program, the five subbasins with the greatest emissions were initially selected as mass emission stations. These included subbasins 12 and 21. A similarly sized group was selected as land-use stations. The results of this monitoring program will eventually become available for model verification and additional model development.

To illustrate the potential uses of the GIS/model for stormwater management, the following two hypothetical scenarios are used as examples. Scenario one uses subbasin 12 (Thousand Oaks drainage) to illustrate the impact of land-use changes on the pollutant annual discharges. Subbasin 12, as shown in Table 3, has 85% open land use. By transforming 20% of the open land-use category to other land-use categories, such as single-family and multifamily, the increase in annual pollutant emissions can be calculated; the results are shown in Table 6. These are potential changes that might occur with increasing population. From Table 6 the pollutant O&G shows a larger increase in the annual loading and a wider range of the percent annual loading increases among the six hypothetical land-use transformations. The smallest and largest increases in the annual loadings impacted from the hypothetical land-use transformation are the single-family and other urban land uses, respectively. The commercial and light industrial land uses also receive significant increases in the annual loadings.

In scenario two we use the GIS/model to illustrate the impact of BMPs on the annual discharge to SMB. The GIS/model can be programmed to predict the impact of BMPs, and two hypothetical BMPs are tested: a campaign to reduce the amount of fertilizer used on lawns of single- and multiple-family housing, and a control program to reduce the oil and grease discharge into the storm drains on commercial and industrial land uses. Both BMPs assume that a 50% reduction in site mean concentration occurs because of the best management practice. For simplicity we assume that 100% of the nitrate in the urban runoff from these land uses is from fertilizer use. Table 7 shows that a 50% reduction in residential fertilizer use (or a 50% reduction in event mean concentration of nitrite and nitrate) reduces annual NO23 emission by approximately 28%. As for the second BMP, a 50% reduction in the amount of oil and grease discharge (or a 50% reduction in event mean concentration of oil and grease) results in close to 14% reduction in the annual O&G discharge. Table 7 also shows the most significant and the least significant subbasin impacted from the two given hypothetical BMPs. Subbasin 21 (Ballona Creek drainage) shows the largest reduction in both the annual NO23 and O&G discharge. Subbasins 1 and 4 (Malibu drainage) show no significant reduction in the annual O&G and NO23 emission, respectively.

The technique shown in these two hypothetical cases may be valuable for city planners and others to mitigate the growth in nonpoint pollution due to the land-use changes. It should also be useful for government agencies to determine the impact and cost/benefit of different proposed BMPs. Such anal-

TABLE 6. Scenario One: Annual Pollutant Loadings in Subbasin 12

Pollutant (1)	ANNUAL LOADINGS OF SUBBASIN 12 (t/yr)						
		20% of Open Land Use Is Transformed to Following Land Uses					
	Open (2)	Single-family (3)	Multifamily (4)	Commercial (5)	Public (6)	Light industrial (7)	Other urban (8)
TSS	8,520	10,038	10,195	10,499	10,145	10,469	10,609
BOD_5	191	340	356	427	400	425	415
COD	2,497	3,532	3,994	3,809	3,631	3,794	4,250
TP	14	20	21	20	19	20	22
SP	4	6	5	7	6	7	6
TKN	68	102	95	97	93	97	99
NO23	33	2	3	3	3	3	3
Total Cu	2	8	11	9	8	9	12
Total Pb	5	12	14	21	20	21	15
Total Zn	10	47	13	51	48	51	45
O&G	138	145	415	501	458	498	458

TABLE 7. Scenario Two: Annual NO23 and O&G Loadings (t/yr)

Pollutant (1)	Santa Monica Bay		Most Significant Subbasin		Least Significant Subbasin	
	Before (2)	After (3)	Before (4)	After (5)	Before (6)	After (7)
NO23[a]	182	133	87[b]	59[b]	0.41[c]	0.38[c]
O&G[a]	1,336	1,103	869[b]	699[b]	0[d]	0[d]

[a]Assumption: 50% reduction in mean events concentration of NO23 and O&G.
[b]Subbasin 21.
[c]Subbasin 2.
[d]Subbasins 1, 3, 4, 5, 9, 15.

TABLE 8. Comparison of Model Predictions with Annual Emissions from Hyperion Treatment Plant

Parameter (1)	Model (1993)[a] (2)	Hyperion (1992)[b] (3)	Total load[c] (4)	D_NPS[d] (%) (5)
TSS	37,000	19,000	56,000	66
BOD	1,600	41,000	42,600	4
TP	80	2,500	2,580	3
NO23	180	132[e]	312	58
Cu	10	16	26	39
Pb	37	1	38	97
Zn	57	35	92	62
O&G	1,300	5,900	7,200	18

Note: Units are all in t/yr.
[a]Based on 1993 land-use data.
[b]Using 1992 annual average data.
[c]Total load = total annual emission of the model and the Hyperion Wastewater Treatment Plant.
[d]D_NPS = model emission (nonpoint source) as a percentage of total load.
[e]Using the nitrate nitrogen (NO_3-N) only.

ysis will help in the development of an optimum stormwater pollution control strategy.

To illustrate the significance of nonpoint source pollution, annual emission data from the Hyperion Wastewater Treatment Plant of the City of Los Angeles (Santa Monica Bay Restoration Project 1993) are compared with the model results. The Hyperion plant and a petroleum oil refinery are the only facilities that have National Pollution Discharge Elimination System (NPDES) permits to discharge into Santa Monica Bay. Hyperion has more than 100 times the flow rate of the refinery, which has an activated sludge plant for effluent treatment. For the purpose of this example, we assume that Hyperion represents 100% of the point source pollution to Santa Monica Bay. Both Hyperion and nonpoint sources are presented in Table 8, which shows the range of differences of the annual emissions. The nonpoint source contribution (column 5) for some pollutants, such as total phosphorus (TP), is quite low (3%). For other pollutants, such as lead, the nonpoint sources are the major sources (97%). In 1993 Hyperion was only capable of treating approximately 50% of the flow to full secondary standards. When construction of the new facilities are completed, and 100% secondary treatment is possible, the relative point source contribution will be much less. This suggests that if further reductions in pollution to Santa Monica Bay are required, nonpoint sources should be evaluated first. Also, the Hyperion plant discharges through a long outfall, and the dilution further reduces its impact. The storm drains discharge in close human contact at the beach or surf, which probably increases their impact.

CONCLUSIONS

In this study we have shown the feasibility of imbedding an urban runoff model into a GIS to estimate the annual pollutant loadings to the SMB watershed. The overall framework takes advantage of the built-in relational database management technology of the GIS to construct an accurate and detailed database. This database depicts the watershed geographic attributes and relates them using the urban runoff model. Critical and sensitive areas of varying sizes within the watershed can be accurately located by using the built-in graphical display capability of the GIS. This integration of a nonpoint source model and a GIS offers a powerful tool to assist watershed managers in developing control strategies to improve water quality within local drainage systems. It also allows the managers to evaluate impacts of various BMPs with given hypothetical conditions.

Many factors need to be considered in evaluating stormwater management alternatives, and cost-effectiveness is a paramount factor. Cost-effectiveness is generally measured by either reduction in specific pollutants or mass removal at least cost. For stormwater measures, costs are generally site specific, which may depend on land cost, availability of funds, and many other factors. The methodology presented in this paper can be further extended by integrating nonpoint source computer models and optimization techniques into the GIS. Within this framework, alternative storm-water management methods can be simulated for specific critical areas in determining the least cost combination of water quality control alternatives.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

AASV = average annual storm volume (m^3/yr);
APL = annual pollutant loadings;
$AREA_i$ = area of catchment i within subbasin j (ha);
ASRF = average storm rainfall;
ASV = average storm runoff volumes;
B_j = estimated annual pollutant loading of subbasin j (kg/yr);
C_i = estimated annual pollutant loading of catchment i (kg/yr);
CF = conversion factor for runoff volume to liters;
COV = coefficient of variation;
EMC = event mean concentration;
G = conversion factor for runoff volume to liters [$m^3 \cdot$ mg/L to kg) $\times 10^{-3}$];
IMP = impervious area (expressed as percentage);
k = land-use type;
M = total number of catchment polygons within subbasin j;
ME = event mean concentration (mg/L);
N = total number of land-use polygons with land-use type k within catchment i;
n = land-use polygon n within catchment i;
RV = runoff coefficient; and
SM = site median EMC (mg/L).